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ORIGINAL PAPER

Temperature changes during cortical bone drilling with a newly designed step drill and an internally cooled drill

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Abstract
Purpose Bone drilling causes an increase in bone temperature, and a temperature above 47°C is critical because it causes thermal bone necrosis. Thermal osteonecrosis is common with the drill diameter of ≥4.5 mm without cooling. The aim of this study was to determine the increase of bone temperature during drilling using newly contructed two-step and internally cooled drills.
Methods An experiment was set up according to a central composite design. An internally cooled drill (3.4 mm and 4.5 mm) and a two-step drill (2.5/3.4 and 3.4/4.5 mm) were used in combination with feed rates of (0.02, 0.04, 0.10, 0.16 and 0.18 mm/rev) and cutting speeds (1.18, 10.68, 33.61, 56.55 and 66.05 m/min) with and without cooling with water of 24°C. Bone temperatures were measured with thermocouples. Drilling was performed on pig diaphyses with a three-axis mini milling machine.
Results Bone temperatures in all combinations of parameters with internal cooling were below the critical 47°C ($p=0.05$). The highest temperatures were detected using a 4.5-mm drill (40.5°C). A statistically significant effect other than cooling was found with the drill diameter and feed. A drill diameter of 3.4 mm with internal cooling developed a maximum temperature of 38.5°C and without cooling 46.3°C. For the same conditions a drill with diameter of 4.5 mm reached temperatures of 40.5°C and 55.7°C, respectively. The effect of feed rate is inversely proportional to the increase in bone temperature. With the feed rate 0.16 mm/rev, temperature was below critical even using the 4.5-mm drill (46.4°C, $p=0.05$). Using the 3.4-mm drill all temperatures were below critical (46.2°C,

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$p=0.05$). The two-step drill compared to a standard drill with the same diameter did not show statistical differences in maximum bone temperatures for all combinations of parameters ($p=0.05$).

Conclusions A two-step drill does not have any advantages over a standard twist drill of the same diameter. An internally cooled drill causes a significantly smaller increase of bone temperature during drilling with water of 24°C. An internally cooled drill is currently the 'ideal' drill for traumatology/orthopaedics because it produces the smallest increase in bone drilling temperature. If internal cooling is used the regulation of other drilling parameters is of no importance.

Introduction

Drills are used as a common step in operative fracture treatment and reconstructive orthopaedic surgery. The heat generated from the metal–bone interface during drilling due to the friction can cause thermal osteonecrosis. The lowest temperature threshold for thermal osteonecrosis is 47°C for one minute [1].

The most important drill and drilling parameters on bone temperature rise are: drilling depth, drill flute geometry and design [2], sharpness of the cutting tool [3, 4], variations in cortical thickness [5], bone density [6], drilling speed, axial force, i.e. pressure applied to the drill [3], use of graduated versus one-step drilling [7, 8], irrigation [9, 10], equipment [11], torque and thrust forces [12]. Most could be varied, but some, such as drill diameter, depend on the biomechanics of specific bone. A drill diameter of 4.5 mm causes the highest increase in bone temperature commonly over the critical temperature of 47°C [9].

The aim of this study was to investigate the bone temperature increase using newly designed spiral drills: a (two)-step drill and an open type of internally cooled drill with the aim to lower the bone temperature below critical even with a 4.5-mm drill.

Methods

Experimental setup

Porcine femura best resemble human samples [13] and were used immediately or within a few hours after the slaughter. To retain the mechanical and thermo-physical properties, specimens not used within a few hours were prepared according to Sedlin and Hirsch [14], i.e., the specimens were kept moist in saline solution and stored in plastic bags at −10°C and used within two days of slaughter. All specimens were males eight to ten months old and 80–90 kg of weight. Femoral diaphyses of hind legs in the length of 75 mm were used with the cortical thickness of 4–5 mm. The periosteum was reflected to prevent the chips being forced under this tissue and clogging the flutes of the drill [12]. Measurements were made on a three-axis mini milling machine, *Flexmatic FA 530 S*, enclosed in a thermally isolated chamber with air and bone temperature maintained at 37°C with a heater *Budget FH 2000* and temperature regulator *Omron E5CS-X*. Temperature was measured with thermocouples *Unitest Therm 100* (range −40 to 1,200°C, reaction time under 0.1 s and accuracy of 0.1°C). The distance between the drilling and thermocouple site was 0.5 mm, and the depth of thermocouple was 3 mm [3, 9, 15, 16]. Two other thermocouples were placed near the drilling site and 50 cm from the drilling site and connected to a data acquisition modular station *National Instruments NI SCXI-1000 DC*. The software programmed in *LabView* had instructions that subsequent drilling could not start until bone temperature was between 36.5 and 38°C and air temperature was between 35 and 39°C in both thermocouples. The cortical temperature was recorded throughout the process of every drilling. Therefore initial bone temperature, maximum bone temperature and time that the temperature was greater than 47°C were recorded. The cooling system consisted of a cooling fluid reservoir with water of 24°C, a motor pump, laboratory voltage source *Labornetzgerät DF-1730B* and a tube connected to a rotor of the main spindle enabling cooling through the tool. Cooling fluid flow was low and constant (0.1 dcl/min=0.16 cm^3/s). The complete process is shown in Fig. 1 and the software in Fig. 2.

Drills tip wear (cutting lips wear) was analysed using macro photography after every 45 drillings of each drill (Olympus E-330, Zuiko Digital 35 mm 1:3.5 Macro, Olympus Macro Flash FS-RF11).

Determination of the drill and drilling parameters

According to the three-level central composite design there were five values of feed (0.02, 0.04, 0.10, 0.16. and 0.18 mm/rev) and cutting speed (1.18, 10.68, 33.61, 56.55 and 66.05 m/min). A drill diameter of 4.5 mm was used causing the highest bone temperatures in previous studies [9]. The other drill diameter was 3.4 mm. The two spiral two-step drills have larger diameters which were the same as the standard spiral drills (2.5/3.4 mm and 3.4/4.5 mm). Drills were made of hard metal, e.g. tungsten cobalt carbide (TM, Čakovec), with two spiral channels through the drill with openings on the drill tip (Fig. 3). Drillings were made with and without internal cooling with water of 24°C.

Statistical analysis

Due to a cut-off temperature of 47°C maximum temperature values were analysed ($p=0.05$) using licenced Statistica 6.1 (StatSoft). Duncan's multiple range test was used for comparison of different combinations of parameters. Regression

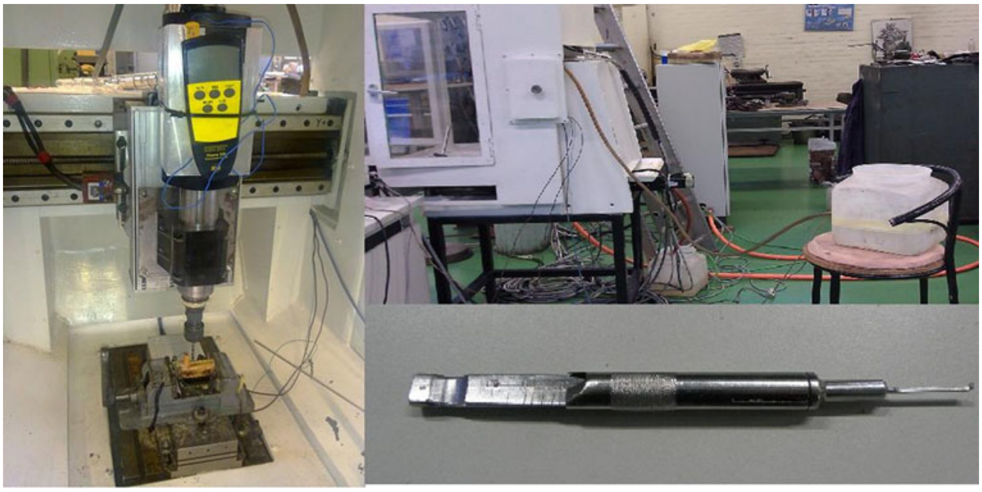

Fig. 1 Complete process of bone drilling and bone temperature measurement. Porcine femoral diaphyses of the hind legs of 75 mm length were used. The maximum bone temperatures during drilling were measured with the thermocouple at a distance between drilling site and thermocouple site of 0.5 mm. All measurements were made on a three-axis mini milling machine, *Flexmatic FA 530 S*, enclosed in a thermally isolated chamber where the air and bone temperatures were maintained at 37°C. The cooling fluid of water at 24°C went through the tool. Cortical thickness was measured with a depth gauge for screws (Synthes, Switzerland)

analysis was used to delineate the strength of relationship between specific parameters and the increase of bone temperature. Partial correlation was used to determine the correlation of two variables (drill parameters) with influence on the third (bone temperature). Regression analysis was used for the correlation between the maximum temperature during single drilling and time period of bone temperature above 47°C.

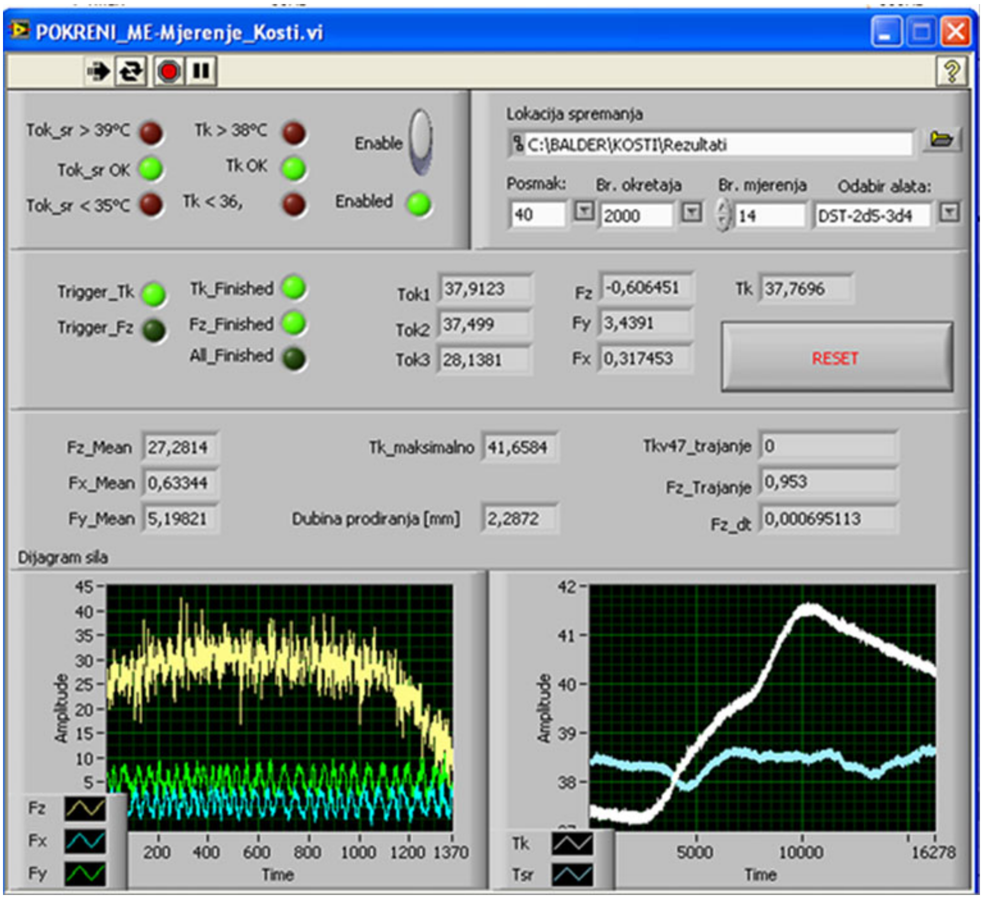

Fig. 2 Specific software developed and programmed in *LabView* providing equal and standardised conditions for every drilling (see text for details)

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Posmak: 40

Br. okretaja: 2000

Br. mjerenja: 14

Odabir alata: DST-2d5-3d4

Tok1 37,9123

Tok2 37,499

Tok3 28,1381

Fz -0,606451

Fy 3,4391

Fx 0,317453

Tk 37,7696

Fz_Mean 27,2814

Fx_Mean 0,63344

Fy_Mean 5,19821

Tk_maksimalno 41,6584

Dubina prodiranja [mm] 2,2872

Tkv47_trajanje 0

Fz_Trajanje 0,953

Fz_dt 0,000695113

Fig. 3 Two-step drill with diameter of 4.5 mm and channels through the drill with openings on the tip where cooling fluid exits

Results

At $p=0.05$ internal cooling is the most influential parameter (F=1626.3), followed by significantly smaller influence of the drill diameter (F=15.30) and feed (F=8.87). Influence of other parameters was not significant ($p > 0.10$) (Table 1).

Using internal cooling, maximum temperatures for all combinations of parameters using all drills were well below 47°C (39.5°C; $p=0.05$) (Table 2). Developed temperatures were comparable and near starting bone temperature (38.1–40.5°C) despite the influence of other parameters (Table 3).

Drill diameter is the second most influential parameter (Table 1). Drills with smaller diameter (3.4 and 2.5/3.4 mm) developed lower bone temperatures (46.9 and 47.8°C) in comparison to larger diameter (4.5 and 3.4/4.5 mm) drills (54.0 and 53.3°C) (Table 2). The only combinations of drilling parameters for larger diameter drills generating temperatures below critical included feed 0.16 mm/rev (Table 3). The Duncan test confirmed significant difference in bone temperature between drills with smaller and larger diameters, while there was no difference between different drill bit geometries of the same drill diameter.

Less increase in bone temperature is found with the increase in feed. The lowest bone temperatures were with feed rates of 0.16 mm/rev (46.4°C), and the highest (58.7°C) with the lowest feed of 0.02 mm/rev, $p=0.05$ (Table 2). The Duncan test confirmed that bone temperature is significantly different between feed of 0.02 mm/rev and all higher values and feed of 0.04 mm/rev and other higher values. There was no significant difference between feed of 0.10, 0.16 and 0.18 mm/rev.

Table 1 Influence of specific parameters on increase in bone temperature

Bone temperature (°C)					
Parameter	SS	Degrees of freedom	MS	F	*p*
Cooling	11606	1	11606	1626.3	<0.001
Drill diameter	1008	3	336	15.30	<0.001
Feed	791	4	198	8.87	<0.001
Cutting speed	57	4	14	0.61	0.655
Drill geometry	0	1	0	0.01	0.930

SS sum of squares, *MS* mean square, *F* indicator of influence

Table 2 Descriptive statistics for the variable *Temperature (with and without cooling)* for each combination of parameters (in °C)

Parameter	*N*	MV±SD	*p* =0.05*
Cooling			
Without cooling	360	45.5±3.6	52.7
With cooling	360	37.5±1.0	39.5
Drill geometry			
Standard	360	41.5±4.9	51.1
Two-step	360	41.5±4.8	50.9
Drill diameter (mm)			
3.4	180	40.2±3.4	46.9
4.5	180	42.9±5.7	54.0
2.5/3.4	180	40.5±3.7	47.8
3.4/4.5	180	42.5±5.5	53.3
Feed (mm/rev)			
0.02	80	43.8±7.6	58.7
0.04	160	42.3±5.2	52.4
0.10	240	41.4±4.3	49.8
0.16	160	40.3±3.1	46.4
0.18	80	40.7±3.7	47.9
Cutting speed (m/min)			
1.18	80	41.5±4.7	50.8
10.68	160	41.2±4.4	49.9
33.61	240	41.9±5.6	52.8
56.55	160	41.4±4.3	49.9
66.05	80	41.4±4.2	49.5

N number of measurements, *MV* mean value, *SD* standard deviation

* 95% upper level of confidence

Table 3 Descriptive statistics for the variable *Temperature (with and without cooling)* with all combinations of parameters (in °C)

Parameter	*N*	Cooling		No cooling	
		MV±SD	*p*=0.05	MV±SD	*p*=0.05
Drill geometry					
Standard	180/180	37.5±1.2	39.8	45.5±3.7	52.9
Two-step	180/180	37.5±0.9	39.1	45.5±3.6	52.5
Drill diameter (mm)					
3.4	90/90	37.0±0.8	38.5	43.4±1.5	46.2
4.5	90/90	38.1±1.2	40.5	47.7±4.1	55.7
2.5/3.4	90/90	37.3±1.0	39.3	43.8±2.4	48.5
3.4/4.5	90/90	37.7±0.6	38.9	47.3±3.6	54.4
Feed (mm/rev)					
0.02	40/40	37.4±0.8	39.0	50.1±5.9	61.6
0.04	80/80	37.5±0.9	39.3	47.0±2.8	52.4
0.10	120/120	37.4±1.0	39.4	45.3±2.3	49.8
0.16	80/80	37.5±1.1	39.8	43.1±1.7	46.4
0.18	40/40	37.7±1.2	40.0	43.7±2.9	49.3
Cutting speed (m/min)					
1.18	40/40	37.0±0.6	38.1	46.0±1.9	49.6
10.68	80/80	37.4±0.8	39.0	45.0±3.2	51.2
33.61	120/120	37.6±1.0	39.6	46.2±4.9	55.7
56.55	80/80	37.6±1.2	40.0	45.1±2.9	50.7
66.05	40/40	37.7±1.1	40.0	45.0±2.5	49.9

N number of measurements (cooling/no cooling), *MV* mean value, *SD* standard deviation

Cutting speed (1.18–66.05 m/min) has no significant influence on bone temperature in the combinations of drill and drilling parameters used ($p>0.05$) (Table 1), generating bone temperatures in a narrow interval (49.5–52.8°C; $p=0.05$) (Table 2). The Duncan test showed that there was no significant difference between any pair of cutting speed values.

Drill geometry (standard spiral and two-step spiral drills) had no significant influence on increase in bone temperature using the same drill diameters (Tables 1 and 2), and also separately with and without cooling. In the cooling group bone temperatures were well below critical for both standard spiral and two-step spiral drills (39.8 and 39.1°C; $p=0.05$) (Table 3). Without cooling, bone temperatures including both drill geometries and diameters were above critical (52.9 and 52.5°C; $p=0.05$) (Table 3).

Regression analysis showed significant correlation between maximum bone temperature (over 47°C) and duration of bone temperature above 47°C ($p<0.05$). According to 95% prediction interval, a bone temperature of 47°C will last (mean value) for 11 seconds (39 seconds with 95% of upper confidence interval). A bone temperature of 50°C will persist above 47°C for a mean of 21 seconds (50 seconds with 95% of upper confidence interval) (Fig. 4).

Drill tip wear (cutting lips wear) analysed using macro photography did not reveal even the slightest wear after 180 drillings (Fig. 5).

Discussion

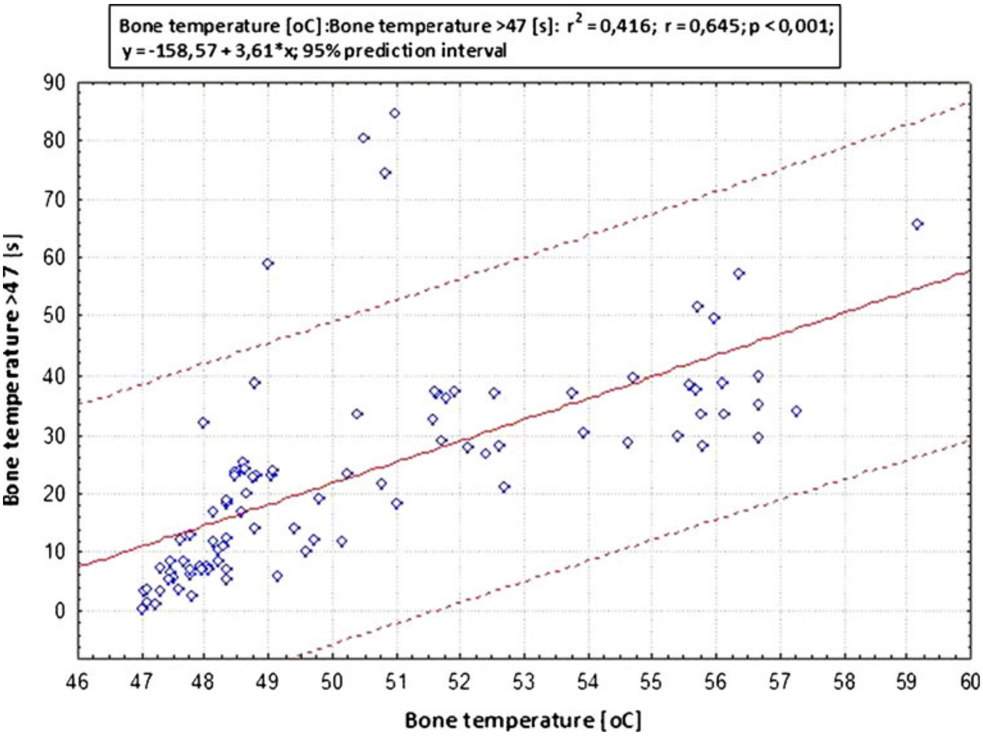
The drill bit is a complex tool whose various elements allow efficient penetration through bone but with the unavoidable side-effect of generating heat. Heat causes an increase in bone temperature and values over 47°C for minute cause thermal osteonecrosis [1]. This leads to loosening of screws and implants leading to implant failure and/or refractures. Therefore, optimal cutting parameters are necessary to minimise the increase in bone temperature [17].

Newly constructed carbide spiral drills with channels through the drill and two-step drills with channels were analysed. Despite different geometry influence of drill and drilling parameters confirm the results from previous studies. A drill diameter of 4.5 mm is critical in causing temperatures over 47°C [9]. Only combinations with a feed rate of 0.16 mm/rev caused temperatures below critical. Therefore if this feed cannot be maintained, irrigation of a 4.5-mm drill is mandatory. Also if such feed cannot be obtained, the highest possible should be used. The same recommendation is for the 3.4/4.5-mm drill. Bone temperatures using smaller diameter drills (3.4 mm and 2.5/3.4 mm) with higher feed (0.10–0.18 mm/rev) are below critical. Lower feed means higher total amount of bone cuttings (more layers cut). Cutting of every layer causes friction with more heat generation and higher increase in bone temperature. A carbide drill is extremely hard and bone as a material does not have a significant resistance to cutting. Therefore a lower total number of cuttings is necessary to form a bore. For other drill materials experiments are needed to define the relationship between feed and increase in bone temperature because it is drill-material dependent.

The drill bit of carbide drills efficiently cuts the layers of bone at every cutting speed causing the same heat generation and the same increase of bone temperature. Inefficient cutting occurs when extremely low cutting speed is combined with extremely high feed. These combinations used in this study are extremes and not applicable in clinical practice.

The result for discussion is that using both drill geometries and drill diameters the bone temperatures increase using a feed of 0.18 mm/rev. Feed of 0.18 mm/rev is extremely high and currently not applicable in clinical practice. One explanation is that axial drill motion is higher than effective cutting of bone layers making the drilling less efficient. Therefore the chips are not removed by cutting

Fig. 4 According to the regression line and prediction interval a bone temperature of 47°C will last (mean value) at that temperature for 11 seconds (39 seconds with 95% of upper confidence interval). A bone temperature of 50°C will be above 47°C for a mean of 21 seconds (50 seconds with 95% of upper confidence interval)



but by bone tearing and a hole is created by cutting and by pushing the material. These processes cause increased friction with more heat generation and a greater increase in bone temperature. During experimental setup using very high feed and very low cutting speed some of the bones broke or the specimen moved or was even pushed from the clamping tool confirming inefficient drilling.

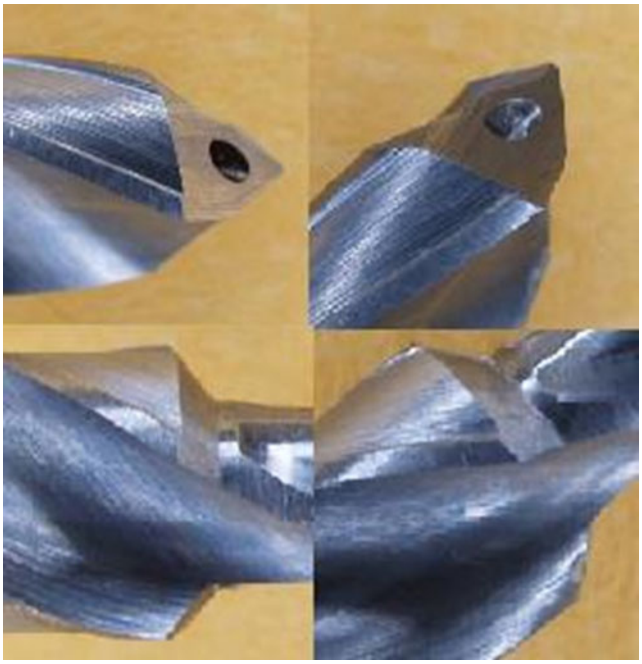


Fig. 5 Cutting lips before and after 180 drillings of 2.5/3.4-mm carbide drill with channels for internal irrigation showing no wear on both smaller diameter drill tip and transitional cutting lips to larger diameter part of the two-step drill

Currently, external irrigation is the single most important parameter that minimises the increase in bone temperature and, when used, all other drill and drilling parameters are of minor importance [9]. Currently there are no studies comparing external and internal irrigation in orthopaedics/traumatology. Such experiments in dentistry due to significantly different drills and drilling parameters cannot be translated to orthopaedics/traumatology practice. Stomatology drills have diameters less than 3 mm (such drills in orthopaedics/traumatology do not cause temperatures above a critical temperature of 47°C [9] and drill speed is up to 300,000 rpm, whereby drill speed in orthopaedics/traumatology is less then 4000 rpm). Internally cooled drills of the open type were introduced to dental surgery in 1975 [18]. Dental articles did not find significant difference between internal and external irrigation [19]. This is partly explained by the fact that maximal temperatures are on the most superficial part of bone due to elimination of heated bone chips exiting the drilling canal [10].

One of the aims of this study was to find out if internal irrigation of the open type is technically feasible for use in orthopaedics/traumatology. There are several advantages over external irrigation: (1) direct lowering of bone temperature on the cutting surface, (2) lubrication of the cutting surface lowering the friction and heat generation, (3) higher efficacy of bone chips elimination due to backflow of the coolant through the flutes which have the highest temperature and which could also obstruct the flutes causing more heat generation and prolong the increased bone temperature, and (4) lesser amount of cooling fluid delivered more efficiently. Irrigation with water temperature of 24°C was used for comparison with previous studies. Absolute value of cooling fluid is not the most important because a range of 10–25°C does not cause significant changes in maximum bone temperature (although lower irrigation temperatures cause lower absolute bone temperatures on superficial parts of the bone) [10]. In our study cooling fluid flow was low (0.1 dcl/min= 0.16 cm^3/s) with pressures near zero without causing damage to surrounding bone and medullary cavity and without significant spread over surrounding structures with lower probability of droplets to rebound from unsterile structures back to the sterile operative field. Using external irrigation only part of the drill outside the bone is cooled directly and due to rotation and centrifugal force droplets are expelled to surrounding tissues. This results in: (a) higher amount of cooling fluid consumed during the same time interval, (b) part of the drill in the bone could be cooled only indirectly with lower decrease of bone temperature at the cutting tip, and (c) higher probability of contamination of the operative field due to bouncing of droplets.

For orthopaedic/traumatology use the open type of internal irrigation is the most efficient parameter for lowering the increase in bone temperature. With its use any other combination of other drill and drilling parameters is of no importance and any of these could be used.

Another aim was to find out if the combined effect of predrilling in only one drilling has significant advantages. Predrilling caused a smaller increase in bone temperature up to 50% [2]. Accordingly, two-step spiral drills made of hard metal, e.g. tungsten cobalt carbide, were constructed to eliminate two drillings as in the predrilling. Hard metal is chosen to eliminate drill bit wear which could influence the increase in bone temperature. The smaller diameter of the two-step drill was 2-mm long without the possibility of injury to surrounding structures when exiting the opposite cortex. The hypothetical advantage of a single drilling to minimise the increase of bone temperature was not found. A standard two-fluted spiral drill and a two-fluted two-step drill (the same drill geometry) developed the same bone temperature when using the same combination of the other drill and drilling parameters. The mechanism is multifactorial. During predrilling the smaller diameter drill performs complete penetration through the cortex. First, bone chips are eliminated throughout the complete length of the drilling path. Second, during replacement with a larger diameter drill, time is consumed (around 30 s) and in this study the bone temperature is lowered for 3°C when drilling without irrigation during that period. Third, the larger diameter drill used in predrilling is at room temperature (20–24°C). During drilling with the two-step drill, transition from the smaller to the larger diameter is from a tenth of a second to a second (depending on the drilling parameters). In such a short period the bone temperature cannot be lowered as in predrilling. Also, further drilling is performed with the same drill that has the same temperature as bone, not room temperature. The result is higher bone temperature with a two-step drill in comparison to incremental drilling during predrilling. Further, the whole cortical channel should be drilled with both smaller and larger diameters of the drill, which results in a longer length of the drilling. The additional length consists of the length of the smaller diameter plus a transitional zone to a larger diameter of the drill. Currently, there is only one study published about the three-step drill showing similar results as a step drill and sequential drilling with increasing drill diameters [20]. We agree that a step drill is a viable alternative to sequential drilling but contrary to the authors' conclusion we could not recommend their three-step drill in human drilling because every step of their drill is 2-cm long; thus, to drill trans-cortex with the largest diameter the drill should be outside the cortex about 4 cm causing surrounding tissue trauma.

The third important conclusion of this study is the relation of maximum bone temperature and the period of that increased temperature over the critical value. Thermal damage to bone is the combined result of the temperature and the duration of elevated temperature. The bone temperature of 47°C lasts for a mean of 11 seconds before decreasing to lower temperatures. More important is the fact that the bone temperature of 50°C will persist above 47°C for a mean of 21 seconds but 95% of results will be around 50 seconds. From the definition of thermal osteonecrosis (47°C lasting for one minute) the temperature of 50°C should never be accepted as a safe margin for avoiding thermal osteonecrosis during drilling.

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Conflict of interest None.

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