Experimental investigations of drilling temperature of high-energy ultrasonically assisted bone drilling

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ARTICLE INFO

ABSTRACT

Ultrasonically assisted drilling as a new type of bone drilling technology has received increasing attention. However, the vibration energy of existing studies was limited. In this study, a robot-based ultrasonically assisted bone drilling experimental setup was designed, and high-energy ultrasonically assisted bone drilling (vibration frequency=24.1–41 kHz, and vibration amplitude=150–160 μm) was applied to bovine cortical bone to investigate the drilling temperature compared with conventional drilling. The effect of drilling speed on drilling temperature was also studied. The experiment results showed that, compared with the conventional bone drilling, high-energy ultrasonically assisted bone drilling had slightly higher drilling temperature (0.36–0.86 °C), which is in direct contrast to previous reports. We hypothesized that this finding was due to the thermal effect of ultrasonic vibration, which the present study confirmed. Moreover, the drilling temperature increased with higher drilling speed.

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1. Introduction

Bone drilling is a basic operation widely used in orthopedic surgery. During bone drilling, heat is generated by the friction between the bone and the drill bit, and also the plastic deformation of the bone material. Due to the low thermal conductivity of bone tissue (in the range of 0.2–2.27 W/mK) [1], the heat of bone drilling is difficult to spread quickly. This results in a relatively high temperature of the drilling part of the bone. Excessive heat generation in bone drilling process can cause necrosis or even osteomyelitis of the bone tissue, which will adversely influence the operation and the postoperative recovery [2,3]. At present, most researchers regard an average temperature of 47 °C for one minute as the threshold above which the drilling heat will cause irreversible thermal damage [4]. Kerawala et al. [5] reported that the temperature near the drilling site can exceed 70 °C in conventional bone drilling. Therefore, it is very important to propose an effective method to reduce the heat of bone drilling.

Vibrational drilling as a new type of mechanical processing method, was proposed by Kumabe in the late 1950s [6], and has a significant effect in reducing the drilling heat in metal processing [7,8]. Recently, vibrational bone drilling has been performed in vitro experiments. In our previous research, we had investigated

low frequency vibrational bone drilling (frequency was within 5–20 Hz, and amplitude was within 100–500 μm). We found that this vibrational drilling method had a remarkable effect in reducing the drilling temperature [9]. Zakrasas and colleagues [10] concluded that low frequency (60–120 Hz) vibrational bone drilling showed 14% reduction in drilling temperature compared to conventional drilling. The current study aimed to extend our previous study to ultrasonically assisted bone drilling (UAD), examining its effect in drilling temperature and comparing this effect with conventional bone drilling (CD).

To date, several investigators have studied the influence of UAD on bone drilling temperature. Alam and co-workers [11] studied the effects of UAD with vibration frequency of 5–30 kHz and vibration amplitude of 5–25 μm on the bone drilling temperature. They found that UAD at frequencies below 15 kHz reduced the drilling temperature when compared to conventional drilling. When the frequency exceeded 15 kHz, however, UAD generated higher temperatures than conventional drilling procedures. Shakouri et al. [12] reported that UAD with vibration frequency of 19.75 kHz and vibration amplitude of 40 μm had lower thrust forces and lower process temperatures as compared to CD at the rotational speed of 1000 r/min. Using diamond-coated abrasive hollow tool in their UAD experiments, Gupta et al. [13,14] found that the drilling temperature of UAD was significantly lower than that of CD when the vibration frequency was 20 kHz and amplitude was 4–20 μm.

Thus, while UAD has been found to have clear advantages over conventional drilling in terms of reducing the drilling temperature,

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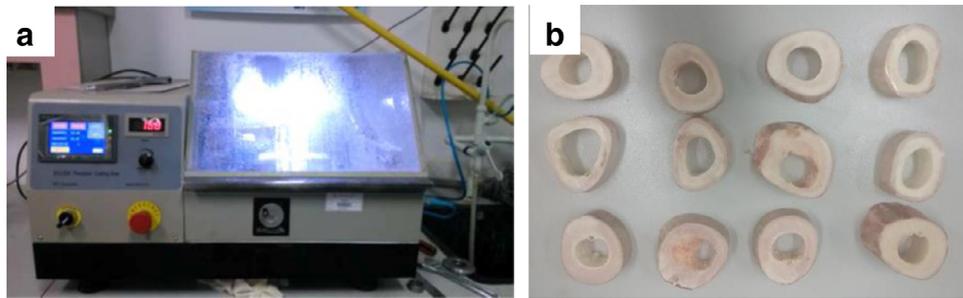E-mail address: wangyu@buaa.edu.cn (Y. Wang).

Fig. 1. (a) Precision cutting machine, and (b) bone specimens.

Table 1
Summary of vibrational parameters in studies about the effect of UAD on drilling temperature.

References	Years	Vibration frequency(kHz)	Vibration amplitude(µm)
Alam et al. [15]	2014	5–30	5–20
Alam et al. [11]	2015	5–30	5–25
Shakouri et al. [12]	2015	19.75	40
Kong et al. [16]	2015	19.5, 30	0–5
Gupta et al. [13]	2016	20	4–20
Gupta et al. [14]	2017	20	16

the range of vibration frequencies and amplitudes studied has been limited to below 30 kHz and 40 um, respectively (Table 1). In a previous study [9] we showed that, in low frequency vibrational bone drilling, the drilling temperature deceased when the amplitude and frequency was increased [9]. In addition, the research conducted by Gupta et al. [13] demonstrated that the drilling temperature decreased with the increasing amplitude when the vibration frequency was 20 kHz and amplitude was 4–20 µm. Consequently, further investigation should be carried out to find out whether the bone drilling temperature decreased when the vibration amplitude and frequency increased to even higher level in UAD.

To address this issue, this study increased vibration parameters of UAD to larger extent. The vibration amplitude was increased to 150–160 µm, which was 4–10 times bigger than past research, and frequencies in the range 24.1–41 kHz were investigated. Since the vibration energy is mainly determined by amplitude and frequency. Therefore, increasing vibration parameters leads to higher vibration energy. In this study, the drilling temperature of high-energy UAD was compared with that of CD, and the influence of drilling speeds was also investigated.

2. Materials and methods

2.1. Specimen preparation

The experiments were conducted on samples of cortical bone derived from a bovine femur (about 18–24 months old) which was obtained from a local butcher 1–2 h before the experiments started. Excess tissue was removed until the shaft was exposed, and the femur was cut into 20 mm slices by a precision cutting machine (KJ type SYJ-200, China; Fig. 1(a)), as shown in Fig. 1(b).

2.2. Experimental setup

A novel ultrasonically assisted bone drilling experimental setup was designed. As shown in Fig. 2(a), the experimental setup can be divided into five components: the robot arm based feed control system, the electric spindle system, the ultrasonic vibration system, the specimen clamping system, and the temperature measurement system. As shown in Fig. 2(b), in this experiment setup the bone specimen was mounted on the top of the ultrasonic transducer, so during the UAD process the bone specimen, instead of the drill bit,
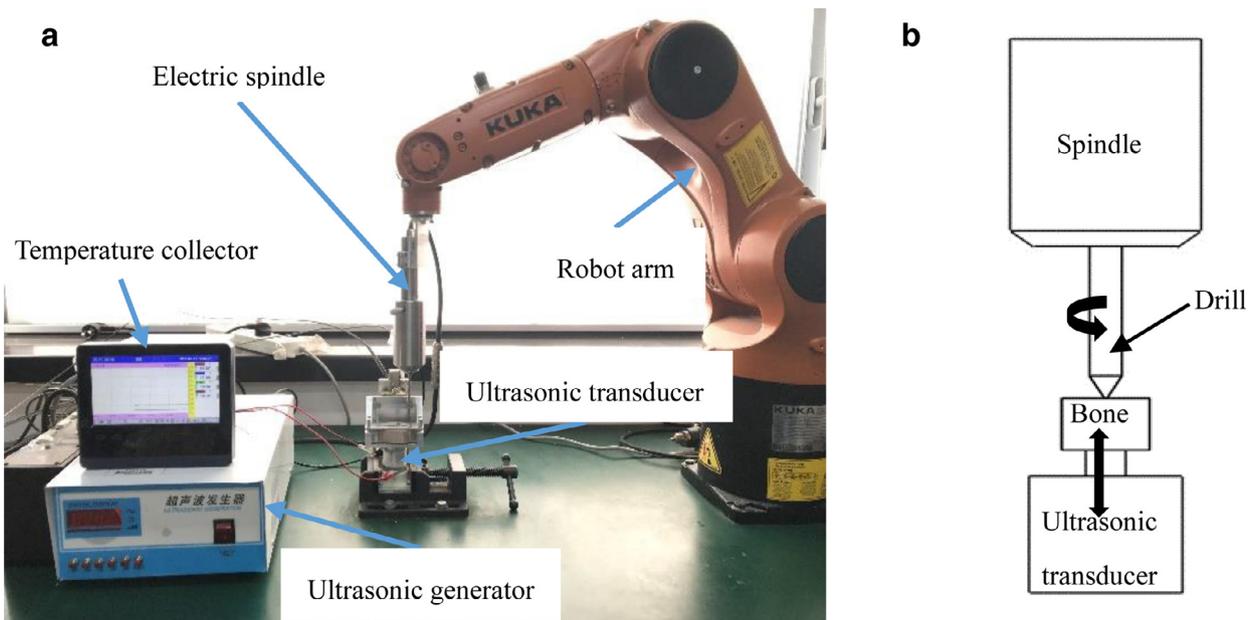

Fig. 2. (a) The experimental setup, and (b) schematic of ultrasonic drilling setup.

Fig. 3. Conventional twist drill bit.

Table 2
Parameters used in the experiments.

Parameters	Value
Drill diameter (mm)	4
Drilling speed (rpm)	3000, 6000, 9000
Feed rate (mm/s)	1
Feed depth(mm)	15
Vibration amplitude (μm)	150~160
Vibration frequency (kHz)	24.1, 31.1, 41

would vibrate. In the meantime, the drill bit was fed into the bone specimen from the top by a high precision robot arm. The advantage of this setup was that ultrasonic vibration and drilling could be exerted to bone specimen separately, so we could investigate the thermal effect of ultrasonic vibration alone on the bone specimen. In this experiment, the conventional twist drill bits (Fig. 3) with diameter of 4 mm was used, considering most surgical drill bit's diameters are in the range of 1.5–5.5 mm [17,18].

The components of the experimental setup are introduced as below.

i. The robot arm based feed control system: A robot arm (KUKA KR-6-R700-sixx) with repeat accuracy of ±0.03 mm was utilized as the feed motion actuator. The feed speed of bone drilling process was 1 mm/s, and the feed distance was 15 mm.
ii. The electric spindle system: The electric spindle (NAKAN-ISHI EM-3030-T) of 300 W was used to generate rotation motion for drilling. The spindle can provide a rotational speed from 1000 rpm to 35,000 rpm. Three drilling speeds (3000 rpm, 6000 rpm and 9000 rpm) were applied in this study.
iii. The ultrasonic vibration system: This system was composed of three interchangeable ultrasonic transducers (24.1 kHz, 31.1 kHz and 41 kHz), and a 500 W rated power ultrasonic generator which can adjust its output power and frequency (from 20 kHz to 80 kHz). The vibration amplitude of these ultrasonic transducers was 150–160 μm (measured with the clamping device and the bone specimen using a high frequency displacement sensor (eddyNCDT 3300, Micro-Epsilon, German)).
iv. The specimen clamping system: The bone specimen was clamped on a clamping device as shown in Fig. 4, and the ultrasonic transducer was installed below it. A linear guide was used to make sure that the vibration direction of the bone specimen and ultrasonic transducer was vertical. During the UAD

process, the bone specimen would vibrate with the ultrasonic transducer in the vertical direction.
v. The temperature measurement system: the drilling temperature was recorded from two measuring sites at the distance of 1.1 mm from the drilling position (shown in Fig. 5(a)), by two K-type thermocouples (measuring range is 0–150 °C with an accuracy of 0.1 °C and resolution of 0.01 °C) as shown in Fig. 4. Each thermocouple was recalibrated within 0–80 °C before being used. During the preliminary experiments, we found that if the drilling depth was not deep enough, a large amount of heat was conducted away by the air, resulting in inaccurate temperature measurement. In order to maintain enough drilling depth, the direction of drilling was longitudinal direction of the bone. Two predrilled holes with a depth of 10 mm were prepared using a guide plate (shown in Fig. 5(b)) to insert the thermocouples. The guide plates consisted of glass fiber, and there was another glass fiber board under the bone specimen, which could effectively prevent the heat from being transferred away from the bone specimen. The temperature change during the entire drilling process was recorded by the temperature monitor.

2.3. Experimental design

The basic experimental parameters are shown in Table 2. The main variables of this experiment were drilling speed and vibration frequency, and each parameter had three values, so there were nine parameter combinations. For each parameter combination, 10 UAD operations and 10 CD operations had been done. Thus, a total of 180 drilling operations were carried out. Each bone specimen
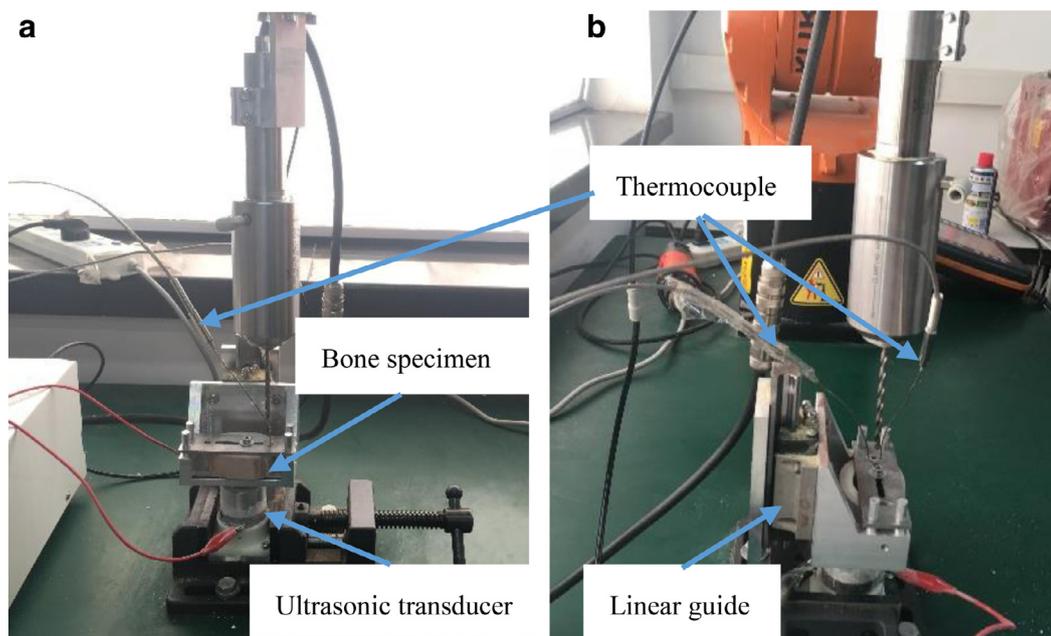

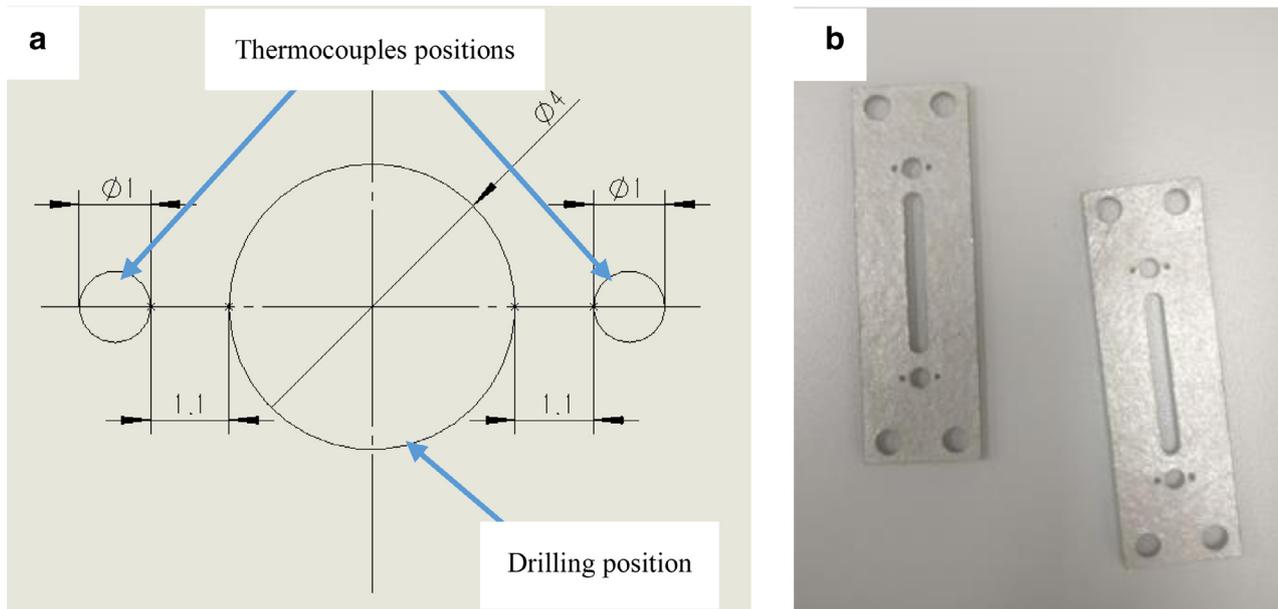Fig. 4. The clamping device, (a) front view and (b) side view.

Fig. 5. (a) Positions of inserted thermocouples, and (b) The guide plates.

was drilled with four holes with an interval of 90°, so 45 bone specimens were utilized.

At the beginning of the experiment, the thermocouples were inserted into the sample. Once the drilling operation had started, the drilling temperature was recorded. In order to make sure that the drill bit did not deviate from the bone during drilling process, the samples with radial thickness less than 6 mm were eliminated. The ultrasonic generator was turned on in UAD experiments and turned off in CD experiments. In UAD process, the ultrasonic generator was turned on only during the tip of drill bit was inside the bone, including feed and exit, which was about 30 s. After each drilling operation, the bone specimen was placed under room temperature for 10 min to allow the temperature of the bone specimen to return to room temperature before the next drilling operation was started.

The experiments were conducted indoors. During our experiments, it was found that room temperature was a very important environmental condition affecting the drilling temperature. However, due to the limitation of the experimental environment, the room temperature of each experiment could not be absolutely consistent. In order to minimize the impact of the varied room temperature, the UAD operation and the CD operation were alternately conducted.

3. Results and discussion

3.1. Experiment results

The average value of the temperatures on two measuring sites was approximate to the bone temperature of the drilling process. During UAD or CD drilling, as shown in Fig. 6, there was no significant temperature rise before the cutting edge of the drill bit penetrated close to the depth where the thermocouples were inserted. When the cutting edge of the drill bit approached the thermocouples, the temperature quickly increased to a maximum value and then decreased at a slower speed. The temperature when the drilling began (start temperature:T^s) and the maximum value (maximum temperature: T^m) in every drilling process were recorded, and the difference between these two values was the temperature rise (T^r). The average temperature of each group is listed in Table 3.
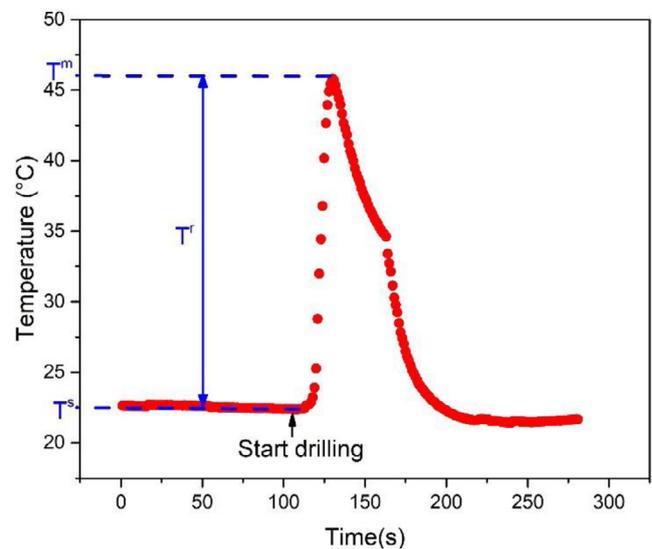

Fig. 6. Temperature change during a drilling process.

Fig. 7 shows the differences of start temperatures between different parameter combinations, which was caused by the changing of room temperature. However, due to the alternately conducting of UAD and CD operations, the start temperatures of the UAD group and the CD group of a same parameter combination were very close, and the average difference was only −0.05 °C. Therefore, the effect of room temperature was negligible in this way.

3.2. Effect of ultrasonic vibration

Fig. 8 shows that the drilling temperatures rise of UAD group were slightly higher than those of CD group, and the differences were between 0.36 °C and 0.86 °C. The unilateral t-test method was used to evaluate the differences of temperature rise between UAD and CD of each parameter combination as showed in Table 3. While the results indicated that the differences were not significant ($p > 0.05$), the UAD group had higher drilling temperatures than CD group for every parameter combination. Interestingly, this

Table 3
Summary of average temperature.

| Parameter combination number	Vibration frequency (kHz)	Drilling speed (rpm)	Start temperature (°C)		Maximum temperature (°C)		Temperature rise (°C)			
			T^s_{UAD}	T^s_{CD}	T^m_{UAD}	T^m_{CD}	T^r_{UAD}	T^r_{CD}	ΔT^r	P(t-test)
1	24.1	3000	23.62	23.62	44.64	44.13	21.02	20.51	0.51	0.32
2	24.1	6000	21.66	21.71	47.86	47.38	26.20	25.67	0.53	0.25
3	24.1	9000	23.93	24.03	48.34	47.58	24.41	23.55	0.86	0.16
4	31.1	3000	21.72	21.88	42.09	41.73	20.37	19.85	0.52	0.14
5	31.1	6000	21.32	21.20	43.24	42.76	21.92	21.56	0.36	0.32
6	31.1	9000	22.15	22.13	46.94	46.14	24.79	24.01	0.78	0.21
7	41	3000	22.79	22.88	44.24	43.85	21.45	20.97	0.48	0.26
8	41	6000	21.36	21.36	50.28	49.79	28.92	28.43	0.49	0.40
9	41	9000	23.74	23.89	50.49	49.92	26.75	26.03	0.72	0.25
Average			22.48	22.52	46.46	45.92	23.98	23.40	0.58	0.26
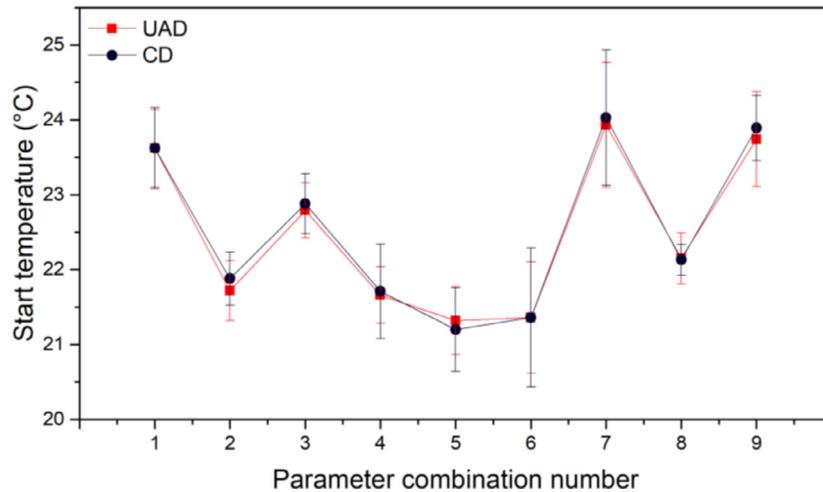
Fig. 7. Start temperatures of different experiment groups, (*Note:* the error bars represent standard deviation).

result is contrary not only to our original hypothesis, but also the findings of previous research.

Based on our observations, we proposed a new hypothesis to explain this phenomenon. It is well known that when the ultrasonic wave propagates in the medium, its energy will be absorbed by the medium and converted into heat, which will increase the temperature of the medium [19]. Therefore, we assumed that the higher drilling temperature of UAD was mainly caused by the thermal effect of ultrasonic vibration. To verify this hypothesis, we conducted a validation experiment. First, the bone specimen was fixed
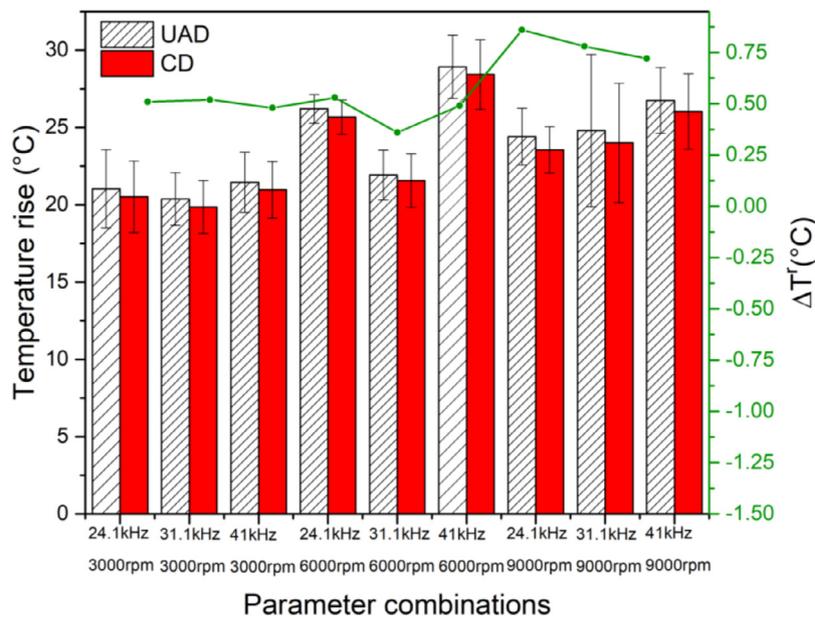

Fig. 8. Effect of ultrasonic vibration on drilling temperature, (*Note:* the error bars represent standard deviation).

Table 4
The testing results of ultrasonic thermal effect.

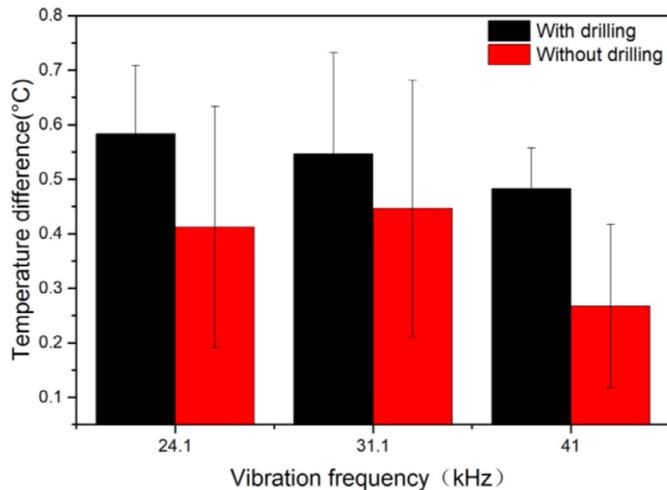| Vibration frequency (kHz)	Temperature difference(°C)										Average(°C)
	1	2	3	4	5	6	7	8	9	10	
24.1	0.48	0.56	0.18	0.46	0.07	0.90	0.23	0.37	0.34	0.54	0.41
31.1	0.48	0.73	0.62	0.19	0.34	0.30	0.32	0.83	0.59	0.06	0.45
41	0.07	0.19	0.12	0.17	0.32	0.16	0.27	0.55	0.48	0.36	0.27

Fig. 9. Average temperature differences of each frequency with and without drilling, (*Note:* the black bars represent the difference in temperature between UAD and CD; the red bars represent the corresponding temperature rise after 30 s of ultrasonic vibration in the absence of drilling. The error bars denote the standard deviation).

in the clamping device, and the thermocouples were inserted in the specimen in the same way as the drilling experiments. The ultrasonic generator was switched on for 30 s without drilling, which is the same vibration time in UAD. Finally, the temperatures of the specimen were recorded before and after 30 s vibration, and the temperature differences were calculated. This experiment was repeated 10 times for each frequency, and the results are shown in Table 4. According to the results, all the bone samples had a certain degree of temperature rise after 30 s of ultrasonic vibration. These results were compared with the drilling temperature differences between UAD and CD groups as showed in Fig. 9. The results confirmed that the thermal effect of ultrasonic vibration was the major cause of the observation that the drilling temperature of UAD group was slightly higher than that of CD group.

3.3. Effect of drilling speed

The effect of drilling speed on drilling temperature was also studied. Fig. 10 shows that whether in UAD or CD groups, drilling temperature mainly increased with increasing drilling speed. The main reason for this result is that increasing drilling speed will lead to the increase of frictional forces and shearing energy between the drill bit and the bone interface [17,18]. However, we also found that when the frequencies were 24.1 kHz and 41 kHz, the temperatures of 9000 rpm were lower than those of 6000 rpm, but still higher than those of 3000 rpm. Clearly, further research is needed to establish the effect of drilling speed.

4. Conclusions

In this work, a novel ultrasonic vibration drilling experimental setup was designed. The ultrasonic vibration was applied to the
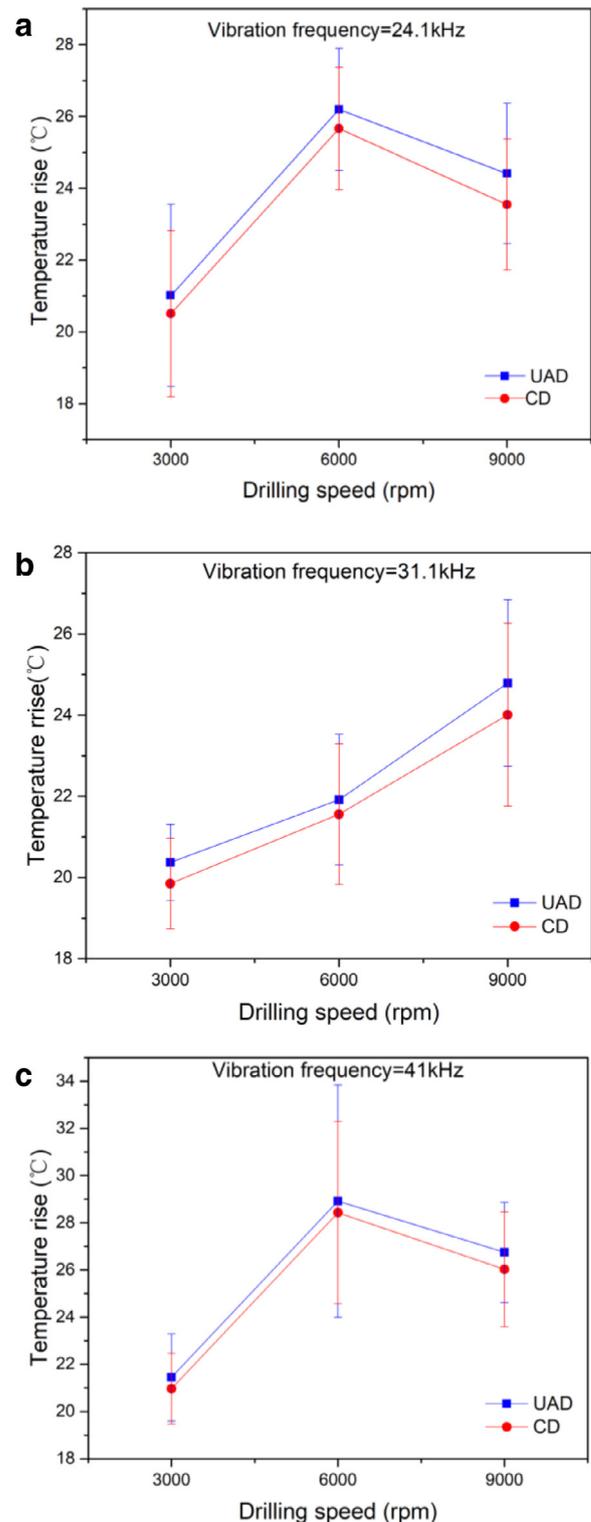

Fig. 10. Effect of drilling speed on drilling temperature rise at (a) 24.1 kHz, (b) 31.1 kHz, (c) 41 kHz, (*Note:* the error bars represent standard deviation).

bone specimen instead of drill bit so we could investigate the effect of ultrasonic vibration alone on bone temperature. The differences in the drilling temperature of UAD and CD were compared, and the effect of drilling speed on bone drilling temperature was also studied. Three vibration frequencies (24.1 kHz, 31.1 kHz and 41 kHz) and three drilling speeds (3000 rpm, 6000 rpm and 9000 rpm) were applied in the experiments.

The results of this study showed that UAD had slightly higher drilling temperature than CD, and the thermal effect of ultrasonic vibration was a main reason for this unexpected phenomenon according to our validation experiment. The drilling temperature increased with the increase in the drilling speed.

When the amplitude and frequency of the vibrations under UAD increased to a higher level, there is a corresponding increase in vibration energy, some of which is converted into thermal energy, which leads to a slightly higher drilling temperature than conventional bone drilling. Based on our findings, however, high-energy UAD does not give rise to a decrease in drilling temperature, which contradicts our original hypothesis. This surprising result suggests that there is an optimal value or range of vibration settings for ultrasonically-assisted bone drilling procedures. In addition to reducing drilling temperature, UAD still has certain positive effects on bone drilling in other aspects, such as reducing the surface roughness of drilling sites and the drilling forces and torques [20,21]. We believe that the full potential of ultrasonically-assisted drilling procedures in orthopedic surgical practice has yet to be fully realized.

Conflicts of interest

None.

Funding

Ethical approval

Not required.

References

[1] Davidson SR, James DF. Measurement of thermal conductivity of bovine cortical bone. Med Eng Phys 2000;22:741–7.

[2] Misch C. Density of bone: effect on treatment, planning, surgical approach and healing. In: Misch C, editor. Contemporary implant dentistry. St. Louis: Mosby; 1993. p. 469–84.

[3] Summers RB. A new concept in maxillary implant surgery: the osteotome technique. Compend Contin Educ Dent 1994;15:152–60.

[4] Pandey RK, Panda SS. Drilling of bone: a comprehensive review. J Clin Orthop Trauma 2013;4(1):15.

[5] Kerawala CJ, Martin IC, Allan W, et al. The effects of operator technique and bur design on temperature during osseous preparation for osteosynthesis self-tapping screws. Oral Surg Oral Med Oral Pathol Oral Radiol Endodontol 1999;88(2):145–50.

[6] Brehl DE, Dow TA. Review of vibration-assisted machining. Precis Eng 2008;32:153–72.

[7] Pujana J, Rivero A, Celaya A, López de Lacalle LN. Analysis of ultrasonic-assisted drilling of Ti_6Al_4V. Int J Mach Tools Manuf 2009;49:500–8.

[8] Chang SF, Bone GM. Thrust force model for vibration-assisted drilling of aluminum 6061-T6. Int J Mach Tools Manuf 2009;49:1070–6.

[9] Wang YU, Cao M, Zhao X, et al. Experimental investigations and finite element simulation of cutting heat in vibrational and conventional drilling of cortical bone. Med Eng Phys 2014;36(11):1408–15.

[10] Zakrasas R, Jurenas V, Baskutienė J. Analysis of compact bone vibration assisted drilling. Solid State Phenom 2016;251:183–7.

[11] Alam K, Mitrofanov AV, Silberschmidt VV. Measurements of surface roughness in conventional and ultrasonically assisted bone drilling. Am J Biomed Sci 2009;2009(1):312–20.

[12] Shakouri E, Sadeghi Mohammad H, Mohammad R K, et al. An in vitro study of thermal necrosis in ultrasonic-assisted drilling of bone. Proc Inst Mech Eng Part H: J Eng Med 2015;229(2):137–49.

[13] Gupta V, Pandey PM. Experimental investigation and statistical modeling of temperature rise in rotary ultrasonic bone drilling. Med Eng Phys 2016;38(11):1330–8.

[14] Gupta V, Pandey PM, Gupta RK, et al. Rotary ultrasonic drilling on bone: a novel technique to put an end to thermal injury to bone. Proc Inst Mech Eng Part H: J Eng Med 2017;231(3):954411916688500.

[15] Alam K, Hassan E, Bahadur I. Experimental measurements of temperatures in ultrasonically assisted drilling of cortical bone. Biotechnol Biotechnol Equip 2015;29(4):753–7.

[16] Kong F, Lee YS. Analytical modeling of ultrasonic vibration assisted drilling of bones for medical surgical applications. In: Proceedings of the international manufacturing science and engineering conference; 2015.

[17] Hillery MT, Shuaib I. Temperature effects in the drilling of human and bovine bone. J Mater Process Technol 1999;92–93:302–8.

[18] Maani N, Farhang K, Hodaei M. A model for the prediction of thermal response of bone in surgical drilling. Therm Sci Eng Appl 2014;6:041005. doi:10.1115/1.4026625.

[19] Humphrey VF. Ultrasound and matter—Physical interactions. Prog Biophys Mol Biol 2007;93:195–211.

[20] Alam K, Mitrofanov AV, Silberschmidt VV. Measurements of surface roughness in conventional and ultrasonically assisted bone drilling. Am J Biomed Sci 2009;2009(1):312–20.

[21] Alam K, Mitrofanov AV, Silberschmidt VV. Experimental investigations of forces and torque in conventional and ultrasonically assisted drilling of cortical bone. Med Eng Phys 2011;33(2):234–9.