APEM journal
Advances in Production Engineering & Management
Volume 16 | Number 2 | June 2021 | pp 199–211
https://doi.org/10.14743/apem2021.2.394
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Bone drilling with internal gas cooling: Experimental and statistical investigation of the effect of cooling with CO_2 on reduction of temperature rise due to drill bit wear

Shakouri, E.[a, b,*], **Haghighi Hassanalideh, H.**[a], **Fotuhi, S.**[b]

[a]Faculty of Engineering, Islamic Azad University-Tehran North Branch, Tehran, Iran
[b]Iranian Tajhiz Sina, its. Co., Tehran, Iran

ABSTRACT

Bone drilling is a major stage in immobilization of the fracture site. During bone drilling operations, the temperature may exceed the allowable limit of 47 °C, causing irrecoverable damages of thermal necrosis and seriously threatening the fracture treatment. One of the parameters affecting the temperature rise of the drilling site is the frequency of applying the drill bit and its extent of wear. The present study attempted to mitigate the effect of drill bit wear on the bone temperature rise through the internal gas cooling method via CO_2 and to reduce the risk of incidence of thermal necrosis. To this end, drilling tests were conducted at three rotational speeds 1000, 2000, and 3000 $r\cdot min^{-1}$ in two states of without cooling and with internal gas cooling by CO_2 through an internal coolant carbide drill bit, along with six drill bit states (new, used 10, 20, 30, 40, and 50 times) on a bovine femur bone. The results indicated that in the internal gas cooling state, as the number of drill bit applications increased from the new state to more than 50 times, the temperature of the hole site increased on average by ΔT = 2-3 °C (n = 1000 $r\cdot min^{-1}$), ΔT = 5-8 °C (n = 2000 $r\cdot min^{-1}$), and ΔT = 5-7 °C (n = 3000 $r\cdot min^{-1}$). Furthermore, the internal gas cooling method was able to significantly reduce the effect of the drill bit wear on the temperature rise of the drilling site and to resolve the risk of incidence of thermal necrosis regardless of the process parameters for drilling operations.

ARTICLE INFO

Keywords:
Bone;
Drilling;
Thermal necrosis;
Tool wear;
Internal gas cooling

**Corresponding author:*
e_shakouri@iau-tnb.ac.ir
(Shakouri, E.)

Article history:
Received 15 March 2021
Revised 18 May 2021
Accepted 19 May 2021

1. Introduction

Bone drilling is a major operation which is extensively utilized in orthopedic surgery. Since in complicated cases of bone fracture, the internal fixation of fracture site should be performed through screws, wires, and plates, thus creation of a hole in the bone through the drilling process is essential [1]. Drilling operation is considered a type of machining process in which a hole is created through physical contact between the cutting edges of a rotational drill bit and applying axial force. As with other machining processes, these operations lead to heat generation in the cutting zone [2]. The major sources of heat generation at the hole site during bone drilling operations are as follows:

The energy exerted to the bone-tool interface to create a plastic deformation in the bone as well as chip formation;
The friction between the drill bit and hole wall;
The friction between chips and the hole wall.

The heat generated during the bone drilling is evacuated in four different ways [3]:

Part of the heat is cleared off the hole site through the blood and interstitial fluids;

Some heat is carried away through bone chips;

A portion of the heat enters the tool and elevates is temperature (Fig. 1);

Finally, some heat enters the hole site of the bone, causing its temperature elevation (Fig. 1).

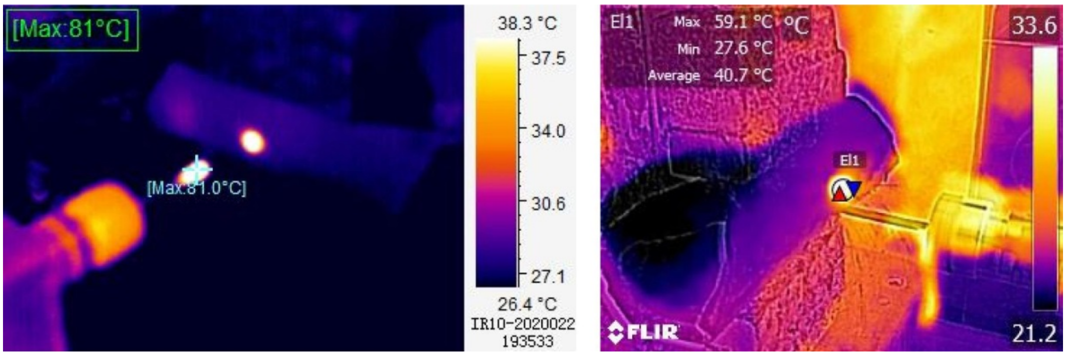

Fig. 1 Samples of thermographic images of bone drilling: heat generation in the drilling site and temperature rise of bone and drill bit

During metal drilling, around 85 % of the heat generated in the process is carried away from the system by chips [4]. However, in orthopedic surgery, as the bone has poor heat capacity and thermal conductivity, the share of the output heat by the chips is far smaller. This means that the heat generated during the bone drilling operations cannot be cleared off the system immediately, causing prolongation of the heat retention time in the bone, and eventually local temperature rise. Heat accumulation at the drilling site can cause irrecoverable damages to orthopedic surgery and patient improvement. The reason is that the local temperature rise can lead to altered nature of the alkaline phosphatase of the bone, incidence of thermal necrosis, cell death, and diminished mechanical strength at the drilling site [5]. The reduction in the mechanical strength of the bone at the hole site may dramatically reduce the success of internal fixation of the fracture site. It is because in the post-drilling stage, self-tapering screws are embedded inside these holes to perform immobilization of the fracture site. Incidence of thermal necrosis, diminished mechanical strength of the drilling site, as well as weakened interaction between the screw and bone, prevent fracture treatment in the desired direction and angle. Thermal necrosis is dependent on two factors: the extent of temperature rise of the bone and the duration of exposure to that temperature. Some researchers have determined a thermal threshold for osteonecrosis, below which no considerable damage is incurred to the bone tissue. However, beyond this temperature, the bone cells are affected; this thermal threshold for incidence of necrosis is exposure to 47 °C for 1 min. *Henriques* has presented a model for thermal damage based on *Arrhenius* relationship. The time-dependent relation of thermal damage is as follows (Eq. 1):

$$\Omega(t) = \int_0^t A.exp\left(\frac{-E_a}{R(T+273)}\right)dt \tag{1}$$

Where, $\Omega(t)$ is the thermal damage, A represents the frequency factor (3.1×10^{98} s^{-1}), E_a shows the activation energy (627×10^3 $J.mol^{-1}$), R denotes the universal constant of gases (8.314 $J.mol^{-1}.K^{-1}$), T is the temperature (°C), and t shows the time (s). According to *Henriques* equation (Eq. 1), per every 1 °C temperature rise, the tolerable time range for the bone diminishes by half, such that beyond 53 °C, thermal necrosis occurs almost immediately [1, 4-8].

Accordingly, controlling the extent of temperature rise in bone drilling operations is a significant issue of interest to researchers in orthopedic surgery and biomedical engineering. Some researchers have tried to determine the optimum machining conditions to ensure the minimum extent of temperature rise through examining the effect of cutting parameters of drilling operations (including the drill bit diameter, drill bit geometry, rotational speed, and feed rate) [9-12]. In spite of the extensive research so far and their valuable results, it has been found that during conventional drilling operations of the bone, despite the possibility of applying suitable process conditions to minimize the temperature rise, thermal necrosis cannot be prevented definitely. This conclusion has prompted researchers to search for alternative methods for conventional drilling in orthopedic surgical operations. Study on modern techniques including high-speed machining of bone [3, 13-15], ultrasonic assisted drilling of bone [16-21], and abrasive water jet machining of bone [22] has been able to mitigate extreme temperature rise in the cutting zone of the bone to some extent and to minimize the risk of thermal necrosis. Nevertheless, the point is that so far none of the alternative methods of traditional machining for the bone have become commonplace and been used in real surgical operations. This can be due to the following reasons:

Most of these alternative methods are dependent on special equipment, which currently have only applications, and their usage in orthopedic surgery suffers technical, health and safety, and financial constraints (the equipment includes high speed spindle for high-speed machining; transducers and ultrasonic power supply for ultrasonic assisted machining; high-pressure pump and jet nozzle for water jet machining).

In spite of achieving relatively desirable results by alternative machining methods, since heat generation is considered an intrinsic property of machining operations, none of the alternative processes have been able to control temperature rise precisely around the allowable range (temperature rise <10 °C) and completely eliminate the risk of thermal necrosis.

Thermodynamically, the most effective method of controlling temperature rise in machining operations is applying coolant fluids; in addition to preventing excessive temperature rise (in the tool and workpiece), these fluids help in transferring the heat from the machining system. This has prompted researchers to examine the effect of applying coolant fluids (water, normal saline) on the temperature rise of drilling site during bone drilling operations [23]. For example, in a research by Augustin *et al*. on porcine femur drilling, it was observed that application of internal water cooling (through the two-step internal coolant drill) caused the hole temperature not to exceed the critical value of 47 °C and grow to at most 40.5 °C [24]. This achievement clearly indicated the effective performance of the coolant fluid in controlling the temperature rise of the bone drilling operation.

Given the remarkable results of applying coolant fluids in controlling the temperature rise of bone drilling, the idea of employing inert gas cooling methods was developed for drilling operations of the bone. In this regard, having created a special drill machine with an internal gas cooling potential (N_2 or CO_2) through internal coolant drill bits, Shakouri *et al*. examined the effect of internal gas cooling on the temperature rise of the bone drilling process. By comparing the obtained results with the observations of conventional drilling as well as the results of drilling with external normal saline cooling, they found that internal gas cooling can constrain the extent of temperature rise at the drilling site during the bone drilling operations within the allowable range (maximum temperature rise as much as ΔT = 10 °C), thereby completely eliminating the risk of thermal necrosis [25]. The internal flow of the inert gas at the site of drilling first provides adequate cooling for both the drill bit and the bone, while also supporting effective evacuation of heat and bone chips. The only notable point in this method is its dependence on the drill apparatus with the ability of gas flow passage plus the internal coolant drill bit.

Concerning bone drilling, the important point which has been observed in previous research is that with increase in the frequency of applying the bit in orthopedic surgery, it gradually wears and becomes blunt over time. This wear can be considered from different aspects:

Bluntness of cutting edges and the flute edges of the bit;

Changes in the point angle of the bit;

Adhesion of a coating made of the bone mineral matrix to the cutting edges and flutes of the bit, and even clogging the flutes of the bit.

Since the extent of sharpness of the drill bit is one of the most important factors affecting the plastic deformation of the material, chip formation, and the cutting efficiency, thus blunt and worn drill bits require exerting more force for the cutting action, causing excessive frictional heating, and eventually generation of more heat during the drilling [7]. Since the mechanical strength of the bone is far lower than that of metal workpieces, thus the forces required for bone drilling operations are not very considerable. Hence, the first two states of drill bit wear mentioned above occur at a very low rate for the drill bits used in bone drilling, and their effects do not emerge at the low frequencies of applying the drill bit. However, concerning the third state of drill bit wear, considering the temperature rise of the drilling site and evaporation of the bone tissue fluids, incidence of adhesion of a coating made of the bone mineral matrix to the cutting edges and flutes of the bit will not be inevitable even at low frequency of applying the drill bit. In a research conducted by Allan *et al*. on the effect of drill bit wear on temperature rise of conventional bone drilling operations, it was found that as the frequency of applying the drill bit increased, so did the extent of temperature rise at the drilling site [8]. In this regard, Staroveski *et al*. monitored drill wear during cortical bone drilling, and found that drill wear resulted in increased temperature and cutting forces [26]. Accordingly, in different studies, to control the course of temperature rise at the site of the drilling and to prevent incidence of thermal necrosis, the maximum allowable frequencies of applying bits has been mentioned as 40 [8, 27, 28]. In some cases, the bit wear challenge has been considered even more critical, and drilling bits have been replaced after 15 times of usage [5].

Since the desirable effect of applying internal gas cooling on significant reduction of temperature rise during the bone drilling operations has been observed [25], now this question arises whether the above method can reduce the wear rate of the drill bit and its resulting temperature rise. The aim of the present research is to investigate the effect of frequency of applying drill bit and its resulting wear on the temperature rise of the drilling site and to test the effect of internal gas cooling on the extent of temperature rise resulting from the drill bit wear (from the aspect of adhesion of a coating made of the bone mineral matrix to the cutting edges and flutes of the bit). Another goal is to determine whether internal gas cooling during the bone drilling operations can reduce the drill bit wear-induced temperature rise. Furthermore, once this internal cooling method is used, the maximum allowable times of applying the drill bit should be tested. The innovation of this research is that so far no documented report has been published regarding the effect of internal gas cooling on the drill bit wear and its resulting temperature rise.

2. Materials and methods

Due to the similarity between the mechanical properties of bovine bone and human bone, as well as its frequent usage in previous studies [1, 3, 9, 10, 12, 13, 15, 16, 22, 25], the present research has used fresh bovine femurs, which had been obtained from a local abattoir. Note that no animal was sacrificed specifically for conducting the tests in this research. Considering the necessity of creating the same conditions for all experimental states, the desirable samples with a width of 15 mm and thickness of around 8 mm have been chosen from the mid-shaft of the bovine femur diaphysis (Fig. 2). The initial temperature (T_0) of the specimens has been 27 °C before the experimental tests. Since the method proposed in this research intends to resolve the effect of drill bit wear on drilling temperature rise through internal gas cooling, thus it was necessary facilitate the gas passage through the spindle and delivering it to the internal coolant drill bit by making changes to the drill machine (Fig. 3). This tool could be made through modifying *Bosch drill GSB 16 RE* according to Fig. 4. Note that the efficiency of this drill machine in effective cooling of drilling site through gas has been demonstrated previously [9, 25]. As a tool for material removal as well as a path for concurrent transference of coolant gas to the drilling site, an internal coolant drill bit (*Mitsubishi materials MVS0320X05S060 MVS series solid Carbide drill*, internal coolant) has been used with a diameter of 3.2 mm possessing two internal channels (diameter is 0.5 mm) for gas passage (Fig. 5). According to the common protocol for temperature measurement at the drilling site in bone drilling operations, a thermocouple has been installed at the depth of 3 mm with a distance of 0.5 mm away from the hole wall [9, 13, 16, 25, 27], whereby the thermal changes have been recorded via *Thermometer Lutron TM-925*. Table 1 presents the different conditions of drilling operations employed in the present research. Based on this table, it is observed that the drilling tests have been totally performed in 36 experimental states for drilling conditions: without cooling and with internal gas cooling, with three rotational speeds (1000, 2000, and 3000 r·min^{-1}), for six states of drill bit (new, after using 10, 20, 30, 40, and 50 times). Note that in order to ensure the accuracy and replicability of the results, every experimental state has been repeated at least three times.

Fig. 2 Bone specimens after cutting

Fig. 3 A schema of drill made with internal gas cooling

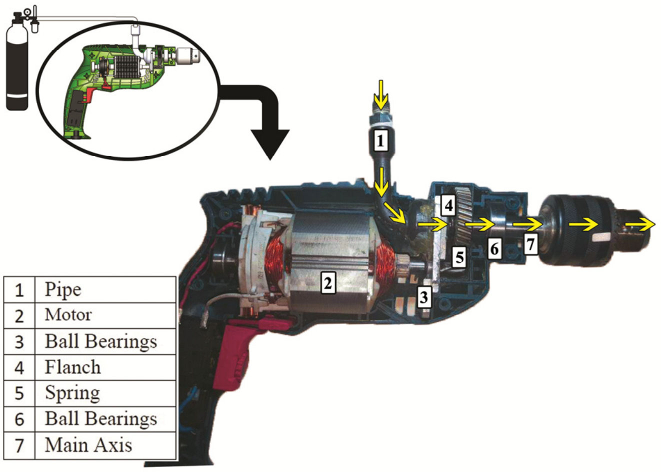

Fig. 4 A schema of drilling machine: The section shows the pathway of gas coolant

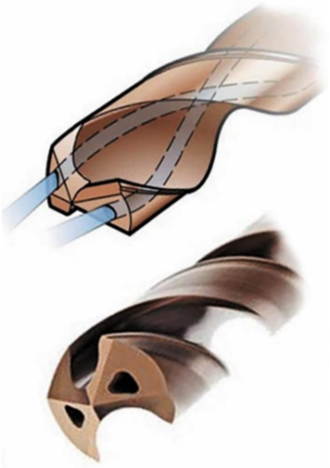

Fig. 5 Internal coolant drill bit.

Table 1 Bone drilling operational parameters

Drill bit diameter (mm)	3.2
Drill bit type	*Mitsubishi materials MVS0320X05S060 MVS series solid Carbide drill*, internal coolant
Rotational speed (r·min^{-1})	1000-2000-3000
Feed rate	Manual
Gas coolant type	CO_2
Coolant flow rate (L·min^{-1})	5
Cylinder pressure (bar)	2
Gas temperature during discharge of drill tip (°C)	-11
Degree of Drill bit wear	New drill bit-& After 10-20-30-40-50 holes
Depth of drilling (mm)	8
Modes of drilling	Without cooling- With internal gas cooling
Number of iteration of tests	At least 3 times

3. Results and discussion

Figs. 6-8 present the results obtained from the bone drilling tests in two states, without drilling and along with internal gas cooling for the rotational speeds of 1000, 2000, and 3000 r·min^{-1}. Based on the above figures, it can be observed that:

In case of not using any coolants, as the frequency of applying the drill bit increased from the new state to more than 50 times, the hole site temperature rise has grown from ΔT = 24 °C to 34 °C for rotational speed of 1000 r·min^{-1}, from ΔT = 29 °C to 37 °C for rotational speed of 2000 r·min^{-1}, and from ΔT = 20 °C to 33 °C for rotational speed of 3000 r·min-1 (on average from the baseline level, T_0 = 27 °C). This suggests that an increase in the frequency of applying drill bit and its resulting wear significantly influence the temperature rise of the hole site. This temperature rise occurred more quickly for the drill bit utilized more than 40 times (which has been mentioned as the last allowable limit for applying drill bits in different references [8, 27, 28]).

The minimum temperature rise for the case of no coolant utilization was ΔT = 20 °C belonging to the new drill bit at 1000 r·min^{-1}, which has been far beyond the allowable limit of temperature rise (ΔT < 10 °C). This means that in conventional drilling, it is not possible to control the extent of temperature rise and prevent the incidence of thermal necrosis. As the frequency of applying the drill bit increases, the conditions become further critical. Although in previous studies, the maximum allowable frequency of applying drill bits has been mentioned as 40, the above figures indicate that when no coolant is used, even new drill bits may lead to excessive temperature rise and incidence of thermal necrosis.

In the case of drilling with internal gas cooling, as the frequency of applying the drill bit increased from new conditions to beyond 50, the hole site temperature rise (ΔT) has grown from ΔT = 2 °C to 3 °C for rotational speed of 1000 r·min^{-1}, from ΔT = 5 °C to 8 °C for rotational speed of 2000 r·min^{-1}, and from ΔT = 5 °C to 7 °C for rotational speed of 3000 r·min^{-1} (from the baseline level, T_0 = 27 °C). This highlights that when internal gas cooling is used, the increase in the frequency of applying the drill bit has had a minor impact on the temperature rise of the hole site.

In case of the drilling with internal gas cooling, the temperature rise of the hole site (ΔT) lied within the allowable range at all rotational speeds and the drill bit wear conditions, and did not exceed the threshold of 10 °C. This suggests that bone drilling with internal gas cooling enjoys the ability of controlling temperature changes and preventing the incidence of thermal necrosis for both new and worn drill bits. Note that the extent of temperature rise has approached the maximum allowable limit only for the drill bit with more than 50 times of usage at 2000-3000 r·min^{-1}. Thus, it can be concluded that bone drilling with internal gas cooling guarantees controlled temperature rise at the hole site and no incidence of thermal necrosis for new and even 50-time used drill bits.

Comparing the results obtained from Figs. 6-8, it can be seen that in both conventional drilling and drilling with internal gas cooling, across all new and worn drill bit states, as the drill bit rotational speed increased from 1000 r·min^{-1} to 2000 r·min^{-1}, the temperature rise (ΔT) was intensified; however, with further increase in the rotational speed from 2000 r·min^{-1} to 3000 r·min^{-1}, the extent of temperature rise of the hole site diminished. Note that, in the drilling without cooling, the minimum extent of temperature rise was obtained at 3000 r·min^{-1}, while in the bone drilling with internal gas cooling, the minimum degree of temperature rise occurred at the rotational speed of 1000 r·min^{-1}.

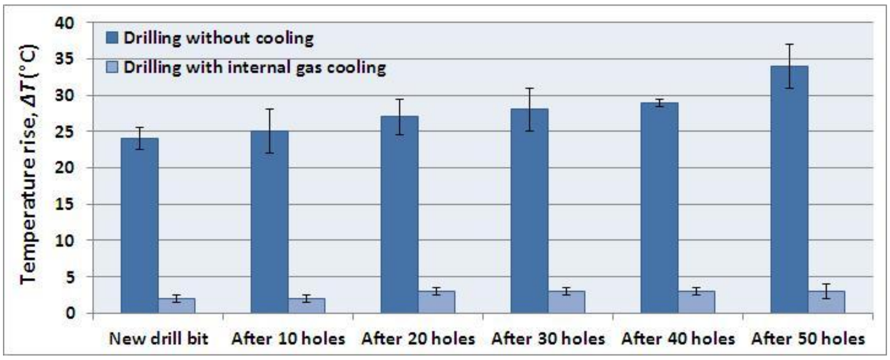

Fig. 6 Temperature change during bone drilling for different modes of drill bit wear (Comparison of drilling without cooling and drilling with internal gas cooling, n = 1000 r·min^{-1})

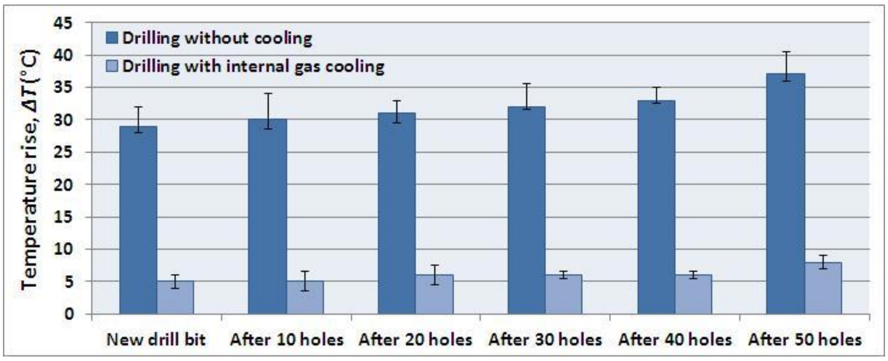

Fig. 7 Temperature change during bone drilling for different modes of drill bit wear (Comparison of drilling without cooling and drilling with internal gas cooling, n = 2000 r·min^{-1})

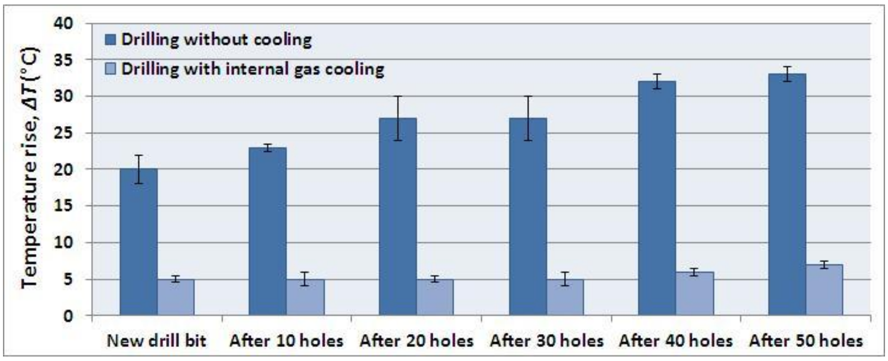

Fig. 8 Temperature change during bone drilling for different modes of drill bit wear (Comparison of drilling without cooling and drilling with internal gas cooling, n = 3000 r·min^{-1})

Based on Figs. 6-8, it is observed that in the bone drilling without internal gas cooling, as the frequency of applying the drill bit increased, so did the extent of temperature rise of the hole site. This is justified considering the gradual increase in the drill bit wear and weakened cutting capability of the drill bit edges. Nevertheless, the important point in the above figures is that the maximum extent of temperature rise has occurred at 2000 r·min^{-1}, while the minimum has been obtained at 3000 r·min^{-1}. As a justification, the factors affecting the temperature rise during the bone drilling operations should be considered:

Reduction of the energy required for chip formation and machine forces in response to elevated rotational speed of the drill bit;

Increased friction and frictional heating in response to augmented rotational speed of the cutting tool;

Increased speed of the chip evacuation in response to the elevated rotational speed of the drill bit.

As the rotational speed of the drill bit was augmented from 1000 r·min^{-1} to 2000 r·min^{-1}, the machining force decreased while the chip evacuation speed increased, causing reduction of heat generation in the process to some extent. Nevertheless, since the effect of friction and frictional heating is dominant, the temperature of the hole site increased. These conditions hold for all states of the drill bit wear.

In the bone drilling with internal gas cooling, two important points are notable:

> Application of internal gas cooling has caused the temperature rise (ΔT) to become constrained within the range less than 10 °C, and allowed 50 times of drill bit usage because of different reasons. They include increased chip evacuation speed, effective cooling of the drill bit and bone, along with diminished effects of the drill bit wear (including bluntness of the cutting edges, adhesion of the bone mineral matrix to the edges and flutes of the drill bit, and clogging of drill bit flutes).
>
> Since cooling with gas is far more effective than increasing the rotational speed of the drill bit for elevating the chip evacuation speed, the rise in the rotational speed from 1000 to 3000 r·min^{-1} did not significantly contribute to faster chip evacuation and only caused an intensified effect of friction and frictional heating. Thus, in the case of bone drilling with internal gas cooling, the minimum extent of temperature rise was obtained for both new and worn drill bits at 1000 r·min^{-1}.

To investigate the signs of drill bit wear, some images of it have been presented in Fig. 9 after 50 times of usage for bone drilling operations without cooling and with internal gas cooling. These images have been prepared after cleaning and rinsing the drill bits, and captured under *Stereo Microscope ST1740* with maximum 50× magnification. By comparing these images with the image of the new drill bit, it can be found that:

> After 50 times of applying the drill bit for bone drilling (in both without and with internal gas cooling), no notable signs of the bluntness of cutting edges and the flute edges of the bit are observed. This is due to the low mechanical strength of the bone, negligible machining forces, and high hardness of the carbide bit used in the present research. This causes minor state of wear. In case of further increasing the frequency of applying the drill bit (beyond 50 times), or using standard surgical drill bit (made of stainless steel), which has a lower hardness compared to carbide drill bit, the signs of this wear will emerge more rapidly.
>
> Considering adhesion of a coating made of the bone mineral matrix to the cutting edges and flutes of the bit, and concerning the substantial impacts on the bits, it is clear that the extent of this type of tool wear has been notable in the drilling without cooling, and some evident signs have remained on the tool surfaces. On the other hand, when using drilling with internal gas cooling, the signs of adhesion of a coating made of the bone mineral matrix to tool surface are very trivial and negligible. This improvement in the qualitative status of the tool and reduction of its wear result from the effect of internal gas cooling on preventing severe temperature rise as well as the effective role of the gas flow in accelerating the chip evacuation rate.

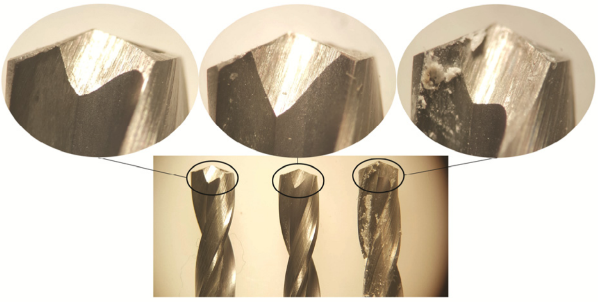

Fig. 9 Images of the abrasion of drill bits in various states (Bottom image is side view of drill bits with10× magnification; Top images are the tool tip section with 25× magnification): The left image is of the new drill bit; the center image is of the drill that had drilled 50 holes (with internal gas cooling), and the right image is of the drill that had drilled 50 holes (without cooling).

Table 2 reports the set of results of the bone temperature rise in drilling operation, obtained in other studies similar to our research. To validate the results of the present research, a comparison has been made between these results and the findings of other studies. Note that in some cases, some differences existed between the drilling conditions of other studies [8, 24, 25] and the process conditions applied in the present research regarding the type of bone, rotational speed, drill bit diameter, and hole depth. Nevertheless, Table 2 indicates that, according to the results of the present research, more frequent use of the drill bit and thus the increase in its degree of wear have led to bone temperature rise [8]. Further, clearly application of internal cooling methods (with liquid or gas) has resulted in a significant reduction of the bone temperature rise. Although the liquid coolant (water or normal saline) outperformed the gas coolant (N_2 or CO_2), both cooling modes (either liquid or gas) have been sufficiently able to effectively cool the hole site and prevent exceedance of temperature rise beyond the allowable limit of $\Delta T < 10$ °C [24, 25].

Table 2 Comparison the results of the present research with other studies

Reference	Bone type	Drill bit diameter (mm)	Degree of Drill bit wear	Rotational speed ($\text{r}\cdot\text{min}^{-1}$)	Hole depth (mm)	Cooling condition	Temperature changes (°C)
Allan *et al.* [8]	Pig mandible	1.5	New	20000	5	Dry	7.5 (0.6-20.5)
			After 600 holes			Dry	13.4 (5.7-28.3)
Augustin *et al.* [24]	Porcine femur	3.4	New	1000	4-5	Dry	8
						Water	0.4
				3150		Dry	9.2
						Water	0.6
Shakouri *et al.* [25]	Bovine femur	3.2	New	1100	7-8	Dry	11.5
						CO_2	3.3
						N_2	4.9
						Normal saline	2.9
				1920		Dry	18.1
						CO_2	2.5
						N_2	5.4
						Normal saline	1.9
				3200		Dry	19
						CO_2	5.6
						N_2	4.8
						Normal saline	5.1
Present study	Bovine femur	3.2	New	1000	8	Dry	24 ±1.5
						CO_2	2 ±0.5
				2000		Dry	29 ±3
						CO_2	5 ±1
				3000		Dry	20 ±2
						CO_2	5 ±0.5
			After 50 holes	1000		Dry	34 ±3
						CO_2	3 ±1
				2000		Dry	37 ±3.5
						CO_2	8 ±1
				3000		Dry	33 ±1
						CO_2	7 ±0.5

In this section, to investigate the influence of each of the input parameters (rotational speed and the frequency of using the drill bit) on the bone temperature rise, and to determine the statistical model for predicting temperature rise, statistical analysis of the results has been performed using *Statistica* software. The relationship between the output variable (temperature rise) and input variables (rotational speed and the frequency of using the drill bit) has been examined using different regression models. Based on the maximum regression coefficient (R) and coefficient of determination (R^2), the most suitable regression model has been chosen, and the coefficients related to the regression model as well as p-value at the level of $\alpha = 0.05$ have been estimated for them. The results of statistical analysis of the bone temperature rise for the modes of bone drilling without cooling and drilling with internal gas cooling are outlined in Table 3. In the bone drilling without cooling, considering the relation obtained for predicting the bone temperature rise (growth regression), it is observed that temperature changes are only dependent on the frequency of applying the drill bit. This means that in this mode, the drill bit wear plays a significant role in the bone temperature rise, while the rotational speed of the drill bit does not have a significant impact on such rise. The independence of the bone temperature rise of the rotational speed when not using the cooling further highlights the effect of the tool wear on the bone temperature rise during drilling. However, for the drilling with internal gas cooling, considering the type of model obtained (linear regression), it can be stated that rotational speed and the drill bit wear have a direct relationship with temperature. Nevertheless, considering the coefficients obtained for these input parameters, it is evident that the tool wear has a greater impact on the temperature rise as compared to the rotational speed.

Table 3 Statistical analysis of temperature rise results.

	Drilling without cooling			Drilling with internal gas cooling		
Regression model	Growth			Linear		
Regression formula	$\Delta T = \exp(b_1 \cdot n + b_2 \cdot B + a)$			$\Delta T = (b_1 \cdot n) + (b_2 \cdot B) + a$		
Regression coefficient (R)	0.803			0.794		
Determination coefficient (R^2)	0.645			0.631		
Regression parameters	b_1	b_2	a	b_1	b_2	a
	−0.00001	0.0067	3.210	0.0014	0.0371	0.96
p-value ($\alpha = 0.05$)	0.691	0.0001	0.000	0.00047	0.027	0.241
Resultant regression equation	$\Delta T = \exp(0.0067 \cdot B + 3.210)$			$\Delta T = (0.0014 \cdot n) + (0.0371 \cdot B)$		

Possibly, one of the major concerns which may challenge the application of internal gas cooling in orthopedic surgery is the probability of incidence of hypothermia or other similar damages to the bone in response to exposure to the cool gas flow. To resolve this challenge, three points should be considered:

To create a hole with a diameter of 3.2 mm, a major part of the bone material exposed to CO_2 gas coolant at −11 °C detaches off the bone as chips and discharges to the outside of the hole.

Similar to the case for thermal necrosis, where temperature rise and duration of exposure to high-temperature were influential factors, for hypothermia, again time is a direct influential factor. This fact cannot be neglected that during drilling with internal coolant drill bit, the bone is exposed to the coolant gas at −11 °C. Nevertheless, since the duration of drilling operation is only some second, the bone tissue of the hole wall is at risk of exposure to the cold gas only for a very short duration, and incidence of hypothermia in the bone is very unlikely.

The overall effect of thermal factors, including: a) temperature rise resulting from drilling, and b) temperature fall due to cool gas flow determine the final temperature of the bone tissue of the hole wall. As also indicated by the results of the present research, cooling with CO_2 at −11 °C in the best mode resulted in temperature rise of 2 °C. This is the temperature measured by a contact thermocouple at the depth of 3 mm and distance of 0.5 mm away from the hole wall. It implies no incidence of over-cooling in the bone site. This means that in the best performance state of the gas coolant, again the bone tissue temperature has not declined in relation to its initial temperature, and has experienced a minimum temperature rise of 2 °C.

The results of the current study revealed that the application of CO_2 gas cooling in the bone drilling operations caused reduced extent of temperature rise and prevented incidence of thermal necrosis. Furthermore, upon the decrease in the blunting rate of the cutting edges, reducing the extent of adhesion of the bone mineral matrix to the drill bit edges and flutes, and by preventing clogging of drill bit flutes, it slows down the drill bit wearing and reduces its impact on