Bone Drilling Parameters and Necrosis: An In Vitro Study

Rajesh V. Dahibhate and Santosh B. Jaju

Abstract Implant screw fixation and bone drilling are the two one after another processes. If certain operating parameters are not observed, necrosis may result. Necrosis can be explained as an unfavorable form of cell injury whereby integrity of cell membrane is lost and the extracellular space if filled with an uncontrolled release of products of cell death. This process starts an inflammatory response in the surrounding tissue which attracts leukocytes and phagocytes which remove the dead cells. However, collateral damage to surrounding tissues by microbial damaging substances released by leukocytes inhibits the healing process and lengthens patient rehabilitation period or even unsuccessful implant fixation and post-operative complications. This research work is initiated with review work, as the literature on this topic is having contrary conclusions and so review of previous investigators experimentation's on the effects of spindle speed, depth of drilling and feed rate on temperature distribution and correlation among them is made. Conclusions based on histopathological analysis and bone mineral density with in vitro study are very important. This review work attempts to organize the previous work on bone drilling parameters and its correlation with necrosis.

Keywords Bone drilling · Histopathology · Microtome · Drilling parameters

1 Introduction

Implant fixation and bone drilling are the two inseparable processes in orthopedic surgery, but with it necrosis also comes into act. Necrosis can be explained as an unfavorable form of cell injury whereby integrity of cell membrane is lost and the extracellular space if filled with an uncontrolled release of products of cell

R. V. Dahibhate (✉) · S. B. Jaju
Mechanical Engineering Department, G. H. Raisoni College of Engineering, Nagpur, India
e-mail: dahibhaterv@gmail.com

S. B. Jaju
e-mail: santosh.jaju@raisoni.net

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death. Here the dead cells are eliminated by an inflammatory response that attracts leukocytes and phagocytes. However, collateral damage to surrounding tissues by microbial damaging substances released by leukocytes inhibits the healing process and lengthens patient rehabilitation period or even unsuccessful implant fixation and post-operative complications. Thus, unnoticed necrosis may be converted and consequence in a build-up of decomposing dead tissue and cell debris around the site of the cell death. The nucleus changes in necrosis are characterized by the manner in which its DNA breaks down, the nucleus fades or the nucleus shrinks, and the chromatin condenses the shrunken nucleus fragments to complete dispersal. Similarly plasma alterations are also observed in necrosis like loss of microvillus and cell blebbing. George Axhausen, (1877–1960) a leading jaw surgeon of his time from Berlin University of Dentistry known for his pioneer studies in the field of jaw, facial surgery, and especially to the palate gaps, focused necrosis.

Denaturing of bone alkaline phosphate above 56 °C is considered to be a reason for necrosis. Other factors responsible for necrosis are toxins, infection, or trauma. Mechanical trauma generally involves cellular physical damage, damage to blood vessels, and associated tissues. In thermal effects, disruption of cells as these are exposed to extremely high or low temperature for external factors result in necrosis.

2 Literature Survey

The authors [1] developed drill bits from stainless steel piping with 4.5 mm outside diameter. *k*-type thermocouples were “bedded” inside at the bottom of hollow pipe. The tip of tube was closed by welding. The drill bit then fluted to helix angle of 23° and ground to 90°, 80°, 70° point angles. For the bone storage, a container with saline water, heating element with thermostat control to maintain human body temperature of 37 °C is used. To calculate bone hardness, simple handheld barber Coleman impresser is employed instead of Rockwell or Brinell hardness tester. During drilling, it is observed that, in case of bovine bones, for a depth of 3 mm, the temperature varies from 38 to 26 and then 29 °C, as speed increases from 400 to 1200 and then 2000 rpm. Whereas for a depth of 9 mm, it ranges 102–117 °C for 400–1200 rpm. In case of human bones for a depth of 5–6 mm, temperature ranges from 80, 68, and 75 °C for 400, 1200, and 2000 rpm. The thrust force measured is 48, 25, and 23 N for 400, 1200, and 2000 rpm, respectively. Thus, temperature drop in both the cases in the range of 400–1200 rpm is related to reduction in thrust force, whereas temperature increase over 1200–2000 rpm is related to drop off in torque rate and thrust change. During the research work, it is also observed that the mechanical properties of bone are anisotropic [1] and density or mass of bone mineral (calcium hydroxyapatite $Ca_{10}(PO_4)_6OH_2$) in a medium consist of biological materials like minerals, bone marrow, muscles, and fats. Observation under optical microscope indicates traces of burning along with faint smell from where drill bit proceeded into the hole. Again bovine bone is more hard and thick (7–9 mm) as compared to human ulna (3–5 mm) and so generates more heat. The authors also pointed that placing of thermocouples on the surface near the drilling sight by earlier researchers gives unsatisfactory results due to insulating property of bone. Point angles of 70°, 80°, 90°, and rake angle 23° have no significant effect on temperature rise and drilling speed of 800–1400 rpm with drill bit diameter 3.2 mm provide temperature to manageable conditions. The heat is dissipated primarily by blood and tissue fluids and partially by the bone chips. Drilling speed and heat generated are proportional parameters. Depth of bone and poor conductivity is the two factors responsible for temperature rise to 55 °C.

The aim of this study [2] is to measure and compare the temperature rise during drilling a femoral cortex of animals and humans. The animals selected are rabbit and dog. In experimental setup, a special drill guide was used to maintain a fixed distance of 0.5 mm between drilling site and heat sensitive thermocouples ample saline cooling at room temperature was maintained. In case of rabbit, for a drilling duration of 5 s, the mean temperature recorded was 40 °C. The temperature increase of 8 °C from initial temperature was rapidly. When drilling stopped, the temperature fell unexpectedly to 32 °C, Bone thickness was 1.5 mm and drill diameter 3 mm, point angle 118° and helix angle 30°. When the same procedure applied for two adult dog's, bone thickness 3.5 mm and duration of drilling is 15 s, temperature recorded was 56 °C in lateral cortex and the peak temperature for medial cortex was 65 °C, i.e., almost increase of 10 °C. In case of human's clinical study, the average time for drilling is 18 s and temperature recorded was 96 °C, even though saline cooling was applied. The cortical thickness was around 6.5 mm. The author also discussed that the experimental conditions vary from situation to another as all measurements were taken on livings under anesthesia and that could be the reason of temperature variation. Another reason is possible drilling techniques in experimental and surgeons. Clogged flutes of drilling tool increases torque and so specific cutting energy and increases temperature, this phenomenon is more prominent as drill depth increases. Another reason is coolant cannot reach the depth of drill. Karaca et al. [3] studied optimum operating conditions to avoid defects during surgeries. The parameters controlled are drill speeds 230, 570, and 1080 rpm for drill tip angle 85°, 118°, and 130° and drill force 50, 100, and 150 N. The specimens selected were fresh male and female calf tibias and multidisciplinary factors like bone sex, bone mineral density were considered. The comments were temperature increases with drill tip angle. Similarly augmented bone mineral density and female samples were the factors favorable for temperature rise. Maximum temperature reduces with hike in feed rate and drill force, and the grounds may be increase in feed rate decreases drill time. Maximum temperature of 73.9 °C was reached at bone mineral density of 2.43 g/cm^2, for corresponding values of drill speed 1080 rpm and drill force of 40 N. Drill tip influences the drill performance and drilling becomes more difficult as inevitably it produces high friction. The authors also discussed two kinds of bone damages, one the necrotic tissue and second the volume of osteocytes responsible in regenerating the bone tissue after drilling. Multiple regression showed a high degree of correlation ($R = 0.85$) between bone mineral density, drill force, and drill speed.

As drilling is performed inside a hole, it prevents most of the direct observation techniques to evaluate the process and so it is difficult to understand the complexity of process [4]. This paper presents three-dimensional thermo-mechanically coupled finite element model of drilling process. The observations are mentioned below. The thrust force can be explained as the force applied by the rotating drill bit to the work piece, and the thrust force increases drastically with increase in cutting speed. Torque is applied by the spindle speed to maintain the drill rotation.

1. Thrust force increase with increase in feed rate due to the fact that the shear area is elevated.
2. Torque also increases with feed rate; however, the consequence of cutting speed on torque was more dominant than cutting speed.
3. Thrust force increases with increase in cutting speed and feed. Changing feed rate has linear effect on thrust force.
4. Cutting speed (v) = drill bit rpm X3.14 × Diameter of drill.
5. Feed rate (mm/min) = drill bit rpm × feed (mm/rev).
6. Time to machine = time/feed rate.
7. Material removal rate = 3.14 × D2.feed rate/4.

The objective of the work of Sean R. H. Davidson et al. [5] was to calculate thermal conductivity of bone. It is a well-known fact that bone is an anisotropic in nature but in this study it is prominently explained that it is isotropic for thermal conductivity. 0.1-cm-thick slices of bovine cortical bone were prepared, with average surface area across which heat applied was 0.1 cm^2. Temperature was measured with k-type thermocouples. The heat flow equation, Fourier's equation $Q = K.A.\Delta T/t$ referred. The conductivity measurement was divided into three groups: longitudinal, circumferential, and radial directions, and the thermal conductivity values were 0.58, 0.53 and 0.54 W/m K, respectively. According to author, this variation is due to difference in animal type, age, and bone site. This also reflects the difference in composition. Largest indicator difference is 0.05 W/m K (8.9%) of mean conductivity is between the circumferential and longitudinal direction, which is negligible. Bone density is considered to be an important aspect as it is closely related to bone conductivity. To measure bone density, single or dual energy absorptiometry (SXA & DXA) projection imaging techniques are used. Other findings related are specific heat capacity of bone is 1256 J/Kg K. Thermal conductivity is 0.53 W/m K.

3 Experimental Apparatus and Procedure

To avoid the vibrations and to achieve accuracy, CNC drilling machine is used. The drill bit specifications can be discussed as, surgical drill bit diameter was 3, 6, and 9 mm, preferred drill tip angle is 118°, and corresponding Rake angle value is 35 °C, whereas helix angle selected is 28°. **The specimen, as earlier researchers preferred bovine or canine, in this research work it is a rib bone of six-month-old sheep collected from a local butcher. The sheep was slaughtered and immediately the rib bone collected, kept in a container filled with saline water and used for drilling**. During the drilling process, it was kept in phosphate buffer solution (sodium salt) with pH of 7.4 for this stock solution A comprised of ($Na_2HPO_4{\cdot}2H_2O$), 0.2 molar solution containing 35.61 g/L or ($Na_2HPO_4{\cdot}12H_2O$), 0.2 molar solution containing 71.64 g/L, whereas Stock solution B comprised of ($NaH_2PO_4{\cdot}2H_2O$), 0.2 molar solution contains 27.67 g/L or ($NaH_2PO_4{\cdot}2H_2O$), 0.2 molar solution containing 31.21 g/L on making the addition of both A and B, (X ml of (A) + Y ml of(B)), diluted to a total solution quantity of 200 ml that is $X = 19.0$, $Y = 81.0$, pH = 7.4. For 100 ml solution quantity, density of solution A is 3.561 g/100 ml and density of solution B is 3.121 g/100 ml. The solution was maintained at 37.8 °C to simulate live body temperature. The temperature at the drilling site is measured with the help of an infrared thermometer. The speed ranges preferred were four and are as 600, 1200, 1800, and 2400 rpm. The speed selection is based on the range of the speeds recommended in the literature for the drilling of bone. The drill bit diameter was 3, 6, and 9 mm, and feed rates used were 0.3, 0.6, 0.9, and 1.2 mm/s. These feeds were chosen arbitrarily, since during orthopedic surgeries, the feed rate varies from operating person, i.e., surgeon to surgeon, and in the case of a particular surgeon, there will also be a variation, since the drill is to be handled manually. After each drilling, the specimens were dipped in bottles containing 10% formalin. After a long gap of 45 days and an interval of every 4 days, the chemical solution was replaced with a new one (Fig. 1 and Table 1).

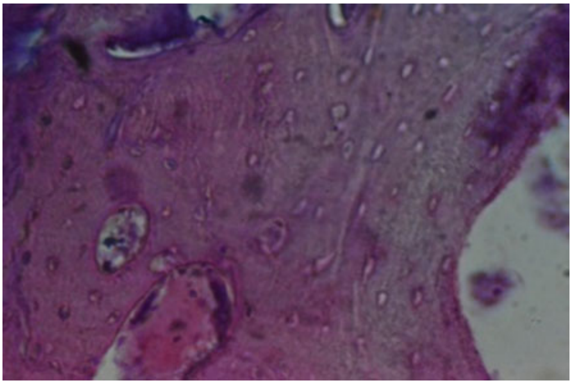

Fig. 1 Histopathological image

Table 1 Temperature generated during related drill speed (rpm) and feed rate (mm/s)

Sr. No.	Drill speed (rpm)	Drill feed rate (mm/s)	Temperature at drill site (°C)		
			3 mm	6 mm	9 mm
1	600	0.3	41.2	46.5	54.2
2	1200	0.6	43.5	47.8	56.5
3	1800	0.9	44.6	49.9	58.4
4	2400	1.2	45.2	51.3	60.2

4 Conclusions

The measurements as recorded by previous researchers when summarized indicate a great fluctuation although the operating principles are same. Use of electrical source and parameters like temperature gradient, heat flow and specimen dimensions were the some aspects. Zelenovs [6] faces the problem that the heat may escape to surrounding instead of through the specimen. Lunskdog [7] used resistive wire to heat the specimen at one end while other end connected to copper heat sink. Temperature was measured by thermocouple placed across the length drilled drills here the heat loss through the specimen and heat sources, and drilled holes have to be considered from above survey we can summarize that the experimental setup is a challenging task for accurate results. The apparatus used by the Biyikli [8] can be considered as an accurate one as in this one-dimensional heat flow was measured by insulating the specimen by which experimental error is reduced but in this also accurate sizing of specimen is achieved by machining which can change the physical properties of bone so if specimen of different dimensions can be adopted, it will be a great feature. Aouzgia [9] noted that circumferential direction temperature rise is less as compared to longitudinal direction and on the basis, anisotropic nature of cortical bone was claimed, contrarily Lunskdog [7] claimed for longitudinal direction. Juenlee [10] the opposing factors like higher heat generation and low thermal conductivity reduces the effect of drilling parameters like speed rate and feed rate. High conductivity of drill bit as compared to bone the drill tool will cool the drilling site by conduction. The chip stream also convects the heat from drilling site. The drill bit material also affects the heat removed by it, about 50–60% of heat generated when steel is used. The thermal conductivity $K = 0.28$ W/m K and $h = 0.182$ corresponding to thermal conductivity 0.42 W may be due to less water content in bone also affects the thermal conductivity also provides the data to calculate the amount of mechanical energy absorbed as thermal power into the bone (0.6–0.7% is converted to thermal power) and here the term torque dominates the power consumption, this mechanical power is converted to heat which is partitioned into drilling tool, chips containing bone debris and bone specimen. Osteocytes begin to die with temperature increase above 50 °C, and if temperature even exceeds 70 °C, enzymes and proteins required for recovery will get damaged concurrent with biochemical damage to cells [9]. The simplest method of evaluating thermal conductivity consists of creating a "1-D" heat flow. Fourier's law is also used to measure conductivity. The use of sensors has limitations as the dimensions of the sensors are relatively large. Larger drills contribute to better elimination of heated bone chips and debris by which more efficient drilling with lesser increase in bone temperature metal chips carry 85% of heat generated but due to poor conductivity bone chips carry lesser percentage of heat. Thermal gradient exists from the heat source as the high temperature to the cooler specimen. Higher temperature gradient more heat transfer will occur and will continue till the gradient is maintained. The balance heat gain and loss will decide the ultimate temperature. When these two phenomenon's are equal, state of equilibrium is achieved, in equilibrium the specimen temperature is a function of exposure temperature and thermal conductivity but in case of biological tissues as the exposure time is usually too short, equilibrium is not reached and so in the non-equilibrium case the temperature is function of temperature exposure and exposure time, whereas the specific heat capacity is constant [7]. usually thermocouples are placed 0.5–1 mm from drilling site used axial positioning of thermocouples [5] also noted that there are significant differences in conduction values across the longitudinal, circumferential direction, and no significant differences along radial and circumferential direction and so the information of two thermal properties of specific heat and thermal conductivity is very essential. Karaca [3] mentioned the difference in thermal properties with respect to species too. Bachus [11], in his paper referred four forces 57, 83, 93, and 130 N. Thermocouples were placed 0.5, 1, and 2 mm away from drilling site. When reading of thermocouple, 0.5 mm distance is observed; it shows 67.24, 47.2, 35.17, and 34.66 °C for thermocouples 1.0 mm distance away from site is observed it shows 57.86, 45.05, 34.50, 33.22 °C, and for 2 mm distant thermocouples 52.79, 41.46, 31.62, 31.88 °C. From this, we can interfere that only at 57 N, local application temperature is above 50 °C, up to 2 mm away from cutting site for 48 s. When a load of 83 N time reduced to 45 s afterward for 93 and 130 N temperatures remain below 50 °C. So we can conclude that as the drilling force is increased, temperature is reduced. The reason behind this may be the time required to penetrate the cortex bone is reduced. But if we observe the research of other investigators, they have not concluded the same interference as Bachus [11] have. The reason is that the cutting tool parameters they have referred are different for example like dental studies utilized speed range from 125 to 100,000 rpm and force between 1.5 and 24 N, with dental burrs, extra skeletal pins, and drill bits, whereas orthopedic researchers had employed 60–700 rpm with 60 and 120 N.

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