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**An analytical modelling with experimental validation of bone
temperature rise in drilling process**

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ABSTRACT

Predicting the bone thermal response in a surgical operation remains a major challenge. In the previous works, metal machining theory has frequently been used to predict bone temperature in drilling process. However, several experimental studies demonstrate that the chip formation process is very complex compared to metal cutting. In the present study, a simplified analytical model based on the moving heat source approach combined with the method of image sources is developed. The heat source due to the drill-bit tip was supposed to be proportional to the cutting energy. The friction at the tool-hole contact was also considered. An experimental study was performed on fresh femur pig bone for cutting speeds from 2 to 20 m/min. Temperature rise, drilling forces and bone volume fraction were measured. The experimental validation showed that the model reproduces satisfactorily the increase in temperature up to the maximum value while it overestimates the temperature during the cooling stage. A parametric study (thermal boundary conditions, lateral friction) was also performed. From the predicted results, it appears that the model can be improved by considering the effects of the bone volume fraction which can present a significant variation in the bone sample.

Keywords

Bone drilling, Bone necrosis, Bone temperature rise, Thermal model for bone drilling, Moving heat source, Axial drilling force and torque, Bone volume fraction.

1. INTRODUCTION

Bone cutting is a common step in bone fracture treatment and implantology. Notwithstanding that bone cutting method includes grooving, sawing, drilling, and milling, the most discussed process in the literature is bone drilling [1]. The reason of

this increasing interest among researchers comes from the fact that drilling process generates significant heat that may lead to thermal injury of bone [2-4]. Hillery and Shuaib [5] report that, for exposure time greater than 30 s, the necrosis threshold in human and bovine bones is 55 °C. According to Bertollo *et al.* [6], Pandey and Panda [1], bone necrosis can appear for very small exposure time when the bone temperature is 70 °C. In spite of the fact that there is no consensus concerning the critical values of exposure duration and temperature magnitude, the typical value of 47 °C during at least 60 s is often used as a reference threshold for the thermal injury apparition [3,7].

Pioneering works related to bone drilling deal about the prevention of osteonecrosis. The key step of these investigations is the assessment of the cutting temperature by using experimental and/or theoretical techniques [1,3,8-10]. Due to the variability of bone samples properties and experimental conditions and to the large number of drilling parameters, these investigations often do not converge towards general conclusions about the temperature rise with respect to the drilling parameters. So, it appears necessary to develop realistic thermo-mechanical models of bone drilling operation to investigate the effect of each parameter, on temperature elevation.

Metal machining theory has frequently been used to calculate drilling heat generated during bone drilling [8,11,12]. The authors assumed that bone behaves like metal when it is machined. Therefore, the deformation in the chip was supposed to be characterized by three zones; the primary deformation zone where the required energy in material shearing is converted into heat; the secondary zone where heat is generated by shearing along the tool rake face and the third zone where friction between the tool clearance face and the new surface of bone produces heat. A similar assumption has been taken by Lee *et al.* [8] to suggest a thermal model for bone drilling. In their investigation, the heat generated in the third zone was assumed to be

negligible for a sharp cutting tool, exactly as in the case of metal cutting. This theory has been extended further upon by Maani *et al.* [12] to develop a mathematical model for predicting the thermal response in the surgical drilling of bone. To determine the temperature rise during drilling, Kalidindi [13] also used the approach developed by Oxley [14].

Other authors investigated the cutting and chip formation mechanism of bone cutting and suggested an alternative view. Jacob *et al.* [15] analysed, through microscopic and SEM images, bone chips shape during orthogonal cutting. They showed that Merchant [16] analysis of orthogonal cutting, commonly used in material cutting, has limited applicability to bone material. Further investigations done by Wiggins and Malkin [17] on the mechanics of orthogonal machining of bone showed that the chip formation process occurred by a series of discrete fractures. Recently, Liao and Axinte [18] identified three different chip formation modes related to the uncut chip thickness. Feldman *et al.* [19] corroborated the observations of Liao and Axinte [18]. They found the bone cutting behaviour changed from a ductile to a fracture cutting mode as cutting depth increases. The threshold cutting depth inducing cracks with chips formation was shown to be 20 μm [20].

Thus, within these experimental investigations, it appears that the chip formation process is very complex compared to metal cutting and that during bone cutting process, chips are formed more by fracture mode than shear mode, regardless of cutting direction, as shown in Fig. 1. Consequently, it seems more realistic to assume that bone behaves like a quasi-brittle material in drilling process. Therefore, whereas for metal cutting the heat sources in the chip are clearly associated to the plastic deformation in the shear zones, the temperature elevation inside bone can clearly not be associated to the same physical mechanisms. As a consequence, analytical models

based on metal machining theory cannot be considered as an appropriate approach to predict the bone temperature rise in drilling. In addition, the source of the heat generated during bone drilling is not clearly defined for a wide range of drilling conditions and needs further investigation.

Recently, new thermal models for bone drilling, based on the moving heat source approach of Jaeger [21], have been introduced by Feldmann *et al.* [19,22]. The interactions between drill tip and bone are modeled by a moving heat source assimilated to a disk source with the size of the drill bit diameter. The authors [19,22] expressed the thermal energy as a function of bone density distribution. With the Green's function of time-dependent moving point source, they determined the temperature distribution in function of time. It can however be noted that the model [19,22] presents different limitations: (i) the bone has been assimilated to an infinite medium (i.e. the bone material fills all the space). As it will be shown in the present work, this assumption may induce an underestimation of bone temperature if the feed rate is not large enough. (ii) during the drill bit penetration into the bone, the distance between the heat source, which moves with the tool, and the measurement position of temperature has been taken constant for a fixed time t , (iii) the heat sources induced by the bone-tool interactions are restricted to the tool tip effect.

As indicated previously, the bone behaves as a quasi-brittle material during cutting process. Therefore, friction between the drilled hole and the tool can affect the bone temperature. In the present work, a simplified analytical model is developed using the following assumptions: (i) bone temperature rise results from two main sources corresponding to the interaction between the drill-bit tip and bone and the friction between the drill-bit side and the drilled hole, (ii) the effect of the point angle is neglected and the heat source associated to the tool tip is assimilated to a disk. The

model was used to analyze the influence of spindle speed which affects the heat generation and the heat transfer through the exposure time. Experimental tests of bone drilling have also been conducted on porcine samples. After a validation study of the model with temperature experimental data, a parametric study has been performed and compared with the results of the experimental campaign.

2. MATERIALS AND METHODS

2.1 Experimental study

Bone samples used in these experiments were extracted from the diaphyseal part of a porcine femoral bone aged of 6 months. The bone was obtained from a local slaughterhouse just after the slaughter of the animal and directly frozen (-20°C). There was no animal sacrifice specifically for this study. Experiments were conducted on bones devoted to food industry. Before sample preparation, bone was thawed to a temperature between 3 and 6 degrees during 24 hours. Bone samples were finally machined at room temperature to get dimensions of approximately 70 mm-long and 10 mm-wide. Fig. 2(a) shows the final state of the sample to drill.

Each bone sample was scanned by X-ray micro-computed tomography (μ CT) machine EasyTom (RX Solutions, Chavanod, France) before drillings tests. The scanning parameters are the following ones: voltage 100 keV, current 50 μ A, exposure time 2.6 s and voxel size 15x15x15 μ m³. Microtomography was conducted on several bone samples but the most homogeneous sample in terms of microstructure (i.e. with a cortical layer of quite constant thickness along the whole specimen) and presenting

the highest thickness of cortical bone was kept for the drilling process and the comparison with the analytical model.

After image acquisition of the bone sample, the drilling experiments were performed on it. A feed per tooth of 0.02 mm was chosen and cutting velocities varying between 2 to 20 m/min were tested. The drilling tests were performed on a three axes CNC milling machine Roeders RP600. A Nobel Biocare twist drill of 3.2 mm diameter with a point angle of 118° and an helix angle of 30° was used. The drilling depth was 4 mm. Drill is made of stainless steel with a diamond-like carbon (DLC) coating. The whole machine, sample, and tool are considered perfectly rigid so that the cutting vibrations are negligible.

Samples were clamped and mounted on a Kistler 9256C2 piezoelectric dynamometer to measure the feed force F and the cutting torque M , see Fig. 2(b). The signal was amplified by a Kistler 5017B charge amplifier and recorded by a National Instrument data acquisition system coupled with a Labview software. Signals obtained were filtered by a Butterworth type filter, traditionally used during the machining data processing.

Temperature data were recorded by two K-type thermocouples OMEGA KMTSS-IM025U-150 with a wire diameter of 0.25 mm implanted in pre-drilled holes. The measuring junctions were positioned precisely at 1.5 mm depth and 0.5 and 0.9 mm from the wall, see Fig. 2(c). A conductor paste was injected through the holes to optimise the conduction from bone to thermocouples.

After drilling tests, microtomography of drilled bone was performed with the parameters presented previously. The reconstruction process of bone sample volume was conducted via RX Solutions X-ACT software. The resetting of drilled and undrilled bone

tomograms was done on Avizo 9 software. By subtracting tomographic images before and after drilling tests, the 3D volume of the drilling zones of bone was obtained to represent our volume of interest. To facilitate the post-treatment, these zones were approximated by the addition of a cylinder and a cone, Fig. 3(a). Bone volume fractions (BV/TV) were then determined within these zones. BV/TV is extracted from each slice through drilling direction of the whole stack of the volume of interest.

2.2 Analytical modelling of bone temperature rise

The temperature distribution in the bone can be obtained from the approach developed by Carslaw and Jaeger [23]. A fixed coordinate system (x, y, z) is associated to the bone sample where the beginning of the drilled hole is located at position $x=0$, Fig. 4. Heat is liberated at time t' , from 0 to t ($0 \leq t' \leq t$), at point $Q(x', y', z')$ where the heat rate $q_c ds$ ($q_c (w/m^2)$) is associated to an elementary surface ds and due to the cutting process. During drilling, the heat source moves with a constant speed V in x -direction so that $x' = Vt'$ as shown in Fig. 4. When the bone sample is assimilated to an infinite medium (i.e. the bone is supposed to occupy all the space $-\infty < x, y \text{ and } z < +\infty$) and according to Carslaw and Jaeger [23], the temperature elevation ΔT at a point $M(x, y, z)$ for time t is given by:

$$\Delta T(x, y, z, t) = \frac{q_c ds}{8\rho c(\pi a)^{3/2}} \int_0^t (t-t')^{-3/2} e^{-\left\{(x-Vt')^2 + (y-y')^2 + (z-z')^2\right\}/4a(t-t')} dt' \quad (1)$$

where ρ , k , c , and a represent respectively the density, the thermal conductivity, the specific heat and the thermal diffusivity. Note that in (1), q_c is time independent. According to Tu *et al.* [24], the thermal properties and the density of pig bone are given by: $k = 0.45 \text{ W/Km}$, $c = 1640 \text{ J/kg K}$ and $\rho = 1640 \text{ kg/m}^3$.

A similar approach has been proposed by Feldmann *et al.* for the tool tip contribution [19,22]. However, there is a difference between the two models. Indeed, during the heat source displacement for $0 \leq t' \leq t$, its vertical position x' was supposed to be equal to Vt in Feldmann *et al.* work [19,22]. This is equivalent to consider that the distance between the heat source $Q(x', y', z')$ and the measurement position $M(x, y, z)$ is constant for $0 \leq t' \leq t$.

Eq. (1) means that elevation temperature distribution at time t is obtained by adding the rise temperature caused by the amount of heat liberated during the source displacement namely when it was at the positions $(x' = Vt', y', z')$ with $0 \leq t' \leq t$.

By introducing the variable $\tau = t - t'$, (1) is reduced to

$$\Delta T(x, y, z, t) = \frac{q_c ds}{8\rho c(\pi a)^{3/2}} e^{-V(x-Vt)/2a} \int_0^t \tau^{-3/2} e^{-\left(\frac{d^2}{4a\tau} + \frac{V^2\tau}{4a}\right)} d\tau \quad (2)$$

where $d = \sqrt{(x-Vt)^2 + (y-y')^2 + (z-z')^2}$ is the distance from the heat source as reported in Fig. 4.

From the close form of the time integral term, we get:

$$\Delta T(x, y, z, t) = \frac{q_c ds}{8\rho c \pi a} e^{-V(x-Vt)/2a} f(d, t) \quad (3)$$

with

$$f(d, t) = \frac{1}{d} \left\{ e^{Vd/2a} \operatorname{erfc}\left(d/2\sqrt{at} + V\sqrt{at}/2a\right) + e^{-Vd/2a} \operatorname{erfc}\left(d/2\sqrt{at} - V\sqrt{at}/2a\right) \right\} \quad (4)$$

The temperature distribution, due to the drill-bit tip contribution, is obtained by adding the temperature rise caused by each elementary heat source $q_c ds$ (q [W/m²]) over the disk surface, see Fig. 4(a):

$$T_{tip}(x, y, z, t) = \frac{1}{8\rho c \pi a} e^{-V(x-Vt)/2a} \int_0^R \int_0^{2\pi} q_c f(d, t) d\theta r dr \quad (5)$$

where R is the drill bit radius and d is expressed in polar coordinates $d = \sqrt{(x-Vt)^2 + (y-r\cos\theta)^2 + (z-r\sin\theta)^2}$. In (5), the bone is considered as an infinite medium.

For drilling operation, the bone can be assimilated to a half space (i.e. the bone sample occupies the half space $x \geq 0$ and its top surface is located at position $x=0$). To obtain the temperature distribution in a semi-infinite medium with adiabatic surface, the image sources $q_{im} ds$ (with $q_{im} = q_c$) are introduced as in Komanduri and Hou [25-27]. These fictive sources move with a constant speed $-V$ in x-direction such as $q_{im} ds$ is located at $Q_{im}(x' = -Vt', y', z')$ where heat is liberated at time t' , from 0 to t ($0 \leq t' \leq t$), see Fig. 4(a). The temperature distribution due to Q_{im} is deduced from (5) by replacing d with $d_{im} = \sqrt{(x+Vt)^2 + (y-r\cos\theta)^2 + (z-r\sin\theta)^2}$ and V with $-V$. Finally, for the bone assimilated to a half space, we obtain:

$$T_{tip}(x, y, z, t) = \frac{1}{8\rho c \pi a} \left\{ e^{-V(x-Vt)/2a} \int_0^R \int_0^{2\pi} q f(d, t) d\theta r dr + e^{V(x+Vt)/2a} \int_0^R \int_0^{2\pi} q f(d_{im}, t) d\theta r dr \right\} \quad (6)$$

The integral terms in (6) are calculated numerically by using Gauss quadrature method. To account for the friction between the drill-bit side and the drilled hole, the depth H of the hole is divided into N small differential elements having ring shape. The height of each element j ($1 \leq j \leq N$) is given by $\Delta h = H/N$, Fig. 4(b).

When the drill bit penetrates deeper into the bone, frictional heat is liberated at time t' , from t_{0j} to t ($t_{0j} \leq t' \leq t$), at point $Q_f(x', y', z')$ where the heat rate $q_f ds$ ($q_f (w/m^2)$) is associated to an elementary surface $ds = R d\theta \Delta h$, see Fig. 4(b). The heat source moves with a constant speed V in x-direction so that $x' = Vt'$ as shown in Fig. 4(b). Following

the drill bit penetration, each source at Q_f is activated at $t' = t_{0j}$ with $t_{0j} = j\Delta h/V + R/V \tan(\psi/2)$. In this equation, the term $R/\tan(\psi/2)$ represents the height of the drill-bit tip and ψ is the point angle, see Fig. 4(a). Thus, at time t , the number of differential elements (elementary rings of Fig. 4(b)) forming the total friction zone is given by the integer part of the ratio $Vt/\Delta h$.

Applying the foregoing approach, the temperature distribution in the bone (modeled as a half space), due to the side drill bit contribution (frictional heat), is as follows:

$$T_{side}(x, y, z, t) = \frac{R \Delta h}{8\rho c \pi a} \sum_j^N \left\{ e^{-V(x+h_j-Vt)/2a} \int_0^{2\pi} q_f f(d, t-t_{0j}) d\theta + e^{V(x-h_j+Vt)/2a} \int_0^{2\pi} q_f f(d_{im}, t-t_{0j}) d\theta \right\} \quad (7)$$

with

$$\begin{cases} h_j = (j-1/2)\Delta h \\ d = \sqrt{(x+h_j-Vt)^2 + (y-R\cos\theta)^2 + (z-R\sin\theta)^2} \\ d_{im} = \sqrt{(x-h_j+Vt)^2 + (y-R\cos\theta)^2 + (z-R\sin\theta)^2} \end{cases} \quad (8)$$

The length h_j is defined in Fig. 4(b) and the integral terms in (7) are calculated numerically by using Gauss quadrature method. Note that in (7), q_f is time independent.

The temperature distribution in the bone, resulting from the two contributions, is given by:

$$T(x, y, z, t) = T_0 + T_{tip}(x, y, z, t) + T_{side}(x, y, z, t) \quad (9)$$

where T_0 is the initial bone temperature.

During cutting operation, the tool-bone interaction changes due to the variation of the bone behavior from the cortical part to the cancellous bone. Consequently to estimate the heat source, we propose to use the average of the maximum and minimum values

of feed force F and cutting torque M denoted by $\bar{F}$ and $\bar{M}$ respectively, see the Results section. Following this approach, the heat source relative to the tool tip is assumed to be constant during drilling, and equal to a fraction $0 < \eta < 1$ of the mean value of the mechanical energy :

$$q_c = \eta (\bar{F} V + \bar{M} \omega) / (\pi R^2) \quad (10)$$

where V and ω represent respectively the feed rate and the rotational speed (rad/s). Eq. (10) corresponds to a heat source which is time independent as in the present thermal model.

The frictional heat induced by the contact between the drill-bit side and the drilled hole is given by:

$$q_f = \mu_f p V_c \quad (11)$$

with μ_f the friction coefficient, p the contact pressure and V_c the cutting velocity ($V_c = \omega R$).

It should be noted that before applying the analytical model to analyse the thermal problem in the bone, we have to calibrate the parameters η and p . The calibration procedure will be presented and discussed in the Discussion section.

3. RESULTS

Fig. 3(a) shows an example of obtained 3D volume rendering. Each curve reported in Fig. 3(b) joins bone volume fractions determined on each slice of the drilled zones in the drilling direction. The typical evolution of bone volume fractions confirms the drilling of two different types of bone. The relatively flat part of the curve denotes drilling through cortical bone whose bone volume fraction is relatively stable (greater than 0.9). The highly sloped part of bone volume fraction curve represents the entrance into

spongy bone where BV/TV can drop to 0.4 at the end of the drilling process. It is also visible that the bone volume fraction highly varies from a drilled site to another, even inside the cortical part of the bone.

The variation of the feed force and cutting torque during drilling is observed in parallel. The curves obtained are reported in Figs. 5(a) and 5(b). The force rapidly increases at the entrance into bone samples to reach a maximum value. Then, the values slightly decrease until the end of the drilling process where the values drop to zero. This diminution trend is similar to the one observed on the BV/TV curves (Fig. 3b). Therefore, it can be deduced that a relationship exists between the evolution of feed force and bone density. Concerning the torques, their evolution with the drilling depth depends on the cutting speed considered. No general trend can be observed.

In order to evaluate the heat source at the drill tip, given by Eq. (9), the average values of feed force $\bar{F}$ and cutting torque $\bar{M}$ are extracted on the curve profiles from the drilling maximal and minimum values, see Figs. 5(a) to 5(d). These figures reveal that $\bar{F}$ varies only slightly with cutting speed v_c while $\bar{M}$ is larger for $v_c \geq 10 \text{ m/min}$ than for $v_c \leq 5 \text{ m/min}$. The obtained values $\bar{F} = 18 \text{ N}$ and $\bar{M} = 0.08 \text{ N.m}$ (mean value for v_c from 2 to 20 m/min) have been used to estimate the heat source (9).

After model calibration (described and discussed in the Discussion section), the predicted temperature of the model and measurement are compared. Fig. 6 shows the comparison for both positions of thermocouples and for each cutting velocity. All curves present two phases with a first one where the bone temperature increases because of the drilling process and a second one illustrating the cooling phase. The culmination of the curve coincides with the end of the drilling stage.

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304 The influence of the heat source due to the lateral friction is reported in Fig. 7(a). As
305 expected, the lateral friction induces an increase in the temperature rise. A modification
306 of the position of the maximum temperature is also observed mainly for the small value
307 of cutting velocity 2 m/min. Thus, the duration of the temperature increase becomes
308 larger. Fig. 7(b) shows how the predicted temperature changes when the bone is
309 assimilated to an infinite or semi-infinite medium. When a semi-infinite medium with an
310 adiabatic surface is considered (i.e. the bone sample occupies the half space $x \geq 0$
311 and its top surface is located at position $x=0$), the temperature rises obtained are
312 higher but the global profiles of the temperature curves remain unchanged. Concerning
313 the comparison of the maximal temperature rises, the increase with v_c from 2 to 10
314 m/min is reproduced by the model, Fig. 7(c). From 10 to 20 m/min, the predicted values
315 tend to saturate while the temperature measurements show a decrease, Fig. 7(c).

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318 **4. DISCUSSION**

319 Heat generation, due to the conversion of fraction of cutting energy into thermal energy,
320 is a critical parameter for thermal modelling of bone drilling. As discussed before, the
321 application of the metal machining theory assumes that the cutting mechanisms are
322 similar in bone and metal: in particular, the shear angle can be estimated from the
323 Merchant law [16]. For instance, Davidson and James [11], Maani *et al.* [12], Lee *et al.*
324 [8] have supposed that a fraction of shearing energy, due to the primary shear zone,
325 goes into the bone. In Maani *et al.* [12], Lee *et al.* [8], this fraction was deduced from

the metal machining theory of Oxley [14] and Davidson and James [11] supposed that it is equal to 0.5.

In the present approach, bone temperature rise results from two main sources: the drill-bit tip (cutting process) and the friction between the drill-bit side and the drilled hole. The values of both sources q_c and q_f are obtained thanks to relationships (10) and (11). Expression (10) requires the determination of average values of feed force $\bar{F}$ and cutting torque $\bar{M}$ which are provided in Fig. 5. As shown in Fig. 5(c), the drilling force $\bar{F}$ is almost constant as a function of the cutting speed. Fig. 5(d) shows two distinct levels for the torque $\bar{M}$: one for the smallest cutting velocities 2 and 5 m/min and a higher value for velocities 10 and 20 m/min. The values used in this work are: $\bar{F} = 18\text{ N}$ and $\bar{M} = 0.08\text{ N.m}$ (average value of $\bar{M}$ for v_c from 2 to 20 m/min). Further investigations with higher values of cutting velocities would have to be conducted in order to complete these first results. Finally, the determination of q_c and q_f requires the values of parameters μ_f , η and p . The value of μ_f was fixed to 0.3 according to data from the literature. Indeed, Rancourt *et al.* report that $\mu_f = 0.3$ for tibial cancellous bone sliding against stainless steel surface [28]. Davim and Marques [29] analyzed the influence of sliding velocity on μ_f for bovine bone-steel contact pair. They indicate that $\mu_f = 0.25$ for sliding velocities from 0.02 m/s to 0.1 m/s. More recently, Zhu *et al.* [30] examined the variation of μ_f in function of contact pressure and sliding velocity with water lubrication for bovine femoral cortical bone-316 L stainless steel contact pair. For sliding velocity of 0.44 m/s and contact pressure of 0.42 MPa, Zhu *et al.* [30] showed that $\mu_f = 0.25$.

348 Concerning parameters η (fraction of mechanical energy resulting from the tool tip-
 349 bone interaction converted into heat) and p (contact pressure between the drill-bit side
 350 and the drilled hole), a calibration procedure was carried out. From the parametric
 351 study reported in Fig. 7(a), it appears that the time t_c , corresponding to the maximum
 352 temperature rise $\Delta T_{\max}$ (t_c is time during which temperature increases), is mainly
 353 dependent on the side heat source (11) (via the contact pressure p) especially for
 354 small cutting velocities. Based on this trend, the calibration of p and η was performed
 355 with respect to the time t_c and $\Delta T_{\max}$ respectively. Thus, the calibration procedure is
 356 based on the following iterative approach. First, the two parameters were varied within
 357 a defined range (for instance $\eta \in [0.1, 0.7]$ and $p[MPa] \in [0, 20]$). Secondly, for each value
 358 of η , pressure p is selected so that the condition $t_c^{model} \approx t_c^{exp}$ is satisfied. Finally, among
 359 all values of η and for each calibrated pressure, the chosen value of η must satisfy
 360 the condition $\Delta T_{\max}^{model} \approx \Delta T_{\max}^{exp}$ (t_c^{exp} and $\Delta T_{\max}^{exp}$ represent the experimental measurements).
 361 According to this approach, η and p were calibrated such as the experimental
 362 temperature and the model prediction are as close as possible for the smallest cutting
 363 speed $v_c = 2 \text{ m/min}$ as reported in Fig. 6(a) (temperature was measured at 0.5 mm from
 364 the drilled hole, see Fig. 2). The values of parameters η and p obtained with this
 365 calibration are $\eta = 0.35$ and $p = 1 \text{ MPa}$. Besides, Fig. 7(c) indicates that the difference
 366 between the temperature elevation when the bone is assimilated to a semi-infinite
 367 medium with adiabatic surface or considered as an infinite medium is more significant
 368 for $v_c = 2 \text{ m/min}$ than for $v_c = 20 \text{ m/min}$. This can be explained by the fact that the feed
 369 rate V increases with the cutting speed v_c and, at low feed rate, conduction

overcomes the convection of heat (thanks to the heat source displacement) so that heat diffusion will extend deep into the infinite medium.

In order to dissociate the effect of the feed rate per tooth f_t from the influence of v_c , f_t is kept constant $f_t = 0.02 \text{ mm/tooth}$. Fig. 6. shows the effect of cutting speed v_c on the bone temperature elevation over time at depth 1.5 mm and for the two thermocouples placed at 0.5 and 0.9 mm from the hole (denoted respectively by 'T_{h1}' and 'T_{h2}', see Fig. 2). As expected, the model results indicate that the temperature is an increasing function of v_c (i.e. the rotational speed ω) while the exposure time decreases with v_c . This temperature growth is more significant for 'T_{h1}' than for 'T_{h2}'.

Overall, the model correctly reproduces the evolution of temperature rise with time t from 0 to t_c (i.e. $0 \leq \Delta T \leq \Delta T_{\max}$). The low heat conductivity and the high heat capacity of the bone result in lower temperatures at the location of the second thermocouple 'T_{h2}', Figs. 6(e)-6(h). Because of keeping f_t constant ($f_t = 0.02 \text{ mm/tooth}$), the feed rate V increases with cutting speed v_c ($V = f_t v_c / (\pi R)$). Consequently, the heat sources increase with v_c while the duration of heat exchange (exposure time) with the bone is reduced. These two opposite effects result in a slowing down in the increase of the maximum temperature with v_c as reported in Fig. 7(c) (the heat sources q_c and q_f are proportional to v_c , see Eq. (10) and (11), but the evolution of the maximum temperature results from the two opposite effects). The model predictions reveal that the growth of cutting speed v_c from 2 to 5 m/min induces an increase of temperature of thermocouple 'T_{h1}' of about 16 °C (8 °C for 'T_{h2}') while it is about 2°C for a variation from 10 to 20 m/min (2 °C for 'T_{h2}'). These tendencies are close to the temperature measurements, Fig. 7(c). It can also be observed from Fig. 7 that the analytical model predicts the maximum temperature rise with a maximum error of 18% for 'T_{h1}' whereas

we have 28% for 'T_{h2}', which is logical as the model was calibrated for the closest position of the thermocouple. The difference between model results and measurements can be attributed to several parameters which are not considered in the present model: (i) the evolution of the bone density during cutting, (ii) the relationship between the bone thermal properties and its density, (iii) the influence of the presence of both thermocouples on the bone temperature distribution, and (iv) the effect of cutting conditions on the model parameters : η , p , $\bar{M}$ and μ_f .

During bone drilling, the temperature rise depends on the bone density (through BV/TV). Fig. 3(b) shows that the ratio BV/TV is much higher for the cutting tests with $V_c = 2$ and 5 m/min than for $V_c = 10$ and 20 m/min . Note also that the thermal conductivity depends on the bone density, see Feldmann *et al.* [31]. These variations are not taken into account in the present approach where the heat sources are supposed to be constant. To improve the model predictions, the effect of BV/TV on the heat generation and on the thermal conductivity have to be considered. Additionally, the model does not reproduce correctly the cooling stage. Indeed to reduce the computational time, the cooling process was estimated from the moving heat source solution by keeping it to zero during the cooling step (i.e. when $t_c \leq t$). To reproduce the bone cooling process when $t_c < t$, we have to consider the numerical solution of the heat problem where the initial temperature distribution corresponds to the solution given by the present model at $t = t_c$.

The thermal damage of the bone is mainly dependent on two factors: exposure time and temperature magnitude. Several parameters affect these two critical factors: drilling conditions, drilling strategies, cooling and thermomechanical bone properties. From the foregoing comparison between the model predictions and the experimental

results, it appears that despite the model simplicity, it can be helpful to examine the bone necrosis in terms of drilling conditions for $0 \leq t \leq t_c$ (i.e. $0 \leq \Delta T \leq \Delta T_{\max}$).

5. CONCLUSION

In the present study, a simplified analytical model based on the moving heat source approach is developed. Besides, to be closer to the boundary conditions of the thermal problem, the method of image sources has been applied. Because of the complexity of the chip formation mechanisms in bone cutting process, the heat source due to the drill-bit tip has been supposed to be proportional to the cutting energy. The friction between the drill-bit side and the drilled hole was also taken into account. Drilling experiments were conducted on fresh femur pig bone. The distribution of bone volume fraction through the drilled hole was determined by microtomography for the bone samples. The present model requires the calibration of two parameters. The experimental validation has shown the model reproduces satisfactorily the increase in temperature up to the maximum value while it overestimates the temperature during the cooling stage. A parametric study, concerning the thermal boundaries conditions (infinite or finite medium) and the lateral friction, was also performed. The results show that the difference of temperature rise between semi-infinite or infinite medium is more pronounced for small cutting velocities. The lateral friction has a direct influence on the duration of the temperature increase, especially for small cutting velocities. Finally, the present simplified approach can be improved by considering the effects of the bone volume fraction which can present a significant variation in the bone sample.

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