HISTOMORPHOMETRIC ANALYSIS OF THE NORMAL ADULT PATELLA

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The patellae of 6 male and 2 female, 40 to 70 year-old individuals, who were healthy at the time of their violent death, were assessed by computer-assisted image analysis. The means of the bone density (percentage of bone in the respective field of interest) ranged from ~20% to ~30% in the central spongiotic zones, from ~40% to ~80% in the superior and inferior peripheral zones, and from ~40% to ~60% in the subchondral zone. Bone densities were greatest in the lateral parts of the subchondral and spongiotic territories. The bony trabeculae were haphazardly distributed in the central spongiotic zones. They were commonly oriented vertically or parallel to the surface of the patella in the peripheral and subchondral zones.

In conclusion, the histomorphometric data presented validate the rationale of reaming the articular aspect of the patella into a dome-shaped configuration with preservation of a circumferential bony bulwark in the preparation for the implantation of a thick polyethylene-based component with a concave undersurface.

Keywords : patella architecture ; histomorphometric analysis ; subchondral bone plate ; total knee arthroplasty.

Mots-clés : rotule ; architecture ; analyse histomorphométrique ; os sous-chondral ; arthroplastie du genou.

INTRODUCTION

Since the studies of Bartel *et al.* on total knee arthroplasties, it is well known that contact stresses are a function of the thickness of the polyethylene component and the conformity of the articulating surfaces (1, 20). The biomechanics of the patellofemoral joint are dictated by forces exercised by the muscles, ligaments and tendons as also the geometry of the patella and femoral trochlear groove (7, 8, 18). The "button" implant and frontal planar cutting of the patella were introduced in the early 1970s. Serving to fix thin implants, the planar cuts were shown to be biomechanically inappropriate (15).

The granulomatous reaction to wear particles is the most frequent cause for failure of artificial joints (2). Increasing the thickness of polyethylene components decreases the stresses within their substance, thus lessening surface damage and generation of wear debris. The thickness of the patellar polyethylene insert of artificial knee joints may be increased by implanting a component with a concave undersurface, conforming with a convex bony surface of the surgically prepared patella. An infrastructure reamed into a dome-shaped configuration enhances the strength of implant fixation as well as facilitates the preparation of a bone-implant complex whose thickness equals that of the patient's native patella (11, 12). The precise knowledge of the structure of the patella permits planning the sur-

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gical preparation such that as much as possible of the original biomechanical properties are preserved while allowing the implantation of an insert with a maximum polyethylene thickness. The present communication describes a computer-assisted image analysis which quantitatively portrays the structure of the patella of healthy individuals.

MATERIALS AND METHODS

Patellae were obtained at autopsies of 40- to 70-year-old individuals (six males and two females) who were healthy until their sudden death. Formalin-fixed samples were trimmed into wafers comprising the posterior (articular), anterior (subcutaneous), superior (quadriceps tendon insertion), inferior (patellar ligament insertion), lateral and medial aspects of the patella. The wafers were embedded in methylmethacrylate. After polymerization at room temperature, the polymethylmethacrylate blocks were sliced on a Buehler low-speed saw. Sections, cut at 4 microns on a Reichert-Jung Polycut microtome, were stained by von Kossa's method with McNeal's counterstain. An interactive computer-assisted image analysis system was used for the histomorphometric study. Images of the "fields of interest", displayed on an 17-inch RGB monitor and processed with the Wscannary image analyzer software operating on a 486 DX-IBM-compatible computer, were captured and digitized, using a color analog charged-coupled device video camera coupled to an internal frame grabbing board.

The "fields of interest" were the articular cartilage-capped posterior aspect (the subchondral zone), the spongiotic bone of the central territories (the central zone), and the superior and inferior aspects (the peripheral zones). For data collection, the bone at a distance of more than 1.1 µm from an imaginary line drawn parallel to the articular, superior and inferior perimeters of the patella was considered to pertain to the central zone. — These zonal boundaries were chosen because the bone structure shifts from spongiotic to cortex-like at a distance of 1.1 µm from the perimeters. The bone density was computed as the percentage of the bone "volume" in the total tissue "volume" (that is, the mineralized bone, osteoid, fibrous tissue, and fatty-hematopoietic marrow (19)).

For determination of orientation of the bony trabeculae, the latter were "sliced", on the monitor-displayed images, by placing marks at the sites where the trabeculae exhibited directional shifts or intersected with one another such that they appeared to constitute 2 distinct objects to the human analyzer ; curvilinear trabeculae were "sliced" at the point of their maximum bending (fig. 1). The program was instructed to record, at intervals of 5°, the direction of the trabeculae in relation to the imaginary lines. The subchondral bone, and the superior and inferior outer aspects were inferred to comprise trabeculae (albeit of a specific type), defined by their maximum Feret diameter. The trabeculae were culled into three groups differing from each other by 30° : Those oriented at 0° - 30° or 150° - 180° were referred to as "parallel to the imaginary lines", those oriented at 31° - 60° or 121° - 150° were referred to as "intermediate in position", and those oriented at 61° to 90° or 91° to 120° were referred to as "vertical to the imaginary lines". The area (in μm^2) and the orientation of each segment of the "sliced" trabeculae were determined in each of the three zones. About 500 to 600 trabeculae were assessed in each of the 8 patellae.

The descriptive statistics displayed the bone density values as the percent of bone present in any unit area of the 3 regions. The means and standard deviations of the measurements were computed. Expressing the statistical significance of multiple comparisons between the bone density values in the different regions of one patella as well as between the bone density values in the different regions of the 8 patellae, the inferential statistics were separately calculated. Multiple comparisons between the matched groups were performed by using Friedman's

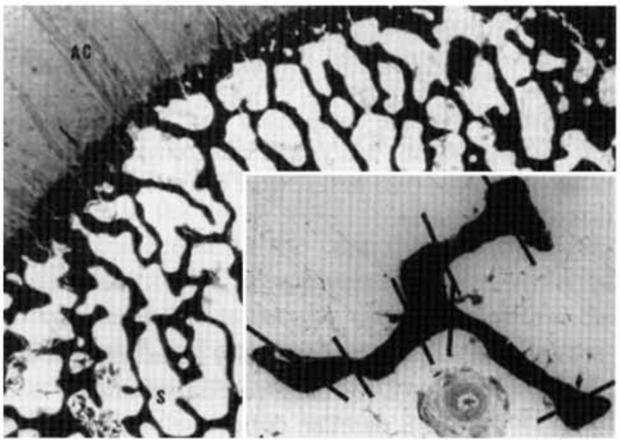

Fig. 1. — The posterior patellar aspect disclosing the articular cartilage (AC), subchondral bone zone (arrows), and the central zone (spongiotic bone, S). The insert exemplifies the step of mouse-mediated "slicing" of a monitor-displayed image of trabeculae at sites where they evidence overt directional shifts or intersect with the nearby trabeculae such that they appear to the human analyzer as distinct objects. Von Kossa's method with McNeal's counterstain, × 30 and × 320 (insert).

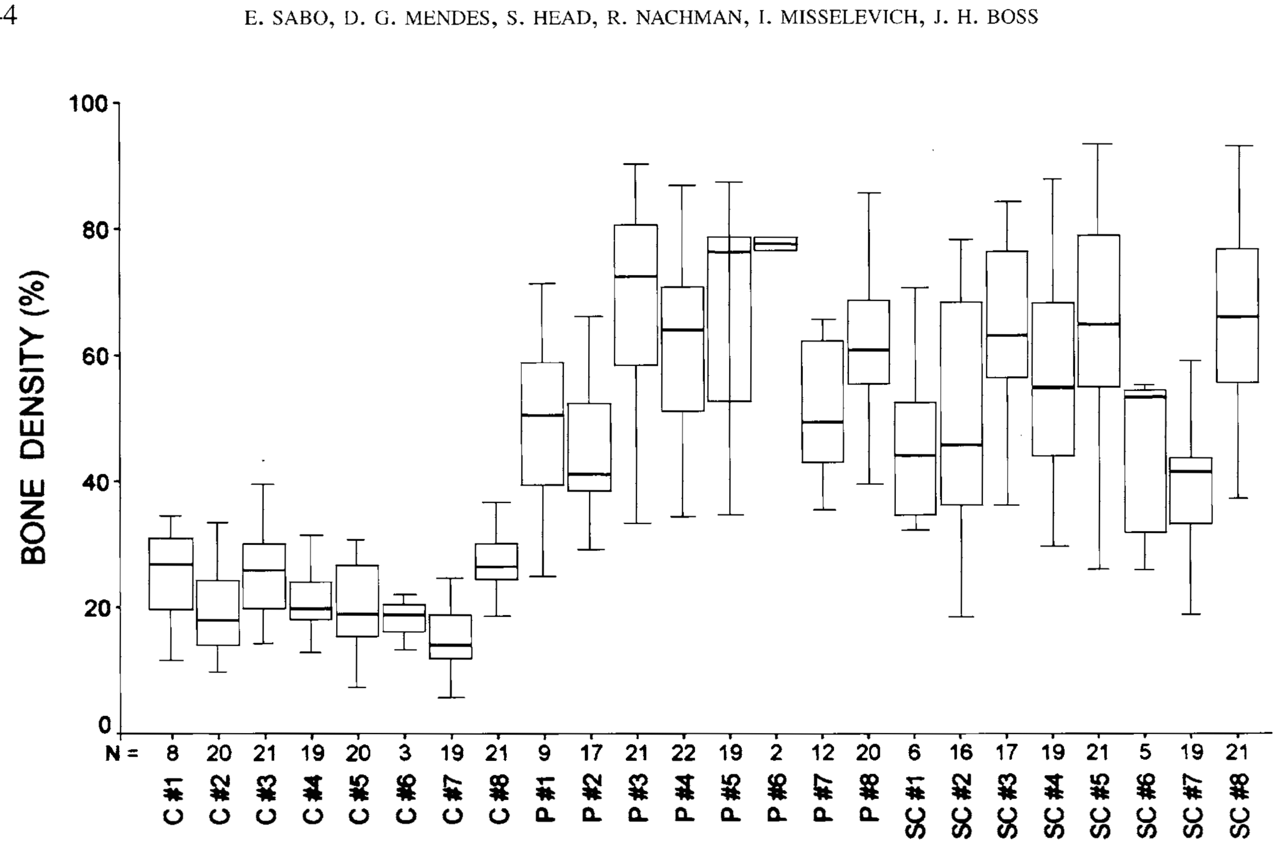

Fig. 2. — Box plots presenting the means of the bone densities in the central zone (spongiotic bone, C), the peripheral zone (superior and inferior aspects, P), and the subchondral zone (SC) of the 8 patellae. N = number of fields of interest gauged in each of the 24 locales evaluated in each of the eight patellae.

ANOVA model followed by the appropriately corrected post-hoc Wilcoxon's test for pairs. Multiple comparisons between unmatched groups were carried out by applying Kruskal-Wallis' ANOVA model followed by Bonferroni's multiple comparison test. The Chi-square test was used for the analysis of categorized data. Two-tailed p values of 0.05 or less were considered to be statistically significant.

RESULTS

The results of the bone density measurement are illustrated in fig. 2 for each patella separately and in fig. 3 for the 8 patellae collectively. The means of the bone density ranged from ~40% to ~70% in the subchondral zones, from less than 20% to almost 30% in the central zones, and from ~40% to ~80% in the peripheral zones. Statistically, the bone "volumes" in the peripheral and subchondral zones did not differ significantly from one another ($p = 0.124$). The bone "volumes" in the subchondral and peripheral zones were significantly larger than those in the central zone ($p < 0.0001$). The parameters of the superior and inferior patellar aspects were essentially identical with each other.

The measurements verified the light microscopic impression that the bone of the subchondral and peripheral zones took on compact-like features (figs. 1 and 4). This characteristic resulted from the span of the trabeculae, their proximity to one another, and their osteonic structure with Haversian systems. The thin trabeculae in the central zone consisted of lamellar-fibred bone. Vessel-bearing fibrous tissue, a few microns across, extended from the marrow into the subchondral and peripheral bone, terminating close to the joint cartilage and entheses, respectively. The thickness of the subchondral bone increased from the middle to lateral sections of the articular aspect. The trabeculae close to the subchondral zone were arrayed nearer

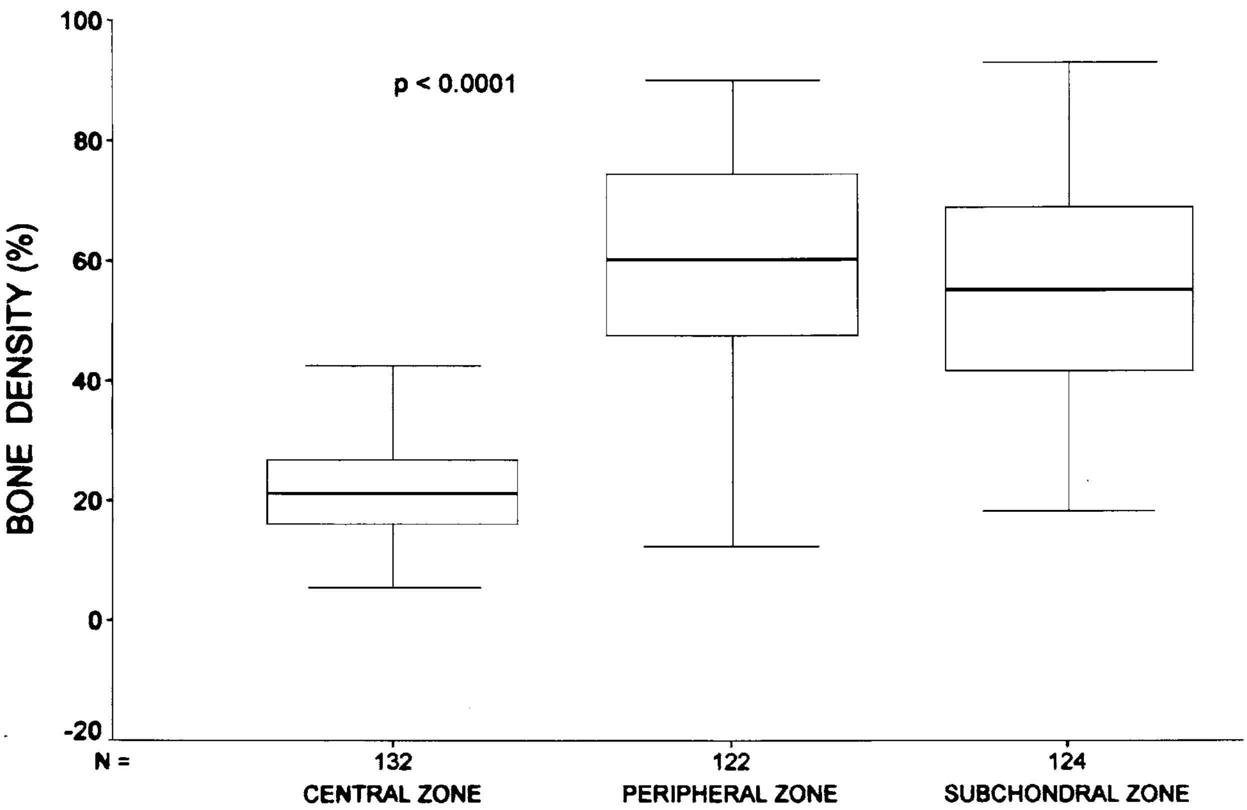

Fig. 3. — Box plots presenting the averaged means of the bone densities of all the eight patellae in the three assessed zones. The differences between the averaged means of the bone density of the central zone, on the one hand, and the peripheral and subchondral zones, on the other hand, are statistically significant. N = number of fields of interest gauged in each of the 8 patellae, C = central zone (spongiotic bone), P = peripheral zone (superior and inferior aspects), and SC = subchondral zone.

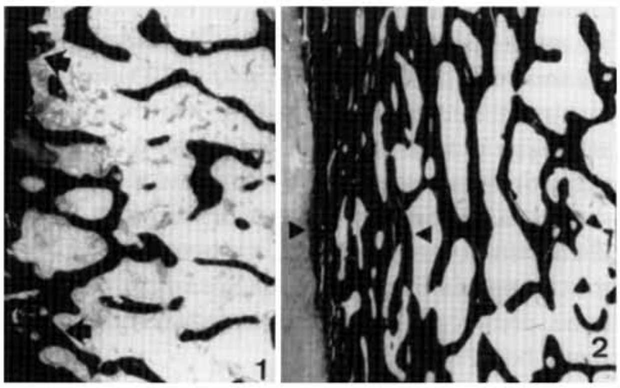

Fig. 4. — The anterior (1 - subcutaneous) and inferior (2 - insertion of the patellar ligament) aspects of the patella. The thin but compact-like anterior aspect more closely resembles cortical bone than the other perimeters of the patella. The bone of the inferior aspect displays closely adjoining and richly linking trabeculae (in between the triangles), which are principally oriented parallel to the surface, and, thus, resembles the subchondral bone zone. Von Kossa's method with McNeal's counterstain, × 30.

to each other in the lateral than in the middle sections. The means of the spongiotic bone density were as low as ~10% in the middle sections and as high as ~60% in the lateral sections. The lateral and medial bony layers were delicate, being ~100 to ~300 µm in thickness.

The trabeculae in the central zones were randomly distributed. In contrast, there were preferred directions in the trabecular orientation within the subchondral and peripheral zones. Trabeculae oriented in an intermediate direction constituted 34%, 29% and 27% in the central, subchondral and peripheral zones, respectively. Vertically oriented trabeculae made up 34%, 44% and 33% in the subchondral, peripheral and central zones, respectively. Parallel oriented trabeculae formed 36%, 30% and 33% in the subchondral, peripheral and central zones, respectively. The differences between the trabecular orientation in the central zone, on the

Table I. — Statistical comparisons of the number of the osseous trabeculae oriented parallel to the imaginary line (A), at intermediate directions (B), and vertical to the imaginary line (C) in the central zone versus the peripheral zone

	Central Zone	Peripheral Zone	p Value
A B + C	494 1011	433 1023	0.08
B A + C	507 998	386 1070	0.0002
C A + B	504 1001	635 821	< 0.0001

Table II. — Statistical comparisons of the number of the osseous trabeculae oriented parallel to the imaginary line (A), at intermediate directions (B), and vertical to the imaginary line (C) in the central zone versus the subchondral zone

	Central Zone	Subchondral Zone	p Value
A B + C	494 1011	460 809	0.058
B A + C	507 998	365 904	0.005
C A + B	504 1001	444 825	0.4

Table III. — Statistical comparisons of the number of the osseous trabeculae oriented parallel to the imaginary line (A), at intermediate directions (B), and vertical to the imaginary line (C) in the subchondral zone versus the peripheral zone.

	Subchondral Zone	Peripheral Zone	p Value
A B + C	460 809	433 1023	0.0004
B A + C	365 904	386 1070	0.18
C A + B	444 825	635 821	< 0.0001

one hand, and in the subchondral or peripheral zones, on the other hand, were statistically significant (tables I to III).

The areas and orientations of the "sliced" trabeculae correlated with each other in the subchondral and peripheral zones but not in the central zone. Bulky trabeculae, ranging from ~100 000 to ~300 000 µm^2, occurred within the confines of the subchondral and peripheral zones. These trabeculae were preferentially oriented at ~40° ± 20° to the imaginary line, thus basically tracing the cardinal directions. The small trabeculae primarily occupied the outlying positions in the subchondral and peripheral zones. The mainly small trabeculae — few having an area over ~120 000 µm^2 — in the central zone were distributed haphazardly.

The richly joined trabeculae of the anterior aspect were close to each other and oriented more or less parallel to the surface (fig. 4). The anterior aspect took on a most nearly compacta-type appearance, including an osteonal architecture matching that of cortical bone at other skeletal sites.

DISCUSSION

The thick subchondral bone plate and the thin layer of the calcified cartilage are indistinguishable from each other on studying von Kossa-stained sections of undecalcified samples of joint surfaces. Playing an equally crucial role in attenuating the axial impact forces during dynamic joint loading, both layers make up a morphological and mechanical unit (13), They are referred to as the "subchondral bone zone". Employing 500 µm-thick, van Gieson-stained sections, Eckstein *et al.* calculated the mean thickness of the subchondral bone zone to measure 620 ± 120 µm and 440 ± 70 µm and its maximum thickness to be 1530 ± 380 µm and 1070 ± 260 µm in specimens obtained at autopsy of men and women, respectively (3). In view of the microscopic characteristics, we view a span of 1100 µm to constitute, on the average, the boundary between the compacta-like and spongiosa-like patterned bone, demarcating the subchondral from the spongiotic bone.

Our computer-assisted image analysis evidences a low bone density of ~20% to ~30% in the central spongiotic zone of the patella. This contrasts with the high bone density, ~40% to ~60%, in the subchondral bone zone. In the context of categorization of bone as cortical (less than 20% porosity) versus trabecular (50% to 90% porosity), the patella is devoid of a cortex in the strict sense (14).

Alternating pressure from different directions patterns the structure of spongiotic bones. Morphogenetically decisive stresses lead to modeling-induced orientation of the trabeculae in the direction of oblique marginal forces. The spongiosa, therefore, assumes a fan-shaped structure (9). An alignment in relation to the principal stresses is optimal when the trabeculae are oriented parallel or perpendicular to compressive loads and at 45° to shear loads (6). Patellar cartilage injuries do not invariably proceed to remodeling at the bone-cartilage interface (5). The degenerated cartilage mediated long-term stress leads to an ample subchondral bone at the patellar lateral facet (4, 20). Excessive bone formation occurs at the site of the insertion of the patellar ligament in patients with degenerative joint disease (17).

The subchondral bone zone increases in thickness from the middle to the lateral regions of the patella. These pillar-like structures form the superior and inferior sidings. Their bone density is high, ranging from a mean of ~40% to ~80%. Many trabeculae in the subchondral bone zone are oriented more or less parallel or vertical to the joint surface. With respect to preparation of the patella for implantation of our novel implant, the findings imply that a rather high-density bone, abounding in trabeculae vertically oriented, remains in situ after reaming the articular aspect into a dome-shaped configuration. The bone in these segments of osteoarthritic patellae is not rarefied. If in fact the remodeled bone is biomechanically sufficient in patients with knee osteoarthritis, reaming of the patella into a dome-shaped form, preserving the superior and inferior sidings, conserves the functionally consequential buttressing constituents essential for the successful long-term performance of our novel patellar implant (11).

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SAMENVATTING

E. SABO, D. G. MENDES, S. HEAD, R. NACHMAN, I. MISSELEVICH, J. H. BOSS. Histomorfometrische analyse van de normale knieschijf bij de volwassene.

De auteurs bestudeerden de knieschijven van 6 mannen en 2 vrouwen, 35 tot 65 jaar oud, die een gewelddadige dood stierven, terwijl ze in goede gezondheid verkeerden. Dit met behulp van computergestuurde beeldanalyse. De gemiddelde botdichtheid (percentage bot in de bestudeerde microscopische velden) bedroeg 20 tot 30% in de centrale spongieuze zones, 40 tot 80% in de proximale en distale perifere zones, en 40 tot 60% in de subchondrale zone. De botdichtheid was het grootst in de laterale delen van de spongieuze en de subchondrale zones. De oriëntatie van de bottrabekels was wisselvallig in de centrale spongieuze zones ; ze was over het algemeen loodrecht op ofwel evenwijdig met het gewrichtsoppervlak in de perifere zones en in de subchondrale zones. Deze histomorfometrische studie steunt dus de visie dat het is aangewezen het gewrichtsoppervlak van de patella koepelvormig, dus convex naar dorsaal, uit te frezen, met behoud van een perifere benige muur. Dit met het oog op het inplanten van een dikke polyethyleenprothese met concave onderkant of vóórzijde..

RÉSUMÉ

E. SABO, D. G. MENDES, S. HEAD, R. NACHMAN, I. MISSELEVICH, J. H. BOSS. Analyse histomorphométrique de la rotule normale chez l'adulte.

Les auteurs ont étudié au moyen d'une méthode d'analyse d'images assistée par ordinateur les rotules de 6 sujets masculins et 2 féminins, âgés de 35 à 65 ans, décédés de mort violente et en bonne santé jusqu'à ce moment. La densité osseuse moyenne (pourcentage d'os dans les champs étudiés) était de 20% à 30% dans les zones spongieuses centrales, de 40% à 80% dans les zones périphériques supérieure et inférieure et de 40% à 60% dans la zone sous-chondrale. Les densités osseuses étaient les plus élevées dans les parties latérales des territoires sous-chondraux et spongieux. Les trabécules osseuses étaient orientées de façon aléatoire dans les parties centrales spongieuses. Dans les zones périphériques et sous-chondrales, elles étaient dans l'ensemble orientées verticalement ou parallèlement à la surface de la rotule.
En conclusion, les données de cette analyse histomorphométrique viennent conforter l'idée de fraiser la surface articulaire de la rotule pour lui donner une configuration en dôme en préservant un mur osseux périphérique pour permettre d'y implanter un composant rotulien en polyéthylène épais et à surface inférieure concave.