Temperature control with internally applied cooling in solid material drilling: an experimental, biomechanical study

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Abstract

Purpose The purpose of this study was to evaluate the different temperature levels while drilling solid materials and to compare different cooling solutions for possible temperature control. An additional purpose was to develop an internal cooling device which can be connected to routinely used manual drilling devices in trauma surgery.

Methods Drilling was performed on a straight hip stem implanted in bovine femora without cooling, with externally applied cooling and with a newly developed internal cooling device. Temperature changes were measured by seven thermocouples arranged near the borehole. Additionally, thermographic scans were performed during drilling.

Results Drilling without cooling leads to an immediate increase in temperature to levels of thermal osteonecrosis (over 200 °C). With externally applied cooling temperatures were decreased, but were still up to a tissue damaging 85 °C. Internally applied cooling led to a temperature decrease to tissue-preserving levels during the drilling procedure (24.7 °C).

Conclusion Internal cooling with HPC-drillers lowered the measured temperatures to non-tissue damaging temperatures and should avoid structural tissue damage.

Introduction

Drilling is a cutting process in solid material such as bone. Drilling into the bone is indispensable in most common techniques of osteosynthesis. The drill bit is a multipoint, end-cutting tool. A feed force and a rotation of the drill bit are necessary for the cutting process. The friction between the drill bit and the material produces heat. This heat can damage the cells as well as the extracellular matrix of the bone. The impact of drilling on the bone has been investigated in several studies [1, 2]. Devitalisation of the bone tissue begins at temperatures of 47 °C and exposure time of 60 seconds [2–7]. The stability of the osteosynthesis is reduced in thermally damaged bone tissue possibly due to reabsorption phenomena around the screws [8].

Several studies have been published about reduction of temperature and its impact on the bone. Intraoperative drilling of the bone and an additional implant may be necessary in some revision procedures such as removal of broken or cold-welded implants. Much higher temperatures are estimated with consequent damage to the bone. Drilling into solid materials such as standard hip prostheses can raise the temperature up to 520 °C in steel [9] or 604 °C in titanium. Our motivation for further investigations in this area arises from an idea to invent a so-called prosthesis drill that enables the surgeon to fix screws into the stem of a prosthesis. This intraprosthetic fixation system could be used in the treatment of periprosthetic fractures. One crucial step in the development process is the reduction of the drilling temperature by developing an internal cooling system [10]. The goal was to reduce the drilling temperature by using a drill with two spiral channels through the tip of the drill for application of the cooling solution.

We anticipated achieving a sufficient temperature reduction by using so-called HPC-drillers (high-performance-cutting) and continuously applying internal cooling. Second,

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Fig. 1 HPC-drill with cooling channels through the tip

we postulated that the temperature decrease would be superior to manually applied external cooling. Furthermore, we expected to achieve temperatures compatible with the preservation of vital tissue even when the drilling solid materials.

Materials and methods

Drilling machine

To test the drilling temperatures without cooling or with externally applied cooling, we used an HSS-E driller (high speed steel; diameter 5.5 mm) (test groups one and two).

An HPC-driller with a custom made internal cooling system was used for the third test group. The channels for the cooling solution were made through the tip of the drill (Fig. 1).

Drillers were mounted on a routinely used testing device with a manually fitted feed force.

Specimen preparation

A standard hip prosthesis (Aesculap type excia with plasmapore coating, basic material TiA16V4 isotan; Tuttlingen, Germany) was implanted into bovine femora. Implantation was secured by using bone cement (Biomet, Warsaw, USA).

In the next step a standardised stationary test design was constructed using an HSS-E drill with a diameter of 5.5 mm (Fa Perschmann 116070, Munich, Germany) and a rotational speed of 500 min⁻¹. The feeding force was manually fed to the driller.

Finally, the construction was integrated into a standardised testing device (Spider 8, Hottinger Baldwin, Darmstadt, Germany) (Fig. 2).

Seven thermocouples were installed to measure temperature development during the drill process. Of these, four thermocouples were placed at 1-mm distance from the drill hole at the surface of the implanted prosthesis to measure boundary temperature development between implant and bone tissue during the drilling procedure. The other three thermocouples were placed horizontally at a distance of 3 mm to each other near the drilling hole to measure temperature development at the boundary between driller and bone tissue (Fig. 3). Placement of the thermocouples was marked with a laser and fitted manually.

Testing procedure

The drilling procedure was performed by using either the 5.5-mm HSS-E drill or a HPC-drill and a drilling time of ten seconds plus an additional 120 seconds to pass through the implanted prosthesis. The drilling procedure was

Fig. 2 Standardised test design for temperature tests

Fig. 3 Arrangement of thermocouples and experimental setup

performed once in each group. Temperature rise at the seven thermocouples was measured. Additionally, thermographic scans were performed using a thermographic camera (Flir Thermacam, thermic sensitivity 0,02 K; Wilsonville, USA). The drilling process and temperature measurement were performed without internal or external cooling, with external cooling and, finally, using an HPC-driller with an internal cooling system. Outcome data were compared first by results from thermography and thermocouples and second by Lundskog-function as a measure for tissue damage.

Developing an internal cooling system for hand drills in trauma surgery

For internal cooling systems, a pressure of six bars is required to ensure permanent volume flow, although the flow required for sufficient internal cooling is not yet known [10]. None of the routinely used laboratory pumps can produce the required pressure. It was necessary to develop a pressure-producing cooling system using sterile saline solution and compatible with surgical hand drills.

This was achieved using a pressure vessel into which sterile pack of saline solution was inserted. Next, the opening of the inserted saline pack was pressed into a flat seal using a pressure spring. This pressure vessel was filled with

compressed air using the standard compressed air connection in the operating room (Fig. 4) [11].

Finally, this cooling device was modified for use with routinely available hand drillers in trauma surgery (Power Drive, Synthes; West Chester, USA) (Fig. 5).

Results

Drilling without external cooling

The drilling process took ten seconds for the bovine femur diaphysis and a further 120 seconds to pass through the implanted hip prosthesis. Thermocouples registered a fast increase in temperature with a maximum of 250 °C measured at the thermocouples T1 and T4 nearest to the implant. At the drill hole surface at a distance of 1.6–2.0 mm to bone tissue, there were still temperatures up to 100 °C (thermocouples T 5,6,7) (Fig. 6). This temperature increase was due to the swarf produced during the drilling procedure.

Thermographic scans of intraprosthetic drilling without any external cooling showed a continuous increase in temperature during the drilling process. It is known that with the use of any type of cooling irrigation surface temperatures measured by thermography are not meaningful [12]. At the interface between bone and implanted prosthesis, there was an

Fig. 4 Temperature trend without external or internal cooling (T1-T7: Thermocouples)

Fig. 5 Thermographic scan and experimental setup

increase in temperature from 90 °C at a distance of 20 mm from the driller core to 150 °C at driller core. At the axis of the driller, temperature increased to 190 °C (Fig. 7).

Drilling with external cooling

In the next step, the drilling process was performed using external cooling with saline solution as usually performed during surgery. Measured temperature increase was slower and lower in comparison with the drilling without external cooling, and reached maximum temperatures up to 85 °C at thermocouples T1 and T4 (Fig. 8). External cooling led to a decrease of drilling temperature to 60 °C at the drill hole surface.

Drilling with an internal cooling system using HPC-driller

The main advantage of HPC-drillers (high performance cutting) is the direct transfer of cooling materials to the point of drilling at the tip of the driller. Cooling materials are injected to the removal materials process—avoiding

surplus. Saline solution was used as cooling material and was transferred into the HPC-driller at a pressure of 6 bars. HPC-drillers require a special fitting with a rotary transmission for liquids to transfer the cooling material. The pressure applied is up to 25 bars.

For this experiment, an HPC-driller (5.5-mm diameter) with reinforced core and a high level of concentricity was used. The cooling material transfer occurs via spiral channels in the drill. Using the WJC-procedure (water jet cutting), an external channel to the internal cooling systems was installed. An external water tank as cooling solution with a pressure of 6 bars was fitted. The cooling solution was at room temperature; the volume flow was 14.1 ml/s. The WJC-procedure uses a suspension of solid materials added to the water jet cutting.

Temperature progressions using an internally cooled driller showed an effective suppression of rapid temperature increases occurring in the groups with external cooling or without cooling. The observed maximum temperature at implant surface was 24.7 °C (Fig. 9).

Lower pressures or volume flows were not compared in this study.

Statistics

Significant differences were found between all tested groups. The group with internal cooling was superior to both other groups ($p = 0.0001$ compared to group without external cooling and $p=0.0003$ compared to group with external cooling, *t*-test). There was also a significant difference between drilling with and without external cooling ($p = 0.0139$, *t*-test) (Fig. 10).

Discussion

This study was performed to compare temperature differences with different drilling methods and with or without cooling. The focus was on drilling solid materials.

Fig. 6 Temperature trend with external cooling (T1–T7: thermocouples)

Fig. 7 Temperature trend with HPC-drillers and internal cooling (T1–T6: thermocouples; T_{imp} temperature at implant surface)

Drilling solid materials such as bone is necessary in all kind of osteosyntheses. The goal of our experimental study was to evaluate different application techniques of cooling whilst drilling solid materials. The clinical background was to evaluate different drilling methods for the feasibility of intraprosthetic screw fixation in the treatment of periprosthetic fractures of the proximal femur.

Our results showed an effective suppression of temperature increase using continuous internally cooled HPC-drillers. In contrast to drilling without cooling or drilling with externally applied cooling, temperatures never passed vital tissue damaging levels.

Our results show that even at the thermocouples with the lowest temperature the limits for irreversible tissue damage as described by Fuchsberger et al. [1] were surpassed immediately when drilling without cooling.

External cooling led to a decrease of drilling temperature to 60 °C at the drill hole surface. But the results during the hole drilling procedure into the implant proved that external cooling was not sufficient to

lower the drilling temperature to secure vital bone tissue. Especially when drilling into the implant and during removal of swarf, the application of external cooling was insufficient. Due to the fact that externally applied cooling is limited to the surface of bone tissue this cooling system is unsuitable for intraprosthetic drilling.

Overall, due to the necessary extension of drilling time the temperature increased even near the borehole to potentially tissue damaging levels.

Temperature progressions using an internally cooled driller showed an effective suppression of rapid temperature increases. The maximum temperature at the implant surface was 24.7 °C. Due to the higher thermal conductivity of bone tissue compared to bone cement, the maximum temperature was reached earlier in bone than in the bone cement, despite the thermal insulating function of the bone cement.

Fig. 8 Graphical illustration of temperature trends

Fig. 9 Internal cooling device for intraprosthetic drilling

Fig. 10 Power Drive® (Synthes) manual drilling system with HPC drill and internal cooling system

Overall, the analysis of the temperatures measured at the borehole and at the implant surface exclude thermal damage to the surrounding vital tissue (Fig. 7).

The most important finding of our study was the decrease in drilling temperature to the vital tissue preserving level using continuous internal cooling.

Earlier investigations have shown a reduction in drilling temperature by external cooling and high feed forces [13–17]. Another study indicated an increase in drilling temperature when using a blunt drill. Matthews et al. demonstrated a reduction of drilling temperature by increasing feed forces as the most important factor for heat development during drilling [18–21]. With a gain of the feed forces by 20 N to 120 N, they achieved a temperature reduction from 80 °C to 50 °C and a reduction of drilling time. Also, increasing the rotational speed during drilling showed temperature reduction [21]. Augustin et al. described the pathophysiological changes drilling heat causes in cortical bone and presented a complete review of current literature focusing on important drill parameters [22]. Osteonecrosis as a dynamic process is caused by drilling heat of 47 °C and a drilling time of one minute leading to a denaturation of enzymatic proteins [22].

Furthermore, we were able to transfer the custom-made HPC-driller to a routinely used manual drill-machine in trauma surgery.

The main study limitation is whether our briefly outlined idea of intraprosthetic screw fixation is useable in the future. Drilling into a medical product nullifies the product liability. On the other hand there remains a need for new techniques to handle a growing number of periprosthetic fractures with a stable implant. Our technique could lead to an increase in primary stability and earlier weight bearing which would reduce the mortality and morbidity.

Another question is whether drilling into an implant weakens the structure of the primary prosthesis. This will be part of our ongoing investigations and part of the design of the next experimental study.

Furthermore, despite achieving adequate temperature reduction with internally applied cooling, lower pressures or

volume flows of the cooling solution were not compared in this study. This will also be part of our ongoing investigation.

To summarise, this study shows a possible reduction of drilling temperature to vitality preserving levels with a new tool offering continuous internal cooling while drilling solid materials.

Conclusion

Externally applied cooling is insufficient to decrease the measured drilling temperature at the implant/bone tissue surface and cannot avoid structural tissue damage.

Internal cooling with HPC-drillers lowered the measured temperatures to non-tissue damaging levels. Integrated into routinely used hand drillers in trauma surgery, internally applied cooling seems to be the method of choice when it comes to drilling at implant surfaces.

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