Experimental investigations and finite element simulation of cutting heat in vibrational and conventional drilling of cortical bone

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\textbf{ABSTRACT}

Heat generated during bone drilling could cause irreversible thermal damage, which can lead to bone necrosis or even osteomyelitis. In this study, vibrational drilling was applied to fresh bovine bones to investigate the cutting heat in comparison with conventional drilling through experimental investigation and finite element analysis (FEA). The influence of vibrational frequency and amplitude on cutting heat generation and conduction were studied. The experimental results showed that, compared with the conventional drilling, vibrational drilling could significantly reduce the cutting temperature in drilling of cortical bone (\(P < 0.05\)): the cutting temperature tended to decrease with increasing vibrational frequency and amplitude. The FEA results also showed that the vibrational amplitude holds a significant effect on the cutting heat conduction.

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1. Introduction

Bone drilling is a fundamental operation of orthopedic surgery, but inevitably generates a lot of heat, which may cause irreversible bone damage. Thermal bone damage can lead to bone necrosis or even osteomyelitis \cite{1}, which will reduce bone strength and causing loosening of internal fixation. So cutting heat will not only affect the post-operational recovery but also adversely influence the operation itself \cite{2,3}. Hence, there is great significance to seeking an effective method of reducing the cutting heat in bone drilling.

Karmani proposed several important factors that contribute to cutting heat in the bone drilling and summarized the influence of drill force, speed, drill condition, coolants and other factors \cite{4}. Augustin et al. \cite{5} studied the effect of drill bit diameter, rotation speed, feed speed, drill bit helix angle and external cooling measures on the cutting heat. Allan et al. \cite{6} presented a relationship between the level of drill bit wear and the temperature of the bone being drilled. Seze et al. \cite{7} established a finite element model of the drill bit and bone to analyze the temperature distribution in different drilling depth. Alam et al. \cite{8} proposed a finite element model of bone drilling, in which the drill was considered as a heat source contacted with the bone continuously.

In the 1960s, Kumabe first proposed vibrational drilling, which adds vibration along the axis of the drill bit \cite{9}. Since then, extensive use of this method has proven its effectiveness over conventional drilling, particularly in reducing cutting heat \cite{10–14}. But it is only in recent years that vibrational drilling had been applied to bones. Alam et al. \cite{15} compared the drilling forces and torques during conventional and ultrasonically-assisted drilling. It was revealed that the ultrasonically-assisted drilling reduced trust force and torque compared to conventional drilling. Khademi et al. \cite{16} also proved that a vibration frequency of 16 Hz and amplitude of 2–30 \(\mu\)m can reduce the feed force by 42%. But there is no attention has been paid to its potential ability of reducing the cutting heat in bone drilling.

In this study, vibrational drilling was applied to fresh bovine bones to research the effects of vibration drilling on cutting heat through experimental investigation and finite element analysis. In the experimental investigation, vibrational drilling of cortical bone was compared with conventional drilling to verify the effectiveness of this new drilling method in reducing the cutting heat. The influence of frequency and amplitude on cutting temperature was also studied. Finally a finite element model was established to simulate
the cutting heat conduction during vibrational and conventional bone drilling.

2. Materials and methods

2.1. Specimen preparation

Studies have shown that bovine bones, which are widely used in bone cutting heat research, have the similar thermal properties to human bones [17]. In this study, cortical bone specimens were cut from the mid-diaphysis of bovine femurs which were obtained from a local butcher and were stored frozen at \(-10^\circ\text{C}\) before the experiment. Firstly, the epiphysis of bovine femurs were cut off, and the mid-diaphysis were cut into 10 mm thick slices by a precision cutting machine (Kj type SYJ-200, China; Fig. 1a). Then the thickness of the thickest part of each slice were measured. The thicknesses were in the range of 8–10 mm. So in the experiment the drilling depth was fixed at 8 mm to ensure the drill would not penetrate. As shown in Fig. 1b, the bone marrow was removed and the point to be drilled was marked on each slice of bones. Prior to drilling, the specimens were completely thawed for 1 h in a thermostat-controlled water bath which was adjusted to room temperature to guarantee that each specimen was at the same temperature at the beginning of drilling experiments.

2.2. Experimental equipment

The experimental setup was shown in Fig. 2. Conventional and vibrational drillings were performed on a dynamic material testing machine (Instron E10000, USA), which can provide adjustable vibration with uniform feed speed. Bone samples were clamped in a vise which is fixed on the platform of the testing machine. A regular hand drill, connected with a flexible drive rod, was used to transfer the rotational torque to a drill bit holder. The drill bit holder was mounted to the testing head of the machine. During experiments, the feed rate was fixed at 40 mm/min, and the rotation speed was fixed at 8000 rpm (revolutions per minute). The standard carbide twist drill bits with a 4 mm diameter were used. The helix angle of this bit is 28°, and the chisel edge angle is 55°. A BP-7033 platinum resistor module with a temperature measurement accuracy of ±0.1% was chosen to measure the temperature of the drilling holes.

The motion of the testing head of the dynamic material testing machine was pre-programed in the WaveMatrix software to realize the feed motion of conventional and vibrational drilling with a fixed frequency and amplitude. Before drilling started, the drill bit was adjusted to just touch the bone surface by manual control. Then the hand drill was turned on, and the testing head would drop 8 mm according to the pre-programmed trajectory to realize the feed motion. When the feed motion was finished the testing head would quickly return to the starting position, so the drill bit was pulled out of the drilling hold immediately. Then the platinum resistor was quickly inserted to the bottom of the drill hole to measure the temperature. We continuously recorded the measured temperature until the temperature began to drop, so the highest temperature was chosen as the actual temperature.

During the vibrational drilling, the amplitude and frequency were adjusted orthogonally, in which amplitude was within the range of 100–500 μm and increased in steps of 100 μm, and the frequency was within 5–20 Hz and stepped up by 5 Hz. Therefore, 20 vibrational drilling groups (experimental groups) and 1 conventional drilling group (control group) were used. And 10 drillings were finished within each group. Totally 210 holes were drilled. In order to avoid excessive friction heat produced by drill bit wear, the drill bit was changed after 10 drillings. The mean temperatures of the drill holes in each group were calculated. The unpaired t-test method was used to evaluate the influence of vibration.

2.3. FEM modeling

During bone drilling there were two reasons why the temperature of bone would rise. One was that the friction between bone and drill bit and the internal structure damage would generate heat. The other reason was that due to the different thermal properties the temperature of drill bit would rise much faster than bone and was always much higher, so the drill bit would conduct heat to the bone. In this study, only the heat conduction between drill bit and the bone were simulated by FEA. A two-dimensional finite element model (FEM), which was generated by the pre-processing software package GAMBIT, was used to simulate the cutting heat conduction. Fig. 3 showed the geometrical configuration of the cutting heat conduction models for both conventional and vibrational drilling.

In order to achieve dynamic analysis of cutting heat conduction in vibrational drilling, the drill bit was constructed to a simple model, in which the screw thread was ignored. And since the temperature distribution in the bone was the research objectives, so the drill bit was constructed as a hollow wireframe model, of which the initial temperature was assigned to the boundary. The diameter of the drill bit was 4 mm, which was consistent with the drill bit used in the experiment. The diameter and the thickness of the bone were 8 mm and 9 mm. In order to consider the impact of air flow on the thermal conduction, an air layer which was 0.1 mm thick was constructed between the drill bit and the bone. There was an air region about 1.5 mm in height above the drill bit to provide the space for the drill bit vibration. The margin of this region was set as the exit of pressure, in which the air could flow freely. The initial position of the drill bit in the vibrational drilling was located at the upper limit position of the vibration, which was associated

with the amplitude of the vibration. As shown in Fig. 3(b), when the amplitude was 500 μm, the distance between the initial position of the drill bit and the bottom of the drill hole was 600 μm, including 100 μm thick air layer. The corresponding finite element models were shown in Fig. 4. The model was constructed using triangular unstructured meshes. In the finite element model of the vibrational drilling, the flow air between the drill bit and the drill hole was simulated using the dynamic mesh. The simulations were performed using the CFD software FLUENT. The initial temperature of the bone was assigned as 20 °C. The thermal properties used in the finite element analysis were summarized in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Bone</th>
<th>Density (kg/m³)</th>
<th>Conductivity (W/m °C)</th>
<th>Specific heat (J/kg °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>1700</td>
<td>0.38</td>
<td>1260</td>
</tr>
</tbody>
</table>

3. Results and discussion

The temperatures of drill holes were recorded experimentally in conventional drilling group and vibrational drilling groups with various vibration parameters. So the effect of vibrational
bone drilling on reducing cutting heat could be verified. And the influence of vibrational frequency and amplitude on cutting temperature in bone drilling could also be concluded. Meanwhile, the finite element models were verified by comparing with the experimental results. Then the influence of vibrational parameters on cutting heat conduction in vibrational bone drilling were concluded via FEA results.

3.1. Experimental results and discussion

The mean values and standard deviations of temperatures of drill holes in each vibrational drilling group were summarized in Table 2. Moreover, the mean value and standard deviation of temperatures of the drill holes in conventional drilling group was 55.41 ± 4.60 °C, which could cause bone thermal damage and is significantly higher than those in vibrational drillings (P < 0.01).

As we can see from Table 2, there was a downward trend in the mean temperatures of the drill holes with the increasing of frequency and amplitude of vibration. The differences of mean temperatures between conventional drilling and the vibrational drilling with lowest parameters (f = 5 Hz, A = 100 μm) was 14.62 °C, and between conventional drilling and the vibrational drilling with highest parameters (f = 20 Hz, A = 500 μm) was 19.03 °C.

As mentioned before, there is a downward trend in the mean temperatures with the increasing frequency and amplitude of vibration. So the effects of frequency and amplitude were investigated respectively.

Fig. 5 showed the effect of frequency on the temperature of the drill hole. Although the influences were not entirely consistent in all groups, it is found that in most groups, when the frequency increased and the amplitude stayed the same, the temperatures of the drill holes tended to decrease. The unpaired t-test method was used to evaluate the influence of frequency, and we can see from Fig. 5 that in several groups the effects of frequency on cutting temperature were significant.

As shown in Fig. 6, when the frequency varied from 5 Hz to 20 Hz, a significant decrease in temperature was observed with amplitude of 500 μm. In these vibrational drilling groups (A = 500 μm), the mean temperature of drill holes with a frequency of 5 Hz was 24% lower than that in conventional drilling group. And the mean temperature with a frequency of 20 Hz was 34% lower than that in conventional drilling group.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Amplitude (μm)</th>
<th>Temperature of drill hole (°C) Mean SD</th>
<th>Frequency (Hz)</th>
<th>Amplitude (μm)</th>
<th>Temperature of drill hole (°C) Mean SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>100</td>
<td>40.79 ± 2.78</td>
<td>15</td>
<td>100</td>
<td>42.91 ± 2.07</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>42.89 ± 4.09</td>
<td></td>
<td>200</td>
<td>42.99 ± 2.94</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>43.66 ± 3.26</td>
<td></td>
<td>300</td>
<td>39.47 ± 1.69</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>41.19 ± 1.26</td>
<td></td>
<td>400</td>
<td>39.46 ± 1.73</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>42.31 ± 1.70</td>
<td></td>
<td>500</td>
<td>37.88 ± 1.67</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>42.87 ± 2.00</td>
<td>20</td>
<td>100</td>
<td>40.65 ± 1.68</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>40.33 ± 2.60</td>
<td></td>
<td>200</td>
<td>35.72 ± 1.27</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>39.19 ± 1.75</td>
<td></td>
<td>300</td>
<td>36.19 ± 1.31</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>38.35 ± 2.55</td>
<td></td>
<td>400</td>
<td>38.74 ± 1.62</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>38.70 ± 1.37</td>
<td></td>
<td>500</td>
<td>36.38 ± 1.32</td>
</tr>
</tbody>
</table>

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The effect of amplitude on the temperature of the drill holes was also examined. The mean temperatures of each group are shown in Fig. 7. Despite a minor inconsistence, it is also found that in most groups, temperatures of the drill holes tended to decrease with increasing amplitude at the same frequency.

As shown in Fig. 8, the temperature of the drill hole deceased by 12% when the frequency was 15 Hz and the amplitude was increased from 100 μm to 500 μm.

3.2. Simulation results and discussion

3.2.1. Model verification

To verify the finite element model, the temperatures of the drill bit were obtained just after drilling from the experiment, then the mean temperature was assigned to the outer wall of the drill bit model. As the drilling time was 12 s in experiment, the FEA simulation was also calculated for 12 s, then the mean temperature of drill hole in FEA model was compared with the mean temperature that was measured in the experiment. In this study, the experimental results of the conventional drilling group and a vibrational drilling group (A = 200 μm, f = 20 Hz) were used to verify the model of the two drilling methods. The temperatures of the drill bit of the conventional drilling group and the vibrational drilling group were 97.05 °C and 59.42 °C, respectively. Fig. 9 showed the simulation results of the two groups after 12 s.

In the experiment, the platinum resistor was manually inserted into the bottom of drill hole to measure the temperature of the drill hole. Due to the manual operation, it could not be guaranteed that the platinum resistor was placed at the same location of the drill hole for each measurement. Therefore, six points from the inner wall of the drill hole were chosen, as shown in Fig. 10. The mean temperature of these six points was compared with the experimental result, and the comparison results were shown in Table 3.

As shown in Table 3, the simulation results were generally higher than the temperature of the drill hole in the experiment. The possible explanation is that in experiments the temperature of the drill bit rose from room temperature (20 °C) to the highest temperature which we measured after drilling for 12 s, so there was a gradual heat transfer process to the bone. However, in the FEA simulation the temperature of the drill bit was kept at the highest temperature obtained by the experiment constantly, so there was a thermostatic heat transfer process. Therefore it is inevitable that the simulation results are higher than the experimental results. On the other hand, the percentages of the temperature difference between the experimental results and the simulation results in both conventional and vibrational groups were about 12%. Hence, it is verified that the finite element models could reflect the influence of the vibrational drilling on the cutting heat to a certain extent.

Table 3
Comparison results between the experimental and simulation results (°C).

<table>
<thead>
<tr>
<th>Simulation results (different points)</th>
<th>Experimental results</th>
<th>Difference</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Vibrational drilling</td>
<td>36.00</td>
<td>39.70</td>
<td>41.55</td>
</tr>
<tr>
<td>(A = 200 \mu m, f = 20 Hz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional drilling</td>
<td>59.59</td>
<td>60.76</td>
<td>61.93</td>
</tr>
</tbody>
</table>

3.2.2. Simulation results and discussion

To study the heat conduction inside the bone, two straight lines perpendicular to the temperature gradient were selected in each FEA model (Fig. 11). One line was \( y = 0.003 \), the other line was \( y = x + 0.003 \). In the simulation process, the temperature of the drill bit was fixed at 70 °C and the time of heat transfer was 5 s. By comparing the temperatures of every points on these two straight lines, the effect of the vibration parameters on the cutting heat was analyzed.

![Fig. 9. Simulation results of the two groups after 12 s. (a) The conventional drilling group; (b) the vibrational drilling group (\( A=200\mu m, f=20\text{Hz} \))](image)

![Fig. 10. Six points on the finite element model.](image)

![Fig. 11. Two straight lines perpendicular to the temperature gradient.](image)

![Fig. 12. Change of temperature with different amplitude (\( f=5\text{Hz} \)); (a) \( y=0.003 \) (b) \( y=x+0.003 \).](image)
To show the influence of the amplitude on the cutting temperature of bones, various amplitudes of 100, 200, 300, 400 μm were used. Figs. 12 and 13 showed when the frequency was 5 Hz and 20 Hz, the temperature has changed with changing amplitudes on these two straight lines. In general, the temperature decreased with increasing amplitude, which means bigger amplitude vibration would help to reducing cutting temperature. And the reason may be that increased amplitude would lead to more air flow, which could take away more cutting heat. According to Figs. 12 and 13, the effect of amplitude on reducing cutting heat was significant.
The effect of frequency on the temperature distribution was also studied and presented in Figs. 14 and 15. As shown in Fig. 14, when the amplitude was 500 μm, various frequencies of 5, 10, 15, 20 Hz were used. Obviously, the temperature difference with increased frequency was not significant. Then the range of frequency was extended and various frequencies of 5, 20, 40, 50, 80 Hz were chosen when the amplitude was 100 μm (Fig. 15). Comparing the temperatures of bone on the same line with different frequencies, there was still no significant difference. So it was concluded that the influence of frequency on the cutting heat conduction was not significant at low frequency (less than 100 Hz).

4. Conclusion

According to the experimental results, vibrational drilling could significantly reduce the cutting heat in drilling of cortical bone ($p < 0.05$). We speculated that there were three possible reasons for this. One was that vibrational drilling could reduce the internal damage of bone at the drill site according to our previous research [18], so it could reduce the cutting heat generated by internal damage of bone. The second reason was that vibrational drilling could reduce the contact time between the drill bit and the bone, so the heat conduction from the drill bit to the bone could be reduced. The third reason was that vibrational drilling could promote air flow around the drill bit, which could dissipate more cutting heat than conventional drilling.

It is also found that with the increasing of vibration frequency and amplitude, there was a downward trend of cutting temperature of bone. Since bigger frequency and amplitude means stronger vibration effects, so this results was consistent with the conclusion that vibration drilling could reduce the cutting heat in drilling of cortical bone.

On the other hand, the FEA simulation results showed that vibration amplitude could significantly affect the heat conduction between drill bit and the bone. The temperature of the drill hole decreased with increasing amplitude at the same frequency. However, the simulation showed that the effect of vibration frequency (less than 100 Hz) on the cutting heat conduction was not particularly obvious.

This study may provide new methods for reducing the cutting heat in bone drilling, which may contribute to post-operative recovery. Further research is needed to be done in several aspects, such as optimization of the temperature measure method to achieve real-time measurement, expanding the range of frequency to ultrasonic vibration, modification of the FEA model to better simulate the drilling process.

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Ethical approval

Not required.

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Conflict of interest statement

None.

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