Study of influence of tool geometry and temperature on bone substructure to reduce bone drilling injury

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Abstract. For multiple piece bone fractures orthopaedic surgeons often prefer bone drilling. During bone drilling (cortical and cancellous) heat is generated. Heat accumulation above tolerance level of bone biomaterial causes permanent bone injury. This leads to delayed restoration period. This can be avoided by controlling drill tool geometrical aspects and in depth information of bone substructure. Among various angles of drill tool, helix angle is very important as it gives way out to bone chip and thereby heat removal from drilling site. Temperature affects bone up to cellular level and so to identify thermal damage, bone substructure has to study. This paper deals with the study of drill tool geometrical aspects that contributes to temperature rise and its effect on bone substructure.

1. Introduction

Osteosynthesis is the basis of modern orthopaedic surgeries. Internal fixations like nails, screws and plates are fixed with the help of bone drilling. These internal fixations provide immobilization to fractured bones which facilitates the natural growth of bone. In this way the principle of internal fixations offers physical functionality and independent mobilization of bone [1]. During bone drilling mechanical energy, shearing of bone material and frictional movement between drill tool and bone generates thermal energy [2]. If heat generation level and quantity of heat accumulation over crosses the normal physiological levels of bone material, it could result in thermal necrosis i.e. bone cell death. Thermal necrosis cause adverse effect on bone substructure and loss of self-healing ability occurs. The mechanical, chemical properties of bone also change. Failure of bone regeneration around fixation cause ineffective grip of bone around internal fixation device or loosening of screw fixations occurs. This defect lead to post-operative complications can be corrected only by reoperation. If the drilling process is not controlled within time for a number of reasons like difficulty in visualizing the path of advancement of drilling tool in the bone [3], insufficient information of bone quality, strength and thickness of bone and over distance travel of drill bit inside bone cross section wise could result in osteonecrosis of the immediate tissue. The nature of bone i.e. cortical or cancellous, the regions of bone to be drilled i.e. proximal epiphysis, distal epiphysis, metaphysis or diaphysis are also correlated with the heat generation level.
Biologically bones are described as calcified connective tissue comprising of minerals, collagenous protein, lipids and water. The bone is physiologically active and reactive tissue. The mineral composition of the bone come close to as Hydroxyapatite (HA) with chemically it is Ca10(PO4)6(OH)2.

2. Influence of Tool Geometry

The drill tool geometry has a direct and profound effect on level of heat generation at drilling site [4] and in other words it can be said that temperature elevation is the manifestation of the cutting forces and energy consumed during shear deformation of bone chip. To explore the consequence of temperature on thermal damage, a precise understanding of drilling temperature is required [5]. The reasons of heat generation during bone drilling includes shear deformation in shear zone, friction amongst the rake face of the drill tool and chip, friction among the flank face of tool and recently formed surface of bone sample [6]. Due to similarity of chip shear failure in drilling and machining, theory of orthogonal cutting is used for design of heat generation. The correlation between threshold temperature and bone exposure time to heat is explained by a number of researchers like 47°C for 60 seconds, 55°C for 30 seconds [7] similarly bone exposed for more than 30 seconds at 50°C cellular necrosis will be tempted [8], while no substantial effects were detected when the heating was done to 44°C for 1 minute [9].Another conversation recognized regarding bone injury is that when bone is exposed to a temperature of 70°C instant damage will occur, and the same outcome is observed for a temperature of 55°C for 30 second and at a temperature of 45°C damaging effects will arise after 5 hour [10].Regarding drill tool geometry, as shown in figure number 1, it is observed that point angle has negligible overall effect [11]. The point angle can be defined as the angle between the extensions of the cutting edges onto a plane passing through the longitudinal axis of the drill-bit. Tool walking over bone surface can be prevented by point angle. Though cutting forces are profoundly influenced by chisel-edge design, it is related to the thrust forces. Besides the geometrical aspect of the drill tool [12], number of flutes also determines the velocity with which the removed chips coming out of the cutting area [13]. The chips take away the generated heat fraction. A rapid chip flow outside the flutes will reduce not only the overall quantity of heat transferred to the bone [14] but also decrease the extreme temperature in the drilling process. The helix angle also determines the cutting edge geometry as well as the fluted section geometry. It also has a significant influence on the temperatures [15]. The helix angle is related to both rake angle and torsional rigidity. High helical angle is always preferable as it provides easy and effective chip removal but high helical angle causes decrease of cross sectional area and this result in reducing the tool cross section and weakening of tool that can cause accidental failure of tool, which is a serious and non-expected happening during surgeries. Relief angle has a dominant influence on the degree of the maximum temperature rise during drilling of bone. When the supplementary parameters are retained constant, increasing the drill-bit diameter upsurges the quantity of heat generation, which outcomes in higher temperatures [16-17]. For the same cause, increasing the feed rate and individually the spindle speed [18] also increases the heat generated. Spindle speed contributes to heat generation in two ways; first it affects the friction rate and seconds the material removal rate. In some cases increased speed strengthened the thermal damage and stretched the healing time [19]. In other cases, the challenging effects of higher local heat generation and less heat transfer to the bone may cancel one another, resulting in heat generation independent of the cutting speeds [21].Though one could believe that lesser feed rate and slower spindle speed are constantly encouraging in decreasing thermal effects. Thermal conductivity value for bovine cortical bone is (0.56 W/m-K) and for drill bit it is (14 W/m-K). This causes more heat dissipation by tool material to the surrounding as compared heat dissipation by bone material. This effect is augmented when external coolant is provided.

The chip flow along the flute takes away the heat with itself from the cutting edge, acting as a cooling instrument. A greater feed rate leads to a quicker chip stream, with greater cooling abilities. It has
been stated in the earlier work that greater spindle speeds may cause in lesser temperatures and less thermal injury during bone drilling, because by this way the thermal exposure duration is shortened.

Figure 1. Drill tool geometry.

Along with tool geometry, drilling parameters like drilling speed, feed rate and related forces also play an important role in heat generation [22]. The noticeable forces are the thrust force and torque generated. Thrust force is the force generated due to pushing action of drill tool. Varying feed rate has linear effect on the thrust forces. The thrust force increases radically with the increase of feed rate. Increasing feed rate increases the thrust force more at higher speed compared to lower speed, the effect of changing feed rate is more important compared to cutting speed. The feed rate is provided manually and so it is sensed physically. This ground for flexibility to apply and divergence in the feed rate as per bone quality. [23]. Torque is the outcome of the interaction between rotating spindle and stationary bone. The torque is amplified with the increase of cutting speed.

3. Bone Substructures
Bone can be studied in hierarchical architecture of scale wise different five levels, as shown in figure 2. These are as follows:
(1) Cancellous and cortical bone is the categorisation at the macrostructure level.
(2) Haversian systems, osteons, single trabeculae are classified under the category of the microstructure level (from 10 to 500 μm);
(3) Lamellae are classified under sub-microstructure level (from 1–10 μm).
(4) Fibrillar collagen and embedded mineral are classified under the nanostructure level (from a few hundred nanometres’ to 1μm).
(5) Molecular structure of constituent elements such as mineral, collagen, and non-collagenous organic proteins are classified under the sub nanostructure level (below a few hundred nanometres’). Figure 2 explains bone substructure.

![Cross section of a bone.](image)

**Figure 2.** Cross section of a bone.

Cells are the basic entities that keep the bone alive. The growth, functionality of bone is due to cells. Three distinctly different cell types of bone are:

a) Osteoblast cells: These cells regulate the mineralization of bone.

b) Osteoclast cells: Resorption also involves release of calcium and repair of micro damage of bone from normal wear and tear.

c) Osteocyte cells: Osteocyte have important role to play in recruitment of the cells that form and resorb bone.

### 4. Effect of Temperature on Bone Tissue Substructure

Friction in between the drilling tool and bone surface causes heat generation. This heat affects the biological structure of bone to the extent that it loses biological functioning. This manifestation has deep rooted reasons that can be explained as:

1) Inactivation of enzymes: Enzymes can be described as biological polymers which act as catalysts to accelerate chemical reactions. These chemical reactions are responsible for conduction of metabolic processes or in other words we can say that metabolic processes and chemical reactions are directed by enzymes. All metabolic processes need enzymes to complete them at faster rate to sustain life. Enzymes found in all tissues and fluids of body and so regulation of enzymes is important to maintain life processes. Majority of enzymes are proteins and they are linear chain of amino acids. Enzymes in plasma membrane govern the catalysis in the cells. Upon enzyme inactivation, metabolic processes come to halt. Enzymes possess active sites. As shown in figure number 3, the molecule that binds to enzyme is called substrate.
The enzyme and substrate form an intermediate and in this way the chemical reaction is catalysed. In other words this can be quoted as:

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\text{Reactant (1) + Reactant (2) = Product} \\
\text{Reactant (1) + enzyme = Intermediate} \\
\text{Intermediate + reactant (2) = Product + enzyme}
\]

Enzymes require an optimum temperature and pH for their maximum activity. The temperatures range more than optimum alters the molecular structure of enzymes. Human enzymes can sustain up to 35-40°C. Temperatures more than this starts denaturation of enzymes and decreases their activity rate. Heating above certain temperature range makes the enzymes inactive.

As shown in figure number 4, for example, the ideal heat level for activity of enzyme for the considered three enzymes was 50°C, while the ideal pH was in the range of 5.0 [23]. At the above
mentioned ideal temperature, amylase activity observed was 9% at pH 5.0, while lipase activity was 5.33% and protease activity was 6.14%.

2] Denaturation of proteins: Denaturation is the process in which proteins lose the followings:
   a) Spatial arrangement of protein subunits
   b) Covalent interaction in amino acid side chains
   c) All regular repeating patterns like alpha helices.
   Common example of protein denaturation is upon heating, egg white is converted to opaque and solid mass.

3] Inactivation of metabolic process: Metabolism involves all biochemical reactions that maintain living conditions of cells in an organism. Inactivation of metabolic process causes death of cells i.e. necrosis happens.

4] Water vaporises causing dehydration of cell, even desiccation, shrinkage of cells and membrane rupture occurs.

5] Carbonisation.

5. Histopathological Approaches
During histopathology it is observed that, there is clear differentiation between the locations of empty vacuoles or lacunas after exposure to heat. A vacuole is a partition in cell filled with life fluid like water. The water contains the organic and inorganic molecules like enzymes. The size, shape and structure vary according to the requirement of cells. The importance of vacuoles varies with type of cell. The general function of vacuoles in animal cell includes containing water in cells, maintaining internal hydrostatic pressure within the cells, maintaining internal pH at acidic. This presence of water represents that the cell is alive. When temperature increases the symptoms like shrinkage of osteocysts cells due to evaporation of water are observed [24]. In some extreme situations even osteocysts density decreases with increase in temperature.

A number of innovative methods have been used by previous researchers regarding temperature estimations [25]. The balance between drill speeds, feed rate, drill tool diameter, depth of drilling in coordination with patient age can prove a key to achieve a necrosis free surgery, early healing and rehabilitation of patients. To control necrosis some researchers suggested temperature fixation during surgeries by improvements in features of orthopaedic surgical drill machine [26].

6. Conclusions
Anisotropic and viscoelastic properties of bone combined with drill tool geometrical aspects make bone drilling a unique environment. Bone is a biological entity and so its properties vary with individuals. The
difficulties of thermal necrosis and bone injury can be solved by observing the temperature level. Tool geometry has profound effect on occurrences of friction, chip removal rate and heat generation is the manifestation of these two factors. The study on tool wear also directs towards disturbed geometry and increased heat levels. Heat affected bone sub-structure studies reveals that external coolant supply can reduce the intensity and chances of thermal necrosis as compared to non-irrigated one.

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