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An experimental investigation on thermal exposure during bone drilling

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ABSTRACT

This study presents an experimental investigation of the effects of spindle speed, feed rate, and depth of drilling on the temperature distribution during drilling of the cortical section of the bovine femur. In an effort to reduce measurement uncertainties, a new approach for temperature measurements during bone drilling is presented in this study. The new approach is based on a setup for precise positioning of multiple thermocouples, automated data logging system, and a computer numerically controlled (CNC) machining system. A battery of experiments that has been performed to assess the uncertainty and repeatability of the new approach displayed adequate results. Subsequently, a parametric study was conducted to determine the effects of spindle speed, feed rate, hole depth, and thermocouple location on the measured bone temperature. This study suggests that the exposure time during bone drilling far exceeds the commonly accepted threshold for thermal injury, which may prevail at significant distances from the drilled hole. Results of this study suggest that the correlation of the thermal exposure threshold for bone injury and viability should be further explored.

1. Introduction

A broad range of orthopaedic surgery operations involves drilling holes in bones as a preparation for mounting screws for anchor plates, attaching prosthetic devices, and fixing bone fractures. The success of such operations is dependent upon the quality of the drilling procedure, while minimizing associated injury to the surrounding tissue. In particular, the heat generated during bone drilling – primarily due to shearing of the material and friction between the drill bit and the bone – may cause thermal injury (resulting in thermal necrosis) in the vicinity of the drilled hole [1,2]. Improving our understanding of the relationship between drilling conditions and the resulting temperature field is of a paramount importance, with the goal of identifying favorable drilling conditions to minimize injury. While thermal effects represent one source for bone injury during drilling, other critical effects are associated with the mechanical load generated during the process of drilling, and, of course, the quality of the medical procedure.

When the temperature exceeds a critical threshold over a corresponding time period, a denaturation process starts to evolve in the tissue, with adverse effects on the mechanical properties of the bone [3]. Several studies have aimed at establishing criteria to identify the typical temperature rise and the corresponding duration that would cause thermal necrosis during bone drilling [1–5]. For instance, Hillery and Shuiab [4] showed that when the temperature rises above 55 °C for more than half a minute, bone undergoes serious damage. In an *in vivo* study [1], the cortical bone of a rabbit exhibited thermal necrosis after 1 min of exposure to 47 °C.

While the specific thermal history that leads to thermal damage may be dependent upon the experimental conditions and the intrinsic properties of the tissue, it is widely accepted that the extent of cell destruction is affected by the combination of magnitude of temperature elevation and the duration of thermal exposure. In order to capture the effects of both temperature and time, the concept of thermal dose has been adopted from the field of radiotherapy [6]. In broad terms, the thermal dose concept is based upon the hypothesis that the probability of cell survival post thermal exposure shows an Arrhenius-type relationship with the time integral of an exponential behavior of the elevated temperature [7,8]. Hence, the thermal dose reflects an equivalent exposure time, which is typically measured in minutes. Sapareto and Dewey [6] suggested an arbitrary reference temperature of 43 °C in their calculations, and ever since the thermal dose is commonly measured in equivalent time at this reference temperature (ET_{43}). To the best of our knowledge, the literature of bone drilling does not offer comparable data in terms of a thermal dose. In the absence of more specific information, thermal exposure of the bone tissue above 50 °C is considered destructive.

Several studies have focused on measuring temperature distribution during bone drilling [1,2,4,5,10–14], where thermocouple measurements is most frequently the choice of practice. While thermocouples are sufficiently accurate, two additional effects must be taken into account: uncertainty in sensor placement and

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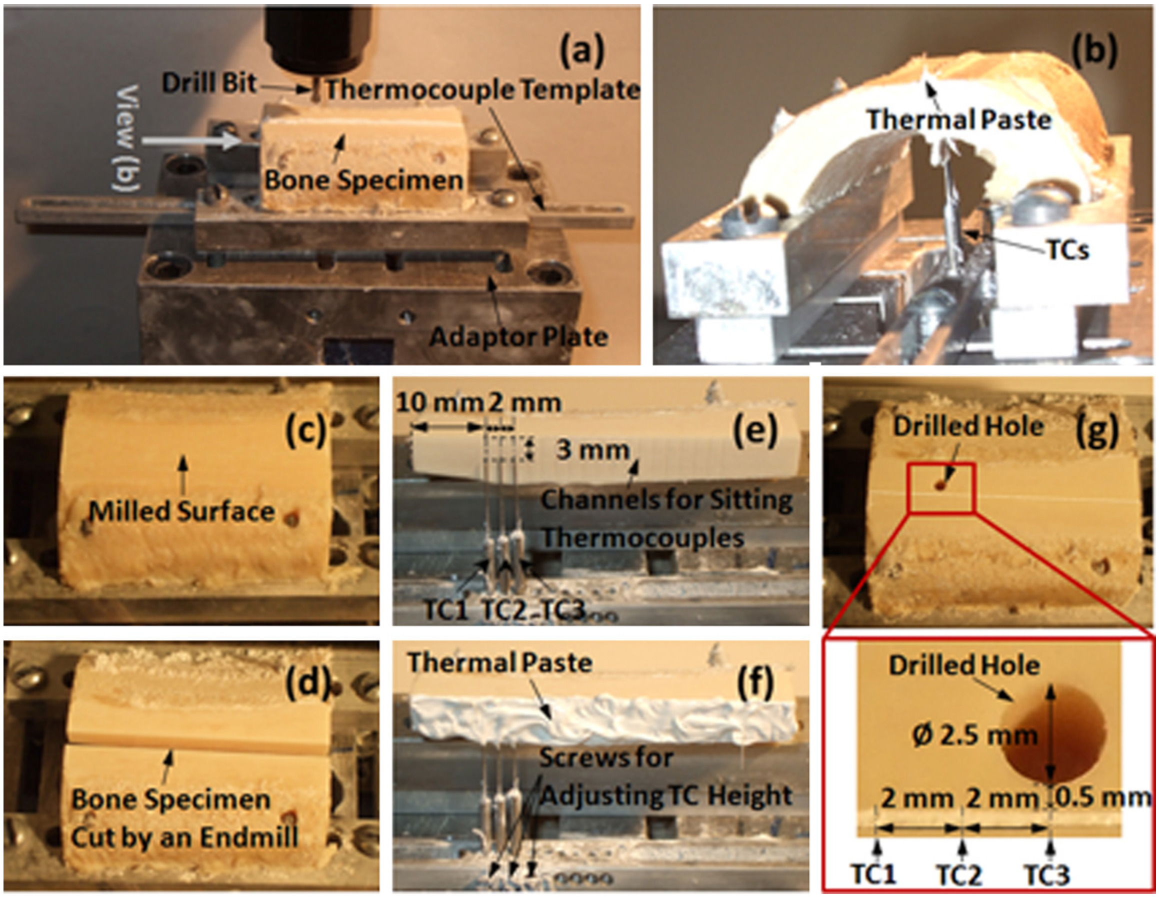

Fig. 1. Experimental setup and procedures: (a) general view of the experimental setup, (b) side view, (c) milled top surface of the bone specimen in preparation for experimentation, (d) vertical planes generated by slicing the bone using an endmill along the bone axis, (e) thermocouples positioning, (f) application of thermal paste before assembly, and (g) a drilled hole on the bone specimen.

heat conduction within the sensor, where the thermal conductivity of the bone is two orders of magnitude smaller than that of the thermocouple wires. With [9] as an example, 2.3 mm holes were drilled to insert 0.25 mm thermocouples into the bone, creating unnecessary interference to heat transfer in the specimen around the thermocouple. In other cases, blind holes were drilled to insert the thermocouples, introducing uncertainty in the location of the thermocouple junction. When a gap is left between the thermocouple and the bone, the void creates a thermal barrier, dramatically affecting the certainty in temperature measurements [15]. An alternative method of measurement is scanning-thermography using infrared techniques [15–18], which is limited to surface measurements and is insufficient for the analysis of a 3D temperature field.

Based on temperature measurements, a number of studies investigated the effects of drilling conditions [3,19,10,20,5], bone type and density [1,3], drill-bit geometry [5,19,10], and the use of irrigation [1,10,21,16,18], on maximum temperatures and exposure times, with the ultimate goal of identifying parameters to prevent thermal osteonecrosis [1,5,10,17,25,13,23,22,26,24]. Some of those studies present conflicting conclusions that may be originated from the sources of uncertainty in measurements rather than from modeling and analysis techniques.

While temperature measurements provide information on the outcome of the total heat generation during drilling, heat is actually being generated due to various mechanisms at different locations around the drill bit. The drilling process progresses by shearing the bone material ahead of the cutting edges (cutting lips) of the drill. The chips created during drilling induce large friction forces to the rake face of the drill bit [24]. The shearing energy increases with the increasing feed per revolution (which in itself is dependent upon both the feed rate and the spindle speed). The friction energy on the rake face increases with increasing spindle speed. A large portion of the shearing energy and the entire friction energy are converted into heat, which increases temperatures of both the drill-bit and bone. Furthermore, since the drill bit material possesses significantly higher thermal conductivity than bone, the temperature of the drill bit raises rapidly. Thus, the heat transferred from the high-temperature drill bit to the bone also increases the temperatures in the bone.

For a given drill-bit geometry [1,17,13], in addition to the thermal and mechanical characteristics of the bone, the heat generation during bone drilling is controlled by the spindle (rotary) speed and the feed rate (penetration speed). Various studies concluded that higher spindle speeds increase the generated heat and, as a result, the bone temperature [1,24]. However, the amount of heat absorbed by the chips and the speed at which the chips are removed away from the cutting zone also increase with increasing cutting speed, thereby reducing the amount of the heat transferred to the bone [25,3,28,27,30,31,29]. For some specific cases, these competing effects may cause the temperature to become relatively insensitive to spindle-speed changes [25,32].

Higher feed rates result in larger shearing and friction energies, which increase heat generation. While the amount of generated heat is important, equally important is the duration of heat exposure. The drilling duration is directly dependent upon the feed rate, where a higher feed rate leads to a shorter drilling duration. Therefore, the feed rate may significantly affect the temperature distribution in the bone [19]. Consistently, several studies have suggested that the increased feed rate results in lower temperatures within the bone [3,5,17,24,33]. Many of those studies used a constant load rather than a constant feed rate during experimentation. It is noted that when all other parameters are kept constant, increasing the constant (axial) load results in, and thus, directly correlates with, increased feed rate.

The current study is focused on an experimental investigation of the effects of spindle speed, feed rate, and depth of drilling, on the temperature distribution during drilling of the cortical section of the bovine femur. In effort to reduce measurement uncertainties, a new approach for temperature measurements during bone drilling is presented in this study, which includes precise positioning of multiple thermocouples and using a computer numerically controlled (CNC) machining system. A battery of experiments was performed to assess the uncertainty and repeatability of the new approach. Subsequently, a parametric study was conducted to determine the effects of spindle speed, feed rate, hole depth, and thermocouple location on the measured bone temperature.

2. Materials and methods

2.1. Experimental apparatus

With reference to Fig. 1, the new experimental apparatus comprises of five key elements:

(i) an adaptor plate, for attaching the experimental setup to a CNC machine (Fadal CNC 88HS, 0.003 mm movement accuracy and 0.001 mm bi-directional repeatability);
(ii) a thermocouple template, to house an array of thermocouples and enable adjusting their placement;
(iii) an array of miniature hypodermic thermocouples (HYP1-30-1/2-T-G-60-SMP-M, Omega Engineering, Inc.; typical uncertainty range of 0.5 °C in the current setup);
(iv) a data acquisition system (OMB-DAQ-55, Omega Engineering, Inc.) to collect the temperature data (typical sampling rate of 1.78 Hz); and
(v) height-adjustment plates to enable experimentation on specimens of various dimensions.

The thermocouple template offers a fixed axial distance between thermocouples of 2 mm, and variable height adjustment, to be selected based on the specimen geometry and experimental parameters. The location of the thermocouple template, together with the array of thermocouples, can be positioned in virtually any location on the adaptor plate.

2.2. Sample preparation

This study uses the mid-diaphysis section of bovine femora as the test model. Bone samples were obtained from a local slaughterhouse shortly after animal death from animals processed for the food industry (no animals were sacrificed specifically for the purpose of the current study). Most specimens were obtained from four animals (labeled as Animals A, B, C, and D below), each yielding up to two samples per bone from each of the four limbs. The bones were cut into half-cylindrical segments with approximate dimensions of 50 mm × 65 mm × 20 mm. The cortical thickness of each specimen exceeded 8 mm. Specimens were maintained in saline solution and kept in a frozen state at −10 °C according to the guidelines specified in [34]. Prior to experimentation, the specimens were completely thawed at room temperature for 24 h and immersed in saline solution until tested.

2.3. Experimental procedure

Ten key steps are used to prepare the experimental setup:

1. The bone sample is fixed onto two separate height adjustment plates by using wood screws from the back side.
2. The sample is attached to the adaptor plate by using four bolts that fix the height adjustment plates to the adaptor plate (Fig. 1(b)).
3. The top of the bone specimen is lightly milled to obtain a flat surface (Fig. 1(c)), which is used as a reference plane for drill bit penetration depth.
4. The specimen is longitudinally sliced into two sections using an endmill with a diameter of 2 mm (Fig. 1(d)).
5. One section is temporarily removed. Grooves are machined on the remaining section along the new surface created in step 4, in 2 mm longitudinal increments. The grooves are machined with a 1 mm in diameter endmill (flute length of 10 mm) across the new surface to a groove depth of 0.15 mm. These grooves are designed to house the 0.30 mm in diameter thermocouples (Fig. 1(e)).
6. By means of the thermocouple template, thermocouples are placed at preselected heights and distances. The template is secured to the adaptor plate, and a still image of the thermocouple-specimen section setup is taken for height verification.
7. The template with the thermocouples was then placed onto the adaptor plate. The location of the template is adjusted until each thermocouple is positioned in the corresponding desired channel (Fig. 1(e)). A digital microscope with up to 200X magnification is used in the process of vertical sensor placement, with an estimated thermocouples placement uncertainty of 0.02 mm.
8. A layer of thermal paste (Chemplex 1381) is applied onto the surface and into the thermocouple-hosting grooves with the aim of decreasing the effect of thermal contact resistance between the bone sections (Fig. 1(f)).
9. The section that was removed in step 5 is now fixed to the adopter plate using bolts, while a C-clamp is used to hold the two sections together.
10. Excessive thermal paste is wiped out from the specimen, and the setup is ready for experimentation. Fig. 1(b) displays the experimental setup at the end of this stage, whereas Fig. 1(g) displays a top view of the two bone sections along the thermocouple plane.

Fig. 1(g) displays the thermocouple locations with respect to the drilled hole, where the radial distances between the edge of the hole and the center of the three common thermocouples are 0.50 mm, 0.81 mm, and 2.78 mm (annotated TC3, TC2, and TC1, respectively; Fig. 1(e)). Additional thermocouples were used in some experiments to identify additional thermal effects, as discussed below. Once the drill bit reaches the target depth, it was immediately retracted at a speed of 2.12 mm/s.

Steps 6 through 10 were repeated up to 4 or 5 times on each specimen, with center-to-center distance of 10 mm between consecutive drilled holes. Each hole was filled with thermal paste before the next hole was drilled. Based on preliminary thermal analysis, a distance of 10 mm was deemed sufficient for thermal effects created around the newly drilled hole to be unaffected by the presence of the previously drilled hole; thermal paste filling was used to further decrease the potential of such an effect. A detailed analysis on the propagation of thermal effects into the bone can be found at [35].

Table 1
Thermal properties of bovine cortical bone, PMMA, carbide, thermal paste, and air [36–40].

	Thermal conductivity (W/mK)	Specific heat (J/kg K)	Density (kg/m^3)	Thermal diffusivity (m^2/s)
Bovine cortical bone (femur) [36]	0.54	1260	1800	2.38×10^{-7}
PMMA [37]	0.50	1297.9	1683	2.29×10^{-7}
Carbide (drill-bit material) [38]	84.02	195	15,800	2.73×10^{-5}
Thermal paste [39]	0.75	704.6	960	1.11×10^{-6}
Air at 27 °C [40]	0.026	1007	1.16	2.23×10^{-5}

2.4. Drill-bit material and geometry

It is well established in the literature that repeated bone drilling causes extensive wear on commonly used stainless steel drill bits, resulting in increased heat generation [14,9,25]. To minimize and possibly eliminate the tool-wear effect, carbide drill bits – having significantly higher resistance to wear than the ordinary stainless-steel drill bits – were used. Each drill bit was used for drilling of no more than 10 holes to further decrease the tool-wear effect on experimentation results. After each experiment, the drill bit was thoroughly cleaned with a brush and moist tissue. In particular, 2.5 mm in diameter drill-bits were used, having a 118° point angle, a 20° helix angle, and straight cutting edges. Those geometrical parameters are common to many standard surgical drill-bits.

2.5. Experimental plan

A full factorial design of experiments (DOE) was conducted for spindle speed rates of 800 rpm, 2800 rpm, and 3800 rpm; feed rates of 0.25 mm/s, 0.75 mm/s, and 1.5 mm/s; and hole depths of 6 mm and 7 mm. The order of experiments was randomized, and each experiment was repeated at least twice to evaluate repeatability.

During the parametric experiments, the vertical location of all thermocouples was kept at a 3 mm distance from the top of the bone sample, where uniform thermocouple locations enabled a comparative study of the various drilling conditions. In an additional set of experiments, the vertical thermocouples location was varied between 1 mm, 3 mm, and 5 mm (for all three thermocouples at the same depth in a particular experiment), to sample the temperature distribution for particular drilling conditions.

All experiments started from room temperature – approximately 26 °C. Between successive experiments, sufficient time was allowed for the bone and the drill bit to return to room temperature, as verified by with the data acquisition system.

3. Results and discussion

3.1. Evaluation of the experimental setup and procedure

The inherent variation in mechanical and thermal properties of specimens taken from different bones in the animal, and from different animals of the same species, results in variations in the measured temperature subject to virtually identical drilling conditions in repeated experiments. In comparison with experimentation on engineering materials, testing of biological materials often calls for a larger frequency of repetitions and potentially more elaborated use of statistical tools. In order to conduct the experimental work in a cost-effective manner, and in order to isolate inhomogeneity and anisotropy effects in the specimen, polymethylmethacrylate (PMMA, with its trade name Acrylic®) has been selected for the first stage of experiments. The PMMA is characterized as a homogeneous and isotropic material, with property values close to those of bone. Specifically, the thermal conductivity of the PMMA is 8% lower than that of a bone, and two orders of magnitude smaller than that of the carbide drill-bit (Table 1). The thermal diffusivity of the PMMA is 4% lower than that of a bone, and

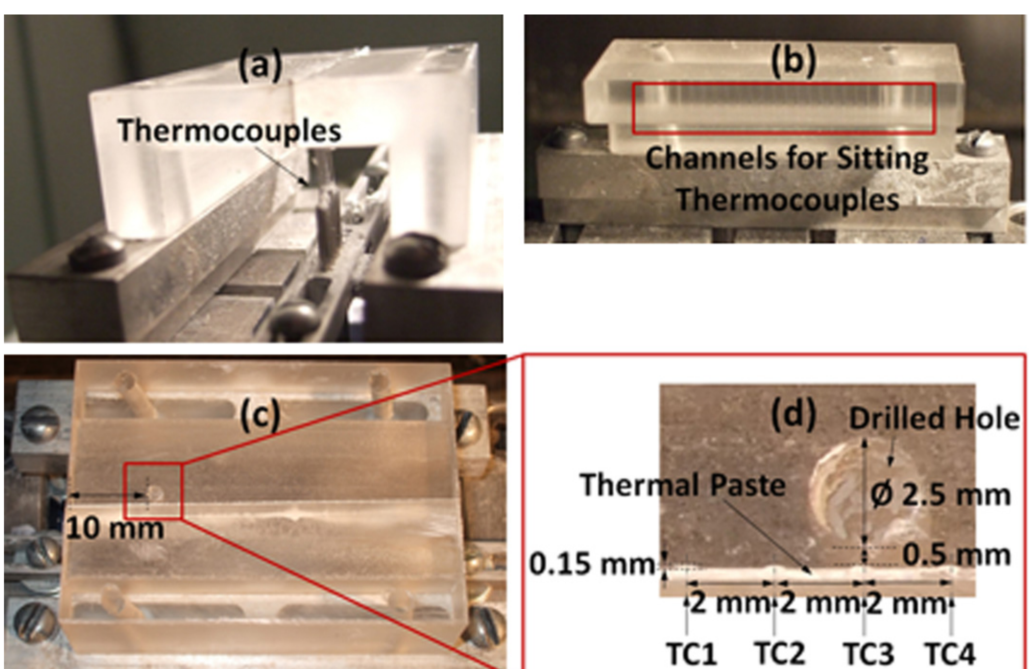

Fig. 2. Experimental setup for benchmark testing on PMMA: (a) side view of the experimental setup, (b) channels fabricated on the PMMA specimen to host the thermocouples, (c) top-view of a drilled hole in PMMA, and (d) closer view of the hole area.

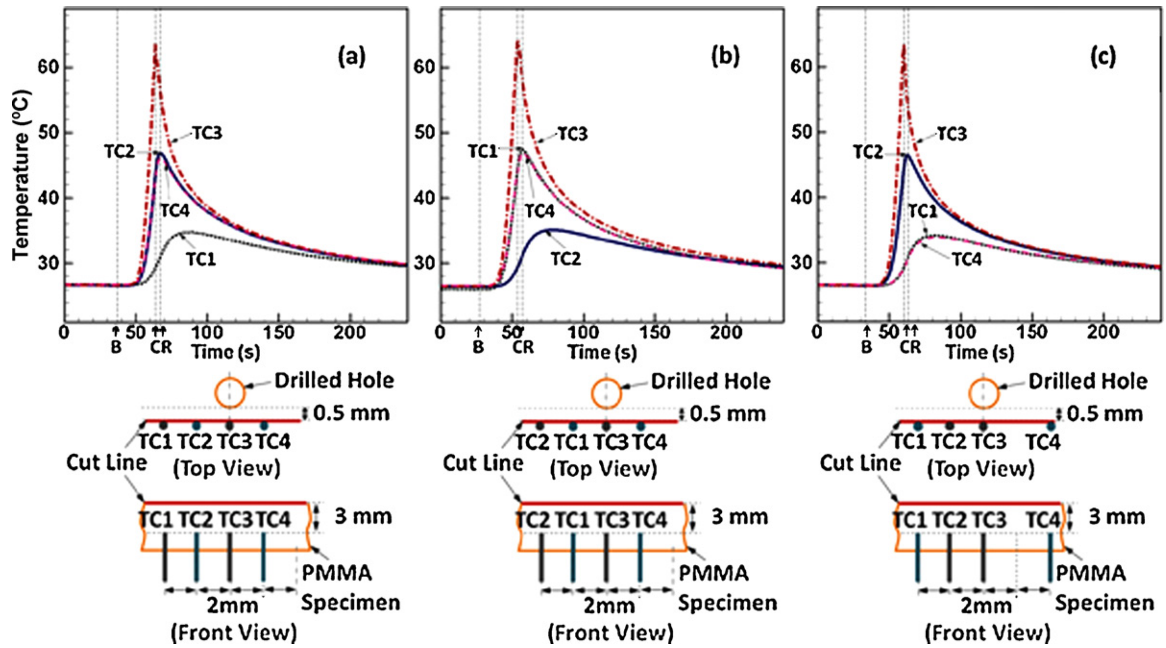

Fig. 3. Temperature history in during PMMA drilling to a depth of 7 mm, subject to a spindle of 3800 rpm and a feed rate of 0.25 mm/s: (a) thermocouples positioned in the same order used during bone drilling and TC4 is symmetrically positioned to TC2; (b) similar to case (a) where TC1 and TC2 are swapped; (c) similar to case (a) where TC4 is symmetrically position to TC1.

two orders of magnitude smaller than that of the carbide drill-bit (Table 1).

Evaluation tests were performed under two representative sets of drilling conditions: (i) 800 rpm spindle speed and 0.25 mm/s feed rate, and (ii) 3800 rpm spindle speed and 0.25 mm/s feed rate. The holes were drilled with a 2.5 mm carbide drill bit to a depth of 7 mm. Experiments were repeated at least four times for each set of conditions.

PMMA evaluation was performed on two samples as displayed in Fig. 2, following the same procedure described above for the bone specimen. These corresponding experiments included an additional thermocouple (TC4 in Fig. 2), to explore effects of thermocouple positioning and relative certainty in measurements, as discussed below. All thermocouples were placed 3 mm below the sample surface in all the evaluation experiments. Fig. 3(a) displays experimental results from selected PMMA experiments, where TC4 is symmetrically placed to either TC2 or TC1, with respect to a symmetry line defined by the line connecting TC3 and the drilled-hole center.

Fig. 2 displays the measured thermal history form selected evaluation tests on PMMA. Table 2 lists the maximum temperatures obtained by each thermocouple, where the uncertainty range refers to the complete set of experiments. It can be seen from Fig. 2 that the symmetrically placed thermocouples virtually display the same thermal history, where maximum temperature differences of 0.7 °C were found between the corresponding sensors. Recall that the uncertainty in a single thermocouple measurement is specified as 0.5 °C by the manufacturer however, since the two thermocouples represent statistically independent measurements, the corresponding uncertainty of the difference is 0.7 °C (the square root of the sum of the square uncertainties). Two thermocouples were further swapped in one experiment (TC1 and TC2 in Fig. 2(b)) with corresponding maximum temperature differences of 0.6 °C, which indicates that experimental results are insensitive to the quality of the hypodermic thermocouple. These temperature differences suggest an adequate experimental setup for thermal measurements, with uncertainties bounded only by the independent uncertainty of the temperature sensor.

As could be expected, the highest temperatures were measured by TC3, which was placed the closest to the drilled hole. Maximum temperature of 45.1 ± 0.6 °C was measured for drilling conditions of 800 rpm spindle speed and 0.25 mm/s feed rate, whereas maximum temperature of 63.9 ± 0.4 °C was measured for drilling conditions of 3800 rpm spindle speed and 0.25 mm/s feed rate. These represent significant temperature elevations from the initial temperature, which calls for further experimental investigation into biological specimens as outlined below.

3.2. The effect of feed rate, spindle speed, and hole depth

A parametric investigation was performed to explore effects of drilling conditions (spindle speed and feed rate) and drilling depth on the temperature elevation within the bone specimen. Fig. 4 displays the thermal histories obtained for a hole depth of 7 mm (Animal A), and for thermocouples placed at a depth of 3 mm. Labels B, C, and R, respectively indicate the beginning of the drilling (first contact with the bone), the completion of the hole, and the end of drill retraction (when the drill-bit tip is aligned with the bone surface). In general, it can be seen that the maximum temperature increases with the increasing spindle

Table 2
Maximum temperatures measured by the three thermocouples shown in Fig. 1 (TC1, TC2, and TC3) during PMMA testing.

Machining conditions		Maximum temperature (°C)		
Spindle speed (rpm)	Feed rate (mm/s)	TC1	TC2	TC3
800	0.25	29.9 ± 0.3	36.0 ± 0.4	45.1 ± 0.6
3800	0.25	34.5 ± 0.3	47.1 ± 0.3	63.9 ± 0.4

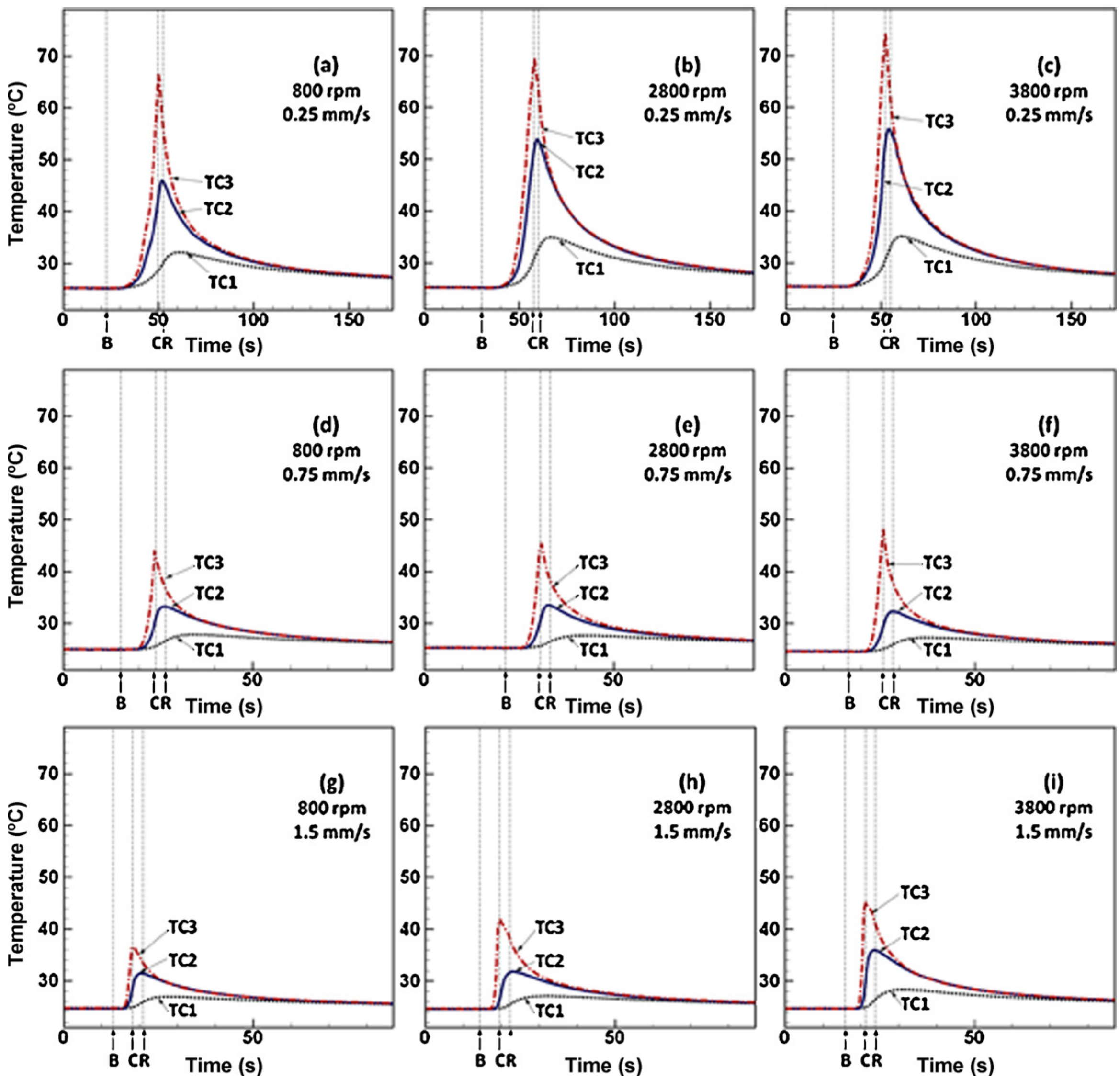

Fig. 4. Thermal history for thermocouples located at radii locations of 0.5 mm (TC3), 0.81 mm (TC2), and 2.78 mm (TC1) from the center of the drilled hole; maximum drilling depth of 7 mm (Animal A).

speed and, independently, decreases with the increasing feed rate.

Maximum temperature of 74.4 °C is found at TC3 for a spindle speed of 3800 rpm and a feed rate of 0.25 mm/s (Fig. 4(c)). However, this drilling process was started with an initial temperature of about 26 °C and not close to normal body temperature, as would be expected during surgery. Since the heat transfer process is strongly dependent upon the heat generation at the drilling site, but weakly dependent upon the convective boundary conditions at the bone surface [35], one could first-order approximate the extent of temperature elevation during *in vivo* experimentation by simply shifting the initial bone temperature from 26 °C to 37 °C (core body temperature). In such a case, one would expect the temperature at the TC3 location to shift from 74.4 °C to 85.4 °C. Of course, this approximation would hold as long as higher-order thermal effects are not involved in the process, such as phase change (boiling) and/or carbonization. Following this approximation, even the lowest temperature elevation from all cases tested – spindle speed of 800 rpm and feed rate of 1.5 mm/s – would lead to approximated *in vivo* temperature of 48 °C, which is well within the destructive temperature range of hyperthermia (the threshold is commonly taken as 43 °C [6,41]).

An effect not simulated by the current experimental setup is the moderating thermal effect of blood flow, where blood perfusion tends to lower the locally elevated temperature. However, it has been suggested previously [14,5] that this cooling effect is likely to be negligible when considering the relatively low perfusion rate in the bone and the confined localized effect of drilling.

A few observations can be made from the thermal histories. First, due to the low thermal conductivity of the bone, there is a relatively long delay between the start of the drilling process and the instant at which the maximum temperature is measured at the thermocouple locations. Similarly, the delay time increases with increasing thermocouple distance from the drilling site. Second, all the thermal histories show a similar trend with time; first an increase in time, reaching a peak (maximum) value, and then a slow decay. Third, as expected, the closer is the thermocouple to the hole, the higher the temperatures are. Fourth, the temperatures closest to the hole location (*i.e.*, TC3) are seen to be most sensitive to both feed rate and spindle speed variations. Indeed, at locations farther away from the hole, the measurement sensitivity to variations in drilling conditions is significantly reduced. Although this observation is somewhat consistent with that of Matthews and Hirsch [14], in contrast to their observations, the newly developed data shows

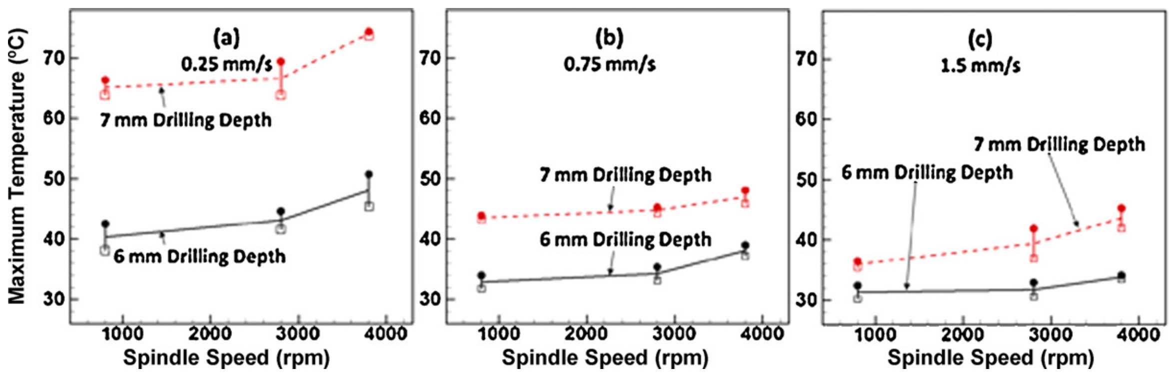

Fig. 5. Maximum temperature at 3 mm depth (TC3) as a function of the spindle speed for hole depths of 6 mm and 7 mm, and for an initial temperature of 26 °C.

variations also at thermocouple locations farther than 0.5 mm. It is possible that the increased accuracy and repeatability of the measurement technique presented here enabled detecting more subtle changes in temperature than before.

Figs. 5 and 6 display the maximum temperature obtained (TC3) for two different drilling depths as a function of the spindle speed and feed rate, respectively (Animals A and B). For all drilling conditions tested, the maximum temperature moderately increases with the increasing spindle speed. It can be seen from Figs. 5 and 6 that a relatively moderate increase in hole depth dramatically affect the measured temperatures – up to 48.5% in maximum temperatures for the same drilling conditions (Figs. 5(a) and 6(a)). At a feed rate of 1.5 mm/s, the maximum temperatures ranged from 31.4 ± 1.1 °C at 800 rpm to 33.8 ± 0.3 °C at 3800 rpm for the 6 mm drilling depth, and from 36.0 ± 0.5 °C at 800 rpm to 43.6 ± 1.7 °C at 3800 rpm for the 7 mm drilling depth. At the lowest feed rate of 0.25 mm/s, significantly higher maximum temperatures are observed, ranging from 40.3 ± 2.2 °C at 800 rpm to 48.1 ± 2.7 °C at 3800 rpm for the 6 mm drilling depth, and from 65.1 ± 1.3 °C at 800 rpm to 74.1 ± 0.3 °C at 3800 rpm for the 7 mm drilling depth. For either drilling depth, the maximum temperatures are shown to decrease rapidly with increasing feed rates for all spindle speeds tested in this study (Fig. 5).

As overviewed in the introduction, increased spindle speed increases the friction energy generation due to the friction forces acting on the rake face of the drill bit (close to the cutting edges). The energy of friction is approximately linearly related with the spindle speed. Since a majority of this energy is converted into heat, it is reasonable to expect increased temperatures at higher speeds [42], as is supported by the current experimental findings. However, at higher spindle speed rates, the chips are moving faster away from the cutting zone, which results in a higher heat transfer rate from this zone with the stream of chips; this stream generates an apparent cooling effect. While this cooling effect is not sufficient to reverse the trend due to the increased friction energy, it may be responsible for the relatively moderate dependency of the temperature with the increasing spindle speed; this observation if consistent with previous studies [5,10,20].

It can be observed from Figs. 5 and 6 that the maximum temperature decreases with the increasing feed rate. For a given spindle speed, the shearing energy required to cut the bone material also increases with the increasing feed rate; a large portion of this energy is converted into heat. On the other hand, the drilling process is completed in a much shorter time at higher feed rates. The shorter drilling time results in not only a shorter time of exposure to the heat generation, but also reduces the heat transferred to the bone from the hot drill bit [19]. Considering the fact that increased load during constant-load drilling increases the feed rate, and thus, reduces the drilling time, this observation is consistent with the literature, where increased load was seen to reduce the drilling temperatures during bone drilling [1,2,5,19,43]. Therefore, even though the temperature of the drill bit may increase at higher feed rates, the maximum temperature inside the bone may decrease due to the shorter exposure time, which is consistent with previous reports [3,10]. Similarly, increasing the drilling depth elongates the exposure time to the heat generation due to the cutting/friction processes, while the thermal effect propagates to farther distances in the specimen, which is also consistent with the literature [1,3]. It can be seen from Fig. 6 that lower feed rates lead to larger differences between the maximum temperatures measured in 6 mm and 7 mm drilling depths. It is noted that the drilling time between 6 mm and 7 mm drilling depths decreased from 4 s at 0.25 mm/s feed rate to 0.7 s at 1.5 mm/s feed rate.

It is noted that although a drill bit with a diameter larger than 2.5 mm has larger heat capacity that allows it to absorb more heat and, thereby, moderate the elevation of bone temperature, it also

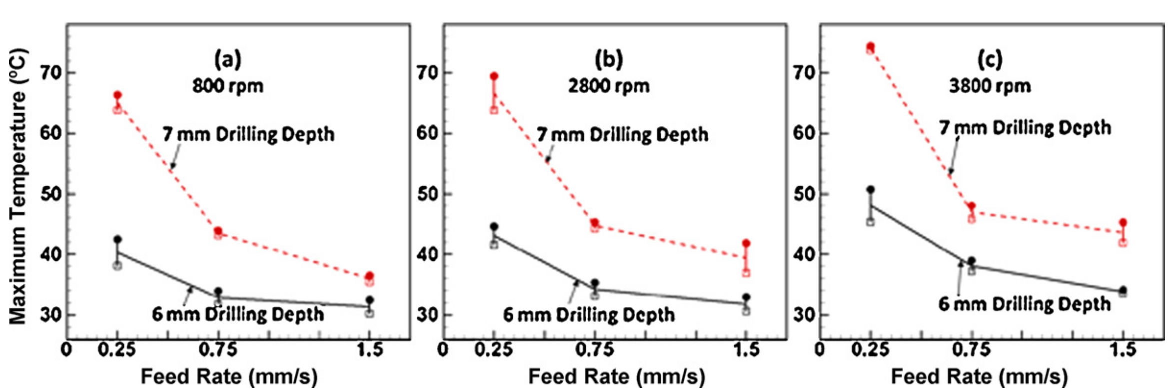

Fig. 6. Maximum temperature at 3 mm depth (TC3) as a function of the feed rate for hole depths of 6 mm and 7 mm for an initial temperature of 26 °C.

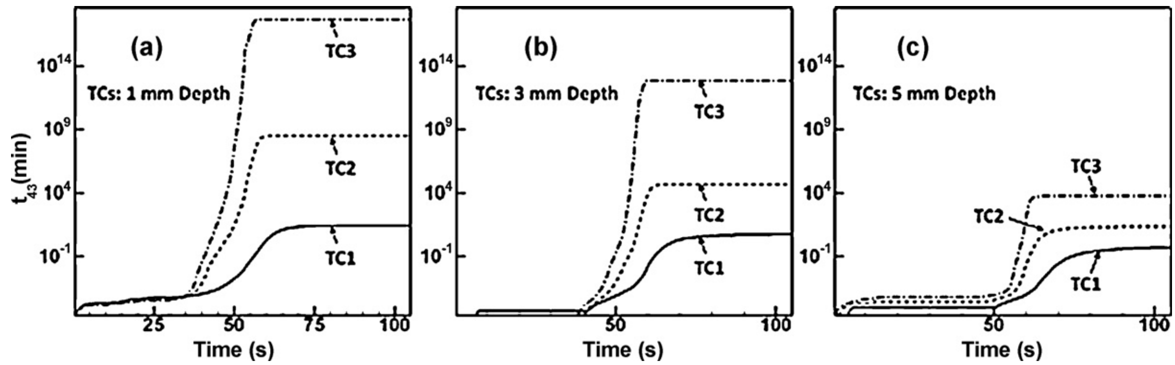

Fig. 7. Equivalent exposure time at 43 °C (t_{43}) as a function of time for a hole depth of 7 mm (Animal C), a spindle speed of 3800 rpm, a feed rate of 0.25 mm/s, and a modified initial condition of 37 °C; thermal histories were measured at radii locations of 0.5 mm (TC3), 0.81 mm (TC2), and 2.78 mm (TC1) from the center of the drilled hole.

has longer cutting edges that increases the heat generation due to increased shearing. These represent competing effects that tend to cancel one another. While it is expected that this conclusion is generally applicable to larger drill bits, a quantitative assessment of this effect must be made by means of experimental studies, using larger drill bits. Furthermore, the experimental approach outlined here can be directly applied for this purpose.

3.3. Thermal exposure

While to the best of our knowledge critical thermal dose data for bone tissue is not available, it is deemed informative to compare it under the current drilling conditions with commonly assumed data. Following this concept, the equivalent thermal exposure is defined as [6]:

$$t_{43} = \int_{t=0}^{t=t_{final}} R(T(t))^{43-T(t)}\,dt, \quad \text{where}$$
$$R(T(t)) = \begin{cases} 0.5 & \text{if} \quad T(t) \geq 43\,^{\circ}\mathrm{C} \\ 0.25 & \text{otherwise,} \end{cases} \tag{1}$$

where t_{43} is the equivalent time to exposure at 43 °C, t_{final} is the duration of exposure, R is a coefficient of exposure, and $T(t)$ is the temperature at the point of interest, measured in degrees Celsius. Initially, Sapareto and Dewey [6] assumed 120 equiv. min at 43 °C (t_{43}) as a general threshold for cell necrosis, but this number has been widely debated in the literature. Today it is commonly accepted that different exposure time values are associated with different tissue types and clinical conditions.

Despite the lack of comprehensive information, anecdotal criteria are suggested in the literature, which may provide some additional insight. For example, Eriksson et al. [1] have suggested that thermal necrosis initiates when the temperature exceeds 47 °C for a period longer than 60 s. These parameters would result in t_{43} = 16 min, which is 15 min shorter than the more commonly accepted magnitude of exposure time for thermal injury.

Fig. 7 displays the thermal dose for the 7 mm hole depth for each thermocouple location and for Animal C. In order to make thermal those calculations based on the current experimental data reflective of *in vivo* conditions, measured temperature histories were shifted up by the difference between the core body temperature of 37 °C and the actual initial temperature in each experiment (see more discussion about temperature shifting in the context of Fig. 4).

It can be seen from Fig. 7 that the thermal dose at the location of TC3 reaches 4.5×10^{17} min, 7.0×10^{12} min, and 5.9×10^{3} min for depths of 1 mm, 3 mm, and 5 mm, respectively. Of course, the only significance of these values is that they are up to many orders of magnitude higher than that of the commonly accepted (and potentially debatable) value of 120 min. It is noted that the value of the thermal dose has a clinical meaning only when found in a scale-range of up to hundreds of minutes. For higher thermal dose values, the concept of thermal dose ceases to exist and the practical outcome can be viewed as *instantaneous injury*. This suggests that a significant thermal damage is expected to occur at the location of TC3. Similarly, the equivalent exposure time at the location of TC2 is 2.9×10^{8} min, 4.8×10^{5} min, and 22 min for depths of 1 mm, 3 mm,

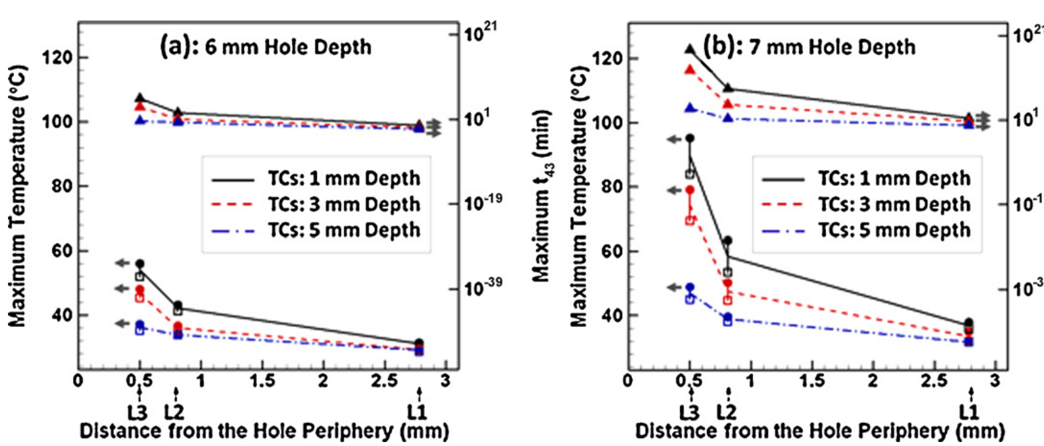

Fig. 8. Maximum temperature for each thermocouple for an initial condition of 26 °C, and corresponding maximum exposure time for an initial condition of 37 °C, for a feed rate of 0.25 mm/s and a spindle speed of 3800 rpm.

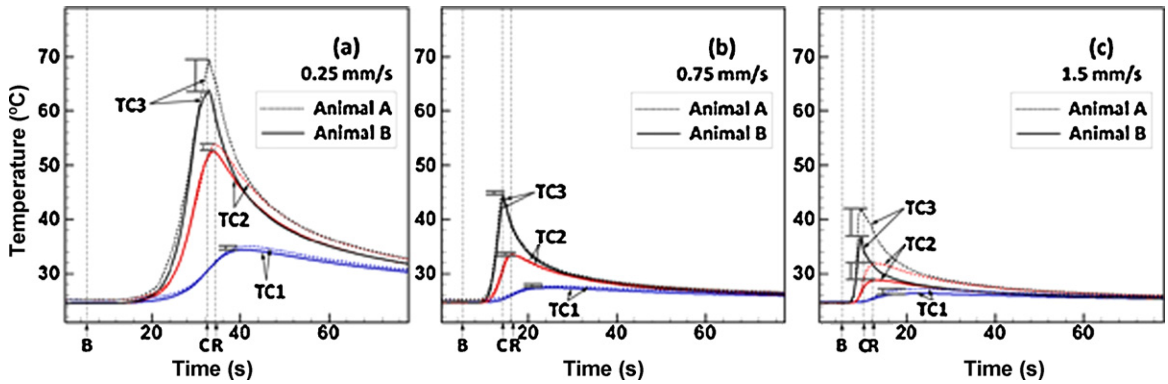

Fig. 9. Thermal history for a hole depth of 7 mm obtained at a spindle speed of 2800 rpm (Animals A and B).

and 5 mm, respectively. The equivalent exposure time for the location of TC1 is measured in a few minutes and is deemed insignificant for the purpose of the current study. The above values illustrate how dramatically the equivalent thermal exposure time decreases with the distance from the drill bit, and how significantly it decreases with the distance from the specimen surface. These values call for a more detail study on the correlation between exposure time and corresponding injury during bone drilling, which is left for future studies.

Fig. 8 displays the corresponding maximum temperatures and equivalent exposure time for each thermocouple, for a spindle of 3800 rpm and a feed rate of 0.25 mm/s (Animal C). It can be seen that the highest temperatures are consistently measured at the location closest to the sample surface. This observation could be expected since the thermocouples placed at 1 mm depth experience longer exposure to the heat transfer originated from the cutting/friction process; an effect which decays with the increasing distance from the drilled hole. The maximum temperature in the corresponding experiments exceeds 95 °C (TC3 at 1 mm depth and a 7 mm hole), which may lead to temperature exceeding 100 °C at the hole wall. Once temperatures exceed 100 °C, water boiling is expected, and thermal analysis of the process becomes more complex. As the temperature exceeds 100 °C, additional effects may take place, with carbonization as an example. Data obtained in the current study do not permit us a detailed analysis of such higher order effects. Either way, such high temperatures well exceed the thermal necrosis threshold even if the exposure time is in the order of a few seconds, which may lead to considerable thermal damage to the surrounding tissue, and further result in structural changes.

3.4. Variations of temperatures between different bones

Fig. 9 displays typical thermal histories obtained at 2800 rpm spindle speed and various feed rates (Animals A and B), while Fig. 10 displays the thermal history for 3800 rpm spindle speed and 0.25 mm/s feed rate obtained from the four different animals (A, B, C and D). Relatively large variations in the maximum temperature were observed between different specimens. At a spindle speed of 3800 rpm and a feed rate of 0.25 mm/s, the maximum temperature varied from 51.6 °C (Animal A) to 45.4 °C (Animal D) for 6 mm drilling depth, and from 79.1 °C (Animal C) to 69.4 °C (Animal D) for 7 mm drilling depth. For all the tested conditions, specimens taken from Animal D consistently exhibited the lowest temperatures. The variation in maximum temperatures between specimens from different animals was found in a range of ±5.6 °C.

It is well established in the literature that tissue characteristics such as bone density vary between animals of the same species due to many parameters such as nutrition, age, and history of physical activity [44–46]. In addition, mechanical properties of the bone may vary with depth (even within the cortical section). Higher shear and friction forces experienced during drilling bones with higher density can cause increased heat generation [21]. Hence, it is expected that both the thermal and mechanical properties of the similar bone sections obtained from different animals may vary. The variation in thermal histories displayed in Figs. 9 and 10 may be attributed to those differences between animals. These variations in thermal properties affected not only on the level of temperature elevation, but also in the time to reach the corresponding maximum temperature. Since the repeatability and certainty in the experimental setup has already been established on synthetic materials, the observed

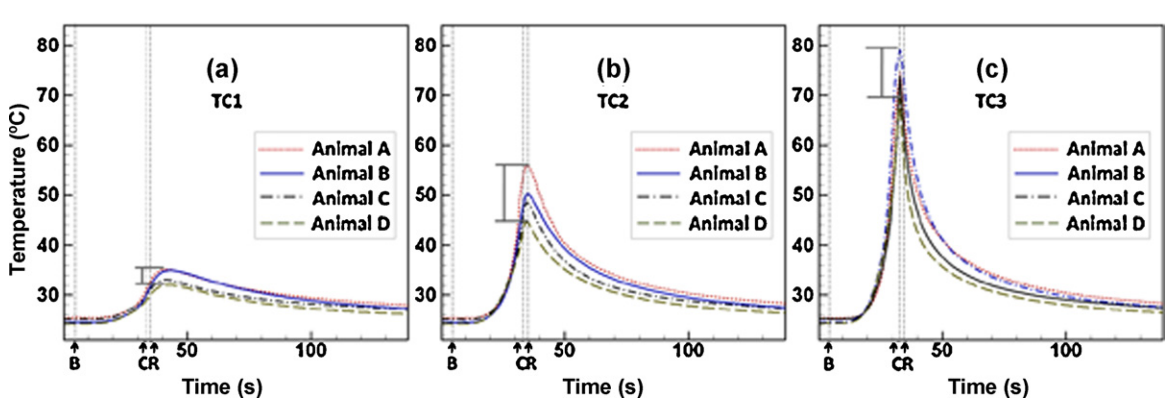

Fig. 10. Thermal history for a hole depth of 7 mm obtained at 3800 rpm spindle speed and 0.25 mm/s feed rate (Animals A, B, C, and D); the bars indicate the variations of the maximum temperatures from the four different specimens, each from a different animal.

variations are attributed directly to the variations in bone characteristics between different specimens.

4. Summary and conclusions

This study experimentally investigates the effects of feed rate, spindle speed, and hole depth on the elevation of bone temperature during drilling in a bovine-femur model. Specifically, a new experimental approach is introduced, including a setup and procedure, which enables measuring temperatures to a significant degree of repeatability and certainty. This study includes a full factorial parametric investigation of the feed rate, spindle speed, and hole depth. An effect not simulated by the current experimental setup is the moderating thermal effect of blood flow, where blood perfusion tends to lower the locally elevated temperature. However, it has been suggested previously that this cooling effect is likely to be negligible when considering the relatively low perfusion rate in the bone and the confined localized effect of drilling.

An assessment of system characteristics has been performed through a series of experiments on PMMA, which represents a consistent and homogenous material with properties similar to those of bone. The evaluation tests conducted on PMMA indicated that the maximum temperatures may be measured within an uncertainty range of 0.7 °C. In addition, repeatability in measurements associated with thermocouple localization and different thermocouples of the same type was found better than 0.7 °C.

Variability in bone properties between different specimens from the same animal and between different animals of the same species ($n = 4$) led to variations of ±5.6 °C in the maximum temperature during drilling.

In general, it was found that the maximum temperature increases with the increasing spindle speed and, independently, decreases with the increasing feed rate. Through analysis of thermal dose, the exposure of the bone to elevated temperatures has been suggested as a potential source of injury, even at relatively far distances to the drilled hole. Preliminary results of this study suggest that a more detailed analysis of the thermal dose threshold for bone injury is warranted.

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Conflict of interest statement

The authors declare that no conflicts of interest associated with the presented work.

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