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RESEARCH ARTICLE

Structural and Histopathologic Changes of Calf Tibial Bones Subjected to Various Drilling Processes

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Summary

Bone tissue damages such as fractures, bone tissue losses, osteolysis and necrosis caused by temperature are the serious clinical concerns in orthopaedics. In order to show the effect of heat generation in bone drilling, temperatures were recorded and analysed for various drill speed, diameter, drilling force and bone densities on fresh calf tibial bones. This study revealed that high drill speeds increase the maximum temperature of the bone while high diameters and drill forces cause a decrease in the drilling temperature. SEM and histopathologic evaluations showed that high values of drill diameter and bone density caused greater damage to the bone and lowered the drill quality around the drilled site by producing rough surfaces and higher loss of osteocytes.

Keywords: *Orthopaedics, Bone drilling, Heat, SEM, Histopathology*

Çeşitli Delme İşlemlerine Tabii Tutulan Sığır Tibia Kemiklerinin Yapısal ve Histopatolojik Değişimleri

Özet

Kırık, kemik kayıpları, sıcaklığın neden olduğu osteoliz, nekroz gibi kemik dokusu hasarları ortopedide ciddi klinik sorunlardandır. Bu çalışmada, kemik delme işlemlerinde meydana gelen ısının kemiğe etkisini göstermek için taze sığır tibiaları kullanılarak farklı matkap devir sayıları, delme kuvveti ve kemik densiteleri için ortaya çıkan sıcaklıklar ölçülmüş ve analiz edilmiştir. Maksimum devir sayısı ve matkap çapında maksimum delme sıcaklığı elde edilirken artan drill kuvveti ile sıcaklığın düştüğü belirlenmiştir. SEM ve histopatolojik incelemeler; büyük matkap çapı ve yüksek kemik densitesinin kemik dokuda daha fazla osteosit kaybına yol açtığı ve kemiğe daha fazla hasar vererek delik bölgesinde kemik kalitesinin düşmesine sebep olduğunu gösterdi.

Anahtar sözcükler: *Ortopedi, Kemik delme işlemi, Isı, SEM, Histopatoloji*

INTRODUCTION

During orthopaedic operations, drilling is the common process and heat generated in bone is inevitable [1]. The heat is a serious clinical concern because of its potential to cause bone damage and bad osseointegration in the implantation processes. The bone consists of organic and inorganic structures which are affected by the temperature rise during drilling, and therefore the bone is likely to be damaged at temperatures higher than 47°C [2]. Such damages occur at the drilling site or within an explanted sample for transplantation. They may result in some complications such as the loss of an implant and aseptic necrosis [3]. Although the mechanical damage of the bone edges at the drill site alone is considered as a minor problem, the quality of bone tissue specimens is essential for the further progress of bone operations [4].

Thermal damages in drilling processes and bone implantation were studied and it was reported that the applied drill force has increased the temperature considerably [5]. The effect of the applied drill force in the generation of heat during the drilling operations of bone screw and pin assemblies was investigated [6]. In a similar

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study, it was reported that the temperature decreased with decreasing drill speed [7]. Sharpness of the dental cutter and the maximum cutting life was determined for various drill speeds [8]. Temperatures were compared at continuous drilling operations, and as expected, the tool wear was to increase the amount of heat [9].

Histology of the tissue damage for different drills used in orthopaedic surgery was examined [10] and it was found that the maximum damage to tissues was caused by the cutter that removes the largest chips from the operational site. To investigate the microstructural changes in bone, Rogers and Daniels [11] examined the bone tissue by subjecting the bones to high temperatures. Surface temperature of cutting tool was measured by the thermographic method and a numerical model was built to show the effects of heat on the bone tissue in artificial joint surgery [12]. In a parallel work, the thermal conductivity measurements were executed on calf femurs at the middle diaphysial [13]. Hamade *et al.*[14] derived various equations for the experimental cutting speed and pressure by using parameters such as drill speed, feed rate and cutting forces as the input parameters.

A number of work in the literature indicated that the drill parameters influence the heat generation in bone drilling [15-17]. If the related studies are examined, it can be seen that researchers generally focused on few drill parameters without considering structural change of bone, due to the complexity of orthogonal heat mechanism. In this study, important parameters which increased the temperature causing possible damage in bovine tibial bone were evaluated in detail. The specimens of a sacrificed tibial bone and temperature affected zones were investigated throughout the SEM and histopathologic analysis.

MATERIAL and METHODS

The use of fresh animal samples or human cadaver bones for the evaluation of the drilling process and subsequent histological examinations, are the adopted standard procedures [18,19]. The animal tibias were provided freshly and randomly choosen from a local slaughterhouse company (ELET Ltd, Elazig) as male and female calf tibias, at 2 years of age and weighing 216±30 kg for each group. Drillings have been performed in air using standard orthopaedic drills (AISI 4020) having the diameters of Æ1.5, 2.7, 3.2, 4.5 and 6 mm with an 85° tip angle. During *in vitro* experiments, temperatures were measured continuously with the use of the T-type thermocouples in the tibial bones. Drill forces (F) of 20 N and 70 N were applied throughout the drilling procedures, using a drilling rig for various speeds (n) between 230 and 1220 rpm. All drills were used no more than 15 times before being replaced with a new one [20]. The samples were divided into two groups and drilled. The standard distances between the drill sites and thermocouples sites were 0.5 mm and the depth in which thermocouples were placed in the cortical bone thickness was 5 mm, on average.

BMD Measurements: Bone mineral density (BMD) measurements were achieved by dual energy X-ray densitometry. The analysis was performed by placing the bones saparetely in the scan group by a dual energy X-ray densitometry device Discovery Wi (S/N 84440).

Temperature Measurements: The drill speed (n), applied drill force (F), drill diameter (D) and bone density (ρ) are determined as thermally effective variable parameters *(Table I)*. The temperature measurement, coupled with SEM and histomorphometry examinations at the drill site were the core of this work. A Dynamyte-2900 CNC (Numerically Controlled) machine was used to drill the bovine tibial bone samples. T-type Teflon insulated thermocouples were used for the continuous temperature measurements during the drilling operations. Fresh cadaveric calf tibias were used in the orthopaedic drilling operations (supplied by ELET Ltd. Elazig, Turkey). The tibial bone samples were separated by sawing them along the trabecular line (part) and kept in a deep freezer for 48 h. The drillings were performed at room temperature. The thermocouple slots were determined via the Master-Cam software. After the thermocouples were mounted around the drill sites, the drilling operations were performed with a precision of 10^{-3} mm by sending the values obtained from this software to CNC machine *(Fig. 1)*. The data transfer from the thermocouples was provided by the data acquisition card (Advantech).

SEM and Histopathologic Analysis: The histopathologic analyses have been executed to observe the effects of different orthopaedic drill parameters and so the temperature on the drill site of the tibial bone. Throughout these investigations some standard preparations were executed to the bone samples. The bone sections have been sawn off by a thin manual saw and then the bone sample was divided transversely into two pieces. The prepared bone samples were wrapped in a sponge with labelling and kept in a nitric acid solution (40 ml 65% vol nitric acid, 20 ml 10% vol formaldehyde and 340 ml distilled water) for ten days. The samples were checked

Table 1. *Partial correlation and standard deviations for different drill speed, force, diameter, bone sex and density*

Tablo 1. *Farklı devir sayısı, delme kuvveti, matkap çapı, kemik cinsiyeti ve kemik mineral densitesine bağlı kısmi korelasyon ve standart sapma değerleri*

Parameter	Partial Correlation (R)	P-Value
Drill Speed	0.4056	0.0320
Drill Force	0.7543	0.00004
Drill Diameter	0.4550	0.0170
Bone Sex	0.7084	0.0021
Bone Mineral Density	0.7485	0.00005
Correlation	R=0.8580	0.00000

Fig 1. Drilling at CNC machine
Şekil 1. CNC makine'sinde delme işlemi

every two days to check whether the decalcification was achieved. The decalcification solution was changed each time for a fresh one. After the decalcification process had finished, the macro sections were taken from the specimens by a microtome cutting apparatus, and then they were prosecuted with separate labelling. The prepared specimens were taken for microscopic examinations and the histograms of those sections were executed by using an optical microscope (OLYMPUS). In the histograms, the bone damage, necrotic zone of the hole-wall, volume of empty lacunas and osteocytes filled lacunas were evaluated, due to heat generation in different drilling parameters. SEM analysis took place in order to evaluate the effect of the drill temperatures on the structural changes in bone. First, the sections were taken from the drilled zone and were kept in ethyl alcohol for 30 min, for dehydration process, they were then cleaned and dried in a furnace (120°C) for 12 h.

Statistics: The Statistica 7.0 software was used for statistic analysis of the drilling parameters. The multiple regression method was used for determination of correlation between the drilling parameters via bone temperature. Partial correlation in regression analysis was used to describe the strength of the drilling parameters for bone temperature, and regression (R) and p values were determined. P=0.05 (95% probability) confidence of interval was evaluated the temperature results.

RESULTS

The prepared bone samples obtained via various drill parameters were studied via maximum temperature evaluation, SEM and histomorphometric examinations. These observations were then compared with the heat-induced alterations found from various drill parameters on the fresh tibial bones. The resistance of compact cortical bone with friction simply causes temperature increase in bone. The cellular damage and death caused by heat during drilling is reported as temperature above 50°C cause irreversible cortical bone necrosis [2].

Through this *in vitro* study, male and female tibial bones at the average age of two were drilled using different feed-rates (30, 50 and 70 mm/min) and drill speeds (200, 400 and

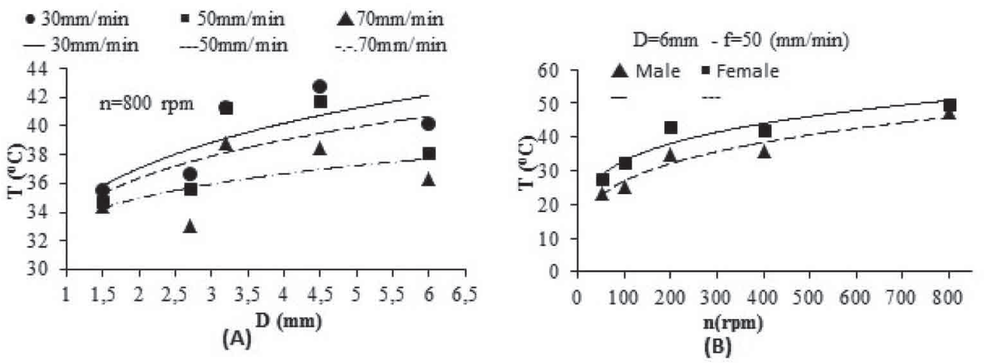

Fig 2. A- Temperature variation with drill diameter and drill speeds, **B-** Temperature variation with drill speed for male and female bone samples

Şekil 2. A- Matkap çapı ve devir sayısına bağlı sıcaklık değişimi, **B-** Dişi ve erkek kemik numunelerde devir sayısına bağlı sıcaklık değişimi

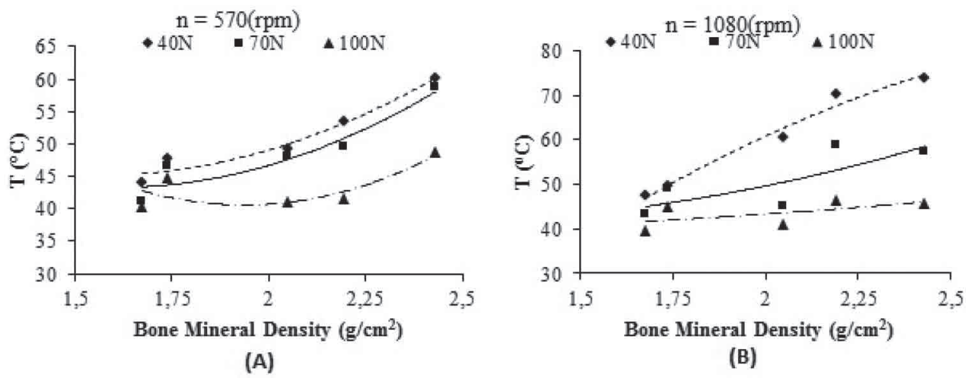

Fig 3. Temperature variations with different BMD: **A-** for n=570 rpm, **B-** for n=1.080 rpm

Şekil 3. Farklı kemik mineral yoğunluğuna bağlı sıcaklık değişimleri: **A-** n=570 d/d, **B-** n=1.080 d/d değerleri için

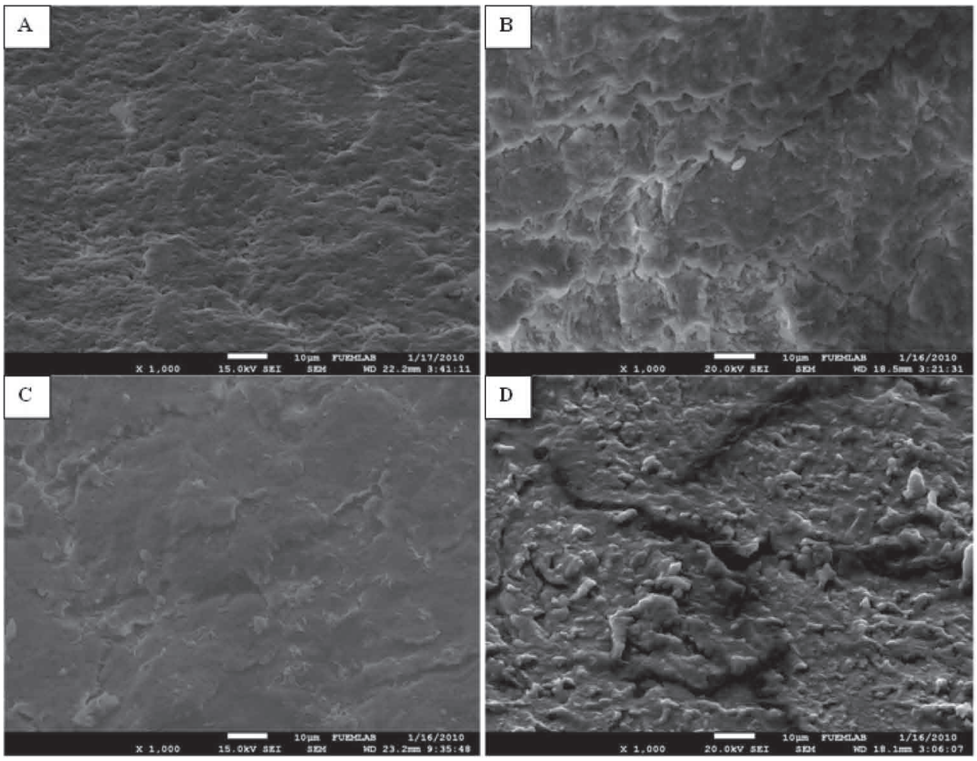

Fig 4. SEM views of drilled bone surfaces: **A-** For drill parameters D=4.5 mm, F=140 N, n=230 rpm, (T_{max}=38°C), **B-** For drill parameters D=4.5 mm, F=140 N, n=1.220 rpm, in dry condition, (T_{max}=87°C), **C-** SEM view for drill parameters of D=4.5 mm, F=40 N, n=570 rpm of the bone sample having density of 1.739 g/cm^2 (47,7°), **D-** 2.430 g/cm^2 (T_{max}=54°C)

Şekil 4. Delinen kemik yüzeylerin SEM görüntüleri: **A-** Delme parametreleri; D=4.5 mm, F=140 N, n=230 d/d (T_{max}=38°C) için, **B-** D=4.5 mm, F=140 N, n=1.220 d/d için, kuru ortamda, (T_{max}=87°C), **C-** D=4.5 mm, F=40 N, n=570 d/d ve 1.739 g/cm^2 kemik densitesi için SEM görünüşleri (47.7), **D-** 2.430 g/cm^2 (T_{max}=54°C)

800 rpm). The changes in temperature with various feed-rates and diameters are plotted in *Fig. 2A* and the influence of bone sex on temperature is given in *Fig. 2B*. In order to show the combined effects of BMD, drill force and speeds on bone temperature change, five different BMD's (1.675, 1.739, 2.051, 2.194 and 2.43 g/cm^2), three different drill forces (40, 70 and 100 N) and two different drill speeds (570 and 1.080 rpm) were used and the plotted results is given in *Fig. 3A-B*. Partial correlation in regression analysis was used for the determination of correlation between the drilling variables whilst influencing the bone temperature. To make multiple regression analysis, the Statistica 7.0 was used. Regression (R) and p values were determined and given in *Table 1*. The drill temperatures are expressed as confidence of interval, P=0.05 (95% probability) and the multiple regression analysis was used to describe the strength of the relationship between specific drilling parameters. SEM view of drilled inner surfaces of the holes by various drill parameters were shown in *Fig. 4A-B*. The effect of the drill speed, applied drill force, bone density and drill diameter and drill environment have been taken into consideration and the obtained SEM structures are shown in *Figs 4C-D*. *Fig. 4C* shows the SEM view of the bone structure obtained for the bone samples having the BMD ρ=1.739 g/cm^2, and in *Fig. 4D* the view of the samples having the BMD ρ=2.430 gr/cm^2. *Fig. 5A-B* show the histograms of the bone samples which were influenced by different applied drill forces on the tibial bone tissue e.g A) F=20 N and B) F=70 N, respectively. *Fig. 5C-D* show the histograms of the samples which were drilled at different bone mineral densities e.g C) ρ=1.739 g/cm^2 and D) ρ=*2.430* g/cm^2 at drill parameters of D=4.5 mm, F=70 N and N=570 rpm at room temperature.

DISCUSSION

Temperature Analysis: *Fig. 2A* shows the influence of drill diameter on the temperature change in bone with feed-rate, at constant drilling speed (n=800 rpm). It can be observed that the maximum reached temperature increased with increasing drill diameter. On the other hand, when the effect of feed-rate is compared, maximum temperatures tend to decrease with increasing feed-rates. As well known from the orthogonal cutting theory, some of the energy is spent for material remove from the surface and some is converted to heat [13]. Such result, therefore, is not surprising, since the length of shearing distance and friction area increase at bigger drill diameter and lowers for small diameters.

Fig. 3 shows the variation of temperature with drill speed, force and BMD. As shown in *Fig. 3A*, temperatures decrease when the drill load increases 40 to 100 N as the similar results are reported in [2]. In addition, this was confirmed in a study [5] that the drilling of bovine bone showed a temperature decrease as the feed-rate increase. The reason for this could be the increase in feed-rate causes a decrease in the drill time, and so the high temperatures in the cutting zone cannot be reached. *Fig. 3B* shows the influence of BMD on drilling temperature. The BMD was influenced by bone hardness and the temperature values were elevated with increased density. Because of this, as given in *Fig. 3A*, the temperature has increased as the bone mineral density increased. It can also be seen that the bone temperature decreased with increasing drill force, and a higher drill force maintained for a shorter drill time. This means the higher temperatures are even harder to obtain at the drill site.

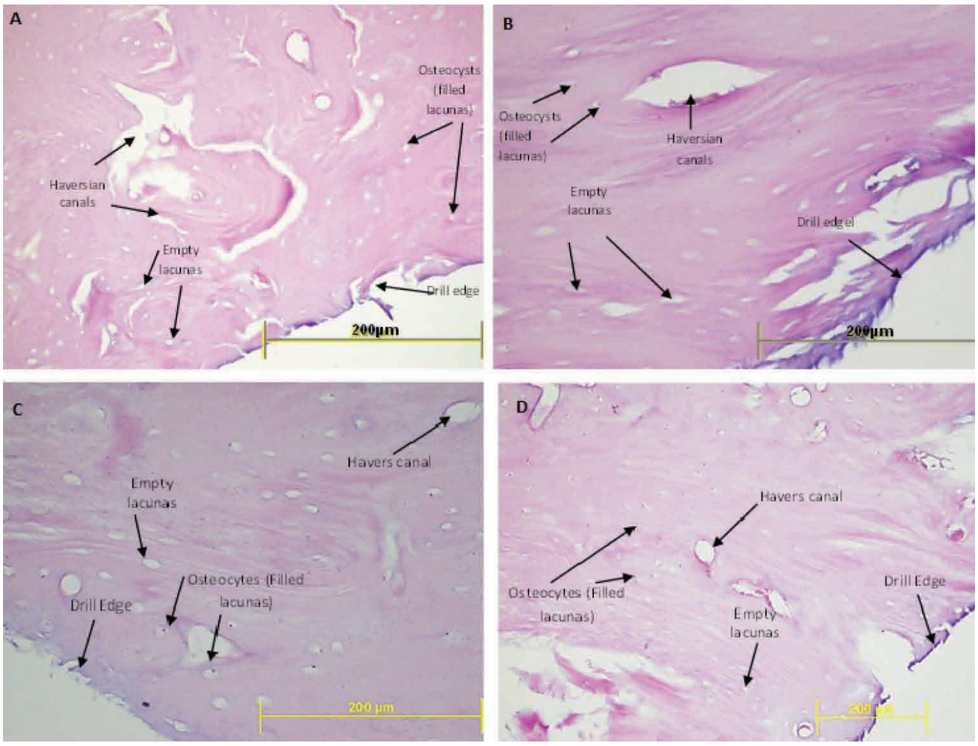

Fig 5. Histograms for drilling parameters: **A-** D=6 mm, F=20 N, n=570 rpm, (T_{max}=60°C), **B-** D=6 mm, F=70 N, n=570 rpm, (T_{max}=45°C), **C-** D=4.5 mm, F=70 N, n=570 rpm for the bone density of 1.739gr/cm^2 (T_{max}=44°C), **D-** D=4.5 mm, F=70 N, n=570 rpm for density of 2.430 g/cm^2 (T_{max}=52°C)

Şekil 5. Delme parametrelerine ait histogramlar: **A-** D=6 mm, F=20 N, n=570 d/d, (T_{max}=60°C), **B-** D=6 mm, F=70 N, n=570 d/d, (T_{max}=45°C), **C-** D=4.5 mm, F=70 N, n=570 d/d ve 1.739 g/cm^2 kemik densitesi için sıcaklık (T_{max}=44°C), **D-** D=4.5 mm, F=70 N, n=570 d/d ve 2.430 g/cm^2 kemik densitesi için sıcaklık (T_{max}=52°C)

A maximum temperature was obtained at the maximum bone density 2.43 g/cm^2 and the bone temperature was elevated with increased bone density *(Fig. 3B)*. On the other hand, increasing drill force has decreased with bone temperature. However, the drill force was reduced with the drilling time so the temperature could not rise to higher values. Because of this, the temperatures have remained at a lower degree when higher forces are used. Although the drill force and drill speed was reported to cause an increase in bone temperature [7], in other works [8,21], it was indicated that drill temperature has decreased significantly with the increasing of drill force.

Statistical Analysis: It was observed from the statistical analysis that the bone sex has a statistically significant effect on drill temperature as the correlation coefficient was found to be $R_{(sex)}$= 0.70 *(Table 1)*. But the feed-rate did not show a statistically significant effect on the bone drill temperature, as the correlation coefficient was found to be $R_{(feed\text{-}rate)}$=0.17. However, the drill speed had a higher influence on the drill temperature since P=0.032 and $R_{(speed)}$=0.77.

SEM Analysis: The effect of drill speed in the drilled hole structure at constant applied force (140 N), drill diameter (4.5 mm) was shown in *Fig. 4A*. The SEM view of the drill site shows that, low drill speed (230 rpm) produced low maximum temperature (38°C), and as a result, a good drill surface has emerged. However, as seen in *Fig. 4B*, a higher drill speed (1220 rpm) caused much higher drilling temperature (87°C) and so the surface was damaged more and some irregularities or ruptures appeared to be deeper in the drilled hole surface. *Fig. 4C-D* shows the effect of bone density on drill temperature and so microstructure of drilled bone. As the structures are shown in *Fig. 4C* and *4D*, respectively, the only slight temperature rise (5°C) was obtained, and this seems to be proportional to the densities varied between 1.739 and 2.430 g/cm^2. However, even such small temperature increase above 47°C was enough to cause bone damages as reported in [3]. *Fig. 4C* shows a diverted surface structure for a lower BMD indicating that a homogeneous and better quality drilled hole surface than that obtained for the higher BMD *(Fig. 4D)*.

Histopathologic Analysis: The effect of the drill diameter on temperature during drilling was studied elsewhere [2,5,20,21]. However, the structural changes and histopathologic evaluation were not considered in detail. In this study, the effect of temperature on bone tissue structure during drilling was evaluated. By comparing these histograms, it can be observed that the recorded maximum temperatures were found higher for lower drill forces. In addition, the osteocyte presence is far less visible in *Fig. 5A* (F=70 N), located at a distance of approximately 350 µm from the drill site, whereas they appear to be closer for a low applied drill force, e.g. F=20 N *(Fig. 5B)*. The reason for this may be due to higher forces in which need lower drilling time, hence the heat have no enough time to diffuse and penetrate into the bone. In other words, the longer drill time and applied drill force causes a higher temperature (60°C), and also damages the bone deeper and destroys the cells, thus resulting in a lower amount of filled- osteocytes. Another indication for deep penetration of heat is the appearance of osteocytes spreading far away from the drill site. The filled- osteocytes shown in *Fig. 5B* are observed to be far away (350 µm) from the drill site and the amount of filled osteocytes are found to be less than that found for

F=70 N *(Fig. 5B)*. As a result, however, although the lower temperature is reached during drilling, high drill forces should be avoided due to the occurrence of a higher bone deformity around the drilling zone.

Fig. 5C-D show the histograms for the tibias that were drilled for the BMD ρ=1.739 g/cm^2, and ρ=2.43 g/cm^2. A slightly higher temperature (52°C) was recorded for the tibial bones having the high density compared to the temperature (44°C) for bones at low density. Both histograms have similar structures in terms of damages at the drill site and the amount of filled osteocytes. When working with high BMD bones, it is necessary to use low drill speed, applied drill force and feed rates.

Higher drill speeds and diameters caused higher drill temperature and also caused more damage around the drill sites of tibial bones. As the applied drill force, and so, feed rate was increased, the temperature was also decreased. In order to avoid any undesired operational bone damages due to high drilling temperature, the applied drill force and feed rates should not be used at high levels. Although the drill temperatures were found at drill speeds of 230 rpm and at high drill forces, the SEM and histopathologic results showed that, some fractures and damages are likely to appear at the drill site. The drill speed should be kept low with a maximum 50 mm/min of feed-rate, and 70 N of drill force should be preferred when high BMD' bones are to be drilled. However, because of too many parameters and their combined effects involved in bone drilling, it is suggested that in order to minimize the bone defects and necrosis, due to high drill temperatures (T_{drill}>45-50°C). The orthopaedic surgeons should consider their specific material conditions and choose their optimum drilling parameters shown through this work.

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REFERENCES

1. Olcay E, Allahverdi E, Gülmez T, Ermutlu CŞ, Mutlu Z: Evaluation of the effects of holes of various sizes on fracture rates in sheep femurs. *Kafkas Univ Vet Fak Derg,* DOI: 10.9775/kvfd.2012.7691, (in press) 2012.

2. Augustin G, Davila S, Mihoci K, Udiljak T, Vedrina SD, Antabak A: Thermal osteonecrosis and bone drilling parameters revisited. *Arch Orthop Traum Surg,* 128 (1): 71-77, 2008.

3. Draenert K, Draenert Y: A new procedure for bone biopsies and cartilage and bone transplantation. *Sandorama,* 3, 254-269, 1987.

4. Bain BJ: Bone marrow trephine biopsy. *J Clin Pathol,* 54, 737-742, 2001.

5. Reingewirtz Y, Moncler SS, Senger B: Influence of different parameters on bone heating and drilling time in implantology. *Clin Oral Implan Res*, 8, 189-197, 1997.

6. Bachus KN, Rondina MT, Hutchinson DT: The effects of drilling force on cortical temperatures and their duration: An *in vitro* study. *Med Eng&Phys,* 22, 685-691, 2000.

7. Shawary M, Misch CE, Weller N, Tehemar S: Heat generation during implant drilling: The significance of motor speed. *J Oral Maxil Surg,* 60 (8): 1160-1169, 2002.

8. Jochum RM, Reichart PA: Influence of multiple use of timedur-titanium cannon drills: Thermal response and scanning electron microscopic findings. *Clin Oral Implan Res*, 11, 139-143, 2000.

9. Allan W, Williams ED, Kerawala CJ: Effects of repeated drill use on temperature of bone during preparation for osteosynthesis self-tapping screws. *Brit J Oral and Max Surg,* 43, 314-319, 2005.

10. Draenert FG, Mathys R, Ehrenfeld MY, Draenert K: Histological examination of drill sites in bovine rib bone after grinding *in vitro* with eight different devices. *Brit J Oral and Max Surg,* 4, 548-552, 2007.

11. Rogers KD, Daniels P: An X-ray diffraction study of the effects of heat treatment on bone mineral microstructure. *Biomaterials*, 23, 2577-2585, 2002.

12. Sugita N, Osa T, Mitsuishi M: Analysis and estimation of cutting-temperature distribution during end milling in relation to orthopaedic surgery. *Med Eng&Phys,* 31, 101-107, 2009.

13. Sean RH, James DF: Measurement of thermal conductivity of bovine cortical bone. *Med Eng&Phys,* 22,741-747, 2000.

14. Hamade RF, Seif CY, Ismail F: Extracting cutting force coefficients from drilling experiments. *Int J Mach Tool Manu,* 46, 387-396, 2005.

15. Holden JL, Phakey JG: Clement Scanning electron microscope observations of heat treated human bone. *Forensic Sci Int,* 74, 29-45, 1995.

16. Lavelle C, Wedgwood D: Effect of internal irrigation on frictional heat generated from bone drilling. *J Oral Surg,* 38, 499-503, 1980.

17. Lekholm U: Clinical procedures for treatment with osseointegrated dental implants. *J Prosthet Dent,* 50, 116-120, 1983.

18. Shawary M, Misch CE, Weller N, Tehemar S: Heat generation during implant drilling: the significance of motor speed. J *Oral Maxil Surg,* 60, 1160-1169, 2002.

19. Chacon GE, Bower DL, Larsen PE, McGlumphy EA, Beck FM: Heat production by 3 implant drill systems after repeated drilling and sterilization. *J Oral Maxil Surg,* 64, 265-269, 2006.

20. Mathews LS, Hirsch C: Temperature measured in human cortical bone when drilling. *J Bone Joint Surg Am,* 54, 297-308, 1972.

21. Karaca K, Aksakal B, Kom M: Influence of orthopaedic drilling parameters on temperature and histopathology of bovine tibia: An *in vitro* study. *Med Eng&Phys*, 33 (10): 1221-1227, 2011.