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# Experimental investigation of the temperature elevation in bone drilling using conventional and vibration-assisted methods

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ABSTRACT

Bone drilling is widely used in orthopaedics for inserting screws and fixing prostheses. Thermal necrosis is one of the major problems that may seriously affect post-operative recovery. Accordingly, this paper mainly focuses on comparing the influences of conventional drilling (CD), ultrasonic vibration-assisted drilling (UVAD) and low-frequency vibration-assisted drilling (LFVAD) methods, and drilling parameters on the temperature elevation in bone drilling process. A full factorial experiment was performed, and the temperatures were measured using an infrared camera. The lowest temperature elevation was obtained by LFVAD compared with CD and UVAD at the same drilling conditions. Setting CD as a reference, the maximum difference between LFVAD and CD was approximately −4 °C, whereas that between UVAD and CD was approximately 16 °C. The temperature elevation increases linearly with the spindle speed and follows an inverted U-shaped curve, with the feed rate having a peak at 40 min/mm in each drilling method. The results were discussed with regard to the features of LFVAD and UVAD. It was expected that the LFVAD could achieve minimal thermal damage and attain better results in the medical bone drilling process.



## 1. Introduction

Bone drilling is frequently required to treat patients with orthopaedic, dental or neural injuries. Because a large amount of heat is generated during the bone drilling process and the osteocyte activity is highly sensitive to heat, irreversible thermal damage will severely deteriorate the strength of bone tissues and reduce the survival rate of the vessels and nerves surrounding the drilling site when the bone temperature exceeds 47 °C for one minute [1–3]. This thermal damage may cause instability in fixed fractures, loosened prostheses, and extended healing times. Therefore, a low temperature must be maintained during the drilling process to avoid post-operative complications.

During bone drilling, heat is generated mainly from the shear deformation process and the friction between the chips and the rake face of the cutting lip [4,5]. The rest of the heat is derived from friction among the bone, the chips and the drill body. Recently, Cseke and Heinemann [6] reported that the heat from friction at the interface of the drill body and the wall of the bone hole is the primary heat source during the bone drilling process. The heat is dissipated simultaneously by heat conduction to bone and drill bit and by heat transfer by means of the extracted chip flow.

The complexity of bone drilling poses a great challenge for research and has attracted many scholars to study it for decades. Many experiments have been performed to investigate the most favorable drilling conditions to obtain better results in bone drilling. Some studies attempted to either improve the geometry of the drilling tools [7–10] or optimize the drilling parameters [11–16] to obtain better results, although their results were sometimes contradictory. Other investigations introduced other drilling methods as alternatives to conventional drilling (CD) into the medical field [2].

The VAD method has been successfully applied in the machining of hard metals and composite materials since the last century. In comparison with CD, VAD enables the effective reduction of the applied drilling force and torque while improving the surface quality and position accuracy [17–19]. Moreover, VAD is a pure mechanical process [20] that does not put patients at additional electrical or chemical risk. Therefore, over the past decade, numerous researchers have studied the application of ultrasonic vibration-assisted drilling (UVAD) in the medical bone

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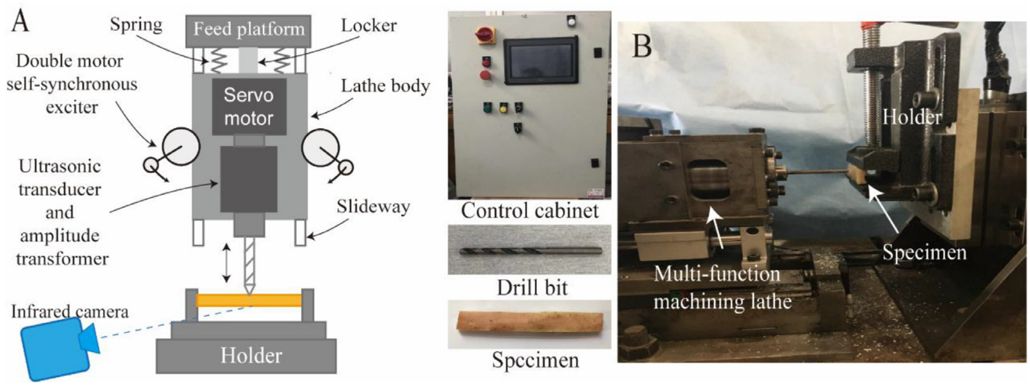


**Figure 1.** The components of the experimental setup (A: Schematic; B: Bone drilling site).

drilling field and attempted to obtain better surgical results. Their reports [21–26] confirmed that a lower applied thrust force and torque, decreased temperature rise ($f$ < 20 kHz), improved surface roughness, greater pull-out strength, and the generation of fewer micro-cracks can be achieved by UVAD compared with CD under similar drilling conditions.

As another branch of the VAD method, relatively few studies have investigated the use of low-frequency vibration-assisted drilling (LFVAD) for drilling bone. Wang et al. [27] found that fewer and shorter micro-cracks formed and that the cutting heat is significantly reduced in LFVAD ($f$ = 5–20 Hz) compared with CD. In the following year, Wang et al. [28] investigated the cutting temperature under vibration conditions of 5–20 Hz and 100–500 µm and found that the cutting temperature tended to decrease with increases in the vibration frequency and amplitude. Balevicius and co-workers [29] investigated the LFVAD machining performance on polymethyl methacrylate at 9 different vibration settings and performed 10 experiments at 60–140 Hz. They reported a maximum temperature reduction of 21 °C at 80 Hz with an excitation voltage of 120 mV. Zakrasas et al. [30] used a similar experimental setup and reported that the drilling temperature on pig rib when using LFVAD (60–120 Hz) was reduced by 14% compared with the values in CD. However, in their experiments [27,28], the effects of drilling parameters were not investigated. The drilling processes in [29,30] were performed by a hand drill, so the feed rate and thrust force were difficult to maintain steady at the desired values during the whole drilling process. Since the temperature is sensitive to the drilling parameters, these results may be affected by the manual operation.

In previous experiments, the main apparatus utilized to measure the temperature included the thermocouple embedded in the bone [31] or drill bit [32] and thermographic camera. Because the measurement using thermocouples depends strongly on the thermal properties of the workpiece [33] and owing to the poor heat conductivity and anisotropic nature of bone [34], many pilot holes must be prepared to insert thermocouples to accurately obtain the thermal field surrounding the drill site. This preparation process demands too much time and experience. In contrast, an infrared camera only requires pre-calibration before measurement. The contactless technology of infrared camera measurements can also avoid some interference, such as loosened contact in the thermocouple approach, during the drilling process.

Since the highest temperature is located at the interface of the chisel edge and the bone [35] and the heat gradually accumulates throughout the drilling process, we suppose that the maximum drilling temperature appears at the moment just before the drill tip penetrates the far edge of the specimen. However, the infrared camera used in recent investigations [33,36] only detected the surface temperatures around the entries of the bone holes. Therefore, the recorded data do not represent the exact highest temperature during the drilling process. In our experiment, an improved approach to temperature measurement was adopted by using an infrared camera.

In this paper, CD, LFVAD and UVAD were respectively employed under the same drilling conditions to investigate their effects on the temperature elevation in the bone drilling process. The results of each drilling method were compared to verify the advantages of LFVAD with regard to its ability to reduce the temperature elevation. The results of the comparison were discussed by means of the different features of VAD in the low-frequency and ultrasonic ranges.

## 2. Materials and methods

Since the mechanical properties of bovine bone resemble those of human bone [11,12], drilling experiments were performed on the fresh diaphysis of bovine femurs in this study. The bones were purchased from a local butcher immediately after the slaughter. The average age of the beef cattle was 1.5 years. No animal was mistreated during this experiment. The attached tissue and marrow were removed completely, and the cortical layer (with a thickness of approximately 8 mm) was cut into blocks longitudinally by a power saw. To prevent dehydration, the specimens were soaked in saline and kept at environmental temperature before drilling. A total of 25 specimens were prepared.

The setup of the drilling equipment and apparatus are shown in Figure 1. Since axial assisted vibration is the most effective type [37], the multi-function drilling lathe used in this experiment can superpose axial vibrations onto the drill bit in both the low-frequency and ultrasonic ranges. The feed platform and the spindle were driven by two servo motors (Mitsubishi, 0.7 kW, 3000 rpm, Japan) and controlled by a programmable logic controller system (Mitsubishi, Fx series, Japan). An ultrasonic transducer module (0.08 kW, resonant frequency = 23 kHz, amplitude = 7 µm) and a double-motor self-synchronous low-frequency exciter (2 × 0.05 kW, axial frequency = 50 Hz, axial exciting force = 150 N, amplitude = 0.05 mm) were equipped on this lathe. The ultrasonic transducer and amplitude transformer were installed between the spindle servo motor and the drill bit clamp in series. The double-motor self-synchronous low-frequency exciter was fixed on the lathe body. As the lathe worked in the CD and UVAD modes, the locker was on to ensure that the connection between the feed platform and lathe body was rigid. When the lathe was working in the LFVAD mode, the locker was dismantled. The connection was then flexible, and the lathe body could slide on the slideway periodically and keep step with the axial frequency of the low-frequency exciter. The vibration parameters

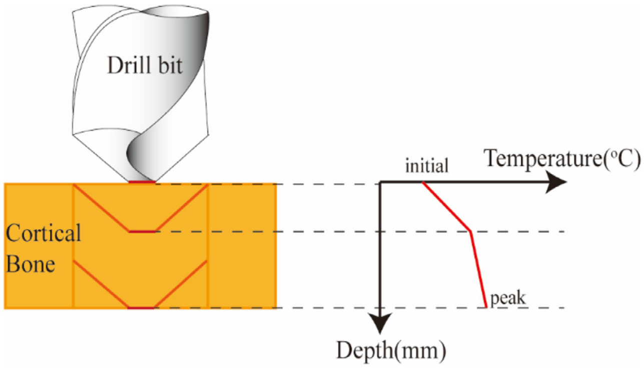


**Figure 2.** The variation in the highest temperature during the drilling process.

**Table 1**
The control parameters and setting levels in the experiment.

| Control factor | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|
| Spindle speed (rpm) | 200 | 400 | 600 | 800 | 1000 |
| Feed rate (mm/min) | 10 | 20 | 30 | 40 | 50 |
| Drilling method | CD | LFVAD | UVAD | N/A | N/A |

were measured by a laser vibrometer (POLYTEC OFV-505/5000, Germany).

An infrared camera (FLIR T1040, U.S.) was used to measure the temperature. The sensitive range of detector head was between 7.5–14 µm, and the sensitivity was less than 0.02 K. The measurement accuracy of the infrared camera was ±1% in the range of 5–150 °C. The camera was pre-calibrated using a contact industrial thermometer. The bone emissivity was approximately 0.96, consistent with the values in studies [38,39].

Since we suppose that the highest temperature of the bone tissue appears at the moment just before the drill tip penetrates the back surface of the specimen (Fig. 2), the infrared camera was located approximately 1 m away from the specimen, and its lens was aimed at the back surface of the bone. The infrared camera started to work as the drill turned and recorded the thermal images manually before the drill tip exited.

A hole diameter of 1.5–5.5 mm is usually adopted in orthopaedic surgery. Hence, a standard twist drill bit (high-speed steel, diameter = 3 mm, not coated) was used for drilling. The drill bit geometry was unified, and no external coolant system was used.

To balance the cost of the experiment and the data integrity, 5 levels were used for each drilling parameter. The values of the drilling parameters employed in this study referred to previous studies [21,23,32,33] and are shown in Table 1. Drilling was performed with random parameters and repeated three times to eliminate errors. To prevent a worn drill bit from imposing a negative influence on the drilling performance, the drill bit was replaced with a new one after every five experiments.

## 3. Results

### 3.1. The effects of the drilling method

The recorded thermography images at the same drilling parameters were primarily compared. Figure 3 shows the images captured when the spindle speed was 200 rpm and the feed rate was 10 mm/min. The recorded highest temperatures using the three drilling methods were 39.8 °C, 37.5 °C and 60 °C, and the background temperatures were 23.7 °C, 24.7 °C and 35.9 °C, respectively. Accordingly, the elevated temperatures were 16.1 °C, 12.8 °C and 24.1 °C for the CD, LFVAD, and UVAD. Obviously, LFVAD exhibited the lowest temperature elevation, while UVAD showed the highest temperature elevation under same conditions.

### 3.2. The effects of the spindle speed

Setting the feed rate as a constant, the effects of the spindle speed on the temperature elevation in each type of drilling method were compared in Figure 4. Compared with the other drilling methods, LFVAD demonstrated the lowest temperature elevation at each sampling point. The trends of the temperature elevations in each drilling method illustrated that the temperature elevation has an approximately linear relationship with the spindle speed and that the relationship was not significantly influenced by the different drilling methods.

The results obtained in this experiment are consistent with those of other studies [33,40] that reported that the increase in the temperature exhibits a linear relationship with the spindle speed. However, the results of this study contradict those of another previous experiment [41] that reported that the increases in the temperature exhibits a decreasing quadratic relationship with increasing spindle speed in the range of 20k–100k rpm during the application of CD. Moreover, the results of these experiments are also distinct from those of Hillery and Shuaib [32], who suggested that the temperature decreases at 400–1200 rpm and slightly increases at 1200–2000 rpm.

The maximum differences among the examined drilling methods occurred in the reference group FR = 40. The detailed values of the reference group are shown in Table 2. While the difference between the CD and LFVAD methods showed an almost constant value, the difference between the CD and UVAD methods exhibited linear increase with the spindle speed (except for a slightly lower value at sample point SS = 600).

### 3.3. The effects of the feed rate

Setting the spindle speed as a constant, the effects of the feed rate on the temperature elevation in each type of drilling method were also compared and are shown in Figure 5. Compared with the other drilling methods, LFVAD again demonstrated the lowest temperature elevation at each sampling point. The temperature


**Figure 3.** The thermographic images of the highest temperature at the back surface of bone specimen (L: CD; M: LFVAD; R: UVAD. Drilling parameters: spindle speed = 200 rpm, feed rate = 10 mm/min. Vibration parameters: LFVAD: $A = 50$ µm, $f = 50$ Hz; UVAD: $A = 7$ µm, $f = 23$ kHz).

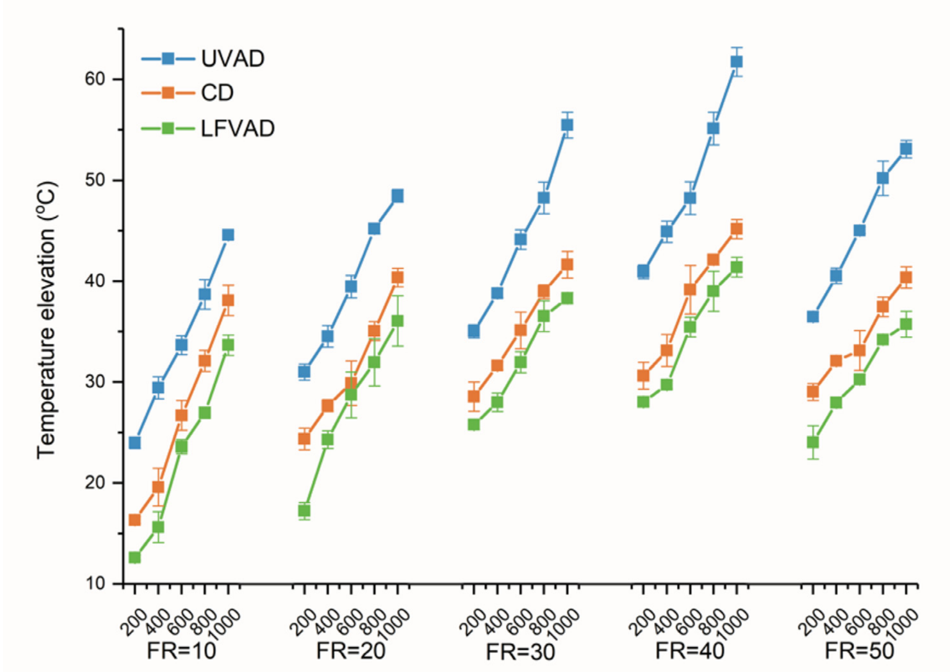


**Figure 4.** The effects of the spindle speed on the temperature elevation in each drilling method (The sample points are at spindle speeds of 200, 400, 600 and 1000 rpm. FR = feed rate (mm/min). Vibration parameters: LFVAD: $A = 50$ μm, $f = 50$ Hz; UVAD: $A = 7$ μm, $f = 23$ kHz. Mean + SD).

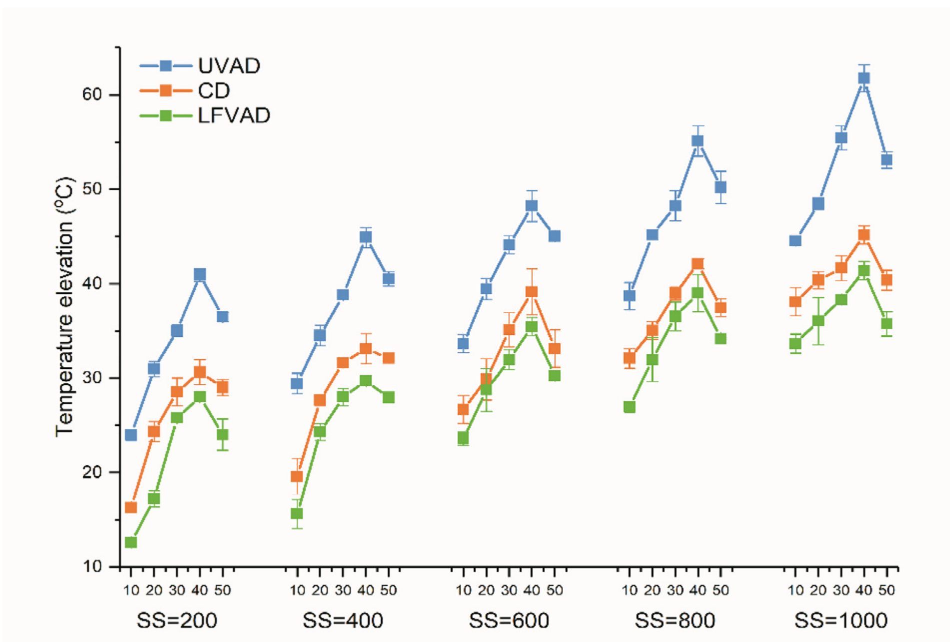


**Figure 5.** The effects of the feed rate on the temperature elevation in each drilling method (The sample points are at feed rates of 10, 20, 30, 40 and 50 mm/min. SS = spindle speed (rpm). Vibration parameters: LFVAD: $A = 50$ μm, $f = 50$ Hz; UVAD: $A = 7$ μm, $f = 23$ kHz. Mean + SD).

**Table 2**
The mean elevated temperatures at FR = 40 for each drilling method.

| Spindle speed (rpm) | CD | LFVAD | | UVAD | |
|---|---|---|---|---|---|
| | $\Delta T$ | $\Delta T$ | Diff. | $\Delta T$ | Diff. |
| 200 | 30.63±1.33 | 28.03±0.50 | −2.60±1.83 | 40.93±0.68 | +10.30±0.14 |
| 400 | 33.13±1.57 | 29.73±0.40 | −3.40±1.92 | 44.90±1.05 | +11.77±0.71 |
| 600 | 39.17±2.40 | 35.47±0.97 | −3.70±1.47 | 48.23±1.61 | +9.07±2.64 |
| 800 | 42.13±0.51 | 39.00±2.00 | −3.13±1.48 | 55.13±1.62 | +13.00±2.04 |
| 1000 | 45.17±0.95 | 41.40±0.98 | −3.77±1.51 | 61.73±1.42 | +16.57±2.32 |

$\Delta T$ and Diff.: °C, MEAN±SD.

elevation increased as the feed rate rose until the feed rate was 40 mm/min, after which it dropped with a further increase in the feed rate. The shape of the curves exhibited an approximately inverted U-curve relationship with the feed rate. The similar trends of the curves demonstrated that the effects of the feed rate were also independent of the different drilling methods.

The observed relationship between the temperature elevation and feed rate is similar to that reported in previous study [40]. Abouzgia and James [42] found a similar relationship between the temperature elevation and force in that the temperature increased

**Table 3**
The mean elevated temperatures at SS = 1000 for each drilling method.

| Feed rate (mm/min) | CD | LFVAD | | UVAD | |
|---|---|---|---|---|---|
| | $\Delta T$ | $\Delta T$ | Diff. | $\Delta T$ | Diff. |
| 10 | 38.10±1.51 | 33.67±1.01 | −4.43±2.32 | 44.57±0.35 | +6.47±1.38 |
| 20 | 40.37±0.92 | 36.07±2.49 | −4.30±1.57 | 48.47±0.64 | +8.10±0.82 |
| 30 | 41.63+1.32 | 38.33±0.55 | −3.30±1.87 | 55.47±1.29 | +13.83±1.22 |
| 40 | 45.17±0.95 | 41.40±0.98 | −3.77±1.51 | 61.73±1.42 | +16.57±2.32 |
| 50 | 40.37±1.06 | 35.73±1.29 | −4.63±1.08 | 53.10±0.87 | +12.73±1.46 |

$\Delta T$ and Diff.: °C, MEAN±SD.

**Table 4**
ANOVA analysis for the mean temperature elevation.

| Item | DOF | Adj. SS | Adj. MS | *F*-value | *P*-value |
|---|---|---|---|---|---|
| A | 4 | 8095.8 | 2023.96 | 1336.48 | 0.000 |
| B | 4 | 4541.8 | 1135.45 | 749.77 | 0.000 |
| C | 2 | 6950.5 | 3475.23 | 2294.79 | 0.000 |
| 2-way interaction | | | | | |
| A*B | 16 | 211.4 | 13.21 | 8.73 | 0.000 |
| A*C | 8 | 94.8 | 11.85 | 7.82 | 0.000 |
| B*C | 8 | 133.2 | 16.65 | 11.00 | 0.000 |
| 3-way interaction | | | | | |
| A*B*C | 32 | 143.7 | 4.49 | 2.97 | 0.000 |
| Error | 150 | 227.2 | 1.51 | | |
| Total | 224 | 20398.4 | | | |

*R*-sq(adj): 98.34%.

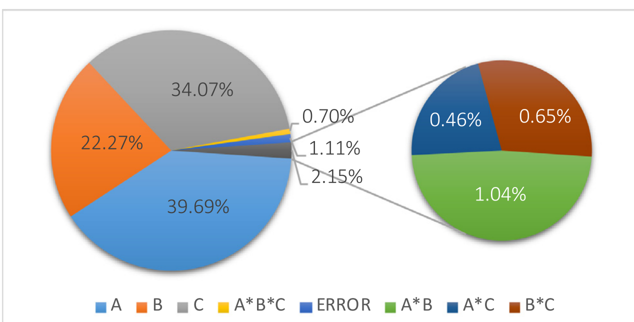


**Figure 6.** The percentage contributions of significant controlling factors.

with the force up to 4.0 N and then decreased at higher forces. Nevertheless, the results from this experiment are distinct from the conclusion in another report [33], which reported that the temperature elevation increased linearly with the feed rate. The results reported herein are also different from a previous examination [31], which demonstrated that the temperature elevation decreased nonlinearly with the feed rate.

The maximum different values in each SS reference group were obtained in reference group SS = 1000. The data are reported in Table 3. While the differences between the CD and LFVAD methods were almost constant, the difference trend between the CD and UVAD methods indicated that the difference also had an inverted U-shape relationship with feed rate.

### 3.4. Statistic analysis

A 3-way ANOVA data analysis was performed to identify the significant controlling factor affecting the temperature elevation and to quantify the weight of controlling factor. The *P*-value in Table 4 (A: Spindle speed, B: Feed rate, C: Drilling method), associating with the percentages in Figure 6, indicated the most significant key factors on the temperature of bone drilling process were spindle speed, drilling method and feed rate in orderly. Apart from that, the 2-way and 3-way interactions were also identified as significant factors, although their weights were much lower. The weights of the interaction of spindle speed and feed rate showed in Figure 7 were almost the sum of the weights of others.

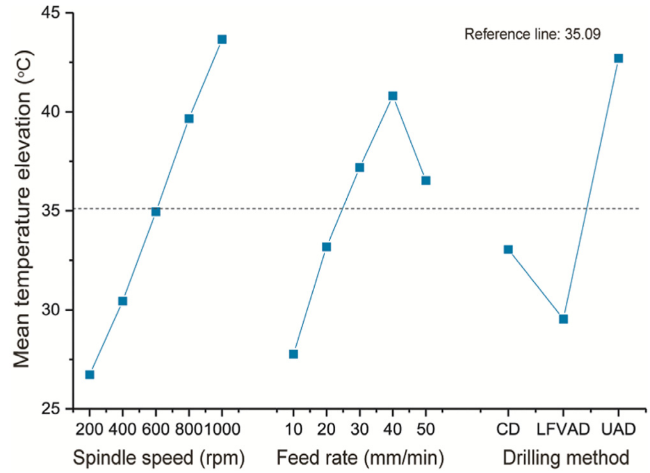


**Figure 7.** The main effects of the controlling factors on temperature elevation.

According to the result of the main effects of the controlling factors, the optimum combination for reducing temperature elevation in bone drilling in our experiment is spindle speed of 200 rpm and feed rate of 10 mm/min by using the LFVAD method.

## 4. Discussion

The placement and velocity of the drill bit in the VAD method are:

$$Z_{VAD}(t) = v_f\ t + A\ \sin(2\pi\ ft) \quad (1)$$

$$\dot{Z}_{VAD}(t) = v_f + 2\pi Af\ \cos(2\pi\ ft) \quad (2)$$

where $A$ and $f$ are the amplitude and frequency of the vibration, respectively, and $v_f$ is the constant feed rate of CD. If the periodic component $2\pi Af$ is greater than $v_f$, which results in $\dot{Z}(t) < 0$, the drill bit will separate from the specimen periodically. The unique drill bit motion method changes the continuous cutting process in CD into a pulse intermittent cutting process in both the LFVAD and UVAD methods. However, because of the differences in the frequency and amplitude between LFVAD and UVAD, there are still some differences between them in thermal conditions during the bone drilling process. To reduce the temperature elevation, it is necessary to either decrease the amount of heat generation, increase the ability of heat dissipation, or both.

For heat generation, the impact property of VAD makes the cutting lips abruptly cut into the workpiece by a pulse intermittent mode, which concentrates the cutting energy, changes the formation mechanics of chips, reduces the chip deformation and makes the cutting process easier [18]. Moreover, the separation and indentation motions between the drill bit and workpiece decrease the mean rate of heat generation due to the decreased mean friction coefficient at the interface of the chips and the rake faces [33]. These advantages imply the lower energy consumption in the cutting process, which results in less heat generated. However, the superposed motion intensifies the friction motion at the interface of the drill body and the wall of the bone hole, which leads to intensive heat generation there.

We supposed that both LFVAD and UVAD benefit from the decreased amount of heat generation during the cutting process. The difference between them is the frictional heat generated from the interface of the drill body and the wall of the bone hole. Although the amplitude of the vibration motion in UVAD is very small, the maximum instantaneous velocity is much higher than the value in LFVAD due to its high frequency. For example, the maximum axial velocities of LFVAD and UVAD in our experiment were approximately 16 mm/s and 1011 mm/s. Since the frictional heat generation is positively correlated with the relative speed, the amount of frictional heat in UAVD should be much higher than that in LFVAD and CD. We obtain the same conclusion as in [33] that the increase in temperature was due to the ultrasonic frequency (greater than 20 kHz) of the vibration energy of drill being dissipated as heat.

For the heat dissipation, the VAD method can produce segmented chips and reciprocating motion can promote the unhindered ejection of bone chips from the flutes [26,43], thereby enhancing the dissipation capacity of the chips. The reciprocating motion also results in an air pump effect to reduce the heat accumulation by boosting airflow at the drill tip [28]. However, according to the much higher amplitude of LFVAD, the maximum velocity of the airflow at the gap between the drill tip and new surface of bone was also supposed to higher than the value of UVAD. The faster airflow takes more heat away. Therefore, LFVAD has a better heat dissipation capacity than UVAD and CD under the same drilling conditions.

As mentioned above, we could draw the conclusion that the lowest temperature elevation of LFVAD reflects the advantages in both heat generation and dissipation. On the other hand, the significantly increased temperature elevation of UVAD is mainly due to the intensified frictional heat generated.

In general, the conflicting results in previous studies and experiments is probably due to the different ranges of spindle speed and (or) feed rate. It is difficult to obtain the similar results, or even the same trends, because of the varied processability of bone material under different stress/strain rate. Moreover, it is worth to mention that there were some experiments using applied thrust force instead of feed rate. The other variables in the previous experiment were geometry parameters of drill bit, such as point angle, rake angle and flute, all have significant effects on heat generation.

Apart from these factors, the properties of specimens are always not the same. Human bone, bovine and pig bone are used in a variety of experiments. Even if some studies using the same kind of bone, there are still some difference because of the natural property of bone effected by too many factors. The subtle differences exist even the specimens made by the same bone.

Furthermore, there are a large number of relevant factors affecting on temperature rising, such as humidity of specimen, ambient temperature, applying irrigation system and measurement technology. That the results were contradictory was unsurprising given the different experimental conditions in each case.

Based on the result of this experiment, we could conclude that as the feed rate is a constant, the increasing spindle speed in all three tested drilling methods leads to thinner uncut chips per revolution, which leads to less energy consumption for the formation of bone chips and thereby less heat generated in the deformation zone. On the other hand, the frictional heat increases since the increased relative velocity between the rake face and the chips. The frictional heat from the interface of the drill body and the wall of the bone hole also increases with the spindle speed. We may conclude that the benefit of the decreased deformation heat was offset by the increased friction heat, and the frictional heat was dominant in this condition in all tested drilling methods. Hence, the temperature elevation has an approximately linear relationship with the spindle speed.

As the spindle speed is a constant, a higher feed rate not only leads to an increased rate of heat generation due to not only the higher material remove rate but also a reduced drilling time in all three tested drilling methods. The temperature elevation curves shown in Figure 5 reflect a competitive relationship between the increased deformation heat and the shortened thermal exposure of the drilling process. Before the feed rate reaches 40 mm/min, the upward trend of the temperature elevation curve means that the effect of increasing the deformation heat overwhelmed the effect of the shortened duration. However, when the feed rate exceeded 40 mm/min, the effect of the shortened duration overwhelmed the rapid heat generation.

According to the curves shown in Figures 4 and 5, the relationships of the temperature elevation and the drilling parameters exhibited no significant difference for the three drilling methods. We suppose that it implies that the axial reciprocating motion only changes the motion of the drill bit and adds new features in the thermo-environment during the drilling process but does not change the fundamental heat conditions of the drilling process. Hence, the effects of the spindle speed and feed rate on the temperature elevation were consistent in all three drilling methods. Nevertheless, there are still some subtle differences between LFVAD and UVAD. The approximately constant difference values between CD and LFVAD reported in Tables 3 and 4 imply that the effect of LFVAD was independent of the varying drilling parameters. In contrast, interestingly, the effect of UVAD was apparently sensitive to the varying spindle speed and feed rate.

## 5. Conclusion

In this paper, experiments were carried out to investigate the effects of the drilling methods and parameters on the temperature elevation in the bone drilling process. According to the results, the LFVAD method can obtain the lowest temperature elevation at the same drilling condition compared to CD and UVAD. We speculate that LFVAD benefits from a low-frequency axial motion that decreases the amount of heat generation and promotes the capacity of heat dissipation. An increased spindle speed leads to a linear increase in the temperature elevation. A larger feed rate leads to a higher temperature until a feed rate of 40 mm/min, which is a peak value, and the temperature drops with a greater feed rate. The relationships of the drilling parameters and temperature elevation were not significantly affected by the different drilling methods. Although LFVAD still requires further research before being put into clinical practice, the results of this study demonstrate that LFVAD has remarkable advantages compared with CD and UVAD with regard to the temperature elevation. Thus, LFVAD may represent a new alternative drilling technique in the medical field. Accordingly, future research will focus on studying the detailed cutting mechanics of LFVAD in the bone drilling process and investigating the influence of LFVAD on the drilling forces.

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## Conflicts of interest

The authors declare that they have no conflicts of interest associated with this paper.

## Ethical approval

Not required.

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## Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.medengphy.2019.06.010.

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