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Effects of various drilling parameters on bone during implantology: An *in vitro* experimental study

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Due to temperature increase during bone drilling, bone necrosis is likely to occur. To minimize bone tissue damage during drilling, a detailed *in vitro* experimental study by using fresh calf cortical bones has been performed with various combined drilling parameters, such as: drilling environment, drill diameter, drill speed, drill force, feed-rate and drill coating. Bone temperatures at the drilling sites were recorded with high accuracy using multi-thermocouples mounted around the tibial diaphyseal cortex. It was shown that temperatures increased with increased drill speeds. It also decreased with a higher feed-rate and drill force. It was also observed that TiBN coated drills caused higher temperatures in the bone than the uncoated drills and the temperatures increased with larger drill diameters. Although the influence of Simulated Body Fluid (SBF) on rising temperatures during drilling was higher for the TiBN coated drills, it was observed that these drills caused more damage to the bone structure. In order to minimize or avoid bone defects and necrosis, orthopaedic surgeons should consider the optimum drilling parameters.

Key words: *orthopaedics, bone drilling, temperature, bone necrosis*

1. Introduction

Drilling of bone is a vital part of the internal and external fixation processes in orthopaedic surgery. Due to the poor conductivity (0.38 ± 23 J/msK) of bone and the difficulty in using a coolant due to the risk of infection around the drilling area, new research is continuing to reduce the drilling temperatures [1], [2]. The heat generated during bone drilling is a complex phenomenon [3], [4]. If thermal insult to bone by drilling is sufficiently high, the resulting thermonecrosis could compromise the fixation and purchase of the threads in the bone [5]. An excessive rise in temperature around a drill site (over 47 °C) will cause thermal necrosis [6]. Although a pilot-hole did not have much effect on temperature, drill force had great influence on temperature increase [7].

The heat generated by friction that occurs during drilling and cutting operations causes tissue necrosis [8], [9]. The temperatures of two fresh-milled surface points and the temperature distribution within the bone were measured [10]. In another work [11], it was noted that the temperatures up to 55 °C were harmless to bone. There was no mention about other effective and optimum parameters. Three different drill tips and the heat generated during drilling were investigated [12] and it was found that drill wear negatively influenced the peak temperatures. The effect of the drill tip geometry on the heat generated within the bone was also studied [13]. In a similar work, the type of drill tips and their performance were also analysed [14]. It was re-

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ported that the applied drill force was an effective parameter in the implantation of bone screws and pins [15]. Histologic damage of bone tissue with commonly used commercial drills was tested and compared to each other [16].

This study presents the effects of various parameters *in vitro* on temperature changes generated during the drilling of cortical bone and shows the level of bone damage via microscopic examination.

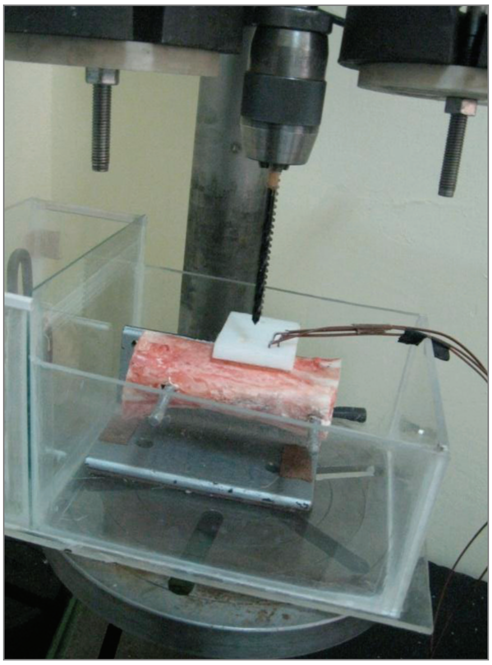
2. Materials and methods

Temperature changes were recorded by a data acquisition card (Advantech). Drill environment (Dry and SBF), five drill speeds (230, 370, 570, 1080 and 1220 rpm), five loads (20, 40, 70, 100 and 140 N) and five drill diameters (1.5, 2.7, 3.2, 4.5 and 6.0 mm) were used. The relevant data are presented in Tables 1, 2 and 3. The experimental parameters were analysed statistically using the Statistica 7.0 program. Drilling temperatures are expressed as the upper limits of $p = 0.05$ and the confidence interval (95% probability). Multiple regression analysis was used to describe the relationship between specific parameters and the increase or decrease of bone temperatures during drilling. Partial correlation in regression analysis was used between drill parameters and their influence on bone temperatures.

2.1. Temperature measurements

T-series thermocouples were used due to their high sensitivity at low temperatures. Three thermocouples were used around each drill site. They were inserted into pilot holes around the drilled holes and were connected to a data acquisition card. The temperatures were recorded from ambient to maximum ones, in both dry and SBF drilling environments (Fig. 1). The temperature of the SBF container was kept constant between 36–38 °C. Recorded maximum temperatures with standard deviations are given in Table 1. The second and fourth columns in this table show the temperatures with respect to various experimental conditions cited in the first and third columns, such as: dry environmental conditions, drill speed (230 rpm), force (40 N) and drill diameter (2.7 mm) given in first line and first column, respectively. The temperatures are given in the same manner for the SBF environment with the same drill parameters in the second line. As shown in Fig. 1c, the thermocouples were inserted in drilled holes with a diameter of 2 mm and 3.5 mm in depth.

a)


b)


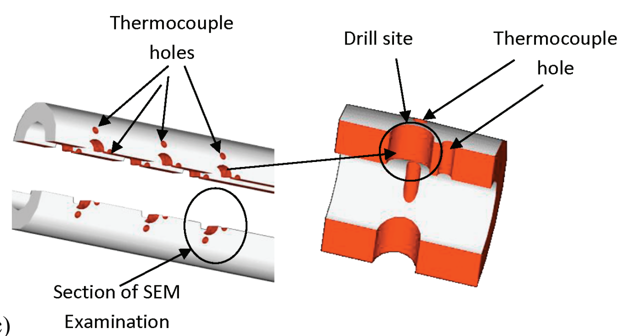
c)


Fig. 1. Bone drilling process set up (a) without SBF (dry), (b) with SBF environment, (c) illustration of thermocouple-drill holes around tibial bone

Table 1. Temperature variation in Dry environment (D) and in SBF environment

Drill configuration	Exp. conditions	Temperature (°C) M ± SD		Drill configuration	Exp. conditions	Temperature (°C) M ± SD	
D-DS1-F2-d2	D230-40-2.7	**60.1**	**± 2.6**	**DS** 3-F2-d4	**570-40-4.5**	72.8	± 2.7
DS1-F2-d2	230-40-2.7	**52.2**	**± 2.7**	D-DS3-F4-d1	**D570-100-1.5**	30.0	± 2.1
D-DS1-F3-d3	D230-70-3.2	**65.3**	**± 2.0**	**DS** 3-F4-d1	**570-100-1.5**	30.0	± 1.1
DS 1-F3-d3	230-70-3.2	**62.0**	**± 2.5**	D-DS4-F5-d2	**D1080-140-2.7**	38.9	± 2.9
D-DSP1-F5-d5	D230-140-6	**38.2**	**± 2.4**	**DS** 4-F5-d2	**1080-140-2.7**	37.2	± 1.8
DS 1-F5-d5	230-140-6	**37.8**	**± 1.8**	D-DS4-F4-d2	**D1080-100-2.7**	53.6	± 2.7
D-DS2-F1-d2	D370-20-2.7	**60.2**	**± 2.4**	**DS** 4-F4-d2	**1080-100-2.7**	41.7	± 1.8
DS 2-F1-d2	370-20-2.7	**58.1**	**± 1.9**	D-DS4-F5-d3	**D1080-140-3.2**	42.5	± 1.8
D-DS2-F3-d4	D370-70-4.5	**47.8**	**± 1.7**	**DS** 4-F5-d3	**1080-140-3.2**	41.3	± 1.5
DS 2-F3-d4	370-70-4.5	**45.5**	**± 1.4**	D-DS5-F2-d1	**D1220-40-1.5**	33.3	± 2.3
D-DS2-F4-d5	D370-100-6	**46.0**	**± 2.0**	**DS** 5-F2-d1	**1220-40-1.5**	31.2	± 1.6
DS 2-F4-d5	370-100-6	**43.8**	**± 1.4**	D-DS5-F3-d2	**D1220-70-2.7**	50.5	± 2.3
D-DS3-F1-d3	D570-20-3.2	**75.1**	**± 2.4**	**DS** 5-F3-d2	**1220-70-2.7**	48.5	± 2.1
DS 3-F1-d3	570-20-3.2	**70.6**	**± 2.1**	D-DS5-F5-d4	**D1220-140-4.5**	86.9	± 2.1
D-DS3-F2-d4	D570-40-4.5	**82.6**	**± 2.7**	**DS** 5-F5-d4	**1220-140-4.5**	45.9	± 1.9

D – dry environment, M – Mean, DS – drill speed, F – drill force, d – drill diameter, SD – standard deviation.

2.2. Materials and drilling

The typical bone samples used were 150 mm in length, and 17 mm in width, and 5 mm in cortical thickness. The orthopaedic drills (AISI 4020) used were: 6 mm × 130 × 50 mm with an 85° tip angle. Drill diameters of 1.5, 2.7, 3.2, and 4.5 mm were used to drill the tibial bones. The drilling was performed on fresh bovine tibias (ELET Ltd., Elazig) for each group. The samples were kept in a deep freezer over night. Drills were classified into two groups, the drills in the first group were standard and uncoated. The second group contained TiBN coated drills. *In vitro* experiments were performed using two year old male and female calf tibias and weighing 80 ± 5 kg each. At least four measurements were performed in each set of experiments. All three thermocouples were nested around the drill holes. A standard distance between the drill site and the thermocouples was 0.5 mm. The distance from the thermocouple holes to the actual drill hole were measured within an accuracy of 10^{-3} mm. As illustrated in Fig. 1a, the fresh bone samples were frozen and the next day they were drilled using a CNC machine (DYNAMYTE 2900). The wear of each drill was not a factor because new drills were replaced after 10 drillings.

2.3. TiBN coating

The second group of drills were TiBN coated at a thickness of 85 μm on average using the PVD method (CFUBMS) and coating conditions of $3 \cdot 10^{-3}$ torr, –70 V, 4 A, 70 min. The drilling was performed with and without an SBF environment and using the standard uncoated, and TiBN coated orthopaedic drills. SEM views of the coated drills are shown in Fig. 2.

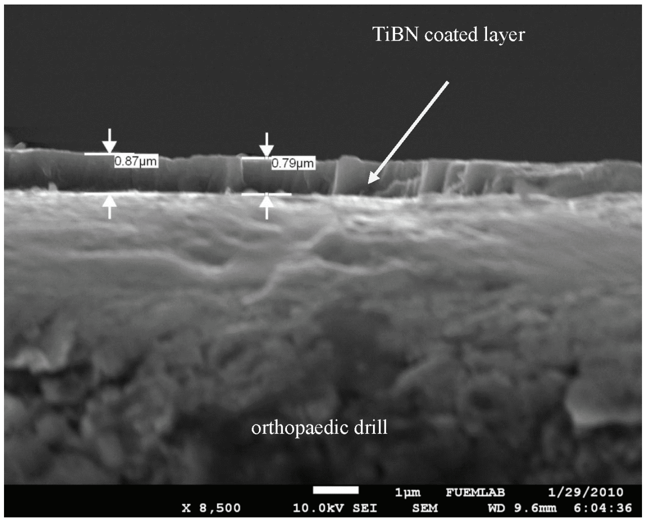


Fig. 2. SEM view of TiBN coated drills (D = 6 mm)

2.4. SEM analysis

SEM analysis was performed in order to evaluate the physical damage caused by various drilling parameters and temperatures. During the analysis, the quality of drilled bone and amount of damage in the drilled holes was observed and the drilled bones were subjected to standard preliminary treatments before the SEM analysis (Figs. 6a and 6b). Sections were taken from the drilled area and the prepared samples were sawn from the drilled holes. They were kept in ethyl alcohol for 30 minutes for the dehydration process. The samples were then cleaned and dried at 120 °C for 12 hours. For better conductivity and resolutions, the bone samples were Au coated for 20 seconds.

3. Results and discussion

Temperatures were measured during the drilling of calve cortical tibias, while changing the drill parameters that were known to influence temperature changes. The most effective parameters and their combined effects coupled with SEM observation were not analysed although the influence of some parameters was considered with limited data from previous studies [17], [19].

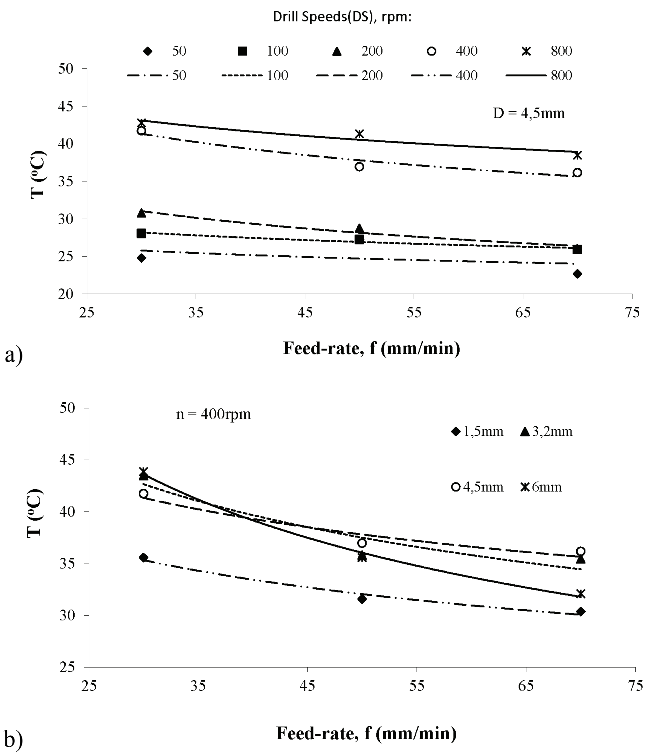


Fig. 3. Effect of feed-rate on drilling temperature
(a) for different drill speeds, (b) for different drill diameters

The influence of the feed-rate on drilling temperatures is given in Figs. 3a and 3b with respect to (a) drill speeds and (b) drill bit diameters. Temperatures decrease with an increased feed-rate and an increase with faster drill speeds using a constant drill diameter (Fig. 3a). Similar results have been reported in [20]. As shown in Fig. 3b, temperatures increase when drill diameters increase and drill speed is kept constant (n = 400 rpm). The length of the shearing distance and friction area increase with bigger drill diameters [12]. Temperatures are directly affected by the frictional forces and are strongly dependent upon the drill speeds. This is responsible for producing high temperatures between the drill and the bone [1].

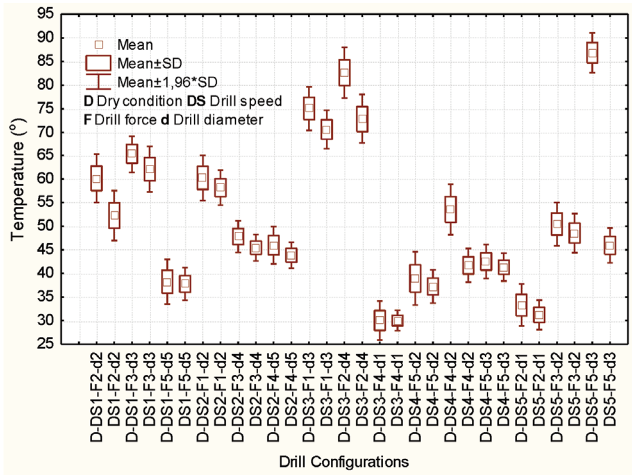


Fig. 4. Box plot for the influence of drill diameter, speed and drill environments on bone temperatures
(related values can be read from Table 1)

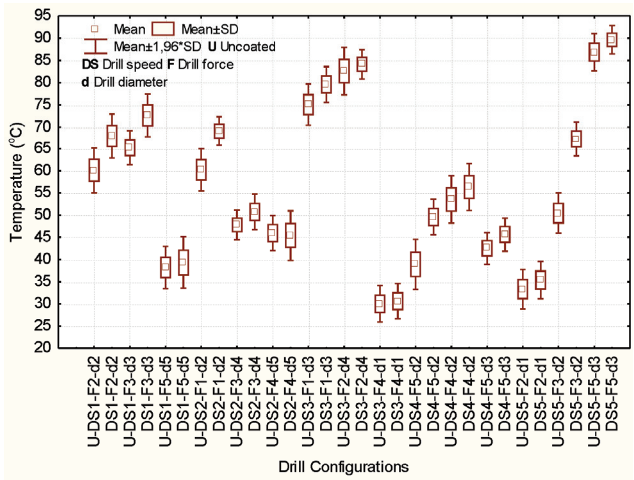


Fig. 5. Box plot for the influence of coated and uncoated drills on bone temperatures
(related values can be read from Table 2)

The recorded temperatures are shown in data compacted box-plots which are given in Figs. 4 and 5. The effects of the drilling environment (with and without SBF) on temperatures are shown in Fig. 4 with the parameters of drill rotation speed (DS), applied drill force (F), and drill diameter (d), respectively. The y-axis shows the recorded temperatures. In the legend in the first line of the *x*-axis the symbols represent: D: Dry conditions (without SBF), DS: drill speeds, *F*: applied drill force, and *d*: drill diameters. The corresponding values of these variables, for example, DS1-F2 and d2 values are given in Table 1 as 230, 40 and 2.7, respectively. Drill parameters in the second line represent the same variables within an SBF drilling environment. Figure 4 shows the influence of the drilling environment (D for dry and the second line for an SBF environment) on temperatures with various drill speeds, drill force and drill diameters at the drilling site. The implant site preparation techniques that are currently in use mostly involve drilling at speeds of 1000 to 1500 rpm [19]. It was reported that in order to prepare potential recipient sites, higher applied drill forces and feed rates reduced drill temperatures, thus decreasing the potential thermal necrosis in and around the drilled holes. The maximum temperature obtained was 87 °C at 1220 rpm, 140 N and a 4.5 mm drill diameter in dry conditions. This result is in agreement with the work conducted on the temperature effect on drill point geometry and rotational speed [24]. The minimum temperature obtained was 30 °C using a drill speed of 570 rpm, a drill force of 100 N and a 1.5 mm drill diameter in a SBF environment. In a related study, two infrared thermometers were used to measure the freshly milled surface temperature at one point. The maximum temperature was extrapolated by a moving plane heat source [3], [8]. Since external irrigation was used in a maxillofacial process previously [17], [21], our current results are not surprising. In a recently published work, internally cooled drills were used in order to minimize the increase in bone temperatures [18]. It was reported that temperatures decreased when using internal cooled drills. As indicated previously [14], due to the difficulty in adjusting fluid flow, the sterilization of surgically removed liquid and external irrigation, this process may be more appropriate in dental processes rather than in orthopaedics. The results obtained with regard to internal irrigation could be interesting for the orthopaedic arena. Providing the optimum drill parameters, body fluid itself may function as a coolant and reduce the drill temperatures. As given in Table 3, the partial correlation coefficients were found to be: $R_{\text{drill force}}$ = 0.56 and $R_{\text{drill diameter}}$ = 0.45. The total correlation coefficients were found to be very low, $R_{\text{drill environment}}$ = 0.23, which indicates that the drilling environment had no significant influence on drill temperatures. The values of P = 0.002 and P = 0.017 (p < 0.05) also indicate that the drill diameter and force are statistically significant parameters affecting bone temperature. Although the tip angle was kep constant in this work, it was reported that the force was reduced with reducing drill tip angle [24]. Throughout the experiments using SBF as a coolant, the temperature trends were similar to those observed in reference [17]. The recorded temperature was 62 °C at 3.2 mm while drilling without using SBF, and 59 °C while using SBF. At D = 4.5, it was 72 °C for dry drilling (without SBF) and when using SBF the maximum temperature was 60 °C. However, by keeping the other parameters constant, the difference in the average temperatures between dry and SBF environments was measured to be only between 5 and 6 °C (Fig. 4) for the particular drill diameters.

Table 2. Temperature variation for the bone drilling by using Uncoated (U) and coated (TiBN) drills

Drill configuration	Exp. conditions	Temperature (°C) M ± SD		Drill configuration	Exp. conditions	Temperature (°C) M ± SD	
U-DS1-F2-d2	U230-40-2.7	**60.1**	**± 2.6**	DS3-F2-d4	**570-40-4.5**	84.1	± 1.7
DS1-F2-d2	230-40-2.7	**67.9**	**± 2.6**	U-DS3-F4-d1	**U570-100-1.5**	30.0	± 2.1
U-DS1-F3-d3	U230-70-3.2	**65.3**	**± 2.0**	DS3-F4-d1	**570-100-1.5**	30.6	± 2.0
DS1-F3-d3	230-70-3.2	**72.6**	**± 2.5**	U-DS4-F5-d2	**U1080-140-2.7**	38.9	± 2.9
U-DS1-F5-d5	U230-140-6	**38.2**	**± 2.4**	DS4-F5-d2	**1080-140-2.7**	49.6	± 2.1
DS1-F5-d5	230-140-6	**39.3**	**± 2.9**	U-DS4-F4-d2	**U1080-100-2.7**	53.6	± 2.7
U-DS2-F1-d2	U370-20-2.7	**60.2**	**± 2.4**	DS4-F4-d2	**1080-100-2.7**	56.3	± 2.7
DS2-F1-d2	370-20-2.7	**69.1**	**± 1.7**	U-DS4-F5-d3	**U1080-140-3.2**	42.5	± 1.8
U-DS2-F3-d4	U370-70-4.5	**47.8**	**± 1.7**	DS4-F5-d3	**1080-140-3.2**	45.6	± 1.9
DS2-F3-d4	370-70-4.5	**50.7**	**± 2.1**	U-DS5-F2-d1	**U1220-40-1.5**	33.3	± 2.3
U-DS2-F4-d5	U370-100-6	**46.0**	**± 2.0**	DS5-F2-d1	**1220-40-1.5**	35.4	± 2.1
DS2-F4-d5	370-100-6	**45.4**	**± 2.8**	U-DS5-F3-d2	**U1220-70-2.7**	50.5	± 2.3
U-DS3-F1-d3	U570-20-3.2	**75.1**	**± 2.4**	DS5-F3-d2	**1220-70-2.7**	67.3	± 2.0
DS3-F1-d3	570-20-3.2	**79.6**	**± 2.0**	U-DS5-F5-d4	**U1220-140-4.5**	86.9	±2.1
U-DS3-F2-d4	U570-40-4.5	**82.6**	**± 2.7**	DS5-F5-d4	**1220-140-4.5**	89.6	±1.6

U Uncoated drill, M Mean, DS drill speed, F drill force, d drill diameter, SD Standard deviation.

Table 3. Multiple regression and correlation analysis for various drill parameters

Parameter	Partial correlation	P value
Drill speed	0.1890	0.3450
Drill force	0.5653	0.0021
Drill coating	0.1650	0.4106
Drill environment	0.2349	0.2380
Drill diameter	0.4550	0.0170
Correlation	$R = 0.6152$	0.0149

To show the drill coating effects in heat generation during bone drilling, the TiBN coated drills were used and the temperatures were compared to those recorded with the uncoated drills. Figure 5 represents a box-plot showing the effect of drill coating (TiBN) on temperature change with respect to the same variables as given in Fig. 4. The first line of the x-axis in Fig. 5 represents the variables for the uncoated (U) drills and second line represents the variables with the TiBN coated drills. Related data for these box-plots are presented in Tables 1 and 2. In the legend under the drill configuration, "D" represents the dry drilling environment; "DS." drill speeds, "F" drill force and "d" drill diameters. The legends under the experimental conditions show, for example, in the first line: D230-40-2.7 which corresponds to drilling that was undertaken in a dry environment (D) using the drill parameters of 230 rpm, 40 N and 2.7 mm drill diameter. The second line represents drilling performed with SBF using the same parameters. The rest of the tables and the box-plots can be read in the same way.

To show the effects of drill bit coating on the temperature, the TiBN coated drills were used for dry and SBF environments. As seen in Fig. 5, the coated drills showed a higher temperature than the uncoated ones. It was thought that the roughness of the surfaces (26 µm) was responsible for this result. The coating has no significant statistical effect on the temperature variation, with $R_{coating}$ being 0.16 (Table 3). As shown in Fig. 6, the maximum temperature was 90 °C for the TiBN coated drill parameters with the drilling conditions of 1220 rpm, 140 N, and 4.5 mm drill diameter. The minimum temperature recorded was 30 °C at 570 rpm, 100 N and a 1.5 mm drill diameter. Using coated drills, the temperatures were slightly higher (71 °C) than temperatures obtained from the uncoated drills. For example, 69 °C for a 4.5 mm diameter drill. The temperatures decreased for a 6 mm diameter drill. This may be because of the roughness of the cutting surface edges measured in the drill holes that increased from 0.12 µm to 0.26 µm due to the TiBN coating. The reason is probably that the larger diameter drills cutting more chips cause more heat to transfer away from the region and so produce lower temperatures [12], [22]. Due to the fact that the coated drills were reported to be more eroded [23], our results show that the coating of drills has no advantage in reducing the drilling temperatures or increases the bone quality at the drill sites. This can also be seen from the correlation coefficients given in Table 3, where $R_{drill\ force} = 0.49$ and $R_{drill\ diameter} = 0.42$. The p values of these coefficients are $p = 0.0085$ and $p = 0.0263$ ($p < 0.05$), respectively. These are the indications of the statistical significance of the drill diameters and drill forces on bone temperatures.

a)

b)

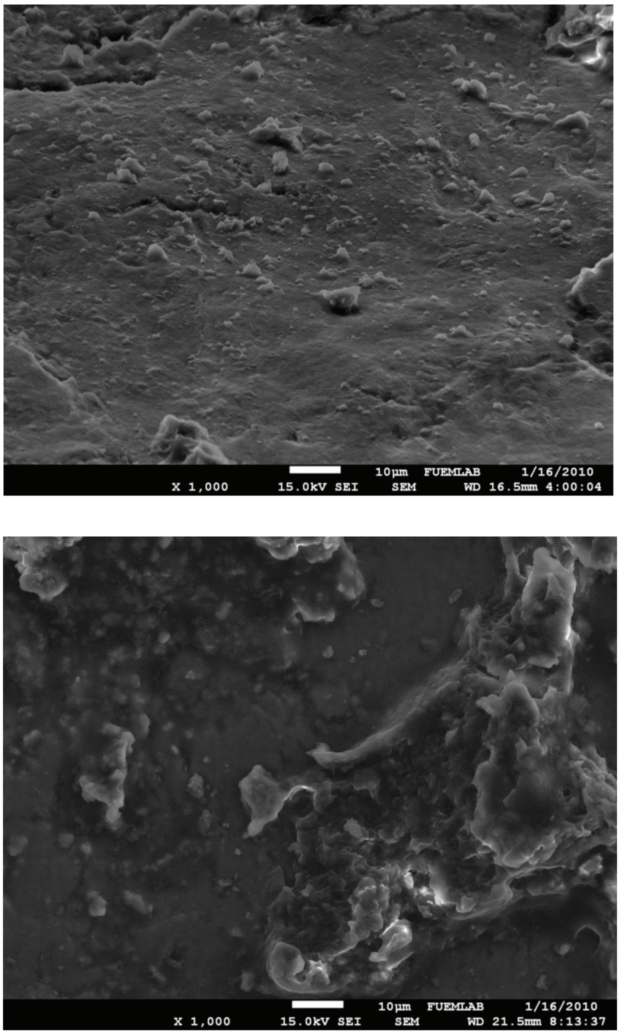


Fig. 6. SEM views of drill hole surfaces: (a) for drill parameters D = 4.5 mm, F = 140 N, n = 230 rpm, (T_{max} = 38 °C), (b) for drill parameters D = 4.5 mm, F = 140 N, n = 1220 rpm, in dry condition, (T_{max} = 87 °C)

Tables 1 and 2 show the measured temperatures with standard deviations (in the third and sixth columns) with respect to various experimental conditions (in the first and third columns); such as uncoated (U), drill speed (230 rpm), force (40 N) and a drill diameter of 2.7 mm are given in the first line and first column, respectively. The temperatures are also given in the same manner for the TiBN coated drills with the same drill parameters in the second line. Multiple regression and correlation analysis for the various drill parameters has been conducted and the calculated data are presented in Table 3. Drill temperatures are expressed as "Confidence Interval", $p = 0.05$ (95% probability). Multiple regression analysis was used to describe the strength of the relationship between specific parameters and an increase or decrease of drill temperatures.

SEM analysis was performed to show the structure of drill hole zones for various rotational drill speeds, for example: 230 and 1220 rpm (Fig. 6a and 6b). Such analysis showed some surface damage of drilled holes with different drilling parameters (Figs. 6a and 6b). The hole surfaces with the drill parameters of: D = 4.5 mm, $F = 140$ N, $n = 230$ rpm (Fig. 6a) produced a maximum temperature of 38 °C. The bone samples which were drilled with the drill parameters of D = 4.5 mm, $F = 140$ N, $n = 1220$ rpm, produced a maximum temperature of 87 °C (Fig. 6b). These results are in agreement with those of reference [19], in which it was stated that high drill forces may effectively reduce the thermal necrosis in the cortical bone. As can be seen in Fig. 6b, the drilled hole surface appears to be more damaged when exposed to higher temperatures. Temperatures have been found to be very close for both samples of uncoated (57 °C) and coated drills (59 °C). Comparing Figs. 6a and 6b, more damage appears to be at the drill site than for the sample drilled by the coated drills.

It follows from these results that assessing the impact alone, and considering only one parameter may not be appropriate, the results should be taken into consideration as a whole. The relative influence and relationship between the drilling parameters and the temperature depending upon each parameter should be evaluated in more detail.

4. Conclusions

The effects of various parameters during drilling have been investigated in detail and the following observations were made:

a) The drilling environment had no significant effect ($p > 0.05$) on temperature when fresh bone was used.

b) The larger the drill diameter, the higher the bone temperature and this applies to various drill parameters.

c) In order to avoid thermal bone necrosis, high drill forces and feed rates could effectively reduce the drilling temperature in the neighboring cortical bone.

d) It was shown that drill temperatures increased with increased drill diameters up to 4.5 mm and then decreased at 6 mm.

e) The influence of SBF on the maximum temperatures during drilling was higher for the TiBN coated drills, however, coated drills such as TiBN caused more bone damage during drilling and did not reduce the bone temperature.

In order to minimize the bone damage and necrosis, orthopaedic surgeons should consider the influence and relationship between the drilling parameters and choose optimum parameters for their specific clinical case and situations.

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