The effect of drilling parameters on bone

Part I *General healing response*

H. OHASHI, M. THERIN, A. MEUNIER, P. CHRISTEL
Laboratoire de Recherces Orthopédiques, UA CNRS 1432, Faculté de Médecine Lariboisière-Saint-Louis, Université Paris VII, 10, Avenue de Verdun, 75010 Paris, France

For biocompatibility evaluation, orthopaedic and dental biomaterials are often implanted into bone after drilling. Bone repair in the drilled hole may be affected by bone damage attributed to drilling, thus influencing the bone response to biomaterials. The drilling parameters (the speed of rotation and irrigation) were investigated histologically. Three holes were drilled in each rabbit tibia with different conditions; three speeds (200, 500 and 5000 r.p.m.) and the use of central irrigation or not. Rabbits were killed immediately, 3 days, 2 weeks or 4 weeks post-operatively. India ink was injected in several rabbits just after drilling to investigate the extent of local ischaemia. The drilling quality was evaluated with regard to hole geometry, initial thermal damage and later bone healing process. For 500 or 200 r.p.m. the initial thermal damage, shown by the degree of ischaemia, was less than for 5000 r.p.m. drilling, but the hole edge was not always cleanly cut. This uneven cut edge was considered not to influence the bone-healing process. Drilling at 200 r.p.m. introduced a lower degree of circularity. The subsequent bone formation was retarded by 5000 r.p.m. drilling, presumably due to thermal damage and vascular obstructions. The irrigation was effective in reducing the ischaemic area. These results suggest that a speed of about 500 r.p.m. may be recommendable for intra-osseous implantation of biomaterials. The central irrigation system is considered effective in reducing the ischaemic area.

1. Introduction

The response of bone to orthopaedic biomaterials is a matter of concern, and its evaluation is usually performed by inserting cylindrical implants into drilled cortical defects. However, the bone response may be affected not only by the implant itself, but also by the implanting conditions. Drilling is an important factor of the implanting conditions. One of the most serious problems in drilling is heat production. A high temperature causes osteonecrosis around the hole, which may affect the bone-healing process and may deleteriously influence the response of bone to implanted materials. Non-cylindrical drilling induces various amounts of bone–implant gap and may impair the implant stability, introducing another factor of variability into the bone–implant relationship.

Drilling in bone has been analysed from several points of view. The required cutting force, heat production and bone damage are the main parameters to be considered when evaluating the drilling performance. The drilling quality is determined by the following factors: the drill geometry and material, the speed of rotation, the torque, the applied force, the use of irrigation, predrilling (i.e. drilling with a drill of smaller diameter before drilling with the definitive diameter) and, finally, the cortical thickness and bone density.

Concerning the drill geometry, several types of twist drills have been investigated [1–4]. Hobkirk and Rusiniak [5] compared six different types of drills and burrs. A spear-point drill and a twist drill were preferred.

Thompson [6] studied the influence of the speed of rotation (from 125 to 2000 r.p.m.) both by histology and by measuring the temperature *in vivo*. A speed over 1000 r.p.m. caused greater temperature elevation and greater thermal damage around the hole, whereas a speed below 250 r.p.m. increased the degree of fragmentation of the hole edge. Accordingly, a speed of about 500 r.p.m. was recommended to reduce the initial damage.

The temperature elevations during drilling have also been measured *in vitro* [7]. The maximum temperatures were not significantly different among three speeds of rotation, 345, 855 and 2900 r.p.m. Ultraspeed drilling, over 200 000 r.p.m., has been recommended for clinical evaluation [8], by temperature measurement [9] and by histological examination of the bone-repair process [10–12].

Mathews and Hirsch [7] also studied the influence of both the applied force and predrilling. They found that an increase in the applied force was associated with a decrease in the maximum temperature, and the use of predrilling limited the temperature elevation.

Address all correspondence to: Dr H. Ohashi, Department of Orthopaedic Surgery, Osaka City University Medical School, 1-5-7 Asahimachi, Abeno-ku, Osaka 545, Japan.

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With one exception [13], the use of irrigation has been demonstrated to limit the temperature elevation [7, 9] and to decrease the bone damage [10, 11]. A flow rate of $> 500\,\text{ml}\,\text{min}^{-1}$ has been reported to be necessary to obtain sufficient effect for cooling [7]. In order to reinforce the effect of irrigation, Eriksson *et al.* [14] recommended the use of internally cooled burrs, which enable the cooling agent to reach the cutting site directly.

By comparing rabbit, dog and human cortical bones, the cortical thickness as well as the bone density have also been reported to influence the temperature elevation attributed to drilling [14].

When drilling bone defects for biomaterial testing, the geometry of the defect and the bone-healing process affected by the thermal damage may be considered as the main parameters that must be taken into account. From the previous literature, the drilling conditions have been evaluated mostly by focusing on initial damage. Few studies have looked at the bone-healing process histologically over a time period, and the insufficient histomorphometrical techniques have limited a precise quantitative evaluation. This study was performed to investigate histomorphometrically the influence of the speed of rotation and irrigation on the resultant hole geometry, initial thermal damage and later healing process by using an image-analysing system.

2. Materials and methods

2.1. Drilling conditions

A semicircular, 4.0 mm diameter drill (IMZ 514021, France-Implants, Vincennes, France) was used (Fig. 1). The drill was driven by a motor system (AEU-717, Aseptico, Washington, USA), which could variably control the speed of rotation (from 100 to 15 000 r.p.m.) and which had an irrigation pump. The speed of rotation was digitally indicated on the front panel. Physiological saline at room temperature (20–22 °C) was used as the irrigation agent and flushed out from the centre of the drill at a flow rate of $60\,\text{ml}\,\text{min}^{-1}$. Six different drilling conditions were created by the combination of three speeds of rotation (200, 500 or 5000 r.p.m.) and the use of irrigation or not.

2.2. Animal experiments

Twenty-three male New Zealand White rabbits, weighing about 3.0 kg, were used. General anaesthesia was induced and maintained by intramuscular injections of Zoletil (Zolazepam + Tiletamine; $20\,\text{mg}\,\text{kg}^{-1}$ body weight) and Rompun (Xylatine; $0.2\,\text{mg}\,\text{kg}^{-1}$ body weight). The operation was performed under aseptic conditions. Both legs were shaved, cleaned and disinfected. In each hindlimb, a 3 cm longitudinal skin incision was made on the anteromedial surface starting from the distal portion of the tibial tuberosity. The *M. tibialis anterioris* and *M. extensor digitalis pedis longus* were separated and the tibia was exposed supraperiosteally. Three holes were drilled in the diaphysis of each tibia, perpendicular to the cortical bone. The drilling condition of each hole was distributed at random. After drilling, bone debris was carefully removed by irrigation in all holes. Muscles, subcutaneous tissues and skin were closed layer by layer. A sterile dressing was applied. After surgery, all rabbits were kept in individual cages and immediate weight-bearing was allowed.

Rabbits were distributed into four groups which were killed immediately, 3 days, 2 weeks or 4 weeks after surgery. Tibiae were fixed in 10% buffered formalin, then dehydrated and embedded in methylmethacrylate. The tibiae were each cut into three parts containing one hole in each block. Each block was cut into a slice with a diamond saw blade, perpendicular to the drilling axis, parallel to the cortical bone at the middle level of cortical thickness (Fig. 2a). The slices were ground down to 100 μm and stained with Paragon. The number of available specimens for each group is listed in Table I.

Another five rabbits were used to investigate ischaemia by using India ink. The operative technique and the drilling conditions were similar to those described above. After the drilling procedure, the abdominal aorta was exposed and was cannulated in the distal direction. First, 5 ml 2% Xylocain was injected

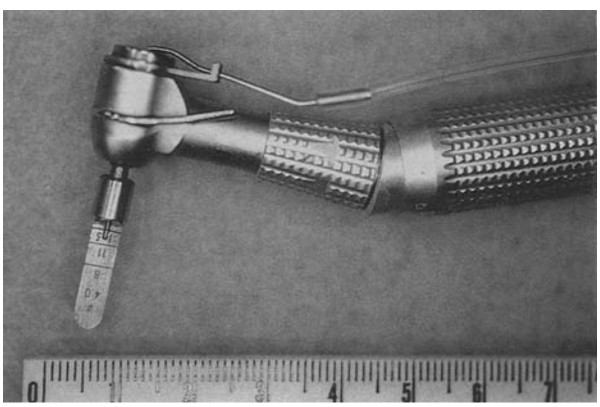

Figure 1 Semicircular drill used in the experiment. The irrigation tube is connected to the nozzle inserted in the centre of the drill.

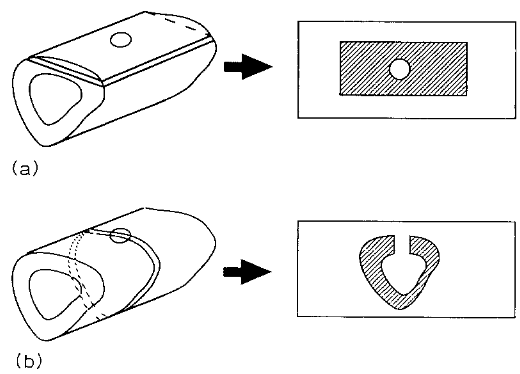

Figure 2 Schematic drawing of bone cutting for the histological specimens. (a) Tibia cut into slice, parallel to the cortical bone at the middle level of cortical thickness and (b) tibia cut transversely for the India ink-injected specimens.

TABLE I The number of available specimens for each group

Speed (r.p.m.)	Irrigation	Specimen				
		0 day	3 days	2 weeks	4 weeks	India ink injection
200	Yes	5	4			5
	No	5	5			5
500	Yes	5	6	6	6	3
	No	5	6	6	6	4
5000	Yes	5	5	6	6	3
	No	5	5	5	6	5

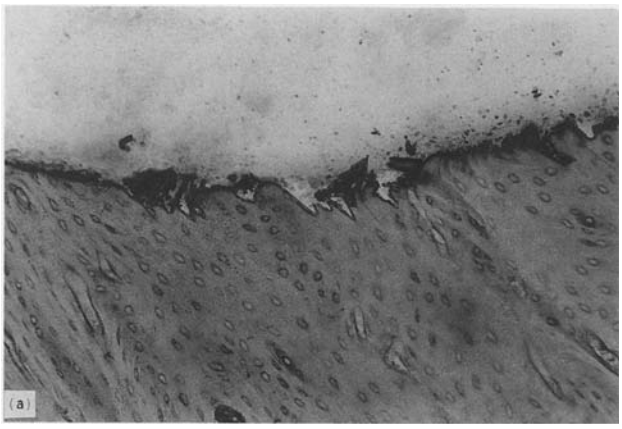

Figure 3 Photomicrographs of edge defects (Paragon stain, × 44). Cells are scarcely seen in these immediately killed rabbit specimens. Upper part is a drilled hole. The bony border shows part of the hole edge. (a) Fragmentation (an uneven edge by scraping off small bone fragments) and (b) microcracks (local cracks with depth < 50 μm).

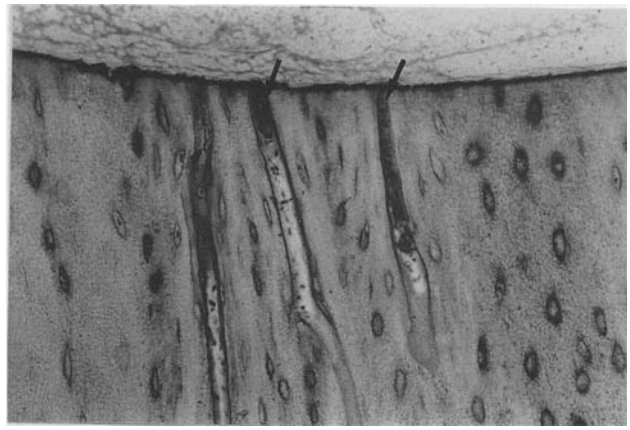

Figure 4 Photomicrograph of vascular obstructions (Paragon stain, × 88). Some vessels around the hole are obstructed by bone debris and clots. (arrows).

to provide a maximal dilatation of the vascular system, then 100 ml contrast medium [50 ml India ink (Pelikan) and 50 ml physiological saline] was injected. During injection blood was withdrawn from the inferior vena cava to equalize the input with output. After injection the limbs were amputated at the knee joint, then immersed in a fixative *en bloc* for 24 h to coagulate and stabilize the medium in the vascular tree. Further dissection was done after this period and fixation was continued. After dehydration the specimens were embedded in methylmethacrylate. Tibiae were cut transversely at the centre level of each hole (Fig. 2b) and ground sections of 500 μm were obtained.

2.3. Histomorphometry

An optical microscope connected with an image analyser (CUE-2, Olympus Co., Tokyo, Japan) was used to measure the lengths and areas in histological specimens.

The drilling quality was evaluated by the hole geometry, initial thermal damage and later bone-healing process. The first two of these parameters were investigated with immediate and 3 day specimens and the last parameter with 2 and 4 week specimens.

The hole geometry was evaluated by two parameters: edge defects and circularity. Defects at the hole edge were determined by measuring the circumferential length of fragmentation and microcracks. Fragmentation was defined as an uneven edge by scraping off small bone fragments, and microcracks were defined as local cracks with depth < 50 μm (Fig. 3a and b).

The circularity was evaluated by the error of circularity defined as

$$\text{Error of circularity} = \frac{\left[\sum_{i=1}^{n}(L - l_i)^2\right]^{\frac{1}{2}}}{nR} \times 100\%$$

where L is the average radius, l_i is the Martin's radius and R is the drill radius. The Martin's radii were calculated every 10° by the image analyser software, thus 36 was used for n to calculate this error.

The initial thermal damage was evaluated by the ischaemia and the number of vascular obstructions (Fig. 4). As India ink is distributed by the bloodstream to the sites of intact circularity, the ischaemia was investigated by measuring the bony length of the India ink-free area at the hole edge (Fig. 5).

The subsequent bone-healing process was evaluated by the circumferential length of bone resorption at the edge (carved hole edge, osteoclasts are sometimes observed) and direct bone apposition on the edge (new bone forms on the hole edge without being resorbed) at 2 weeks post-operatively. The newly formed bone area in the hole was measured at 2 and 4 weeks post-operatively.

Student's t-test was implemented throughout the statistical analysis.

3. Results

3.1. Hole geometry

The circumferencial lengths of fragmentation and microcracks were calculated as percentages of the drilled hole circumference. The remaining part of the hole edge was smoothly cut. The percentages of fragmentation and microcracks decreased in association with increasing speed of rotation, and were both

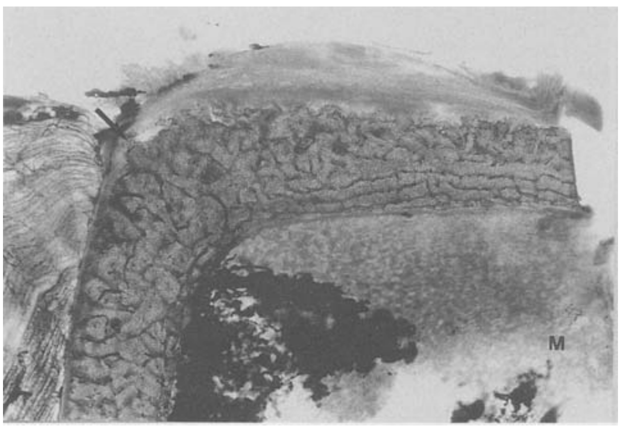

Figure 5 Photomicrograph of India ink-injected specimen (× 4.4). As tibia is cut transversely, right empty space is a drilled hole and the right bony end is the hole edge (M, medullary space). The vessels are filled with India ink except for the ischaemic area. The arrow indicates the margin of the ischaemic area.

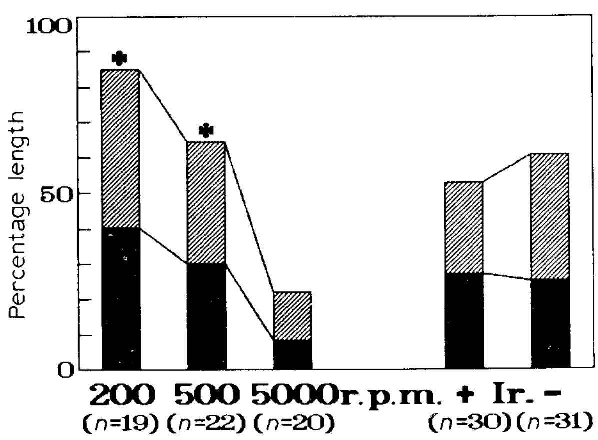

Figure 6 Percentage length of (■) fragmentation and (▨) microcracks. Ir.+, with irrigation and Ir. −, without irrigation. *$P < 0.01$ versus 5000 r.p.m.

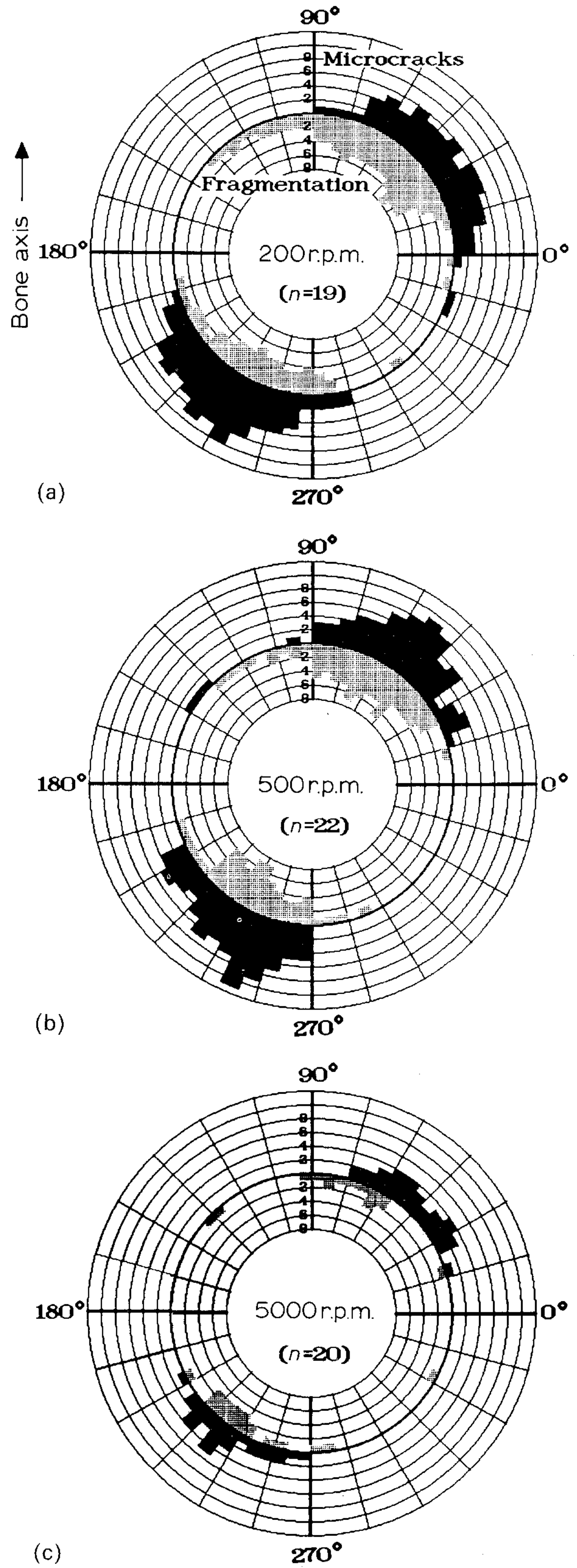

Figure 7 Angular location of fragmentation (inside) and microcracks (outside). The views are looking from the endosteal surface in a radial direction. The bone axis from proximal to distal corresponds to the downwards direction in the images. The histogram represents the number of specimens showing the defined feature in each location.

significantly lower at 5000 r.p.m. ($P < 0.01$; Fig. 6). However, there was no obvious effect with regard to the irrigation. The angular location of the damage is shown in Fig. 7a–c. These images show the holes viewed from endosteum to periosteum, and the frequencies were represented as a histogram every 5°. The frequencies were again lower at 5000 r.p.m., and the angular locations of both were almost the same among the three speeds of rotation, about 45° from the bone axis.

The errors of circularity of proximal and middle holes were not significantly different among all drilling conditions, whereas the error of the distal hole was significantly higher for 200 r.p.m. than for 5000 r.p.m. drilling ($P < 0.02$). The values were $4.1 \pm 1.1\%$ at 200 r.p.m. and $1.6 \pm 1.1\%$ at 5000 r.p.m.

3.2. Initial thermal damage

The length of India ink-free bone area was almost the same for 200 and 500 r.p.m., and it was significantly longer for 5000 r.p.m. ($P < 0.03$; Fig. 8). By using irrigation, this length was reduced by about one-half ($P < 0.03$).

Vessels about the hole were obstructed by bone debris or clots. The number of vascular obstructions was a little higher for 5000 r.p.m. without irrigation and significantly higher at 5000 r.p.m. with irrigation ($P < 0.02$; Fig. 9). However, this number decreased after 3 days.

3.3. Bone-healing process

As the edge defects and the initial thermal damage did not show a great difference between 200 and 500 r.p.m., further 2 and 4 week experiments were performed to compare two speeds of rotation (500 and 5000 r.p.m.) by drilling two holes in each tibia. The hole edge at 2 weeks exhibited three types of healing process: bone resorption only, bone apposition after resorption and direct bone apposition on the hole edge. The circumferential lengths of resorption and direct apposition were also calculated as percentages

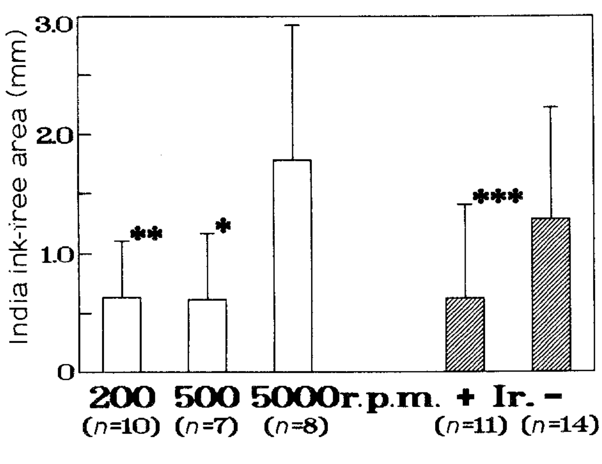

Figure 8 Bony length of India ink-free area. Values are expressed as means and standard deviation. $*P < 0.03$ and $**P < 0.01$ versus 5000 r.p.m. and $***P < 0.03$ versus drilling without irrigation.

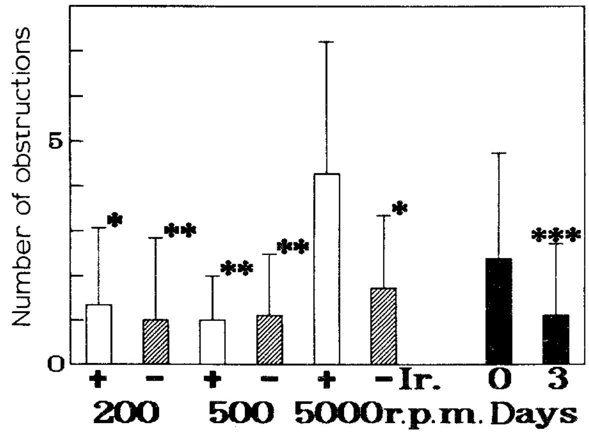

Figure 9 Number of vascular obstructions. Values are expressed as the mean and standard deviation. $*P < 0.02$ and $**P < 0.01$ versus 5000 r.p.m. with irrigation, and $***P < 0.02$ versus 0 day.

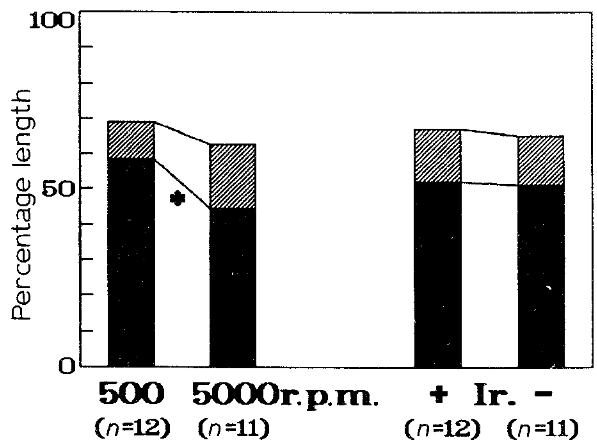

Figure 10 Percentage length of (▨) bone resorption and (■) direct bone apposition. The percentage length of apposition for 500 r.p.m. is significantly higher ($*P < 0.01$).

of the drilled hole circumference. At 5000 r.p.m. the percentage of bone resorption was higher, whereas the percentage of direct bone apposition was significantly lower ($P < 0.01$; Fig. 10). Irrigation did not display a significant effect. The angular locations of the bone resorption or apposition areas were quite different from those of fragmentation and microcracks (Fig. 11a and b). These distributions were spread all along the hole edge.

The area of newly formed bone was calculated as the percentage of the drilled hole area. The bone formation was significantly greater for 500 r.p.m. at both 2 weeks ($P < 0.05$) and 4 weeks ($P < 0.02$) post-operatively (Fig. 12). With irrigation, the percentage area increased slightly, but there was no significant difference.

4. Discussion

Fragmentation and microcracks could be distinguished histologically, but their frequencies and angular location showed the same tendency. It is therefore considered that they were caused by nearly the same

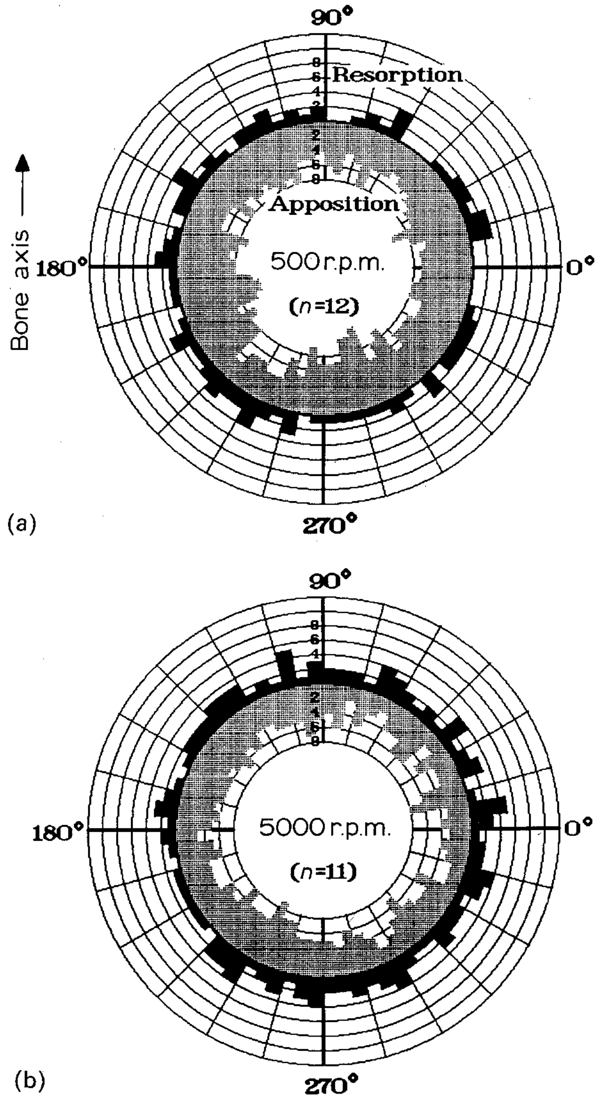

Figure 11 Angular location of bone resorption (outside) and direct bone apposition (inside). The images are shown in the same manner as Fig. 6.

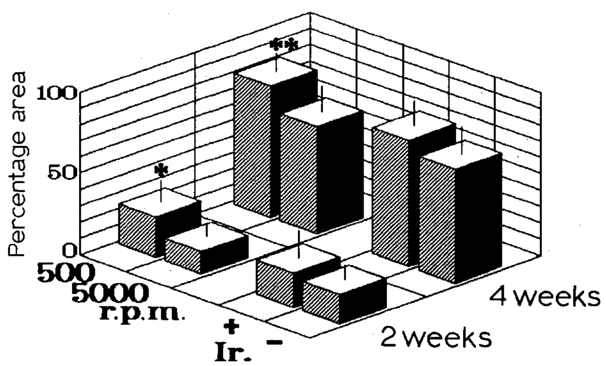

Figure 12 Percentage area of newly formed bone at 2 and 4 weeks post-operatively. Values are expressed as the mean and standard deviation. $*P < 0.05$ and $**P < 0.02$ versus 5000 r.p.m.

mechanisms. Their frequencies were higher in low-speed drilling as reported by Thompson [6]. Their locations are assumed to depend on the angle between the drill edge and fibre bundles of lamellar bone at the cutting site. As the bone has an anisotropic structure, the cutting angle always varies when a rotational cutting tool is used. Fragmentation and microcracks may be formed where the cutting angle is not adapted to the drill edge. The irrigation did not reveal a great effect with regard to the edge defects, so it is considered that irrigation fluid does not play a role as lubricant. It is assumed that the flow rate of 60 ml min^{-1} is insufficient for the irrigation fluid to act as lubricant.

The circularity was less perfect only at the distal hole created by 200 r.p.m. drilling. In this situation the drilling time was prolonged by both the low speed of rotation and the thick cortical bone. The cortical thickness of rabbit tibia was 0.73 ± 0.07 mm at the proximal level, 0.96 ± 0.10 mm in the middle level and 1.13 ± 0.09 mm at the distal level. The long drilling time was assumed to increase the risk of a non-circular drilled hole. Based on clean edge cutting and correct hole geometry, the best results were obtained by using a 5000 r.p.m. drilling speed.

Ischaemia is secondary to thermal damage and vascular obstructions. The India ink-free area corresponds to the ischaemic area, and its bony length was about three times longer at 5000 r.p.m. In spite of the relatively low flow rate, compared with the literature [7], the irrigation was effective in reducing the ischaemic area. It is assumed that this cooling effect was obtained through the central irrigation system that enables the cooling agent to reach directly to the cutting site from the onset to the end of the drilling procedure.

Vascular obstructions were most frequently observed for 5000 r.p.m. with irrigation. It is considered that 5000 r.p.m. drilling produces finer bone debris which is easily pushed into vessels, especially with the flow of irrigation. The 5000 r.p.m. drilling speed may also cause blood coagulation by heat production. However, some of these clots will probably be cleared off by blood pressure following surgery. Accordingly, the initial thermal damage was greater at 5000 r.p.m. and the degree of ischaemia was reduced by using irrigation.

Bone healing in the drilled hole was investigated in relation to the edge defects and the initial thermal damage. The angular locations of bone resorption and direct bone apposition at the edge were observed diffusely 2 weeks post-operatively with no apparent relation to the location of fragmentation and microcracks. Thus, the edge defects may be considered not to influence the bone-healing process.

The threshold level for thermal bone necrosis has been investigated by extensive histochemical studies on rabbits [15]. It has been reported that the threshold temperature for osteocyte necrosis was 50 °C and irreparable damage occurred at the temperature higher than 70 °C. Thompson [6] compared the temperature elevation and the histological changes. The temperature elevation during drilling was < 43.8 °C at 500 r.p.m. and > 65.5 °C at 1000 and 2000 r.p.m. Histologically, chemical alterations of the matrix of the necrotic bone around the hole were presented by a deeper blue staining with haematoxlin and eosin. The width of this border was wider above 1000 r p.m. Once bone necrosis occurs, necrotic bone is usually replaced by living tissue through a slow process of repair:

resorption and new bone formation [16]. In our experiment the extent of bone resorption was greater and the newly formed bone area was smaller at 5000 r.p.m. Thus 5000 r.p.m. drilling is considered to cause more thermal damage and retards the bone-healing process.

Irrigation did not affect the bone-healing process. It is assumed that the flow rate of 60 ml min^{-1} is still insufficient to protect bone from thermal damage. However, the use of a large amount of fluid will increase the possibility of vascular obstructions.

These results indicate that the speed of rotation and the use of irrigation affect the hole geometry, the initial thermal damage and the later bone healing process. Drilling at 500 r.p.m. while causing slight initial thermal damage, induced a greater bone formation. Thus, it is assumed that a rotation speed of about 500 r.p.m. may be recommendable for intra-osseous implantation of biomaterials. The central irrigation system was considered effective, as it was shown to reduce the ischaemic area.

Acknowledgements
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