DOI: 10.7860/JCDR/2020/45110.14052

Review Article

Biotechnology Section

Inventive Methods Used to Study and Control Thermal Necrosis: A Review

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ABSTRACT

Orthopedic surgeries use screw and plate fixations. Bone drilling is performed for smooth and minimum damage to bone surface during screw insertion. Bone drilling creates a hole with circular cross-section. This process involves cutting and material removal with a helical drill tool. Heat is generated at the drilling site due to cutting, shearing of bone material by drill tool and friction between drill tool and bone surface. Previous research studies found that if temperature at drilling site reaches 47°C and remains the same for one minute, irreversible cell damage i.e. thermal necrosis can occur. Thermal necrosis causes ring sequestrum around the pin; this leads to a vicious cycle involving secondary infection, discharge and pin loosening. This postoperative complication can only be rectified by removal of pin and sequestrum, curettage of the tract and pin replacement and so thermal necrosis- the root cause must be avoided and attended very seriously. To avoid thermal necrosis, postoperative complications and delay in patient rehabilitation, researchers are studying bone drilling in detail. In this review paper, a discussion is made on different innovative methods that are turning points in the study of thermal necrosis and the latest technologically improved equipment devised by researchers. These inventive methods have used experimental set ups, software-based simulations and training programs. The author also conducted experiments on female goat rib bone and based on these observations an improved drilling machine is suggested.

Keywords: Coolant, Infrared thermometer, Robotic drill machine, Thermography

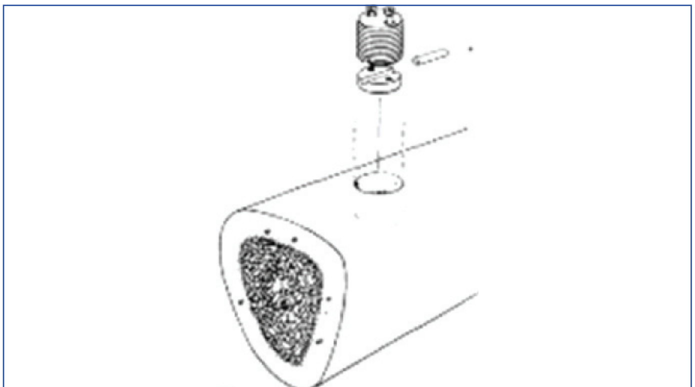
INTRODUCTION

Bone drilling involves making a hole of required diameter in bone surface by the conversion of solid bone at drilling site into bone chips along with a rise in temperature. Temperature rise above 47°C at drilling zone is the threshold limit for thermal necrosis in heat affected zone. This temperature rise is caused by friction and cutting of comparatively soft bone biomaterial by drill tool made of high-speed steel (HSS]. Thermal osteonecrosis occurs when the drilling heat affects osteoclastic and osteoblastic activities along with denaturation of enzyme and membrane proteins. In implant surgery, the progress of bone healing dictates the success of the implant and so thermal necrosis has to be prevented during orthopaedic surgeries. Thermal necrosis in bone drilling is the most challenging and multidimensional aspect as it involves simultaneous interaction between three factors; 1] the skill and surgical technique of surgeon, 2] a mechanical device i.e. drilling machine with drill tool, 3] bone material's special properties like inhomogeneity, varying values of physical properties along different directions and presence of both viscous and elastic properties during deformation. Inappropriate action of factor 1 and 2 would ultimately result in thermal insult of the bone.

In this review paper, the literature is summarised with the intention to contribute towards the work of earlier researchers who gave direction to the study of thermal necrosis. In the following literature survey, all authors have contributed to the study of thermal necrosis. The first paper describes necrosis and heat effect with experimentation on bone growth of a rabbit with growth chamber instrument. The second paper focus on bone histology. Third paper demonstrates changes in bone deformation characteristics with temperature. Fourth paper explains variation in bone thermal conductivity along different directions. Fifth paper with experimentation suggests an innovative drill tool to know the exact temperature at the bottom of drill hole. Sixth paper suggests improvements in drill tool referred in fifth paper. The seventh paper deals with thermography camera to know temperature distribution in cortical bone during drilling. Eighth and ninth papers refers to use of simulation techniques based using finite element analysis on Abaqus software. Tenth paper demonstrates a robotic drill machine and last but not the least eleventh paper explains the importance of training surgeons to control thermal necrosis.

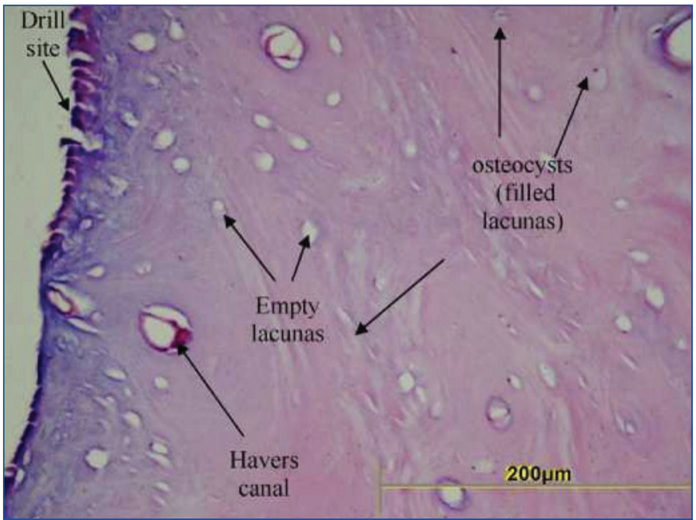
Methods to Study Thermal Necrosis

In this very interesting research work, the heat effect at microscopic level on living rabbit bone tissue regeneration is made. The concept of bone growth chamber [Table/Fig-1] is proposed which is a 7 mm diameter and 6 mm heighted titanium implant, composed of an upper and lower section. These two sections were connected together by two connecting screws, one on the left and right side each. At the contact surface between the two sections, a 1 mm wide and 7 mm long canal pierces along the length of the chamber. The growth chamber and the surrounding bone were heated by a heating element with voltage regulation facility. The growth of bone tissue along the implant's transverse canal was observed and the effect of heat on cell damage and cell regeneration was studied. The growth chambers were opened after four weeks via surgeries. It was found that in samples heated to 50°C, regenerative capacity of bone was completely extinguished, whereas in samples heated to 47°C, the adverse effect was reduced and below that normal bone growth is observed [1]. The information about routine clinical techniques regarding bone preparation and the fact that utmost care should be taken towards thermal necrosis is also highlighted. They concluded that temperatures below the denaturation point of Alkaline Phosphatase (53°C] could be considered harmful to the reparative capability of bone, as burning and resorption of fat cells together with sluggish blood flow were observed.



[Table/Fig-1]: Bone growth chamber.
Source: Journal of Oral and Maxillofacial Surgeries. 1984; 42:705-11

In an in-vitro study, the influence of drill temperature was histologically analysed in terms of osteocyte density, empty and filled lacunas, the haversian canals and the distance between the drilled site and the filled osteocyte, as in [Table/Fig-2]. It was observed that, increasing drill speed increases temperature and increasing feed rate and drill force decreases temperature. Increase in bone mineral density also contributes to an increase in temperature. Five bone samples of calf tibias with mineral densities (1.675, 1.739, 2.051, 2.194, 2.43 g/cm^2), three drill forces (40, 70, 100 N) and two drill speeds (570, 1080 rpm) were selected for this purpose. With the combination of three parameters i.e. bone mineral density of 2.43 g/cm^2, drill force 40 N and drill speed 1080 rpm, maximum temperature of 73.9°C was recorded. A high degree of correlation, with correlation coefficient (R=0.85] was observed between bone mineral density, drill force and drill speed [2].

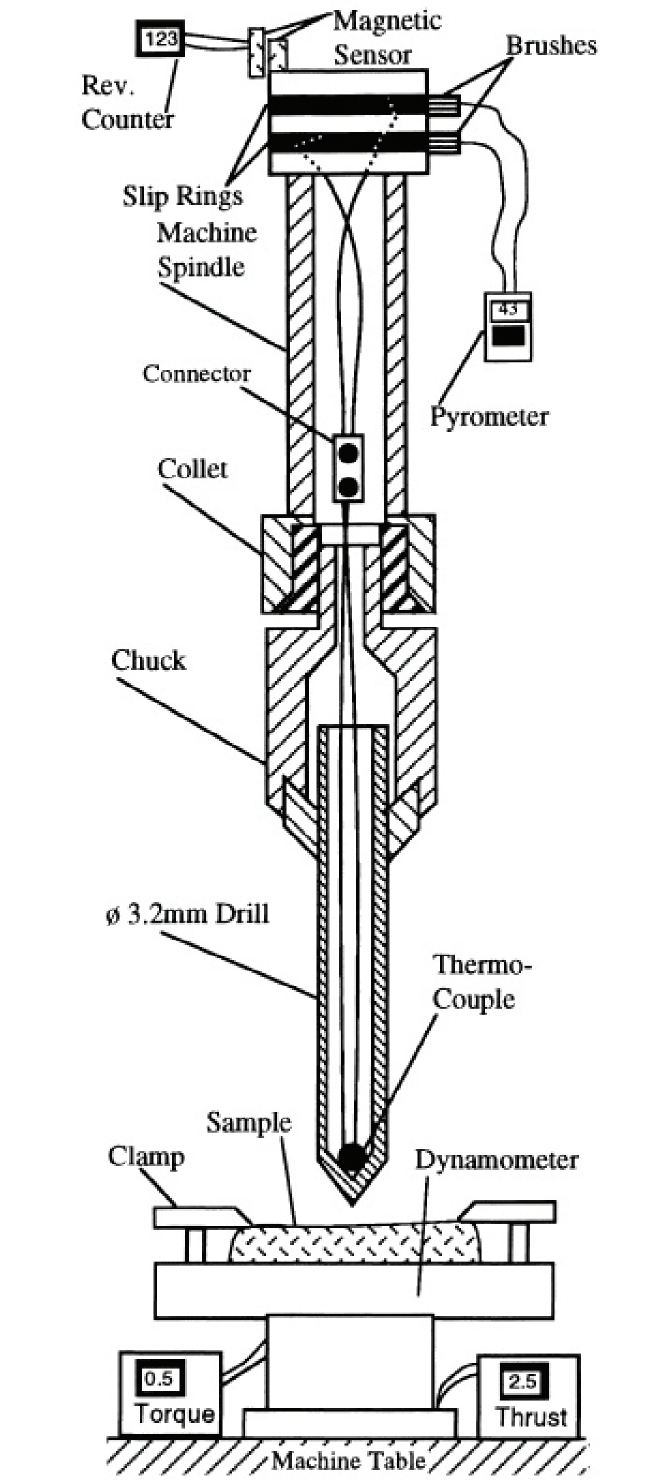


[Table/Fig-2]: Histology of bone tissue.

Some investigators studying thermal necrosis were motivated to know the biomechanical properties of bone like the bone deformation characteristics and heat conductivity. In this study, cortical bone deformation characteristic is measured as a function of temperature. Equipment's like strain gauges and thermocouples were used for this purpose. The temperature range considered was -58°C to 90°C. The effect of temperature between 50°C to 90°C which is most relevant to this paper explains that, in this temperature range bone does not deform as a coherent or unified whole, but in separations. This is due to the weakening of bonds between collagen and hydroxyapatite at this temperature. This factor is equally important since the orientation of collagen structure is the primary cause of deformation [3,4]. The structural changes in this temperature range are irreversible in nature.

On one hand the heat effect damages cell tissues, on the other hand it is also used to destroy lesions and tumours that could otherwise affect the working of central nervous system and brain. Information about thermal conductivity of concern specimen is important and relevant to this study. Thermal conductivity is the rate of heat transfer by conduction through the specimen. Specimens from the mid-diaphysis of bovine femora were studied and the rate of heat transfer in three orthogonal directions was measured. The conductivity was found to be 0.58±0.018 W/mK in the longitudinal direction, 0.53±0.030 W/mK in the circumferential direction and 0.54±0.020 W/mK in the radial direction. As there are negligible directional differences, uniform conductivity was considered [5]. In other work, the results for the values of thermal conductivity and thermal capacity are given as 7×10^{-4} cal/cm/s/°C and 0.73 cal/cm^3/°C and with uniform thermal conductivity along all directions [6]. Contradictorily, some other research work mentions different values of heat conductivity along radial, longitudinal and circumferential directions [7].

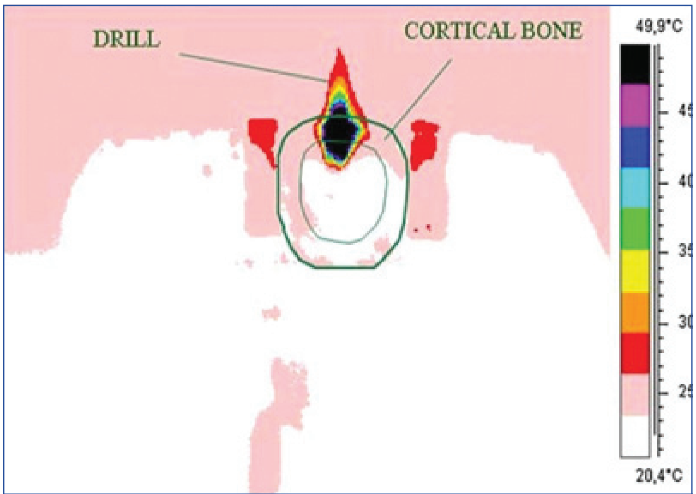
Measuring temperature at the bottom of a drill is always a difficult work. Though thermocouple placed at depth can give an approximate reading but the factors like thermal conductivity of bone material, initial bone temperature can put a limitation on reading of thermocouple. In order to overcome this limitation, a drill was constructed of a hollow piping of stainless steel with an external diameter of 4.5 mm and internal diameter of 0.1 mm, as in [Table/Fig-3]. The tip of the tube is closed through welding. A Helical groove with helix angle of 230 is maintained over the piping surface. The K-type insulated thermocouples were placed and glued inside the drill at the bottom end. It was found during experimentation that with speeds in the range of 800-1400 rpm and the drill tool diameter of 3.2 mm, a manageable temperature level i.e. below 47°C was possible [8] and provides a good operating environment. This study is more relevant in support of other researchers who claim that the heat generation and drilling speed are proportional to each other.



[Table/Fig-3]: Thermocouple placed inside bottom of a drill.
Source: Journal of Materials Processing Technology.1999; 92-93: 302-8

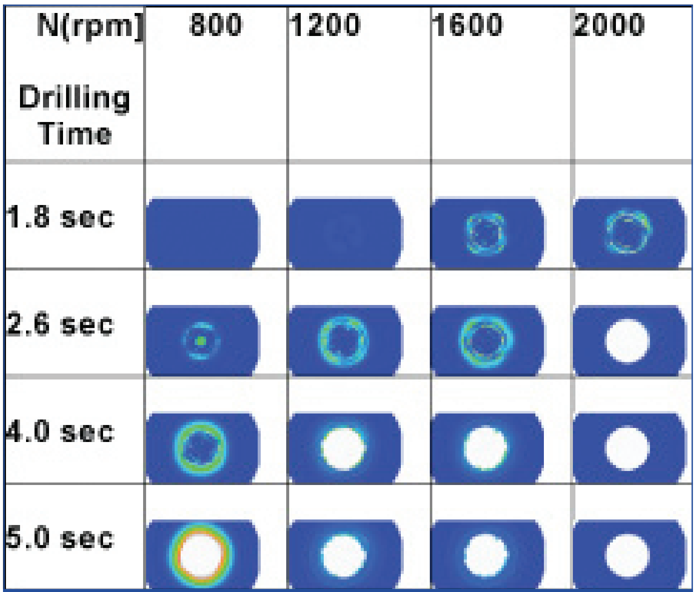
In the above method of drill temperature measurement, a temperature sensor was placed inside a drill at the bottom end and to accommodate the sensor a bore is made centrally. However, it was observed that there is difference of rotational speed between the hollow drill bit and the thermocouple placed inside hollow drill bit, due to which friction occurs between them. This friction generates heat and ultimately thermocouple gives an intensified temperature reading, which is more than the actual drill site. In order to overcome this limitation, a mercury containing sling ring is provided around the sensor in the next study to avoid the sensor drill friction and subsequent heat generation. At the same time to prevent error due to temperature recording of the surrounding and heat loss, a thermoconductive paste is applied on sensor. The sensor used has a diameter 0.019 inches and has an accuracy possibility error of 0.4% with responding time of 3 m/s when the sensor is linked to computer system through signal conditioner circuit and data acquisition board. It was observed that in comparison to previous study's temperature observations, a fall of 8°C is possible [9].

In continuation of progress done by the previous studies, an infrared thermography camera was used to get a close insight on temperature variation at drilling sight and to capture and visualise images from different projections of porcine bone. Thermography camera generates image by using infrared radiation and with the help of different colours the heat distribution in the object is presented. The thermography reports generated and analysed gives the spatial dispersal of bone temperature. The shape and color of temperature distribution images is correlated with temperature range [Table/Fig-4]. In regions of dense and compact bone material, higher drilling friction results in temperature rising above 47°C. This region is indicated by black color. The color is green in the medullar cavity which is a gelatinous structure as the region solely contributes to thermal dissipation [10].



[Table/Fig-4]: Thermographic image during drilling.
Source: Archives of Orthopaedic and Trauma Surgery. 2009; 129:703-9; Source: Medical Engineering and physics. 2011; 33:1221-27

In practice, the placement of thermocouples is a decisive factor in experiments involving temperature measurement. Thermocouple is an electrical instrument and produces temperature related voltage signal, that can be read from a meter distance. Thermocouples cannot be placed at a distance less than 0.5 mm of drilling zone due to chances of drill bit-thermocouple collision and accident. This difficulty can be solved using simulation. Simulation uses a computer program or software and after providing relevant inputs the behavior of real-world situation can be predicted. During this study, 3D simulations using a finite element model with elastic-plastic dynamic properties are performed. Commercial ABAQUS software was used to simulate 56,116 eight-node hexagonal elements with a total node count of 64,342 nodes. The parameters used were a drill bit diameter (2.5 mm), coefficient of friction (0.3), tool point angle (118°) and tool helix angle (30°). The investigation assumed an initial bone temperature of 37°C, drill bit angle of 30°, force values of 10, 20, 40 and 60 N and drilling speed of 800, 1200, 1600 and 2000 rpm. The investigation revealed that within a distance of 0.5 mm from drill, temperature gradient is of 6°C. Peak temperature decrease of 8°C is observed, if drilling speed increases from 800 to 1200 rpm and drilling force is increased from 10 to 60 N. Maximum temperature occurs when drilled for 5 seconds at 800 rpm as presented in [Table/Fig-5]. The decrease in temperature values is attributed to reduced drilling time by increasing applied force and speed [11]. The maximum variance amid the values projected by the planned equation and the numerical model is less than 3.5%.

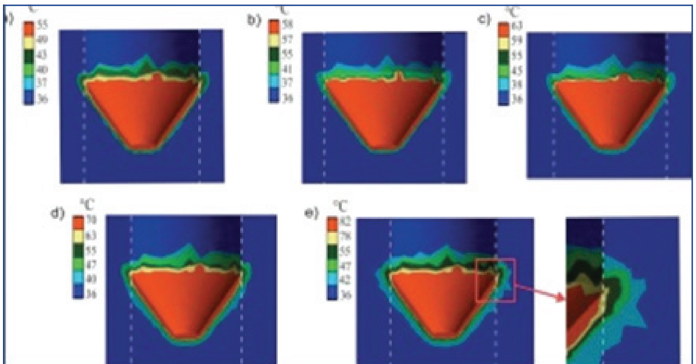


[Table/Fig-5]: Bone temperature contours for different drilling times and drilling speeds.
Source: IEEE, 2011; 978-1-4244-5089-3/11

In another study, the functional properties of drill were studied by numerical and experimental analysis using finite element method [Table/Fig-6]. The aspects related to drill tool geometry like tool point angle and drill tool rotational speed(n) were considered and found to directly affect the amount of heat generated. The amount of heat generated per unit cutting time unit is equal to the total cutting power Pc, which can be determined by the following equation.

$$Pc=Pf+Pm \qquad (I)$$

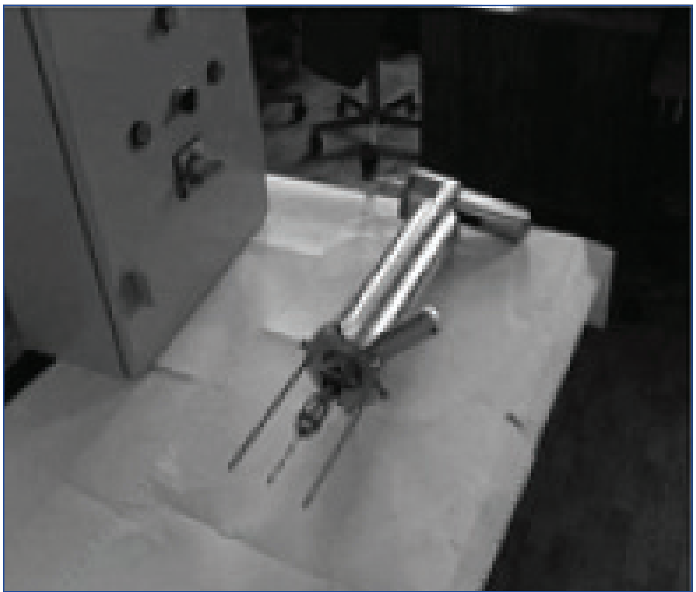
Where Pf is the power derived from the feed component of cutting power and Pm is the power derived from cutting torque. Experiments were performed for two tool point angles 900 and 1200. It was found that for tool point angle 1200 and 900 rotational speed should be equal to 250 rpm and 365 rpm respectively in order to maintain temperature below 55°C [12]. Thus, high point angle provides the freedom to work at lower drill speeds. Low drill speed make operating situations more manageable, specifically for the purpose of temperature control by drill machine handling.



[Table/Fig-6]: The temperature distribution in the femur during drilling using a drill with point angle of 900 for speeds- a] n1=250 rpm, b] n2=365 rpm, c] n3=500 rpm, d] n4=710 rpm, e] n5=1400 rpm.
Source-Acta of Bioengineering and Biomechanics.2011; 13, No. 4:32-3

Methods to Control Thermal Necrosis

It is possible to eliminate subjective factors through automation. Robotic bone drilling technology could avoid necrosis and breaking of blood vessels. Inspired by these thoughts, a robot application in surgery is proposed. The parameters like resistant force due to variable bone mineral density, mechanical torque and linear speed are considered by the robot. The components used in the robot [Table/Fig-7] are 1] Linear actuator, 2] Stepper motor with embedded screw, 3] Brushless DC motor, and 4] Controllers of two types, a] controlling device and b] power drive. Force sensor contributes information regarding bone's resistant force. Thermal sensor uses an electromagnetic radiation non touch temperature gauging instrument. The control algorithms are implemented using a specialised program language TMCL-IDE (Trinamic Motion Control Language-Integrated Development Environment). A plug-in temperature sensor is used to confirm the temperature recorded earlier, during and after the drilling process. The machine is constructed and designed for easy and safe sterilisation. The robot works on two modes-drilling, first to an initial chosen depth and second through entire bone. Experimental results show that temperature is limited to 34°C with the established depth of 20 mm, feed rate of 2 mm/s (linear) and speed of 800 rpm (angular) [13]. The maximum temperature is limited to 43°C in breach mode. After that, the surgeon can continue or go back to the original position.



[Table/Fig-7]: Robotic drill machine.
Source: IFAC Proceedings volumes.2009;42, Issue 16:499-04

The continuous supply of cooling fluid can help dissipate heat from drilling area, but the infiltration of coolant to bottom is not assured due the centrifugal force created by chips of bone debris that expels the coolant from drill sight and also leads to wastage of coolant. An innovative internally cooled drill was proposed to overcome this hurdle. A tungsten cobalt carbide drill bit is centrally bored with openings on the drill tip. The coolant at 24°C and flow rate of 0.16 cm^3/s is supplied with a motor pump through the drill tool [14]. Due to this design, the coolant first reaches to the bottom of drill tool through drilled hole and then flows from the bottom to top. This arrangement also aids the removal of sticky debris chips that often stick to the helical grooves of drill tool. These chips get flushed out as the backflow pressure of coolant coming from drill depth flushes the debris and carries away the heat [15].

A novel approach for training and assessing the drilling skills of orthopaedic surgeons in the laboratory outside the operating theatre is proposed. The training parameters measured included 1] drill tool's orientation and vibration, 2] drill tool's placement over penetration area, 3] applied force on drill machine, 4] drill machine's speed, 5] drill tool skiving over bone surface, 6] drill tool temperature and 7] drill tool kinematics, specifically drill orientation (roll, pitch, and yaw). These drilling parameters are ultimately related to thermal necrosis.A combination of a multiple degrees of freedom orientation sensor and an external calibrated camera is mounted on the training drill machine. Performance improvements observed in trainee surgeons included 1] reduction in over penetration from 28.8 mm to18.2 mm, 2] reduction in skiving from 22% to 6% and 3] reduction in preparation time from 27.3 seconds to 9.65 seconds [16] which is quite impressive.

Improved Drilling Machine

The author conducted a study on thermal necrosis. The study steps involved drilling on six-month-old female goat rib bone specimen. Histopathology [17] for confirmation of heat affected specimen was also conducted. To study the effect of drilling parameters [18], three parameters i] drilling speed (rpm), ii] drilling feed rate (mm/min) and iii] drill tool diameter (mm) were considered [Table/Fig-8].

Drilling control factors	Stage 1	Stage 2	Stage 3
Drill tool diameter (mm]	2.5	3.2	4.5
Feed rate (mm/min]	50	60	70
Spindle speed (rpm]	1000	1500	2000

[Table/Fig-8]: Drilling process control factors at different stages.

Using an optimisation technique, it was revealed that drill diameter has the largest contribution (90.71%), followed by feed rate (5.69%) and the least is drill speed (2.22%) on temperature generation. During surgery, the drill diameter has to be selected as per bone size and feed rate is a manual parameter depending on bone resistance or bone density and so drill speed is the only parameter that can vary. The proposed modified drilling machine consists of an infrared thermometer attached to drilling machine. The infrared thermometer measures the temperature distantly. Electronics circuits receive temperature reading and when threshold limit i.e., 47°C is reached, an alarm buzzer gives cautionary signal to surgeon, so that the speed of drilling can be reduced.

CONCLUSION(S)

Data collected through experiments makes it possible to develop complex robotic equipment to assist surgeons to conduct a surgery efficiently. In the early phase, when the values of biological and mechanical properties of bone were not available, the knowledge from other subjects based on similarity was correlated for example structural, mechanical engineering concepts were correlated with bone structure, accordingly conclusions were drawn, but these conclusions were very accurate. This was the foundation stone for the study of thermal necrosis.

Later, drill machine related experiments and studies focused on drill tool specifications like drill tool diameter, point angle, helix angle and drilling process parameters like drill speed, drill feed rate, chip flow and in support of this heat balance equations were presented. At the same time, researchers established values of thermal conductivity and thermal capacity of bone and their peers successfully overcame the difficulties in placing the thermocouples. There was concern over the difficulty of external saline coolant reaching inside the bone during drilling. To alleviate this, concern researchers have proposed drill tools with coolant flowing inside the tool. The author of this review has no doubt that in near future, robotic drill machines would occupy a place in the surgery environment.

Acknowledgement

Authors would like to thank Dr. Manojkumar Z Chopda, Zoology Department, Moolji Jaitha College, Jalgaon, Maharashtra, India for the histopathology analysis.

Ethical approval: The female goat rib bone sample was collected from a local butcher after it was slaughtered during the practice of their routine trade. The female goat was not slaughtered for the purpose of this research work. The authors are not related directly with any live animal hence, ethical approval was not required.

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PLAGIARISM CHECKING METHODS: [Jain H et al.]

- Plagiarism X-checker: May 20, 2020
- Manual Googling: Aug 18, 2020
- iThenticate Software: Aug 27, 2020 (8%)

ETYMOLOGY: Author Origin

AUTHOR DECLARATION:

- Financial or Other Competing Interests: None
- Was Ethics Committee Approval obtained for this study? NA
- Was informed consent obtained from the subjects involved in the study? NA
- For any images presented appropriate consent has been obtained from the subjects. NA

Date of Submission: **May 19, 2020**
Date of Peer Review: **Jul 01, 2020**
Date of Acceptance: **Jul 11, 2020**
Date of Publishing: **Sep 01, 2020**