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An Experimental Investigation in Temperature during Bone Drilling: A Comparative Study

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Abstract

Drilling of the bone is commonly performed by surgeons for fixing fractured bones. During drilling process temperature of bone could increase above 47 °C and causes thermal osteonecrosis. In this study an attempt has been made to investigate the effects of surgical drill size, spindle speed and feed rate on the temperature generation during drilling of cortical section of caprine femur bone. Temperature measurement was done in three different mode such as drilling at ambient temperature, using normal saline solution and pre-cooled saline solution as coolant in range (15-20 °C). Further, temperature analysis has been done at different penetration angle i.e. 0°, 15°, and 30°, as surgeons need to do fixation of bone in case of fractures at a different angle. K-type thermocouples at three different sections upper, middle and lower were inserted in holes of cortical section at near about 0.5 to 1 mm from drilling site. From the experimentation carried out most significant parameters which affects the temperature rise was feed rate and drilling speed. It is also found that cooling modes also plays an important role. Since feed rate plays significant role, as surgeons uses hand drill, maintaining feed rate is also important to avoid temperature rise. Comparison of different cooling modes were analyzed for temperature rise.

Keywords: Bone drilling, osteonecrosis, orthopaedic surgery, temperature rise, surgical drill, fracture.

1. INTRODUCTION

Today in day to day life, humans has become very busy. Due to rush and busy life no. of accidents are increasing day by day. Which might cause bone fractures resulting in increased surgeries in hospitals. It is possible to re-join the broken bone medically with re-fixing the bone at normal condition by external means. For holding and aligning bone at proper state drilling is done and plates are attached with screws to fix them firmly, which is known as implantation [1]. So it is necessary to do drilling in case of bone fracture during orthopaedic surgery. Obviously as drilling is done on bone, during drilling temperature of bone rises by some amount due to friction and material removal. If value of temperature exceeds above 47ºC for one minute [2], it causes failure of bone growth and resulting in the loosening of implant, this is known as Thermal Osteonecrosis. To avoid thermal necrosis it is necessary to control temperature rise above critical limit. The effect of irrigation during bone drilling is investigated by many researchers [1-9]. They have used saline solution at different temperatures. It has been observed that irrigation reduces the temperature induced during drilling significantly. George D. Strbac et al. [3] have used combined irrigation i.e. both internal and external irrigation at same time. The aim of this in vitro study is to investigate the bone temperature by varying various parameters and cooling techniques (Irrigation).

2. MATERIALS AND METHODS

Experiments were carried out to determine the effect of various parameters such as spindle speed, feed rate, penetration angle, surgical drill size and irrigation techniques in temperature generation.

2.1 Bone specimen

In the present investigation drilling operation were performed on cortical part of caprine femur bone. The bone were cleaned and pre-drilled for thermocouple insertion by 2 mm drill bit. After pre-drilling bones were stored in deep freezer at temperature of -40 °C for preservation. Bone were allowed to reach temperature of near about 33 to 35 °C before experimentation. A special fixture was used to hold bone firmly while drilling which is made up of ABS (Acrylonitrile-Butadiene-Styrene).

2.2 Experimental setup

Temperature measurement setup is developed for this experimentation for easy and accurate data acquisition. Data acquisition is done by using Arduino based microcontroller to which different temperature sensors output were given. Schematic of experimental setup is shown in Fig.1.

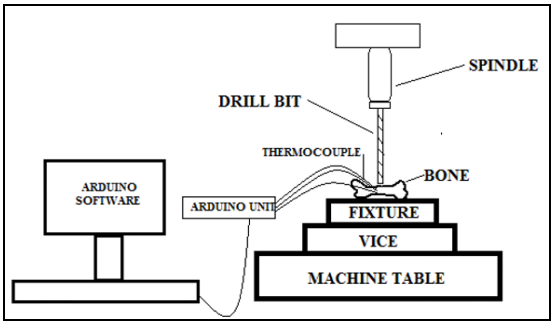

Fig. 1. Schematic of Experimental setup

With sampling rate of one sample per second, temperature readings were plotted on serial monitor of Arduino. For temperature measurement of bone, three k-type thermocouples and two LM35 sensors were used to record the ambient temperature at time of experimentations. It also helped to calibrate the readings of k-type thermocouples with LM35 at start. AD595AQ amplifier was used to convert output signal

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from k-type thermocouple, which gave output signal of 10 mV per ºC to Arduino.

2.3 Methodology

Series of experiments were performed on CNC HASS milling machine. Input parameter were feed rate, spindle speed and output parameter was temperature. Feed rate of 0.02, 0.04 and 0.10 mm/rev were used. Drilling was also done by varying penetration angle. Spindle speed used were 200, 400, 600 and 1000 rpm. Surgical drill bit of 2.5, 3.2 & 4.5 mm diameter were used. For irrigation purpose saline solution was used. Flow rate was controlled by roller clamp mechanism of saline line. Saline was kept in deep freezer before using for pre-cooled irrigation. While drilling at an angle fixture was held at an angle, inclination was measured using inclinometer application of smartphone.

Fig. 2. Femur bone pre-drilled for thermocouple insertion

Experiments were divided in five groups. For group II to V surgical drill size of 4.5 mm was selected, depends on size of bone. K-type thermocouples were inserted in pre-drilled bone which is shown in Fig.2 at upper, middle and lower section.

1. Group-I

In this group experimentation were done without using any irrigation method. Experimentation were done at ambient temperature of 36°C. Three different drill bits were used of diameter 2.5 mm, 3.2 mm and 4.5 mm. Total 27 no. of experiments were carried out for Group-I. Feed rate and rpm of drill were varied.

Table 1
Input parameters and their levels for group-I is shown in table 1

Input Parameters	Levels for group I		
	1	2	3
Drill size (mm)	4.5	3.2	2.5
Spindle speed (rpm)	200	400	600
Feed rate (mm/rev)	0.02	0.04	0.10

3. Group-II

In this group pre-cooled saline solution was used for cooling purpose. Temperature of solution used was in the range of 15 to 20 °C. Drill size was kept constant. 4.5 mm drill bit was used. Flow rate of solution was kept constant. 9 ml/min flow rate was used. Total 9 no. of experiments were carried out for this group. Input parameters and their levels for group-II and III is listed in Table 2.

Table 2.

Input Parameters	Levels for group II and III		
	1	2	3
Spindle speed (rpm)	200	400	600
Feed rate (mm/rev)	0.02	0.04	0.10

4. Group-III

In this group saline solution at ambient temperature (35° to 36 °C) was used for cooling purpose. Drill size was kept constant. 4.5 mm drill bit was used. Flow rate of solution was kept constant i.e. 9 ml/min. Total 9 no. of experiments were carried out in this group.

5. Group-IV

In this group feed rate of 0.10 mm/rev was kept constant. Drilling was done at three different penetration angle. 0, 15 and 30°. Total 9 no. of experiments were designed for this group. Input parameters such as spindle speed and penetration angle varied at constant feed of 0.10 mm/rev for group- IV as shown in Table 3.

Table 3

Input Parameters	Levels for group IV		
	1	2	3
Spindle speed (rpm)	200	400	600
Penetration angle (°)	0	15	30

6. Group-V

Additional experimentation were performed to see effect of spindle speed on temperature in different cooling modes. Spindle speed was kept constant at 1000 rpm during experimentation. Drill size used was 4.5 mm diameter. Total 9 no. of experiments were carried out in this group. Three experiments were carried out for each mentioned cooling method.

Table 4

Input Parameters	Levels for group V		
	1	2	3
Cooling Method	Without irrigation	Pre-cooled saline	Saline at ambient temperature
Feed rate (mm/rev)	0.02	0.04	0.10

Input parameters and their levels for group- V is listed in table 4. Total 63 number of experiments were performed.

7. RESULTS AND DISCUSSION

Analysis is done by graphical representation of magnitude of the output temperature with respect to input parameters. Variation in temperature rise during drilling is plotted. Maximum temperature generated from all of the experiments is taken as output.

3.1 Effect of spindle speed on temperature

Fig.3 shows graph of temperature vs. speed at different feed rate and constant drill size (Ø 4.5 mm). It is observed that

temperature crossed limit of 47 °C at speed of 1000 rpm. Highest value of temperature recorded was 54.69 °C at speed of 1000 rpm and feed rate of 0.04 mm/rev. It is noted that as spindle speed increases, temperature increases. As the spindle speed increases, friction get increases because of this, the bone temperature increased.

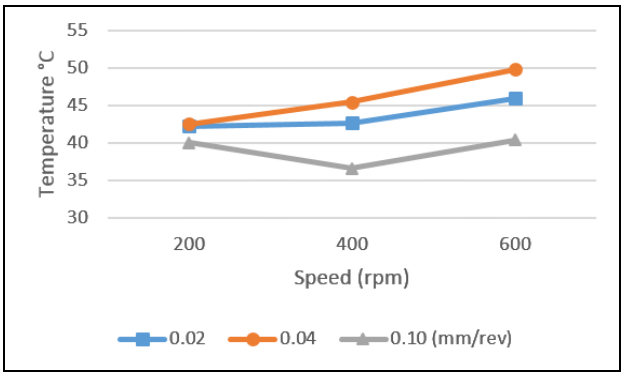

Fig. 3. Temperature vs. Speed (Drill size 4.5 mm)

3.2 Effect of feed rate on temperature

Fig.4. shows graph plotted between feed rate and temperature. It is observed that at feed rate of 0.04 mm/rev, temperature was higher than that of 0.02 mm/rev. Further increase in feed rate to 0.10 mm/rev, temperature got reduced. This is due to shorter drilling time and thereby lesser heat transfer to the bone.

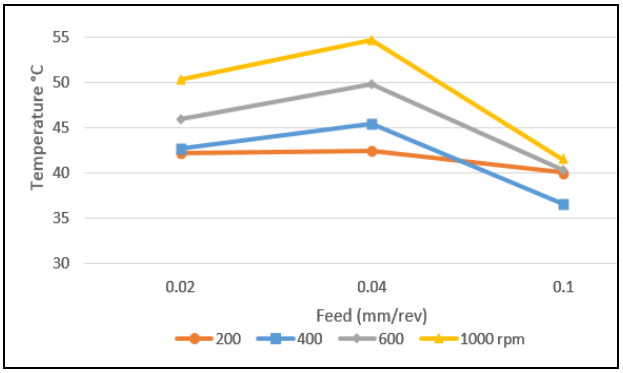

Fig. 4. Temperature vs. Feed (Drill size 4.5 mm)

3.3 Effect of drill size on temperature

Fig.5 shows effect of drill size on temperature. It is observed that with increase in drill size temperature also got raised. This was due to greater drill bit diameter and the larger contact area between the drill bit and bone. A larger contact area leads to increase in friction heat generated in the region. No significant variation is found between 3.2 and 2.5 mm diameter drill bit. But temperature generated by 2.5 mm drill bit was less.

3.4 Effect of penetration angle on temperature

Fig.6 shows graph plotted between penetration angle and temperature. It is observed that temperature increases with increase in penetration angle. This may be because of increase in contact area of bone cortical section with drill bit. Temperature rise of 5 ºC is observed at 30º penetration angle compared to 0º penetration angle.

3.5 Effect of irrigation on temperature

From Fig.7, 8 and 9 it can be seen that, temperature rise in pre-cooled saline irrigation is less than ambient saline irrigation.

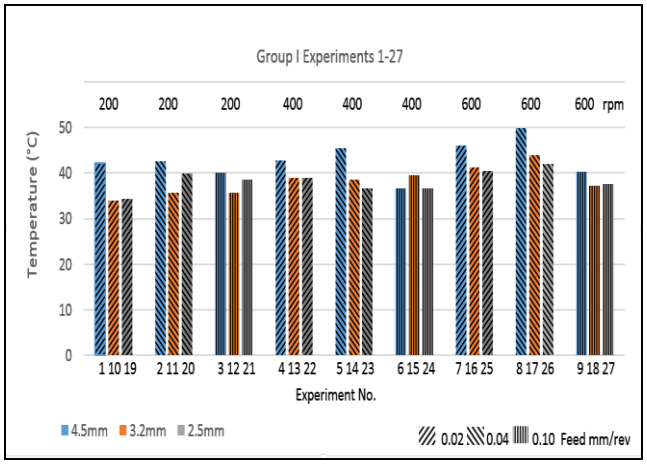

Fig. 5. Temperature plot for different diameter drill bit

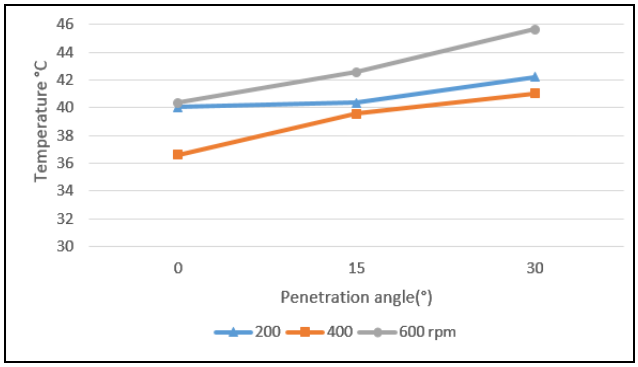

Fig. 6. Temperature vs. Penetration angle (Drill size 4.5 mm and feed 0.10 mm/rev)

It is observed that fragments of bone tend to flow by drill flute during irrigation, which also helped to diminish friction between drill and bone and promotes cooling and self-cleaning. Temperature generated by without use of coolant was higher with increase in speed. It is also observed that in case of pre-cooled and ambient irrigation at speed of 1000 rpm temperature got down. It can be seen that at feed rate of 0.10mm/rev no significance difference was found between all three modes. Fig.7, 8 and 9 shows graph plotted between temperature generated and different cooling techniques at varied feed rate.

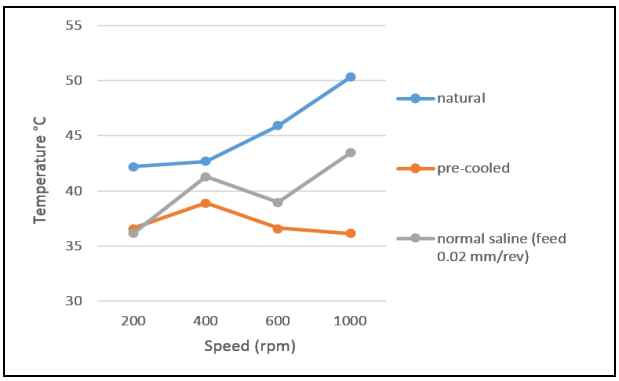

Fig. 7. Natural vs. Pre-cooled irrigation vs. ambient irrigation (feed 0.02 mm/rev)

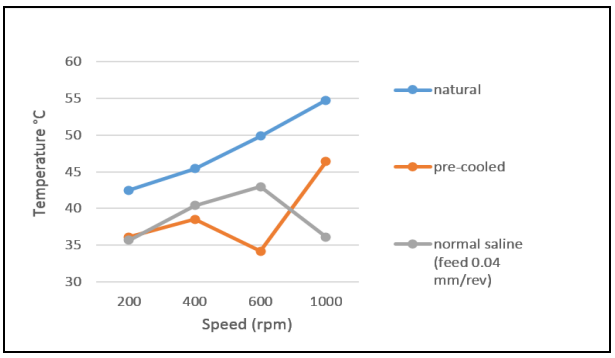

Fig. 8. Natural vs. Pre-cooled irrigation vs ambient irrigation (Feed 0.04 mm/rev)

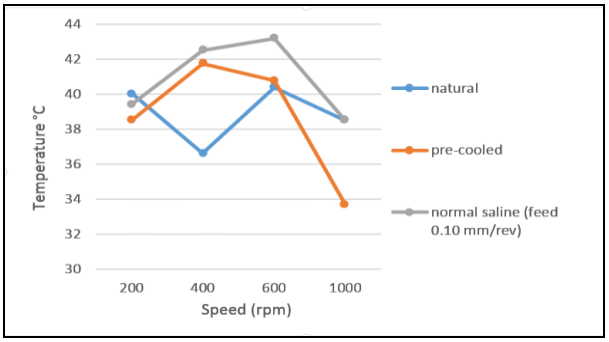

Fig. 9. Natural vs. Pre-cooled irrigation vs. ambient irrigation (Feed 0.10 mm/rev)

3.6 Mean Effective plot on temperature

Fig.10 shows mean effective plot for experimentations done. It can be seen that temperature got increased with increase in spindle speed. For pre-cooled irrigation lowest temperature is observed. Also minimum temperature is observed for 0.10 mm/rev feed rate.

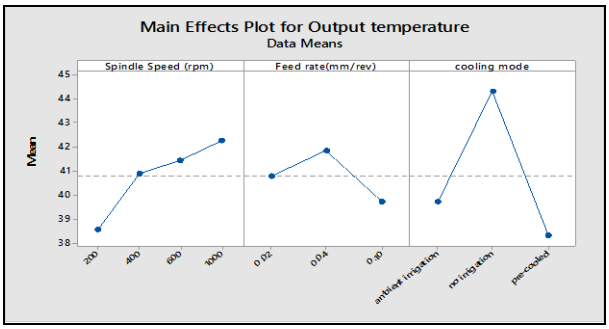

Fig. 10. Main effective plot for feed rate, spindle speed, cooling mode vs. Temperature (Group-I to V Drill size 4.5 mm)

4. CONCLUSIONS

1. Increasing the drill speed, resulting in more amount of heat generation. At speed of 1000 rpm and feed rate of 0.04 mm/rev highest temperature observed was 54.69 °C. Lesser the speed temperature observed was less. Temperature was minimum at 200 rpm followed by 400 rpm and within safe limit (below 47 °C) in all of the experimentations. So it is recommended by experimental results to use moderate speed between 200 rpm to 400 rpm.

2. Increasing in feed rate temperature got rise, but further increase in feed rate temperature got decreased which is due to less contact period of drill and bone. So it is recommended to use feed rate of 0.10 mm/rev to control and avoid temperature rise.

3. Temperature generation got affected by penetration angle. Temperature rise of 5 ºC is observed at 30º penetration angle compared to 0º penetration angle. So it is recommended to avoid drilling at an angle wherever applicable.

4. Increase in drill bit diameter resulting in more temperature generation, less temperature generated was at Ø 2.5 mm drill bit and more generated at Ø 4.5 mm. There is no much difference found between Ø 3.2 mm and Ø 2.5 mm drill bit.

5. Use of irrigation showed significance difference between temperature generations. Lowest temperature is recorded by use of pre-cooled irrigation technique, also moderate in ambient saline cooling and then more at ambient conventional drilling. So it is recommended to use at least ambient saline cooling to avoid temperature rise.

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