EXPERIMENTAL STUDY

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Effects of bone drilling on local temperature and bone regeneration: an in vivo study

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Objective: The aim of this study was to examine the influence of bone drilling on local bone temperature and bone regeneration and determine optimal drilling speed and pressure in an animal model.

Methods: The study included 12 skeletally mature New Zealand white rabbits, weighing between 2.8 to 3.2 kg. Rabbits were divided into 2 groups and euthanized at the end of Day 21 (Group A) and Day 42 (Group B). The same drilling protocol was used in both groups. Three drill holes with different pressure (5, 10 and 20 N) were made in each rabbit tibias using 3 different rotational drill speeds (230, 370 and 570 rpm). During drilling, local temperature was recorded. Rabbit tibia underwent histopathological exam for bone regeneration.

Results: Bone temperature was affected by drilling time and depth. Lower drill speeds reduced the bone temperature and revealed better bone regeneration when compared to the drilled bones at higher drill speeds. Titanium boron nitride coating on the drill bits had no significant effects on bone temperature and structure. Bone regeneration was superior in Group B rabbits that had drilling at 230 rpm and 20 N.

Conclusion: Our results suggested that lower drilling speed with higher pressure is necessary for better bone regeneration. The optimal drilling speed is 230 rpm and optimal drilling pressure 20 N.

Key words: Bone healing; bone regeneration; drilling; histopathology.

Keeping bone damage and necrosis within the minimum levels is extremely important during implant surgery. In this context, the effects of the heat generated during drilling on bone should be meticulously analyzed to minimize the risk of thermo-necrosis and to promote proper bone regeneration.[1,2] Although various studies have addressed the influence of drilling in bones, the literature still lacks information about the relations between effective drilling parameters and histopathology of bone regeneration.[3-5] It was reported that, in some instances, bone regeneration involves endochondral ossification, and cortical bone regeneration occurs secondarily as a slow and complex process.[6] However, no study showing bone regeneration *in vivo* after drilling operation has been performed. In order to identify pertinent models for bone regeneration after drilling operations, we compared bone qualities using various drilling parameters at a constant drill diameter and drilling environment.

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Table 1. Drilling parameters used during the experiments.

	Drill type																	
	Uncoated									TiBN-coated								
Drill speed (rpm)	230			370			570			230			370			570		
Drill Force (N)	20	10	5	20	10	5	20	10	5	20	10	5	20	10	5	20	10	5
Experiment No. Based on Groups																		
Day 21	A1-1	A1-2	A1-3	A2-1	A2-2	A2-3	A3-1	A3-2	A3-3	A4-1	A4-2	A4-3	A5-1	A5-2	A5-3	A6-1	A6-2	A6-3
Day 42	B1-1	B1-2	B1-3	B2-1	B2-2	B2-3	B3-1	B3-2	B3-3	B4-1	B4-2	B4-3	B5-1	B5-2	B5-3	B6-1	B6-2	B6-3

The aim of this *in vivo* study was to examine the influence of drill force, drill speed, drilling depth, times and drill types on bone structure and regeneration in an animal model.

Materials and methods

The study was approved by the Animal Ethics Committee of Firat University (2010/7 Ethical No: 30). The study included 12 skeletally mature New Zealand white rabbits weighing between 2.8 and 3.2 kg. Animals were housed in individual acclimatized cages and standardized conditions for 10 days. Food and water were made available ad libitum to all animals.

All operations were performed under semi-aseptic conditions in the lab of Technology Faculty of Firat University. Rabbits were anaesthetized with intramuscular dose of 45 mg/kg ketamine (Ketasol 10%; Interhas, Ankara, Turkey) and 5 mg/kg xylazine HCl (Rompun 2%; Bayer, Istanbul, Turkey). The right tibia was shaved and the cutaneous surface was disinfected with a povidone-iodine solution prior to surgery. After longitudinal skin incision of 3 cm was made over the tibia, a periosteal flap was elevated and the medial surface of the proximal metaphysis of the tibia was exposed. The skin was sutured with 2/0 absorbable sutures. Intramuscular 20 mg/kg cefazolin sodium (Cefamezin 500 mg; Eczacıbaşı, Istanbul, Turkey) and 3 mg/kg ketoprofen (Profenid 100 mg; Eczacıbaşı, Istanbul, Turkey) were administered for 3 days postoperatively. Sutures were removed on Day 10.

Rabbits were divided into two groups of 6 rabbits. Rabbits were sacrificed at 21 days in Group A and at 42 days in Group B using CO_2 and drilling operations were performed. Three drill holes with different pressure (5, 10 and 20 N) were made in each rabbit tibias using 3 different rotational drill speeds (230, 370 and 570 rpm) (Table 1).

A modified drilling machine (Fig. 1a) was used in all rabbits. Standard surgical drills (AISI 4020) with a total length of 130 mm, cutting length of 50 mm and helical angle of 15° were used. The full vertical drilling distance in cortical bone tibiae was nearly 5 mm. Three thermocouples (T-type, Cu-Const. 0.2 mm dia. Teflon-insulated ELIMKO) were embedded at 3 mm depth of the cortical bone while measuring the temperature during drillings (Fig. 1b). The distance to the center of the drilled hole was 0.5 mm.

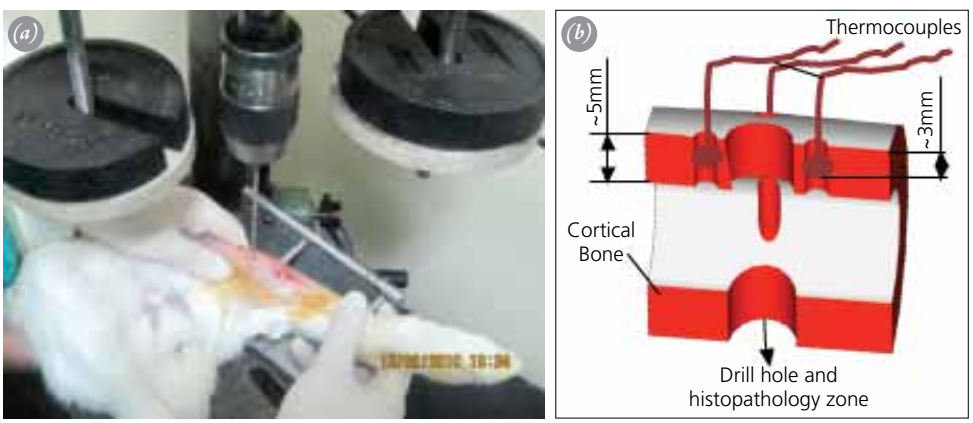

Fig. 1. **(a)** A view of in vivo drilling process. **(b)** Histopathology section of the drill hole, thermocouple locations and drilling depths. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

In the first group, standard, uncoated drills (TIPMED, Izmir, Turkey) with a diameter of 2.7 mm were used. In the second group, standard drills of the same diameter with a titanium boron nitride (TiBN) coating of a thickness of 85 μm were used. The PVD (Physical Vapor Deposition) method was used at coating conditions of 3.10-3 mmHg, -70V, 4A, 70 min in the Laboratory of Surface Technologies (Ataturk University).

Three holes were drilled in the right tibias from the proximal to distal of each rabbit via different drill speeds and times. Right legs of the rabbit tibias were used for drilling operations. Drilling speeds of 230, 370 and 570 rpm were used at 5, 10 and 20 N drilling forces. The first hole on the tibiae was drilled at 20 N drill force, the second at 10 N and the third hole at 5 N using a 230 rpm drill speed. Drill speed was adjusted to 370 rpm and then 570 rpm and drilling was repeated on a second and then a third rabbit accordingly for the same drilling forces (5, 10 and 20 N).

Group A and B bone samples were kept in 10% formalin solution for a minimum of 48 hours in separate glass containers. Samples were washed with tap water and soaked in a graded series of 50 , 60, 70, 80 and 90% ethanol for 30 minutes, and then in 95 and 99.8% ethanol for one hour. Samples were then held in a solution of 99.8% ethanol and xylene at a 1:1 ratio for 30 minutes, before being embedded in paraffin and held at 60°C for one hour to make paraffin blocks. Transverse sections (5 μm) were taken from the blocks and prepared for histochemical and immunohistochemical staining. Hematoxylin-eosin (H&E) staining for histological observation and solochrome cyanine staining for demonstration of myelin were used. Sections were stained with solochrome cyanine solution (Eriochrome cyanine RC, Sigma E-2502; Sigma-Aldrich Corp., St. Louis, MO, USA) for 15 minutes. After washing with tap water, they were incubated in iron-alum solution (ammonium iron [III] sulfate dodecahydrate, Merck A993675; Merck KGaA, Darmstadt, Germany) for 10 minutes followed dehydrating with ethanol and mounting in Entellan® (Merck Millipore Corp., Billerica, MA, USA). The prepared samples were analyzed by a pathologist in blind manner by using a BX40 light microscope (Olympus Corp., Tokyo, Japan). In the histograms, the damaged or necrotic zone at the drill site was evaluated for different drilling parameters by considering the volume of the fibrosis tissue and regeneration cells.

The influences of drilling parameters on drilling temperature and therefore on regeneration of newly formed bone tissue during 21 and 42 days of *in vivo* survival times were evaluated.

Table 2. Multiple regression analysis for various drill speeds.

Parameter	Partial correlation	p
230 rpm	0.8176	0.0016
370 rpm	0.9285	0.0001
570 rpm	0.5650	0.0180
Correlation	0.99	0.0044

Multiple regression analysis was used to describe the relationship between drill speed and drill temperature. Partial correlation in regression analysis was used for the determination of the correlation for the drill speed while influencing the temperature. Statistical significance was set at $p<0.05$.

Results

Temperature during drilling increased with increasing drill speed (Fig. 2). Peak temperature of 50°C was reached at 12 seconds and 2 mm of drilling depth at 230 rpm. At 370 rpm, peak temperature of 75°C was obtained at 23 seconds and 3.5 mm of drilling depth. These results suggest that higher drill speeds cause high peak temperature and hence increase the risk of necrotic bone tissue. The effect of drill speed on drill temperature was evaluated statistically in Table 2. There was a significant relationship between drill speeds and drill temperatures. Partial correlations were determined from the multiple regression analysis as; R(230rpm)part=0.81, R(370rpm)part=0.92 and R(570rpm)part=0.56 (Table 2). Although all three drill speeds had a positive effect on drill temperature, the 370 rpm drill speed had maximum effect on the temperature elevation.

Drilling force affected temperature as drilling time and thickness was varied as drilling progress perpen-

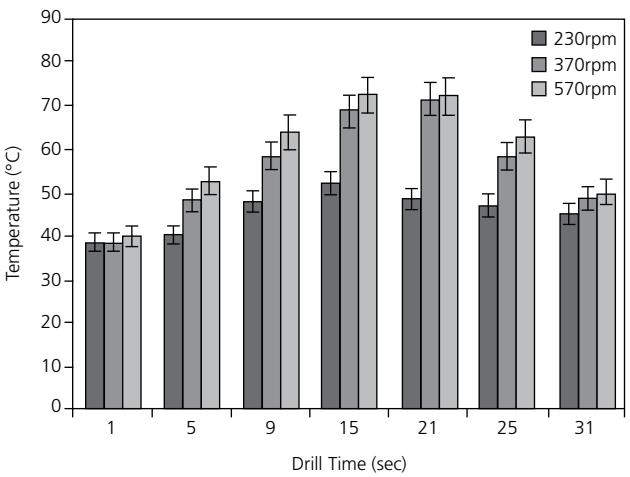

Fig. 2. Variation of temperature with drilling time and drill speed (230, 370, 570 rpm) at 40 N drill force.

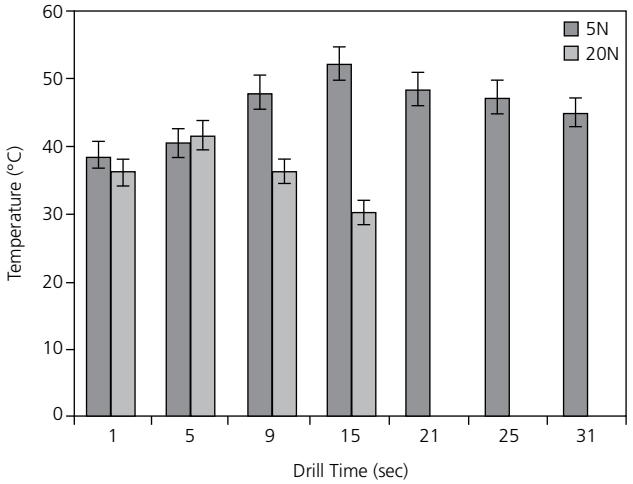

Fig. 3. Temperature variation with drilling time for different drill forces (5N-20N at 230 rpm).

dicularly into the bone. The temperature reached a peak value in 5 seconds at 20 N drill force, whereas the peak value was reached at 15 seconds when 5 N force was used (Fig. 3). The drilling feed-rate in the cortical bone was 0.5 mm/sec at 20 N, and such feed-rate was nearly three times higher than that of the samples drilled under 5 N of force. The drill bit reached a depth of 3.5 mm and produced a maximum temperature (58°C) in 5 seconds at 20 N, whereas to achieve the same depth within the bone took about 15 seconds at 5 N. Thus, drilling time is almost reduced by 2/3 when 20 N drill force is used.

Figure 2 shows variation of the temperature with drilling time and drill speed (230, 370, 570 rpm) at 40 N drill force and Figure 3 variation of the temperature for different drill forces for the same drilling time (31 seconds) at 230 rpm. Drilling feed-rate was 0.16 mm/sec during experiments at 5 N drill force. As the drilling was completed in 15 seconds at 20 N force, columns for drilling at 20 N force after 15 seconds do not exist in

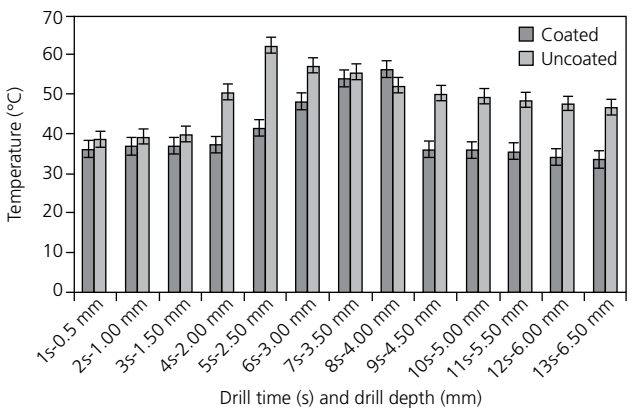

Fig. 4. Temperature variation with drilling time for coated and uncoated drill bits (230 rpm and 20 N).

Figure 3. The influence of drill bit coating with respect to drilling time and depth at 20 N drill force and 230 rpm drill speed is shown in Figure 4 for coated and uncoated drill bits. As shown in Figure 4, peak temperature was 62°C at 2.1 mm depth for 5 seconds drilling time for TiBN-coated drills. Peak temperature was 56°C for the uncoated drill at 4 mm depth and 8 seconds drilling time.

Figures 5a and 5b show the histograms of the sample drilled at 230 rpm and 20 N and 5 N drilling configurations with 21 days survival time. Figure 6 shows the histogram of the sample drilled at 570 rpm and 20 N with 21 days survival time. From the comparison of Fig. 5a and Fig. 6, there were considerable differences in terms of tissues and cell modeling. Although primary bone remodeling was observed at 570 rpm and 20 N with 21 days survival time, bone remodeling was rather completed at 230 rpm and 20 N and 5 N drilling configurations with 21 days survival time.

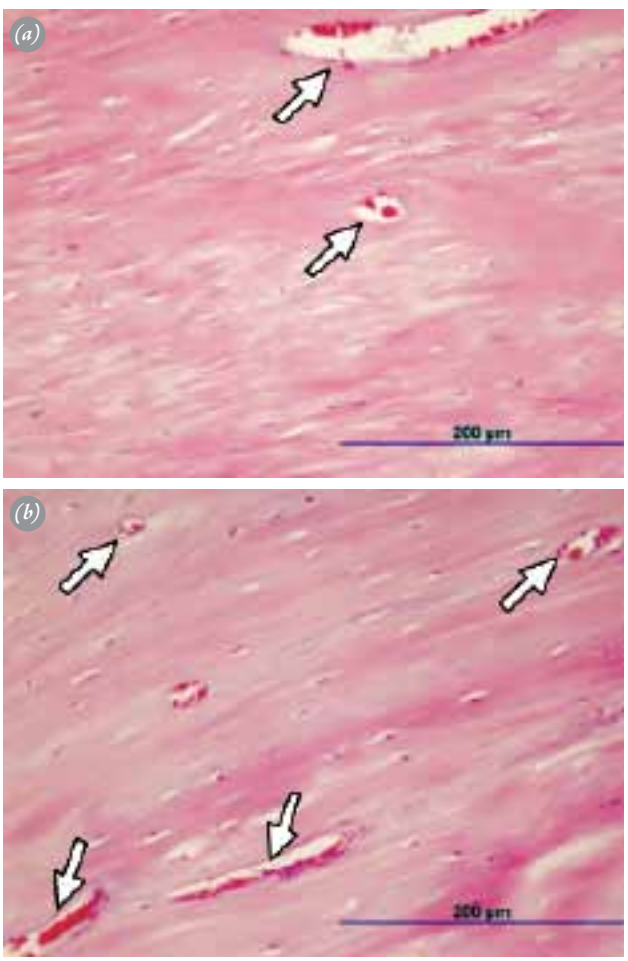

Fig. 5. Histograms of the drilled samples at the end of 21 days of survival times at **(a)** 230 rpm and 20 N and **(b)** 230 rpm and 5 N with uncoated bits (arrows showing cortical bone proliferations). [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

Discussion

Various studies have been performed to discern the relationship between drilling conditions and bone damage. With bone temperatures above 47°C, the osteocytes begin to undergo necrosis.[7] Sugita et al. calculated the temperature distribution inside bone using a semi-infinite linear model and thermographic measurements.[8] The fresh-milled bone surface temperature was measured using two infrared thermometers.[9] Augustin et al. evaluated the influence of different drill parameters on the increase of bone temperature.[10] Tu et al. used an elastic-plastic dynamic finite element model to simulate the bone drilling process.[11] The effect of thermal energy due to drilling around the facial nerve canal was evaluated on the facial nerve in a guinea pig model.[12] A robot-assisted procedure was developed to prepare for tibial drilling during total knee arthroplasty.[13] Bachus et al. reported the differences in applied drilling forces effecting the bone temperature of cortical tissue near the drilling site in an *in vitro* study.[14] Sharawy et al. measured the heat generated from three drilling speeds and reported that drilling speed also directly correlated to drilling time.[15]

It has been reported that the threshold level for bone survival during implant site preparation was only possible by keeping the drilling time below 1 min.[1] As the cortical bone thickness of rabbit tibias was approximately between 1 and 1.3 mm, the drilling time of such operations was too short. During the current drilling operations, shorter drilling times were achieved by increasing the drilling force. Thus, drilling operation times were kept well below 1 min and the drilling processes were kept in regeneration limits of the bone remodeling.[1] However, extremely high drill force applications may cause undesired bone fractures.

In order to show the effect of drill bit coating, TiBN-coated drill bits were used. The coated and uncoated drill bits were compared in the same drilling process with respect to drilling time and depth. Although the coated drills reached peak temperature at 5 seconds and 8 seconds for uncoated ones, the coated drills caused a slightly higher drill temperature than the uncoated ones (Fig. 4). As a result of these minor differences in temperature, there was no significant difference in the histopathologic evaluation. In the present study, temperature increase was considerably reduced with increased drill force, whereas in other studies with similar results, temperatures rose with increasing drill speeds.[16,17]

Histopathologic examinations were performed to determine the effect of drill parameters on bone morphology and structure. As drilling force has been reported to be the statistically significant parameter in bone drilling,[10,18] some structural differences in the bone are detected among the applied drill forces. No marginal tissue or cell differences between the samples drilled at 20 N and 5 N at 230 rpm were detected. The severity and distribution of fibrous connective tissue formation at 370 and 570 rpm can be directly related to the higher drill speeds and the lowest applied force of 5 N.

Figure 7 shows the histogram of newly generated bone tissues drilled by the TiBN coated drill bits at 21 days of survival times. Newly formed fibrous connective tissue exhibited rich fibroblasts and capillary blood vessels. The amount of connective tissue formation was

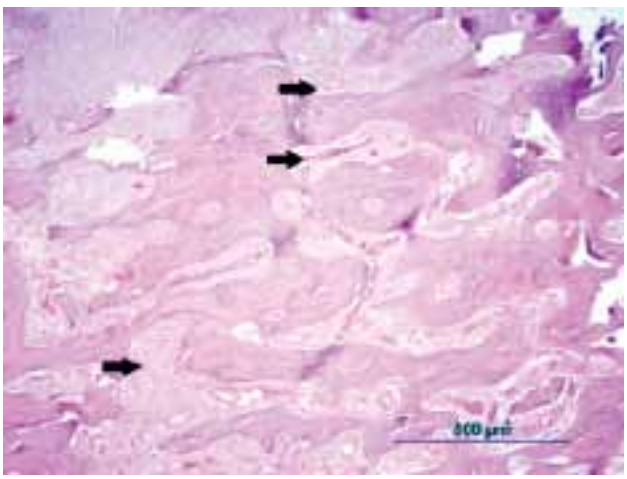

Fig. 6. Fibrous connective tissue proliferation (arrows) and newly formed bone at 21 days of survival time (570 rpm, 20 N, uncoated bit). [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

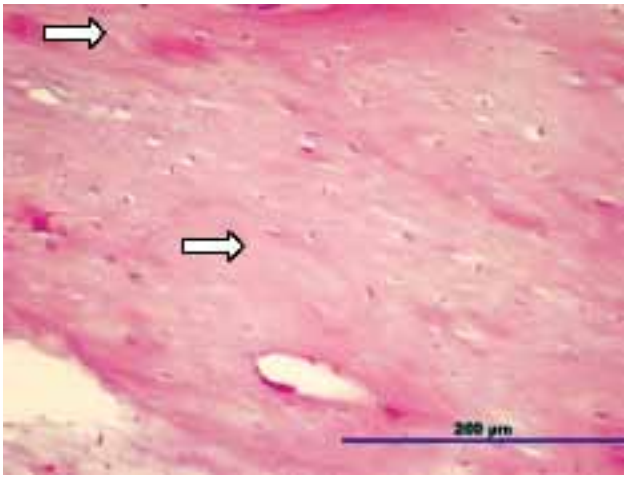

Fig. 7. Cortical bone tissue generated for TiBN-coated sample at 21 days of survival time (230 rpm, 20 N). [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

greatest when the drilling was performed with TiBN-coated bits at 230 rpm with a force of 20 N at Day 21 (A4-1 group) in which the fibrous connective tissue was almost equal to the bone tissue (Table 1). Although it has been reported that the ceramic drilling tools exhibited heat elevation compared to standard medical stainless steel,[19] in our study, the TiBN coating had no significant effect on temperature and or bone regeneration. Peak temperature was a bit higher (5°C) for the uncoated drill (Fig. 4). Due to the high possibility of necrotic risk above 47°C,[1,18] the obtained peak temperatures reached during *in vivo* experiments (56°C and 62°C) are a potential necrotic risk for the bone. However, both were still at 12-14 seconds, well below the critical thereshold of 1 minute (Fig. 2). Higher drilling forces reduced the drilling time and decreased the heat affected time. There were no significant structural differences between the coated (Fig. 7) and uncoated (Fig. 5a) drill bits and these two figures were similar. Bone tissue remodelling was nearly completed and the normal bone tissue appeared within the cortical bone structure.

The newly formed bone was remodeled into compact cortical bone after 42 days after surgery (Fig. 8). At the end of the 42nd day, completely normal (cortical) bone tissue was generated in B1 groups where drilling was made at 230 rpm with uncoated bits (Table 1). In B2 and B3 groups, where drilling was performed with uncoated bits on Day 42 at 370 and 570 rpm, respectively, the only lesion detected was the remodeling characterized by new bone formation (Table 1). At the end of the 42nd day, a well-remodeled bone tissue structure generation was obtained for the sample (B1-1) drilled with the minimum drilling speed of 230 rpm and maximum drill force of 20 N (Fig. 8). With the same drilling parameters at the end of 21 days, well-regenerated bone tissue also appeared (Fig. 5a). Bone healing of drilled holes at the minimum drilling speed and maximum force in both survival times (21 and 42 days) resulted in intramembranaous bone formation.

When 230 rpm drill speed (min. drill speed) and 20 N drill force (max. drill force) are used, bone tissue completed remodelling in 21 days (Fig. 5a). On the other hand, with a 570 rpm drill speed and 20 N drill force, bone tissue were rather affected by temperature elevation. An uncompleted bone tissue occurred at the end of 21 days at 570 rpm and 20 N (Fig. 6). Moreover, at the end of the 42nd day, bone tissue regeneration was fully completed (Fig. 8). However, in the sample drilled at 570 rpm and 5 N (Group B6-3), bone remodelling was not fully completed at the 42nd day (Fig. 9). Therefore, it can be concluded that drilling at 230 rpm and 20 N at 42 days is the optimal configuration in terms of fully completed bone regeneration.

Histology examinations of the drilled zones revealed the presence of fibrous tissue within the cortical bone. However, the amount of cortical bone formed within 21 days of the drilled holes appeared to be less than at 42 days. At the 21st day, fibrous connective tissue proliferation and newly formed bone tissue were detected in the higher drill speed (A2 and A3) groups. Fibrous tissue and remodelling were detected in the lower drill speed group (A1). The lowest drill speed (230 rpm) with the highest force (20 N) resulted in the best bone regeneration.

In conclusion, bone temperature is affected by drill-

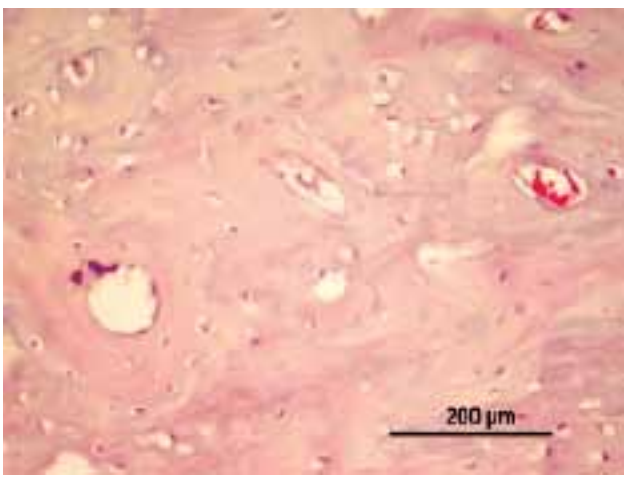

Fig. 8. Normally generated (cortical) bone tissue at the end of 42 days of survival time (230 rpm, 20 N, uncoated bit). [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

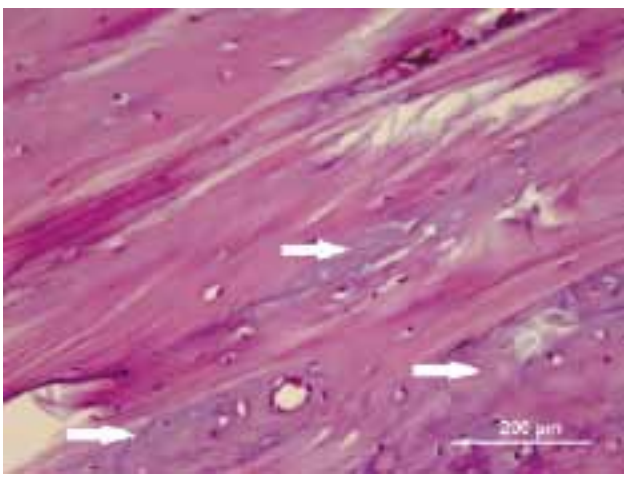

Fig. 9. Incomplete bone remodeling (arrows), at the end of 42 days of survival time (570 rpm, 5 N, coated bit). [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

ing time and depth. Lower drill speeds reduced bone temperature and revealed better bone regeneration when compared to the drilled bones at higher drill speeds. TiBN coating had no significant effects on bone temperature and structure. Drilling at 230 rpm and 20 N for 42 days of survival time provided better bone regeneration. The main structure was fibrous tissue after 21 days and normal cortical bone tissue after 42 days following the drilling or survival period.

Conflicts of Interest: No conflicts declared.

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