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RESEARCH ARTICLE

A Study of Heat Generation in Orthopaedic Bone Drilling Process

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Reconstruction and repair of a complete bone fracture requires surgical drilling of bone in order to create holes which support easy insertion of screws. The objective of the research is to optimize kinematic parameters when drilling bone in order to avoid bone necrosis and increase the capacity of bones to retain the surgical screws. In literature there are presented attempts to measure the temperature of bones by introducing thermocouples into bone near the drill path which is not a satisfactory method. In this research it is proposed a new method for measuring temperature by means of a digital infrared thermometer oriented on bone surface where holes are made. We have drilled animal bones and represented the experimental curves of temperature for a wide range of kinematic parameters that are supposed to be used during orthopaedic operations. It is concluded speeds ranges that can be used when drilling bone holes, which ensures good cutting conditions and temperatures at a level which does not affect the quality of the assembly.

Keywords: orthopaedic surgery, surgical drilling, bone necrosis, temperature measurement, cortical screw

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Introduction

Bone fracture is common due to traumatic accidents or other causes. Broken bone produces cells that tend to reestablish connection between broken pieces. But the principal method for reconstruction and repair of a complete bone fracture is achieved by bone surgical drilling to create holes which support screws and pins easy insertion that allow adjacent bone fragments alignment, as well as application of fracture plates [1].

In current clinical practice, electrically-powered handheld drills are frequently used for bone drilling. This is somehow in contradiction with modern surgery where procedure can be conducted off-site by teleoperation [2], or drilling may be supported by haptic systems equipped with force and torque transducers [3], or with CO2 pulsed lasers [4].

In some situations depending on feed rates, mainshaft speeds, drill bit geometry and outer diameter, drill bit wear and type of bone nonoptimal forces and torques can be generated at interface between drill bit and bone which have the effect to raised temperatures that may cause bone necrosis and a poor quality of guide holes, resulting in poor screw fixation [5].

Thermal conductivity of cortical bone in body is located in the range of 0.64 ± 0.04 W/ mK for bovine cortical bone and 0.68 ± 0.01 W/mK for human cortical bone [6], which is quite poor. On the other hand it is not recommended to use a coolant during drilling because of the danger of causing infection to the area [7].

The phenomenon of high temperature generation is mainly due to friction between drill bit and bone likewise deformation of the bone, the bone chip being removed [8]. Even if the presence of blood fluids and tissues can dissipate some of the heat generated during drilling and chips can absorb some of the heat, the temperature that results at the cut edge of a cortical hole is significantly high [9]. About 40% of the heat generated is absorbed by treated bone while 60% dissipates in bone chips [10].

For these reasons, generation of high temperatures during drilling process becomes a problem due to the bone sensitivity to the temperature and the difficulty of evacuating temperature in the area [11].

The research purpose is to accurately measure the temperature at interface between cutting edge and bone surface when drilling bone, to determine variations of bone temperature during bone drilling depending on the geometric and kinematic parameters of the drill bit. The particular emphasis is to examine effect that temperature rise has on the bone structure physical aspect in order to optimize parameters which avoid bone necrosis and increase the bone capacity to retain a surgical screw.

Methods

We started the research from observations that the phenomenon of thermal generation may produce bone necrosis [12], especially if it is exceeded temperature of 45°C more than 5 hours, or temperature of 55°C more than 30 seconds, or even for a moment the temperature of 70°C [13,14].

Previous scientific research in literature indicates that for exceeding temperature of 55°C for longer than 30 seconds, the bone is severely damaged and recovery takes several weeks [15]. Consequently, temperature control at drill bite bone interface is a clinically relevant topic.

But, in the orthopaedic surgery temperature control at drill bite bone interface is not monitored. Orthopedic sur-

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geons usually use manual drilling machines, and adjust the mainshaft speed according to the surgical procedure performed. The drill advancement speed in the bone is subjectively controlled, depending on the surgeon's skill. One way to improve this process is by performing pre-operative BMD scans of the patient, which would allow for engineering predictions of kinematic parameters of bone drilling, supplemented with the use of manual drilling machines equipped with electronic display devices, which allow better control of kinematic parameters of bone drilling.

Because there is a great diversity of cutting geometries of the drill bit, in literature there is no consensus regarding influences generated by drilling forces, feed rate and rotational speed of the mainshaft on bone peak temperature [10].

In literature there are presented attempts to measure bones temperature by introducing thermocouples [16, 17, 18, 19] into the bone near the drill path, which give temperature indications as drill advances in hole. The research results concluded that cutting speed has a limited effect on temperature changes above 55°C, while the drill force which is driving drill bit causes a much higher temperature rise [20].

From literature it can be concluded that methods of measuring the temperature of drilled bone with thermocouples placed in cortical bone at a certain distance from drilled area have led to contradictory results without consent of researchers [11].

In conclusion, due to the bone structural inconsistency and its reduced conductivity, the heat transfer modeling is difficult and incorporation of thermocouples neighboring drilled area is not an effective way to investigate effects of high temperatures on bones.

In order to overcome this drawback and to develop a simplified method, easy to reproduce in laboratories, but with scientific relevance for research, in this study it is proposed a new method for measuring the temperature by means of a digital infrared thermometer oriented on the surface of the bone where holes are made. This allows real-time temperature measurement at hole surface and recording instantaneous temperature values.

After fitting thermometer properly with support of additional guidance devices, bone drilling experiments were performed on animal bones with cortical bone thickness of approx. 14 mm, which were obtained from a local slaughterhouse. These were kept before study in the freezer, wrapped in vacuumed plastic bags at temperatures that dropped below -20°C. Before experiment with more than 12 hours the bone specimens were removed from the freezer and kept on a flat surface in vacuumed plastic bags at room temperature. It was sprayed with saline water solution to prevent dehydration.

After that it was determined the drilling location. Bone specimens were mounting into a vice, the place where the hole was to be made was measured and it was drawn with a marker. Due to geometric and dimensional variability of biological bones, a common reference dimension has been established and calculated for all bone specimens. Thus relative position of the drilling site reported to one end of the bone was determined as a relative dimension 1/4,…,1/2%.

It was assembled the test setup for surgical bone drilling research. The vice rigidly hold bone specimens in proper position. Before actual drilling on the marked place it was created a point pressed which was later used for a good guidance of surgical drill bit during experiment. The bone was tight in vice with the point pressed on the axis of the drill bit chuck. The perpendicularity between the bone and drill bit axis was verified by means of a leveling gage. Then surgical drill bit was chosen which was used in drilling experiment. The choice was based on surgical procedure that requires a pilot hole, the type of the drilled bone, and the particular research question being asked about drill bit: drill bit diameter, drill bit geometry, etc. In our experiment we started from the raw data for hole drilling tests which evidence dimensions of the 4 screws that are usually used in orthopaedics (Table I, column 2) with thread diameter 1.5,…,4.5 mm. The drilling tests were performed with 4 drill bits of diameters 1.1 – 2 – 2.5 – 3.2 mm.

If hole length is same in the 4 situations, 14 mm, the Surface Area of the contact between drill bit and bone ($SA=\pi \cdot D \cdot L$) is computed in Table I, column 5. This allowed a normalization of the conditions for caring out testing.

Then the actual bone drilling experiment was conducted which led to the creation of pilot hole. The desired size drill bit was inserted in the chuck and positioned above bone specimen that was fixed in a vice at approximately 25 mm. After that, it was started the drilling process on the automatic drilling machine to which they were set feed rate and mainshaft speed within typical ranges used clinically.

Holes were practiced with a surgical drill whose rotation speed and feed rate were controlled by means of a professional drilling machine which allowed keeping constant the kinematic parameters of drilling. In the performed tests were used 4 speeds for mainshaft varying between 560,…,2,100 rotations/minute and 4 feed speeds between 0.5 and 2 millimeters/second. Drilling process was performed until drill bit reached the set depth. Then the drill bit was withdrawn to the starting position, drilling machine was stopped and bone was removed from the vice.

During the whole drilling process a digital infrared thermometer mounted on a support near vice measured temperature of bone during drilling (Figure 1). Temperature on thermometer was recorded on video, which allowed collection of results for later data analysis.

Table I. Raw data for hole drilling tests

No.	Thread diameter [mm]	Drill bit for threaded hole [mm]	Hole length [mm]	Surface Area [mm2]	Mainshaft speed [r/min]	Feed speed [mm/s]
1	2	3	4	5	6	7
1	1.5	1.1	14	48.35	560	0,5
2	2.7	2	14	87.92	900	1
3	3.5	2.5	14	109.9	1200	1,5
4	4.5	3.2	14	140.67	2100	2

Fig. 1. a. Experimental setup for drilling into bone; b. Temperature measurement in the guide hole during drilling; c. Temperature measurement in the guide hole after drilling

Pilot hole photos and videos, as well as bone fragments generated in drilling process, allowed examination of bone surface for evaluation if there is a change in color and if necrosis occurs.

Results

Variation law of drill diameter on bone temperature during drilling process was explored for speed of mainshaft 2,100 rot/min and feed speed 1.5 mm/s. Four drill diameters were used: 1.1 mm, 2 mm, 2.5 mm, 3.2 mm. The corresponding time-dependent variation curves of temperature are presented in figure 2.

From its analysis it can be seen that all four temperature variation curves have a ∧ shape during the drilling process. The maximal drilling temperature (the lowest) 36°C is accomplished earlier at 3 seconds for the 1.1 mm drill, while maximal drilling temperature (the highest) 47°C is accomplished later at 5 seconds for the 3.2 mm drill. This result reflects that bone temperature increases with incense of drill bit diameter if other drilling parameters are constant.

Variation law of mainshaft speed on bone temperature during the drilling process was explored for 3.2 mm drill under 0.5 mm/s feed speed. It was used four speeds of mainshaft: 560 r/min, 900 r/min, 1,250 r/min and 2,100 r/min. These kinematic parameters have been selected to exceed the speeds recommended in literature for bone drilling. The corresponding time-dependent variation curves of temperature are presented in figure 3.

From its analysis it can be seen that all four temperature variation curves have a ∧ shape during drilling process. After 15 seconds since drilling process started the maximal drilling temperature was achieved at measuring point. At same time for mainshaft speed of 560 r/min, 900 r/min, 1,250 r/min and 2,100 r/min the bone temperatures are 37°C,… , 45°C. This result reflects that bone temperature increases together with mainshaft speed if other drilling parameters are constant.

Variation law of feed speed on bone temperature was studied for a 3.2 mm drill bit diameter rotating with 2,100 r/min speed of mainshaft. It was explored four feed speeds: 0.5 mm/s, 1.0 mm/s, 1.5 mm/s and 2.0 mm/s. These val-

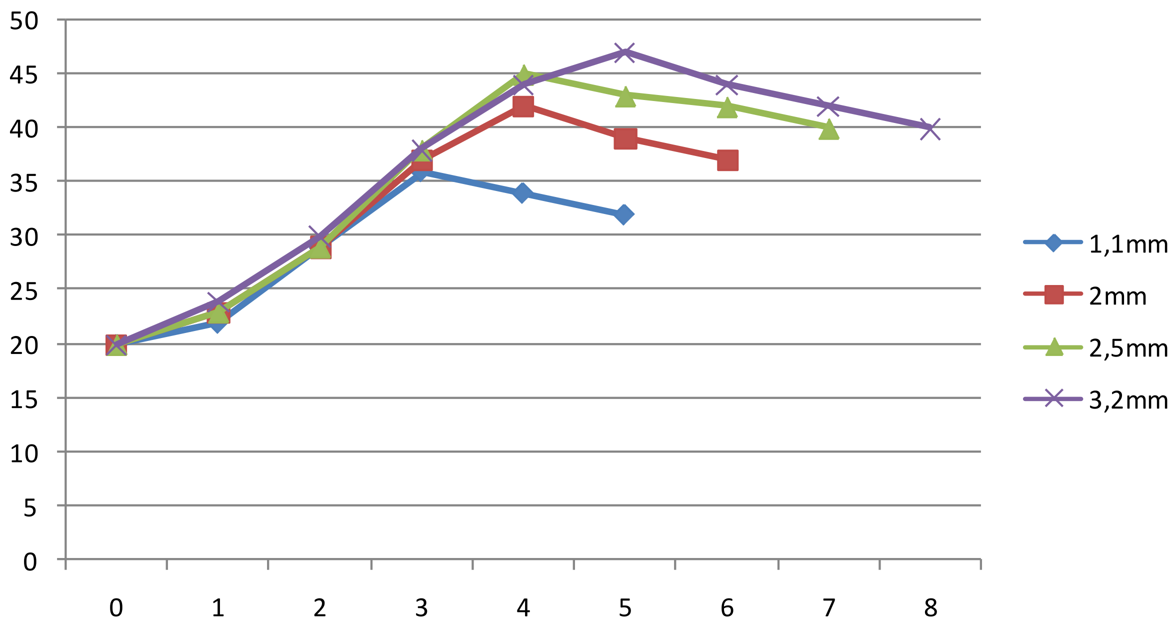

Fig. 2. The experimental curve of temperature change in bone versus time with different drill bit diameter for threaded hole (2,100 rot/min, 1.5 mm/s)

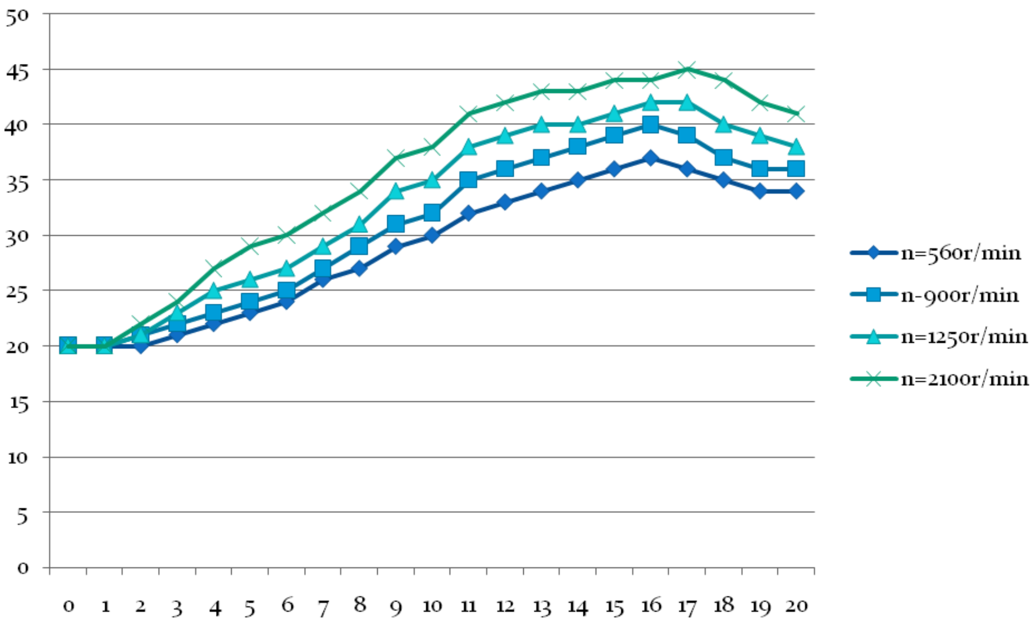

Fig. 3. The experimental curve of temperature change in bone versus time with different revolution (3,2 mm, 0.5 mm/s)

ues have been arbitrarily chosen over a wide range, because in orthopedic practice they are variable from surgeon to surgeon as drilling machine is manually controlled. The corresponding time-dependent variation curves of temperature are presented in figure 4.

From its analysis it can be seen that all four temperature variation curves, in first part of the drilling process, increase and then decrease. The maximal achieved drilling temperatures are 39°C,…,36°C. This demonstrates that drilling temperature and mainshaft feed speed is in an inversely proportional relationship.

Discussion

Orthopaedic surgeons use electrically operated drills and drill bit advancement is achieved empirically by skill. As a consequence, temperatures generated at contact between drill bit and bones are influenced by cutting parameters which may generate bone necrosis.

In order to study these influences we conducted in our research an experiment in which we performed hole drilling tests with 4 drill bits of diameters 1.1 – 2 – 2.5 – 3.2 mm and a wide range for kinematic parameters for the mainshaft speed 560,…,2,100 rot/min and feed speed 0.5,…,2 mm/s, that are usually used in orthopaedics.

The variation laws of bone temperature during bone drilling depending on geometric and kinematic parameters of drill bit reveal increase with drill bit diameter and the mainshaft speed but also decrease with feed speed. This can be an important observation with clinical relevance for orthopaedic surgeons when selecting these parameters.

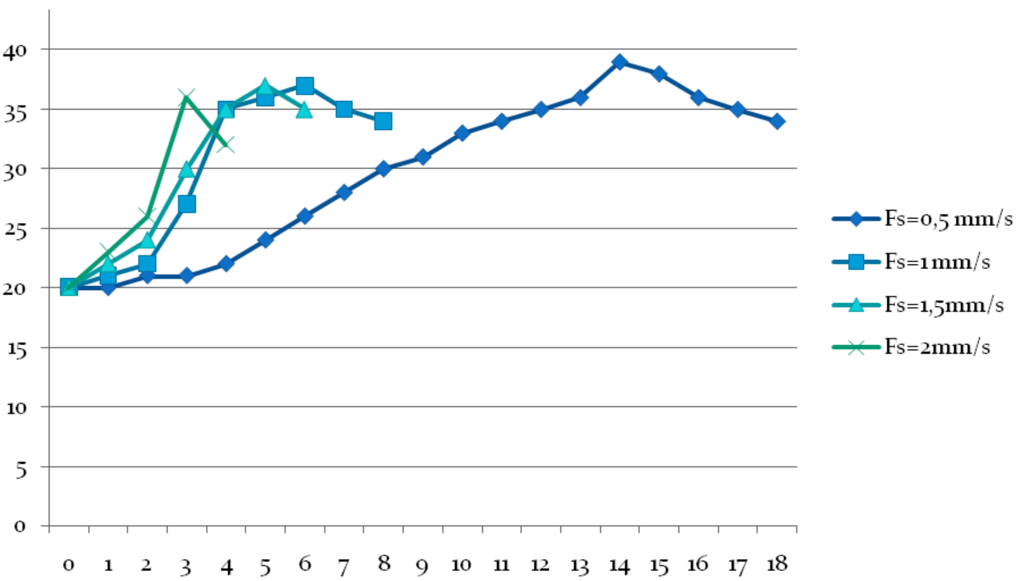

Fig. 4. The experimental curve of temperature change in bone versus time with different feed speeds (d=3.2 mm, 2,100 r/min)

The variation law shapes of various kinematic parameters as function of bone temperature during the drilling process: drill diameter, mainshaft speed, feed speed are of equivalent forms with similar studies [13, 16, 18] but with slightly different values of the measured temperatures, usually 10% lower due to the different conditions and limitations in which each of these studies was performed.

The proposed method employing a digital infrared thermometer is validated in practice, being able to measures bone temperature during drilling and predicts if raised temperature may cause bone necrosis.

Process optimization requires preoperative BMD scans of patients to allow engineering predictions about appropriate drilling parameters: drill bit diameter, speed of mainshaft and feed speed.

The study limitations occur because temperature is measured at bone surface. Inside it can be higher and further study is needed to determine temperature gradient in the vicinity of drilling wall as a function of bone surface temperature and its BMD characteristics. In this way a correction coefficient can be deduced for measurement of temperature inside the bone. Another limitation of the study is that bone drilling experiments were performed on devitalized animal bones. In vivo, the biological conditions are slightly different, for example, the blood flow may influence the local temperature.

Conclusion

In these circumstances we can conclude that temperature generated when cutting hole, has high values being located within the limits presented in literature, without visibly affecting the hole bone area and compromising cortical screw assembly.

It can be concluded that speeds of 560,…,2,100 r/min can be used when drilling holes with diameters of 1.1,…,3.2 mm, which ensures good cutting conditions while temperatures are at a level which does not affect quality of screw assembly.

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Authors' contributions

FM (Data curation; Investigation; Methodology; Writing – original draft)

TB (Conceptualization; Formal analysis; Supervision; Validation; Writing –
review & editing)

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