Thermal Damage Done to Bone by Burring and Sawing With and Without Irrigation in Knee Arthroplasty

ABSTRACT

Background: Heat from bone resecting tools used in knee surgery can induce thermal osteonecrosis; potentially causing aseptic implant loosening. This study compared oscillating saws to burrs in terms of temperature generation and histological damage. Use of irrigation to reduce bone temperature was also investigated.

Methods: Temperatures were recorded during sawing and burring with/without irrigation (uncooled/cooled). Histological analyses were then carried out. Differences between groups were tested statistically ($\alpha = 0.05$).

Results: On average, burring produced higher temperatures than sawing ($p < 0.001$). When uncooled irrigation was used, bone temperatures were significantly lower in sawed bone than in burred bone ($p < 0.001$). Irrigation lowered temperatures and thermal damage depths, and increased osteocyte viability ($p < 0.001$).

Conclusion: These results suggest that irrigating bone during resection could prevent osteonecrosis onset.

Keywords: osteonecrosis; bone buring; bone sawing; knee arthroplasty; bone overheating; irrigation

INTRODUCTION

Total knee arthroplasty (TKA) operations are becoming increasingly common in developed countries due to an ageing population and a rise in obesity prevalence [1-5]. Reducing the chances of, or preventing the need for surgical re-intervention are therefore essential to ensure that healthcare systems maintain the ability to cope with annual increases without negatively impacting on the quality of care offered [6,7].

Heat from high powered orthopaedic tools can irreversibly damage or kill bone cells – a process known as osteonecrosis [8-10,11]. Presently, it is agreed that bones exposed to temperatures of >47°C for 60 seconds or longer are at risk of osteonecrosis [9-13]. This leaves the implant exposed to necrotic tissue, reducing bone-implant incorporation, as well as healing processes [9,12].

Although thermal osteonecrosis has been well described in current literature most studies are drill based [15-19] as drills are the most commonly used tool in dentistry; a field where thermal osteonecrosis is a prominent problem [19]. Few studies have investigated the effects of sawing and burring in arthroplasty on bone health.

Robotic computer assisted surgical devices favour the use of a burr over a saw blade for bone resection, as burrs provide more accurate bone preparation than saws. As these devices are newly developed, little research has been carried out into the effects of burring on bone.

The amount of heat generated by a tool has been found to be positively correlated with the extent of thermal damage done to bone [11]. However, most studies which have investigated thermal damage done to bone do not agree on the maximum temperatures generated by sawing and burring [18-22].

Another common controversy in the literature is the use of irrigation in orthopaedic surgery. Based on previous studies it is not clear whether using a cooling agent on the cutting surface can reduce the temperature enough to lessen the thermal damage done to bone [12, 25-28].

To increase our understanding of the relationship between high powered orthopaedic tools and heat-induced osteonecrosis, we aimed to (1) compare the thermal damage done to bone by sawing and burring, (2) determine whether there were temperature differences between sawing and burring bone, and (3) investigate the effect on temperature of irrigation whilst cutting the bone.

Materials and Methods

Bone Preparation and Resection

Bovine femora (n=17) were sourced from an abattoir on the day of animal sacrifice, and immediately prepared for resection. The diaphysis of each bone was fixed in a vice, with the anterior side of the femur orientated superiorly, exposing the medial and lateral condyles for cutting. The anterior and posterior facets of each condyle were cut, allowing temperatures from both sites to be recorded during resection.

Bones were burred with a NavioPFS™ handheld robotic device (Blue Belt Technologies Inc.), which was connected to an Anspach console. Identical spherical burrs of 6mm diameter were used throughout the duration of this study [23, 28]. Burrs were renewed after 10 uses [23]. Tools with higher rotational cutting speeds generate less heat in bone than the same tools at lower speeds [16,21,29-31]. Based on this information, and on advice given by an orthopaedic surgeon who uses the device, burring speed was controlled with a foot pedal at 80,000rpm; the maximum burring speed. Jaramaz & Nikou [32] found that it took surgeons approximately 4 minutes to burr a femoral condyle facet for implant placement; hence, burring time was controlled at 4 minutes.

An oscillating saw designed by Stryker Corporation sawed the bones in this study. Stryker Performance Series™ sagittal blades were used (cut edge: 25.0mm, cut depth: 90.0mm, thickness: 0.97mm). Blades were renewed after 10 uses [23]. The anterior facet of the condyles were cut in the coronal plane, and bone from the posterior facet was resected in the transverse plane. Bone sawing was done in 2 minute sessions. This was intentionally shorter than burring, as the cutting process itself is faster. This time included the time it took to realign the saw between cuts.

All cutting procedures were performed by a single author, after training from a consultant orthopaedic surgeon. To best replicate the operative scenario, both anterior and posterior facets of each condyle were cut. This allowed temperatures generated from two sites per condyle to be recorded. The same surface area of bone was cut by both tools. Furthermore, the same cutting style was always used on the same condyle (e.g. sawing on anterior and posterior facets of medial condyle, and burring on anterior and posterior facets of lateral condyle). The condyles which were burred and sawed were alternated per specimen, to ensure that results were recorded from both lateral and medial condyles by both tools.

It should also be noted that during training, the appropriate software was used to map the surfaces of specimens. This provided the user with surgical plans, thus the areas of bone removed were equivalent to those adequate for implantation. During the testing, the user aimed to burr and saw a similar area of bone to that which was removed during training sessions.

Temperature Capture

Temperatures were recorded with a visual infrared (IR) thermometer (Fluke® VT04 Model, measurement accuracy ±2°C or ±2%). In order to ensure both cutting styles were comparable, temperatures were recorded every 5 seconds when sawing, and every 10 seconds when burring. Hence, 24 temperature readings were captured with each resection. Temperatures of samples at 0 seconds were also recorded to allow temperature elevations when cutting to be determined. A volunteer operated the camera as the author resected bone samples.

Irrigation

Plastic tubing and a hollow metal wire conveyed the cooling agent from a bag to the cutting site. 0.9% saline solution bags were prepared using sodium chloride and water. Flow rate was controlled by the Anspach console when burring and sawing. Six of the sawed and burred femora were not irrigated during cutting, another 6 were irrigated with room temperature saline, and the remaining 5 were irrigated with cooled saline (4°C).

Histomorphometric Analyses

On completion of bone sawing and burring, approximately 1cm^3 samples were removed from the cut surfaces and immersed in tissue fixative. All samples were processed and sectioned perpendicularly to the cut made by the orthopaedic tools. Control samples were also prepared. Following this, H&E standard staining protocol was used to stain the sectioned samples. Images of control, burred and sawed tissue were taken with a microscope.

Twenty fields from histological sections of control, sawed and burred bone were randomly chosen, and the percentages of viable cells relative to lacunae were calculated for each field. Lacunae which had distinguishable osteocytes within them were characterised as living (viable) cells, whereas empty lacunae were classified as dead (non-viable) cells. Additionally, the distance between the burred or sawed surface and first visible osteocyte was calculated for all images.

Statistical Analyses

Two-way ANOVA tests were carried out to test differences between groups. Non parametric tests were carried out where appropriate. For the purposes of this study, the level of significance was set at $\alpha=0.05$ (ver. 16, Minitab Inc., State College, PA, USA).

Results

Temperature Generation

As the bovine femora were not at body temperature on arrival to the laboratory, temperature elevations from the initial readings were calculated for all measurements in each data set. Initial bone temperature was subtracted from each measurement. Average body temperature (37.00°C) was added to these values. These adjusted values were used to analyse the results as they are easier to interpret.

Mean temperature at the surface of the bone increased suddenly on initiation of burring and sawing (Fig. 1). Following this, it increased at a slower rate towards a point where an apparent peak occurred. It took longer for irrigated bones to reach mean temperatures of at least 47°C, with non-irrigated burred and sawed bones taking as little as 20 seconds to reach 47°C. Critically, mean temperatures remained beyond 47°C for >60 seconds in non-irrigated bone as well as in bone burred with room temperature irrigation (Fig. 1). With the use of cooled irrigation, a mean temperature of >47°C was not reached, regardless of the cutting tool used (Fig. 1).

On average, the mean temperature in burred bone was higher than sawed bone (table 1). Examples of the temperatures reached during burring and sawing can be seen in figure 2. A two-way ANOVA with cutting modality and irrigation modality as factors identified that both factors significantly affected bone temperature (both $p < 0.001$).

Bonferroni-adjusted post-hoc tests identified that, on average, burring bone resulted in temperature 1.2 degrees higher than sawing ($p < 0.001$), whilst the absence of irrigation led to a mean bone temperature 3.5 degrees higher than in bone irrigated by room temperature irrigation ($p < 0.001$) which, in turn, was 2.2 degrees greater than cooled irrigation ($p < 0.001$). The significant interaction effect between these factors warranted further examination. Without irrigation, burring and sawing created the same temperature (independent t-test, $p = 0.821$); likewise when cooled irrigation was used ($p = 0.08$). However, when room temperature irrigation was used, bone temperature was reduced by 3 degrees more during sawing than during burring ($p < 0.001$).

Extent of Thermal Damage Done

It is generally accepted that exposing bone to temperatures of >47°C for a period of 60 seconds or longer increases the risk of osteonecrosis [13-14]. Figure 1 showed that the mean temperature was likely to remain >47°C for greater than 60 seconds if the bone was resected without irrigation, or if it was burred with room temperature saline.

Further analysis was carried out to investigate the relationship between tool type and length of exposure of bone to temperatures of 47°C or greater. Six consecutive values of >47°C in burred bone suggested that the tissue was in danger of osteonecrosis, whereas 12 consecutive values of >47°C suggested risk of osteonecrosis in sawed bone (due to the different sampling rates used).

Our results showed that burred bone was at high risk of developing osteonecrosis, even when irrigation at room temperature was used (table 2). Despite the fact that mean temperature was lowered with the use of irrigation when burring (figure 1, table 1), the likelihood of temperatures to exceed 47°C for >60s remained unchanged. This likelihood was greatly reduced by the use of cooled irrigation. However, 20% of samples still reached 47°C and remained at or above this threshold for >60s, despite the fact that the irrigation had provided some cooling effect (figure 1, tables 1&2). Conversely, irrigation at room temperature was effective at reducing the likelihood of osteonecrosis arising in sawed bone. In fact, on no occasion did the temperature exceed 47°C for >60 seconds when sawing with irrigation.

Histomorphometric Analyses

Images of control samples, and bone samples which had been burred or sawed are seen in figures 3 and 4. Bone samples which had been cut by both tools showed increased numbers of dead cells compared to the control specimens ($p < 0.001$; two-way ANOVA).

Removing the control group, a subsequent two-way ANOVA investigating the effect of irrigation and cutting modality on the percentage of dead cells suggests that cutting modality has no effect on this variable ($p = 0.311$) but irrigation does ($p = 0.001$). There was no interaction effect. Bonferroni-adjusted comparisons identified that no irrigation and room temperature irrigation were not significantly different in their percentage dead cells (41.3% vs 45.3% respectively), whilst there were significantly less dead cells in bone irrigated by cooled saline (32.9%, $p = 0.035$ and $p = 0.001$ against no irrigation and room irrigation respectively). The mean percentages of non-viable osteocytes are shown in figure 5.

The distances between the burred surfaces and first visible viable osteocyte were calculated for all fields (i.e. minimum thermal damage depth). A 2-way ANOVA was used to analyse damage depth. The depth did not vary with cutting mode. However, cool irrigation damage depth (13.7 μm) was 12.9 μm less compared to no irrigation (26.6 μm, $p = 0.002$) and 16.0 μm less compared to room temperature irrigation (29.7 μm, $p < 0.001$).

Discussion

Temperature

According to Fig. 1, there was a particular trend to the temperatures generated with time. The initial increase in temperature was expected, as bone has been found to retain heat caused by frictional forces generated by orthopaedic cutting tools [22]. The following decrease in temperature has also been previously reported by Shin & Yoon [21] when burring, and by Dolan *et al.* [31] when sawing bone. This may be explained by a theory proposed by Gehrke and colleagues [13] which states that cortical bone is more likely to overheat than trabecular bone due to its higher thermal conductivity value. Therefore, temperatures are likely to be higher in cortical bone. This theory also describes a temperature decrease as cut depth is increased in trabecular bone, which was also observed in this study. Peak temperatures may correspond to the time at which the border between both bone types was reached by the cutting tools [21, 32-34].

Results from our study also agreed with the majority of studies to date who have reported that tools used to resect bone without irrigation generate temperatures of up to 100°C [20-21, 24, 35-36].

To be able to cut the facets of the femoral condyles properly when burring, the burr needed to remain in contact with the tissue for the majority of each 4 minute session [32]. Hence, it was unsurprising that on average, burring led to higher temperatures in bone.

When the effect of irrigation was taken into consideration however, only bones which had been sawed and burred with room temperature irrigant showed significant differences. It is possible that these results were observed due to the nature of the irrigation methods. When sawing, the cooling agent was applied directly to the bone by the volunteer. When burring however, the tubing which conveyed the saline solution to the cutting site was attached to the drill. The cooling agent therefore made contact with the hot burr before being applied to the tissue. In addition to this, the drill itself quickly became very hot as the device was used – potentially heating the saline as it was conducted from the bag to the cutting site. Unfortunately, the same irrigation methods could not be implemented, as unlike the burring tool, the saw did not have a channel through which the irrigant could be delivered to the operative site.

According to our results, uncooled irrigation was effective at reducing the mean temperature of sawed bone to <47°C ($p < 0.05$). Baker *et al.* [38] reported that sawing bone with room temperature irrigation reduced the temperature at the cut surface by a mean of 4°C. This agrees with results found in our study.

Matthews & Hirsch [39] reported that temperatures of bone drilled with a cooling agent were between 40 and 50°C. Our results from burred bone agreed with this. In our study, cooled irrigation was required to reduce the mean temperatures of bone <47°C. This cooling agent was also needed to reduce exposure of the tissue to temperatures of >47°C for >60 seconds when burring. Similar studies have not burred bone for a long enough period to be able to fairly compare results, therefore further investigation is merited here [15, 21, 40].

Overall, our results suggest that sawing with any irrigation reduced the risk of osteonecrosis; but when burring, irrigation at room temperature had little effect. Hence, cooled irrigant should be used to reduce the risk of irreversible cell death when burring bone.

Histomorphometry

James *et al.,* and Karaca *et al.* [23-24] stated that histomorphometric analyses can quantify the amount of thermal damage done to bone by staining the tissue with haematoxylin and eosin (H&E). According to their study, heat damage decreases affinity for extracellular protein collagen, reducing the eosin stain and increasing haematoxylin staining. Hence, by seeing where the colour of the tissue changes, an estimation of tissue damage depth could be made. In addition to this, areas of bone tissue which have been irreversibly damaged by heat lack osteocytes within their lacunae. This makes it possible to examine osteocyte density within the sample as a measure of bone damage, as well as estimate depth of thermal damage by staining.

In our study, the same percentages of cells were non-viable in non-irrigated sawed and burred bone. This could be explained by the fact that these bones were exposed to similar temperatures throughout the cutting processes.

It was found that mean percentages of non-viable cells were greatest in bone which had been cut with irrigation at room temperature ($p < 0.001$), despite the fact that the temperatures of the cut surfaces were higher in non-irrigated bone. One possible reason for this is that these irrigated bone samples were exposed to toxic solutions during the processing stages for a longer period of time than the other bone samples. Another is that that the saline may have negatively impacted on the cell viability to a certain degree. Moreover, bone samples from the femora were not removed immediately after the animal was sacrificed. Although it was known that the animals had been sacrificed on the same day, the length of time between sample removal and death of animal was unknown.

Dull surgical tools have been found to increase the amount of heat generated at an operative site [42]. By reusing the blades and burrs, it is possible that the temperatures observed in this study were higher than normal. Consequently, cell-viability may have been

affected. This gives another potential explanation for the unexpectedly higher percentage of non-viable cells in bone irrigated with room temperature saline.

In this study, the mean minimum depth of thermal damage decreased with the use of irrigation ($p < 0.001$). Considering the effect irrigation had on temperature, this was not unexpected.

One previous study has also investigated the depth of thermal damage by looking at histological sections; however, the depth of thermal damage was measured as the distance from the cut surface to the deepest empty osteocyte lacuna in the field of view i.e. the estimated maximum thermal damage depth [23]. In this study we measured minimum thermal damage depth. This was believed to be a more reliable way of calculating thermal damage depth, as it is not possible to confirm that the lack of osteocytes throughout the tissue was caused by exposure to high temperatures. As the methods used in both cases were different, our results could not be fairly compared to those discussed by James *et al.* [23]. It can be estimated however, that if our study had used the same methods as James *et al.* [23], the potential depth of thermal damage in our study would have been greater.

Further research is required to investigate the effect of heat on thermal damage depth, as current results vary widely. One study found that necrotic zones of up to 1.9mm could be caused by high temperatures in bone where no irrigation had been used [21]. Conversely, an older study by Lundskog [13] believed that exposure to temperatures of at least 50°C caused injury for up to 1mm.

Limitations

Further limitations to this study included the fact that all specimens had a thick and even cartilaginous layer – synonymous of good quality cartilage, suggesting that the quality of the bone underlying this cartilage was also good. This is unlike the bone of subjects undergoing TKA. Osteoarthritic subchondral bone is likely to be sclerotic, potentially increasing temperature observed during bone removal. Furthermore, there are variables which come into consideration when cutting bone in theatre which could not be mimicked in the laboratory such as blood circulation and soft tissue presence. Collectively, these variables could have affected the amount of temperature generated when cutting bone.

Conclusions

The results from this study showed that without irrigation, sawing and burring bone generated temperatures which were high enough to cause irreversible histological changes to bone, including cell death. Although the risk of developing osteonecrosis was high in non-

irrigated bone, the temperatures were low enough to be reduced by applying a cooling agent to the cut surface.

These results imply that irrigating the bone in orthopaedic procedures such as TKA is a feasible approach to reduce the temperature at the cutting site, and thus decrease the risk of heat induced osteonecrosis. This could be most applicable for procedures which replace the diseased joint with cementless implants, where the only source of heat comes from the tools used, and no cement is available to bridge any gap between the implant and healthy bone.

Overall, based on these results it is advised that cooled saline should be used in orthopaedic procedures such as TKA when burring and sawing bone, to reduce the chances of irreversibly thermally damaging the bone. If irrigation is unavailable, intermittent bone cutting is suggested, to prevent onset of osteonecrosis.

References

[1] Suri, P., Morgenroth, D.C. Hunter, D.J. Epidemiology of osteoarthritis and associated comorbidities. Phys Med & Rehabil 2012; 4:S10-9 DOI: 10.1016/j.pmrj.2012.01.007

[2] NHS (2013). *Knee replacement: NHS Choices* [Online] Available at <http://www.nhs.uk/conditions/Knee-replacement/Pages/Kneereplacementexplained.aspx> [Last Accessed: 22nd January, 2015]

[3] US Department of Health & Human Services (2012). *National Statistics on All Stays: H.CUPnet* [Online] Available at < http://hcupnet.ahrq.gov/> [Last Accessed: 18th August, 2015]

[4] Apold, H., Meyer, H.E., Nordsletten, L., Furnes, O., Baste, V., Flugsrud, G.B. Weight gain and the risk of knee replacement due to primary osteoarthritis. A population based, prospective cohort study of 225,908 individuals. Osteoarth Cartilage 2014; 22: 652-658 DOI: 10.1016/j.joca.2014.03.002

[5] Wells, V.M., Hearn, T.C., McCaul, K.A., Anderton, S.M., Wigg, A.E.R., Graves, S.E. Changing incidence of primary total hip arthroplasty and total knee arthroplasty for primary osteoarthritis. J Arthroplasty 2002; 17(3): 267-273

[6] Schroer, W.C., Berend, K.R., Lombardi, A.V., Lowry Barnes, C., Bolognesi, M.P., Berend, M.E., Ritter, M.A., Nunley, R.M. Why are total knees failing today? Etiology of total knee revision in 2010 and 2011. J Arthroplasty 2013; 28(S1):116-9 DOI: 10.1016/j.arth.2013.04.056

[7] Mahomed, N.N., Davis, A.M., Hawker, G., Badley, E., Davey, J.R., Syed, K.A., Coyte, P.C., Gandhi, R., Wright, J.G. Inpatient compared with home-based rehabilitation following primary unilateral total hip or knee replacement: a randomized controlled trial. J Bone Joint

Surg Am 2008; 90(8):1673–80. Available at: http://jbjs.org/content/90/8/1673.abstract [Accessed April 10, 2015] DOI: 10.2106/JBJS.G.01108
[8] Eriksson, R.A, Albrektsson, T. The effect of heat on bone regeneration: An experimental study in the rabbit using the bone growth chamber. J Oral Maxillofac Surg 1984; 42: 705-11
[9] Toksvig-Larson, S., Ryd, L. Temperature elevation during knee arthroplasty. Acta Orthop Scan 1989; 60(4): 439-442
[10] Lee, J.E., Rabin, Y., Ozdoganlar, O.B. A new thermal model for bone drilling with applications to orthopaedic surgery. Med Eng Phys 2011; 33: 1234-44 DOI: 10.1016/j.medengphy.2011.05.014.
[11] Birkenfeld, F., Becker, M.E., Kurz, B., Harder, S., Kern, M and Lucius, M. Changes in human mandibular bone morphology after heat application. Ann Anat 2010; 192: 227-31 DOI: 10.1016/j.aanat.2010.06.001
[12] Toksvig-Larson, S., Ryd ,L., Lindstrand, A. On the problem of heat generation in bone cutting. Studies on the effect of liquid cooling. J Bone Joint Surg 1991; 73-B: 13-5
[13] Lundskog, J. Heat and bone tissue. An experimental investigation of the thermal properties of bone and threshold levels for thermal injury. Scand J Plast Reconstr Surg1972; 9: 1-80
[14] Stańczyg M., and van Rietbergen, B. Thermal analysis of bone cement polymerisation at the cement-bone interface. J Biomech 2004; 37: 1803-10
[15] Gehrke, S.A., Bettach, R., Taschieri, S., Boukhris, G., Corbella, S., Del Fabbro, M. Temperature changes in cortical bone after implant site preparation using a single burr versus multiple drilling steps: An in vitro investigation. Clin Impl Dent Res 2013 DOI: 10.1111/cid.12172
[16] Davidson, S.R.H and James, D.F. Drilling in bone: Modeling heat generation and temperature distribution. J Biomech Eng 2003; 125: 305-14
[17] Gaspar, J., Borrecho, G., Oliveira, P., Salvado, F., Martins dos Santos, J. Osteotomy at low-speed drilling without irrigation versus high-speed drilling with irrigation: An experimental study. Acta Med Port 2013; 26(3): 231-6
[18] Gehrke, S.A., Neto, H.L., Mardegan, F.E.C. Investigation of the effect of movement and irrigation systems on temperature in the conventional drilling of cortical bone. Br J Oral Maxfac Surg 2013; 51: 953-7 DOI: 10.1016/j.bjoms.2012.10.023.
[19] Augustin, G., Zigman, T., Davila, S., Udilljak, T., Staroveski, T., Brezak, D., Babic, S. Cortical bone drilling and thermal osteonecrosis. Clin Biomech 2012; 27: 313-25 DOI: 10.1016/j.clinbiomech.2011.10.010.
[20] Hillery, M.T., Shuaib, I. Temperature effects in the drilling of human and bovine bone. J Mater Process Tech 1999; 92-3: 302-08

[21] Shin, H.C and Yoon, YS. Bone temperature estimation during orthopaedic round bur milling operations. J Biomech 2006; 39: 33-9
[22] Sugita, N., Osa, T., Mitsuishi, M. Analysis and estimation of cutting-temperature distribution during end milling in relation to orthopaedic surgery. Med Eng Phys 2011; 31: 101-7 DOI: 10.1016/j.medengphy.2008.05.001
[23] James, T.P., Chang, G., Micucci, S., Sagar, A., Smith, E.L. Effect of applied force and blade speed on histopathology of bone drilling resection by sagittal saw. Med Eng and Phys 2014; 36: 364-70 DOI: 10.1016/j.medengphy.2013.12.002.
[24] Karaca, F., Aksakal, B., Kom, M. Influence of orthopaedic drilling parameters on temperature and histopathology of bovine tibia: An in vitro study. Med Eng Phys 2011; 33: 1221-7 DOI: 10.1016/j.medengphy.2011.05.013.
[25] Ark, T.W., Neal, JG., Thacker, J.G., Edlich, R.F. Influence of irrigation solutions on oscillating bone saw blade performance. J Biomed Mat Res 1997; 43(2): 108-12
[26] Farrell, M., Mathieson, A., Chung, P., Heller, J., Clarke, S.P., McDonald, M.K., Cardoni, A. In vitro performance testing of two arcuate oscillating saw blades designed for use during tibial plateau leveling osteotomy. Vet Surg 2011; 40: 694-707 DOI: 10.1111/j.1532-950X.2011.00855.x.
[27] Fukushima, H., Hashimoto, Y., Yoshiya, S., Kurosaka, M., Matsuda, M., Kawamura, S. and Iwatsubo, T. Conduction analysis of cement interface temperature in total knee arthroplasty. Kobe J Med Sci 2002; 48: 63-72
[28] Trisi, P., Berardini, M. Falco, A., Vulpiani, M.P., Perfetti, G. Insufficient irrigation induces peri-implant bone resorption: an in vitro histologic analysis in sheep. Clin Oral Impl Res 2013; 25(6): 696-701 DOI: 10.1111/clr.12127
[29] Smith, J.R, Riches, P.E., Rowe, P.J. Accuracy of a freehand sculpting tool for unicondylar knee replacement. Int J Med Robot Comp 2013; 10(2): 162-9 DOI: 10.1002/rcs.1522
[30] Reingewirtz, Y, Szmukler-Moncler, S., Senger, B. Influence of different parameters on bone heating and drilling time in implantology. Clin Oral Impl Res 1997; 8: 189-197
[31] Wang, W., Shi, Y, Yang, N, Yuan, X. Experimental analysis of a drilling process in cortical bone. Med Eng Phys 2014; 36: 261-266 DOI: 10.1016/j.medengphy.2013.08.006
[32] Wang, Q., Chen, H., Wu, W., Qin, J., Heng, P.A. Impulse based rendering methods for haptic simulation of bone-burring. IEE ToH 2012; 5(4): 344-355
[33] Jaramaz, B., Nikou, C. Precision freehand sculpting for unicondylar knee replacement: Design and experimental validation. Biomed Tech (Berl) 2012; 57(4): 293-9 DOI: 10.1515/bmt-2011-0098
[34] Dolan, E.B., Vaughan, T.J., Niebur, G.L., Casey, C., Tallon, D., McNamara, L. How bone tissue and cells experience elevated temperatures during orthopaedic cutting: An

experimental and computational investigation. J Biomech Eng 2014; 136(2) 021019 DOI: 10.1115/1.4026177
[35] Strbac, G.D., Giannis, K., Unger, E., Mittlböck, M., Watzek, G., Zechner, W. A novel standardized bone model for thermal evaluation of bone osteotomies with various irrigation methods. Clin Oral Impl Res 2013; 25(5): 622-31 DOI: 10.1111/clr.12090
[36] Strbac, G.D., Giannis, K., Unger, E., Mittlböck, M., Vasak, C., Watzek, G., Zechner, W. Drilling- and withdrawing-related thermal changes during implant site osteotomies. Clin Implant Dent Res 2013; DOI: 10.1111/cid.12091
[37] Krause, W.R., Bradbury, D.W., Kelly, J.E., Lunceford, E.M. Temperature elevations in orthopaedic cutting operations. J Biomech 1982; 15(4): 267-75
[38] Ark, T.W., Neal, JG., Thacker, J.G., Edlich, R.F. Influence of irrigation solutions on oscillating bone saw blade performance. J Biomed Mat Res 1997; 43(2): 108-112
[39] Baker, R., Whitehouse, M., Kilshaw, M., Pabbruwe, M., Spencer, R., Blom, A., Bannister, G. Maximum temperatures of 89°C recorded during the mechanical preparation of 35 femoral heads for resurfacing. Acta Orthop 2011; 82(6): 669-73 DOI: 10.3109/17453674.2011.636681
[40] Matthews, L.S., Hirsch, C. Temperatures measured in human cortical bone when drilling. J Bone Joint Surg 1972; 54(2): 297-308
[41] Piqué-Vidal, C. The effect of temperature elevation during discontinuous use of rotatory burrs in the correction of halux valgus.J Foot Ankle Surg 2005; 44(5): 336-44
[42]Evans, J.M. How to handle the bone considerations in manipulation and alteration of bones during orthopaedic surgery. Oper Techn Sports Med 2011; 19: 217-219

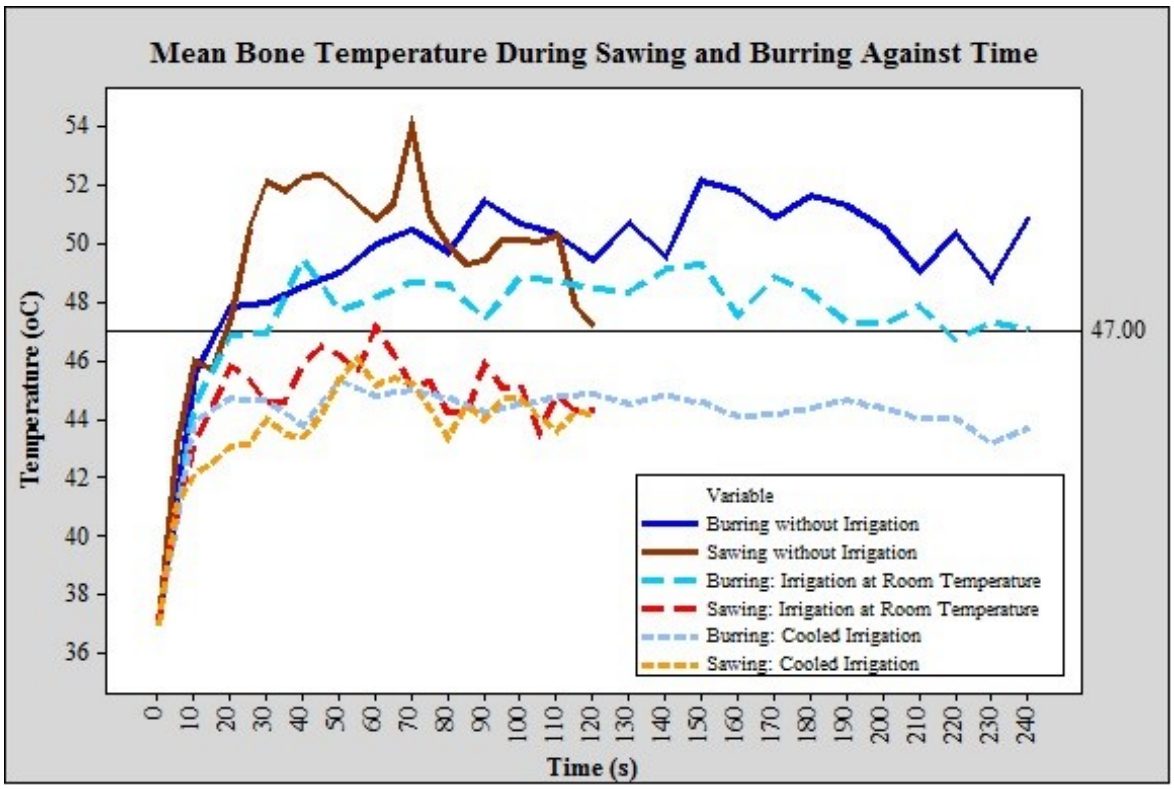

Fig. 1: Mean temperature measurements recorded every 10 seconds when burring and every 5 seconds when sawing with and without irrigation.

Table 1: Mean temperatures of the bones when burring and sawing.

Condition	Mean Temperature (range) of Burred Bone (°C)	Mean Temperature (range) of Sawed Bone (°C)
Non-Irrigated	49.98±0.32 (41-59)	49.87±0.34 (41-55)
Irrigation: Room Temperature	47.93±0.34 (37-55)	44.96±0.22 (39-49)
Irrigation: 4°C	44.44±0.18 (41-49)	44.02±0.15 (41-47)

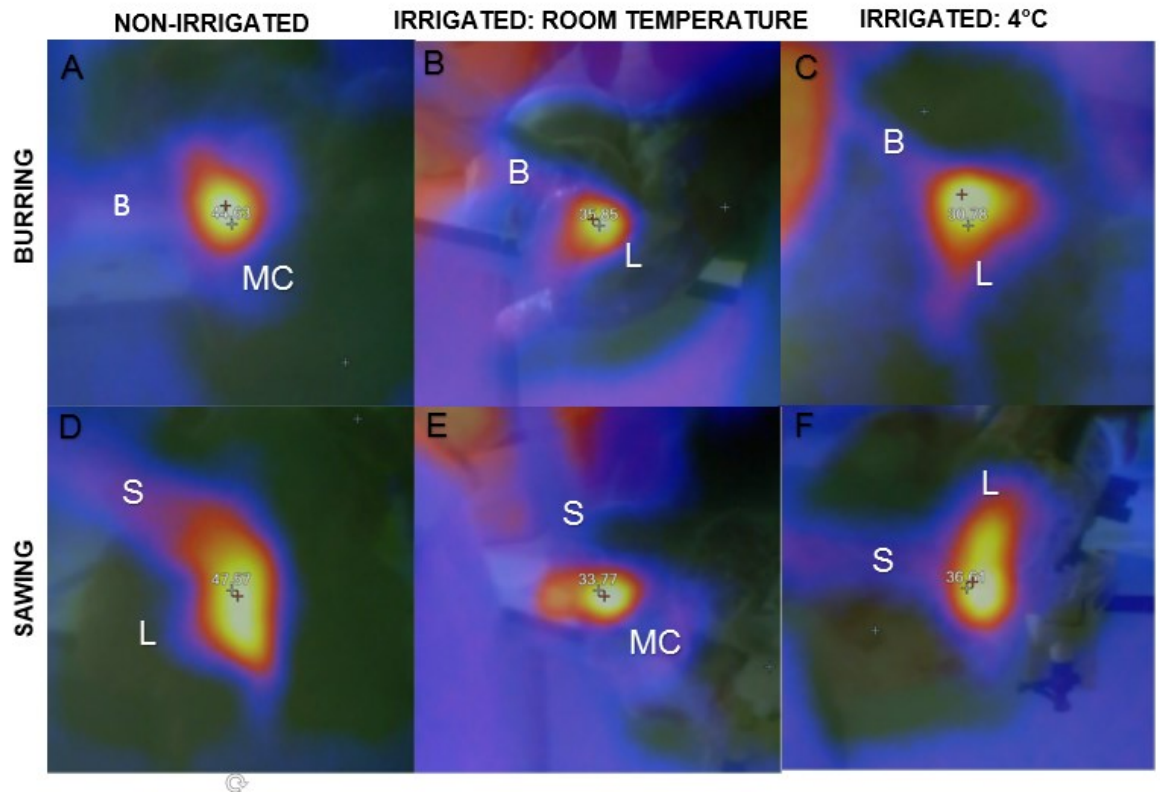

Fig. 2. (A) Non-irrigated burred bone; (B) Burred bone cooled with room temperature irrigation (C) Burred bone cooled with 4°C irrigation; (D) Non-irrigated sawed bone; (E) Sawed bone cooled with room temperature irrigation; and (F) Sawed bone cooled with 4°C irrigation. *Crosses correspond to 'Maximum Temperature' (red) and 'Centre-point Recorded Temperature' (white) (**B** – Burr, **LC** – Lateral Condyle, **MC** – Medial Condyle, **S** – Saw blade)*

Table 2: The percentage of burred and sawed condyle facets which would have reached temperatures of >47°C for a period of 60 seconds or longer if initial bone temperature was 37°C.

Cutting Condition	Burred Bone	Sawed Bone
Non-Irrigated	83.3%	58.3%
Irrigation at Room Temperature	83.3%	0.0%
Irrigation at 4°C	20.0%	0.0%

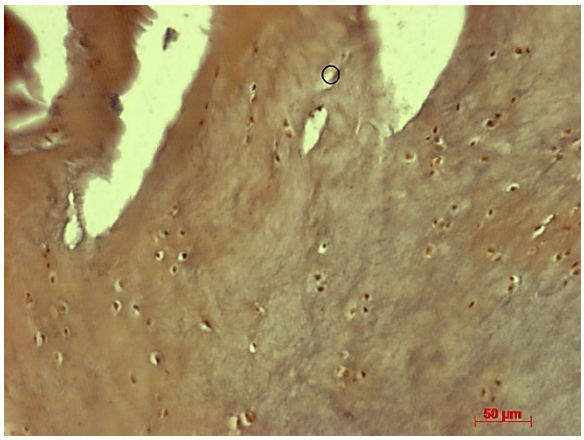

Fig 3: Example of a control specimen which had not been cut by the burr or saw prior to analysis. Black ring highlights empty osteocyte lacuna. The tissue was H&E stained. Image at x20 magnification.

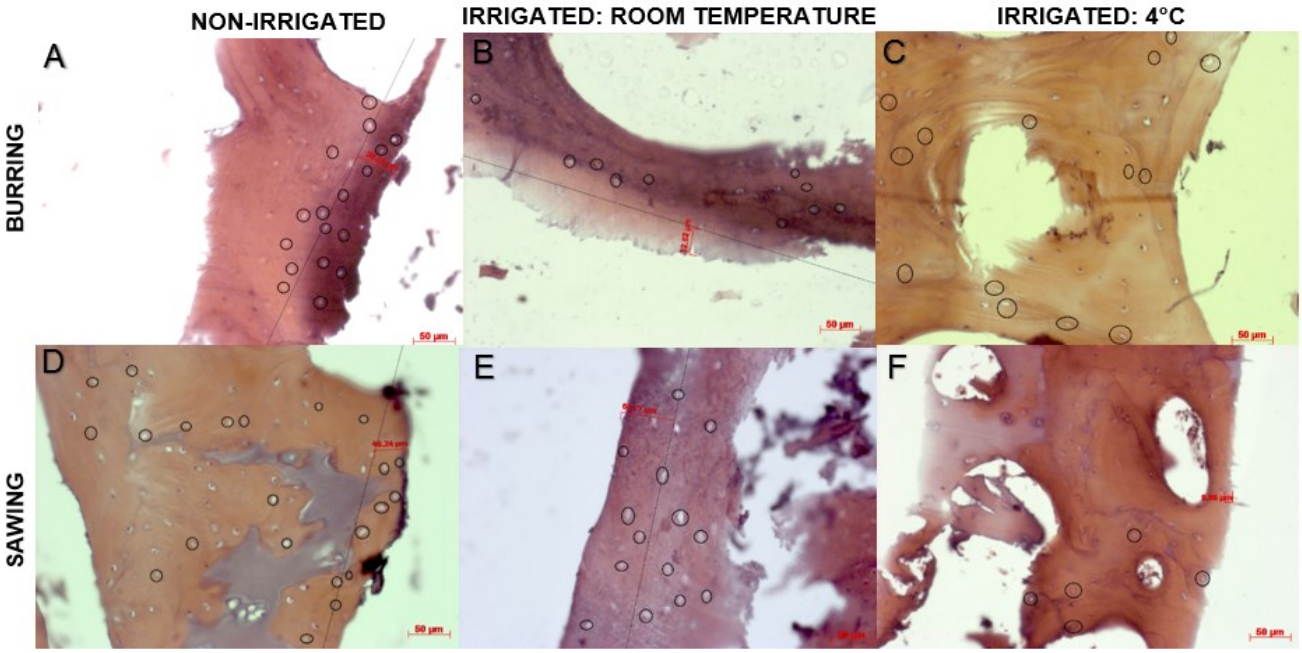

Fig. 4. Histological images of non-irrigated and irrigated bone at 6µm taken by a light microscope. (A) Non-irrigated burred bone; (B) Burred bone cooled with room temperature irrigation (C) Burred bone cooled with 4°C irrigation; (D) Non-irrigated sawed bone; (E) Sawed bone cooled with room temperature irrigation; and (F) Sawed bone cooled with 4°C irrigation. *Black rings highlight empty osteocyte lacunae (H&E stained; x20 magnification). Lines correspond to estimated tissue damage depth.*

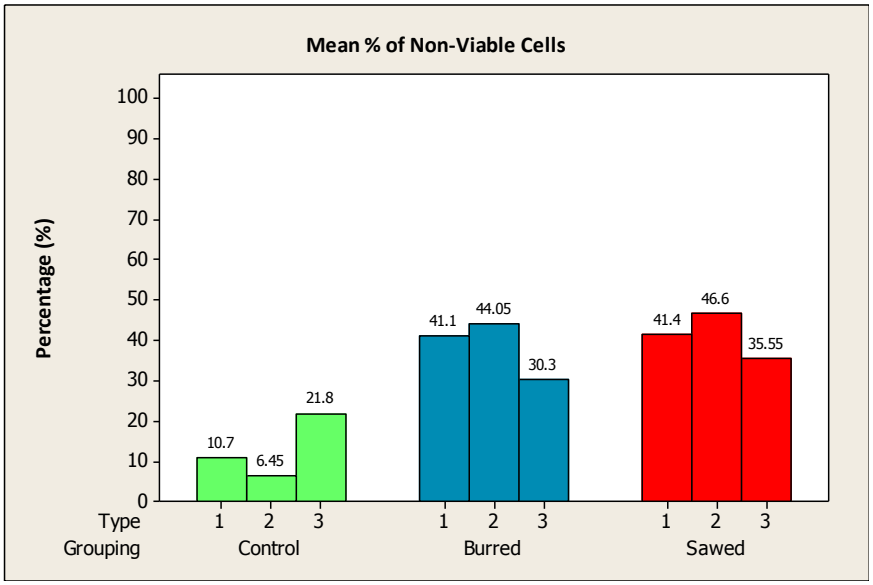

Fig. 5: Bar charts showing the mean percentages of empty osteocyte lacunae present within one field of view in control, burred, and sawed bone which were not irrigated (Type 1), irrigated with saline at room temperature (Type 2), and irrigated with saline at 4°C (Type 3) (n=20).