Surgical and Radiologic Anatomy

Surgical and Radiologic Anatomy

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Journal of Clinical Anatomy

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Table of contents

Volume 15 Number 4, 1993

(Contd. next page)

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Surgical and
Radiologic
Anatomy

Founded as Anatomia Clinica
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Journal of Clinical Anatomy

Table of contents

Volume 15 Number 4, 1993 (continued)

Indexed in Current Contents and Index Medicus (MEDLINE data base)

Springer International

Surg Radiol Anat (1993) 15 : I-VII

Surgical and Radiologic Anatomy
Journal of Clinical Anatomy

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La liste des membres du CMFPA sera désormais publiée tout les deux ans, avec la liste des membres de l'AEAC. La prochaine mise-à-jour aura lieu en 1994.

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Original articles

Cartilage degeneration in the human patellae and its relationship to the mineralisation of the underlying bone: a key to the understanding of chondromalacia patellae and femoropatellar arthrosis?

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Summary. According to the literature subchondral bone plays a significant role in the transmission of load through joints and in the pathogenesis of osteoarthrosis. Therefore the degeneration of the articular cartilage was investigated in the patellae from 30 dissecting-room specimens and of 20 patients, previously submitted to arthroscopy, and subchondral mineralisation of their underlying bone was at the same time assessed by means of CT osteoabsorptiometry. Lateral cartilage lesions were localised over highly mineralised subchondral bone; these appear to be due to long-term stress. They were mainly found in the older specimens and showed a high rate of progression with increasing age. Medially localised cartilage lesions, on the other hand, were situated in a transitional region between moderate and slight subchondral mineralisation; they may be caused by infrequent stress peaks and by shear stress in the articular cartilage, the very medial part of the joint being deprived of mechanical stimulation for much of the time. These lesions were to be found predominantly in the younger specimens and showed little progress with advancing age. Patients with lateral cartilage degeneration exhibited higher, patients with medial chondromalacia patellae lower mineralisation than normals. Their density patterns therefore indicate a different mechanical pathogenesis of the cartilage lesions in the lateral and medial facet. It could be shown that CT osteoabsorptiometry allows an assessment of the mechanical situation, present in individual femoro-patellar joints, and that this situation is highly relevant for the pathogenesis of patellar cartilage degeneration.

Etude de la relation entre la dégénérescence cartilagineuse et la minéralisation de l'os sous-chondral de la patella. Est-ce une façon pour comprendre la pathogénie de la chondromalacie patellaire et de l'arthrose fémoro-patellaire ?

Résumé. Selon la littérature, l'os sous-chondral joue un rôle important dans la transmission des forces à travers les articulations et dans la pathogénie de l'arthrose. C'est pourquoi la dégénérescence du cartilage articulaire a été étudiée sur les patellas de 30 sujets anatomiques et de 20 patients venant de subir une arthroscopie et dont la minéralisation sous-chondrale de l'os sous-jacent avait été appréciée au même moment par absorptiométrie osseuse par scanner. Les lésions cartilagineuses latérales étaient situées sur de l'os sous-chondral fortement minéralisé ; elles paraissent êtres dues à des contraintes à long terme. Elles furent principalement trouvées sur les spécimens âgés et montraient un fort taux de progression en fonction du vieillisement. A l'opposé, les lésions cartilagineuses médiales étaient situées dans une région de transition entre des minéralisations modérée et faible ; elles pourraient être dues à des pics de contrainte intermittents et à des contraintes en cisaillement sur le cartilage articulaire, la partie la plus médiale de l'articulation étant privée de stimulations mécaniques la plupart du temps. Ces lésions furent trouvées essentiellement sur les sujets les plus jeunes et montraient peu de progression avec le vieillissement. Les patients présentant une dégénérescen-

Correspondence to : F Eckstein

ce cartilagineuse latérale avaient une minéralisation supérieure à la normale, les patients présentant une chondromalacie médiale avaient une minéralisation plus faible que la normale. La distribution de la densité indique donc un mécanisme pathogénique différent pour les lésions cartilagineuses sur les facettes latérale et médiale. L'absorptiométrie osseuse par scanner permettrait donc d'apprécier la situation mécanique individuelle de chaque articulation fémoropatellaire. Cette situation est fortement corrélée à la pathogénie de la dégénérescence du cartilage patellaire.

Key words: Patella — Cartilage degeneration — Subchondral mineralisation — Chondromalacia patellae — Femoropatellar arthrosis

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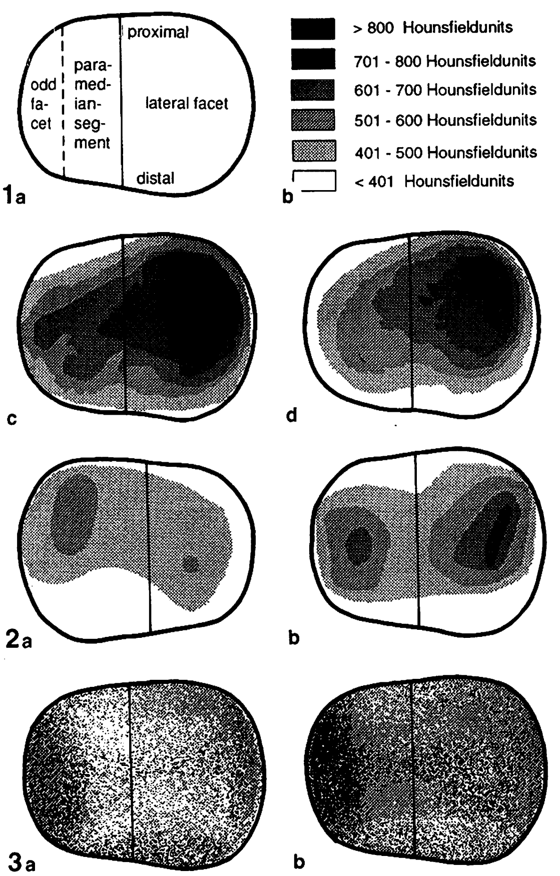
It is widely accepted that mechanical factors play an important part in the initiation and progression of osteoarthrosis in general and chondromalacia of the patella in particular [11, 25]. Nevertheless, the exact nature of the mechanism leading to joint damage, and the exact localisation of the initial changes in cartilage degeneration are still a matter of discussion and disagreement [17]. Radin and Paul [26] and Radin et al [28] were able to show that the ability of a joint to attenuate "longitudinal impact loading", which is an important factor in the pathogenesis of osteoarthrosis [27], is principally determined by the stiffness of the subchondral bone. As against this, the articular cartilage is supposed to contribute to reducing friction during movements of the joint. These authors even suggest that it is a change in the nature of the subchondral bone, i.e. an increase in its stiffness, which represents the first step in the development of osteoarthrosis [29]. Up to now it has not been possible to assess such changes in the living satisfactorily. Subchondral sclerosis, although accepted as a criterion for the radiological diagnosis of osteoarthrosis, does not permit quantitative evaluation of the relative distribution of subchondral mineralisation in the joint surface to be made. However, computed tomography osteoabsorptiometry (CT-OAM) [18, 19] has recently provided a method for assessing the surface distribution of subchondral mineralisation in the living subject in terms of the Hounsfield scale. We were able to establish in a previous investigation [5] that the pattern of mineralisation in the patella does in fact reflect the biomechanical situation present in the femoropatellar-joint. According to Hvid et al [12], the mechanical properties (and particularly the stiffness) of the subchondral bone can, with certain reservations, be inferred from this mineralisation pattern. The aim of this investigation is therefore to compare the localisation of macroscopically visible cartilage degeneration with the radiological (CT osteoabsorptiometric) density of the underlying bone in the human patella, which according to Ficat and co-workers [7, 8] offers an "observatoire ideal" of arthrotic degeneration.

Material and methods

We first examined 30 formalin-fixed specimens of the knee-joint taken from dissecting-room subjects, selecting the youngest subjects available. Those with systemic disease of the locomotor apparatus or severe arthrosis of the knee-joint were excluded from the investigation. The ages of the 7 female and 23 male subjects ranged from 47 to 90 years. We divided these into two groups: 15 specimens of less than 60 years (mean age 53) constituted Group Y, and 15 of more than 60 years (mean age 74) Group O. Twenty patients were then selected from the Department of Surgery, on whom arthroscopy had been carried out for various reasons (mostly because of suspected damage to the meniscus). In each case, a CT osteoabsorptiometric examination was made within 48 h of arthroscopy. The criterion for inclusion was the presence of circumscribed damage of grades 1 or 2 [21] to the articular cartilage of the medial or lateral facet, or of the primary ridge. There were no gross changes in the AP, or lateral radiographs, nor any severe disease of the femoropatellar-joint. Nine women and eleven men between the ages of 16 and 61 were examined, the average age being 31 years.

Investigation of the subchondral mineralisation

The knee-joint specimens and the knees of the arthroscopy patients (30° of knee-flexion) were examined in a CT scanner (Siemens Delta scan 50 FS 2). Sectional images between the upper pole of the patella and the tibial plateau were made at intervals of 4 mm. CT osteoabsorptiometry [18, 19] was used to obtain isodensities (i.e., contour lines joining points of equal density). The projection of their subchondral extension was marked on the surface of each section, and these marks transferred into the corresponding position of the section in a template of the articular surface (Fig. la). Six Hounsfield ranges (<400 HU - >800 HU) were reconstructed for the specimens, and seven (<300 HU - >1050) for the patients. The distribution pattern was then digitalised (Hewlett Packard, Scan Jet Plus) and read into an Apple Macintosh Computer, where it was provided with standardised grey values (Fig. 1b), using a grey scale of 256 steps. Image summation was finally carried out in the computer in order to produce average pictures. By means of program software, the original pictures were laid together successively in pairs, one upon the



Figs. 1a-d, 2a, b, 3a, b
1a Outline template of the articular surface of the patella built up from measurements of 30 specimens. **b** Grey values of the Hounsfield ranges examined in the specimens. **c** Summation picture for Group Y (age < 60 yrs, n=15). **d** Summation picture for Group O (age > 60 yrs, n=15). **2** Surface distribution of subchondral mineralisation in the patella of a patient suffering from left-sided poliomyelitis. **a** Left patella. **b** Right patella. **3** Surface distribution of cartilage degeneration in the patellae of 30 anatomical specimens. *white*, intact cartilage; *grey*, mild degeneration (degree 1); *black*, severe cartilage damage (degree > 1). **a** Summation picture for Group Y (age < 60 yrs, n = 15). **b** Summation picture for Group O (age > 60 yrs, n = 15)

1a Tracé du contour de la surface articulaire de la patella, bâti à partir des mesures de 30 spécimens. **b** Echelle des gris des niveaux de densité Hounsfield trouvés sur les spécimens. **c** Shéma récapitulatif pour le Groupe Y (âge < 60 ans, 15 cas). **d** Shéma récapitulatif pour le groupe O (âge > 60 ans, 15 cas). **2** Distribution de la minéralisation sous-chondrale sur les patellas d'un patient atteint de poliomyélite latéralisée à gauche. **a** Patella gauche. **b** Patella droite. **3** Distribution de la dégénérescence cartilagineuse sur les patellas de 30 spécimens anatomiques. *Blanc*, cartilage intact; *gris*, dégénérescence légère (degré 1); *noir*, dégâts cartilagineux sévères (degrés > 1). **a** Shéma récapitulatif pour le groupe Y (âge < 60 ans, 15 cas). **b** Shéma récapitulatif pour le groupe O (âge > 60 ans, 15 cas)

other, and the grey values of corresponding pixels were fused to a value lying exactly between them in the grey scale. Intermediate grey values obtained from the single summation steps were redefined in a final step as the closest neighbouring grey value in order to restore the original isodensities.

Examination of the cartilage degeneration

The grade [21] and extent of the cartilage degeneration in the patellae of the 30 specimens were pictorially recorded, using the joint template mentioned above. The distribution pattern was digitalised, and distinguishing grey values allotted to the different degrees of degeneration. In this case, the computergraphic method for producing the summation pictures depended upon a program which at each step picked up 50% of the pixels from each of two originals. In the summation pictures obtained in this way, the grey value of the pixels reveals, as in the single pictures, the degree of cartilage degeneration, and their density the frequency of the cartilage damage in the corresponding area of the joint. The grade and localisation of the cartilage degeneration in the patients was recorded on an arthroscopy form.

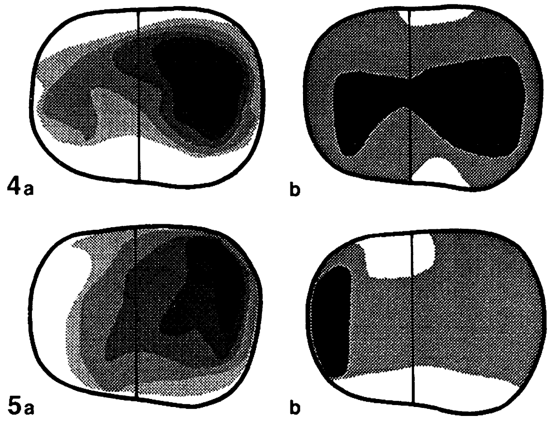
Comparison of the subchondral mineralisation with the cartilage degeneration

After comparison of the distribution patterns in the single pictures, the grades of cartilage degeneration and the locally corresponding Hounsfield range were read from 38 measuring points regularly distributed over the articular surface. The percentage distributions of grades of cartilage degeneration in the Hounsfield ranges were calculated for all the specimens added together, and the level of significance of the differences between the density ranges statistically tested. The percentage distribution of the grade of cartilage degeneration in the different Hounsfield ranges was also determined separately for Groups Y and O. Differences in the percentage of severe cartilage damage present in the Hounsfield ranges of the two groups were tested for statistical significance.

Results

Subchondral mineralisation

Maximum subchondral mineralisation was found in the proximal part of the lateral facet in all the patellae examined. This amounted in the anatomical specimens to 600-1000 HU, and in the patients to 450-1100 HU, and decreased more or less steeply towards the periphery. Whereas there was little difference in the principal distribution of the mineralisation (high density, lateral; low density, medial) in Groups Y (Fig. 1c) and O (Fig. 1d), the younger individuals displayed a slightly greater mineralisation of the subchondral bone (shown by the somewhat wider extension at all density levels). In one 33 year-old patient, who had suffered from poliomyelitis from the age of four years, and in whom there was marked muscle wasting of the whole left lower limb, the right patella (Fig. 2) was more highly mineralised than the left by 300 HU.



Figs. 4a, b, 5a, b
4 Single example of lateral cartilage damage over highly mineralised subchondral bone. **a** Surface distribution of subchondral mineralisation. **b** Surface distribution of cartilage degeneration. *white*, intact cartilage; *grey*, mild degeneration (degree 1); *black*, severe cartilage damage (degree > 1). **5** Single example of medial cartilage damage over poorly mineralised subchondral bone. **a**. Surface distribution of subchondral mineralisation. **b** Surface distribution of cartilage degeneration *white*, intact cartilage; *grey*, mild degeneration (degree 1); *black*, severe cartilage damage (degree > l)

4 Exemple de dégâts cartilagineux latéraux sur de l'os sous-chondral fortement minéralisé. **a** Distribution de la minéralisation sous-chondrale. **b** Distribution des lésions cartilagineuses dégénératives. *Blanc*, cartilage intact; *gris*, dégénérescence légère (degré 1); *noir*, dégâts cartilagineux sévères (degrés > 1). **5** Exemple de dégâts cartilagineux médiaux sur de l'os sous-chondral faiblement minéralisé. **a** Distribution de la minéralisation sous-chondrale. **b** Distribution des lésions cartilagineuses dégénératives. *Blanc*, cartilage intact; *gris*, dégénérescence légère (degré 1); *noir*, dégâts cartilagineux sévères (degrés > 1)

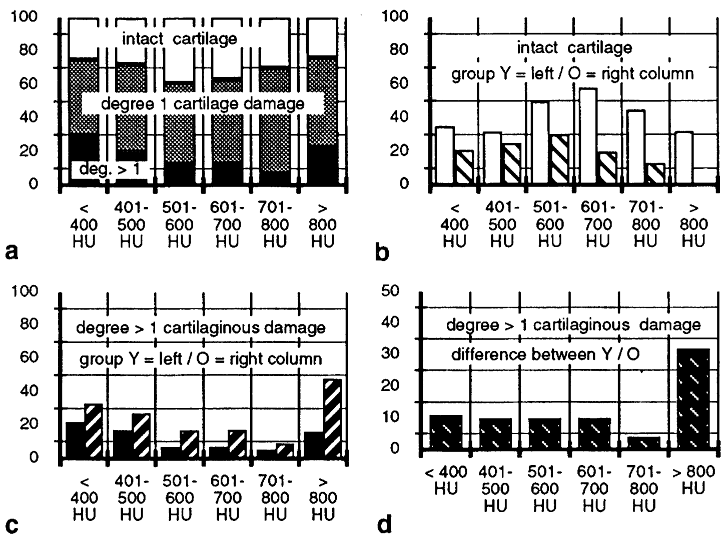


Fig. 6a-d
a Percentage distribution (% total articular surface) of intact cartilage, mild damage (degree l) and severe damage (degree > l) in the Hounsfield ranges (< 400 HU - > 800 HU) from all 30 anatomical specimens. **b** Percentage distribution of intact cartilage in Group Y (age < 60 yrs/L cols) and Group O (age > 60 yrs / R cols) in the different Hounsfield ranges. **c** Percentage distribution of severe cartilage degeneration (degree > l) in Group Y (L cols) and Group O (R cols) in the different Hounsfield ranges. **d** Difference in the percentage of severe cartilage degeneration (degree > l) between Groups Y and O in the different Hounsfield ranges

a Distribution en pourcentage (rapporté à la surface articulaire totale) du cartilage intact, des lésions légères (degré 1) et des dégâts sévères (degrés > 1) dans les niveaux de densité Hounsfield (< 400 HU - > 800 HU) de 30 spécimens anatomiques. **b** Distribution en pourcentage du cartilage intact dans le groupe Y (âge < 60 ans, colonnes de gauche) et du groupe O (âge > 60 ans, colonnes de droite) dans les différents niveaux de densité Hounsfield. **c** Distribution en pourcentage des lésions cartilagineuses sévères (degrés > 1) dans le groupe Y (colonnes de gauche) et dans le groupe O (colonnes de droite) dans les différents niveaux de densité Hounsfield. **d** Différence dans les pourcentages des dégénérescences cartilagineuses sévères (degrés supérieurs à 1) entre les groupes Y et O dans les différents niveaux de densité Hounsfield

Cartilage degeneration

Although the pattern of subchondral mineralisation is relatively constant, the localisation of the cartilage degeneration, both in individuals and on comparison between the age groups, is rather variable. In the younger group, degeneration predominates medially and peripherally in the joint (Fig. 3a), whereas central lesions of the lateral facet and near the principal ridge become more noticeable with advancing age (Fig. 3b).

Comparison of subchondral mineralisation with cartilage degeneration

It can be shown in individual cases that degeneration of the lateral facet (Fig. 4b) is localised over areas of greater subchondral mineralisation (Fig. 4a), whereas lesions in the medial compartment (Fig. 5b) are found together with a lower density (Fig. 5a). If one examines the distribution of the grades of cartilage degeneration throughout different Hounsfield ranges (Fig. 6a), it is obvious that the articular cartilage is less often intact, and more often severely damaged, over regions of both very high and very low density than in association with bone showing an average amount of subchondral mineralisation ($p < 0.01$). If the distributions for Groups Y and O are examined separately, differences in the amount of intact (Fig. 6b) and severely damaged cartilage present (Fig. 6c) can be observed. The difference in the percentage of severe cartilage degeneration (> grade 1) between the two age groups is less at a level below 800 HU (average difference = 9% of the surface area) than above this figure (difference between Groups Y and O = 29%). This difference is significant at a level of 1%. In the group of arthroscopy patients without cartilage degeneration the summation picture for subchondral mineralisation displays a considerable island peak of bone den-

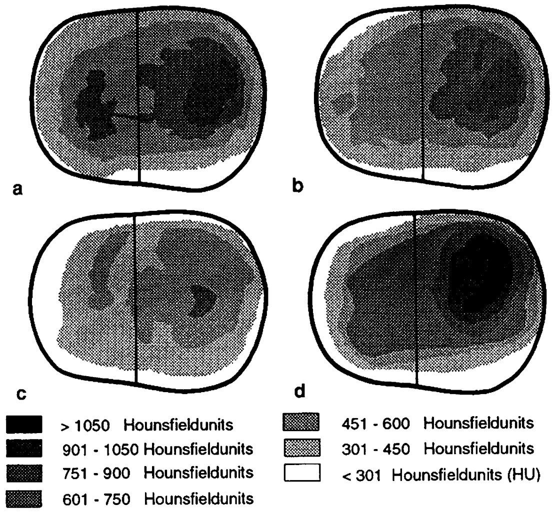


Fig. 7a-d
Surface distribution of subchondral mineralisation in the patellae of patients examined arthroscopically. **a** Summation picture for group without cartilage degeneration (n = 6). **b** Summation picture for group with central cartilage degeneration (n = 8). **c** Single example of patient with medial cartilage degeneration. **d** Single example of patient with lateral cartilage degeneration

Distribution de la minéralisation sous-chondrale des patellas des patients examinés par arthroscopie. **a** Shéma récapitulatif pour le groupe sans lésion cartilagineuse (6 cas). **b** Shéma récapitulatif pour le groupe présentant des lésions cartilagineuses centrales (8 cas). **c** Exemple d'un patient avec une dégénérescence cartilagineuse médiale. **d** Exemple d'un patient avec une lésion cartilagineuse latérale

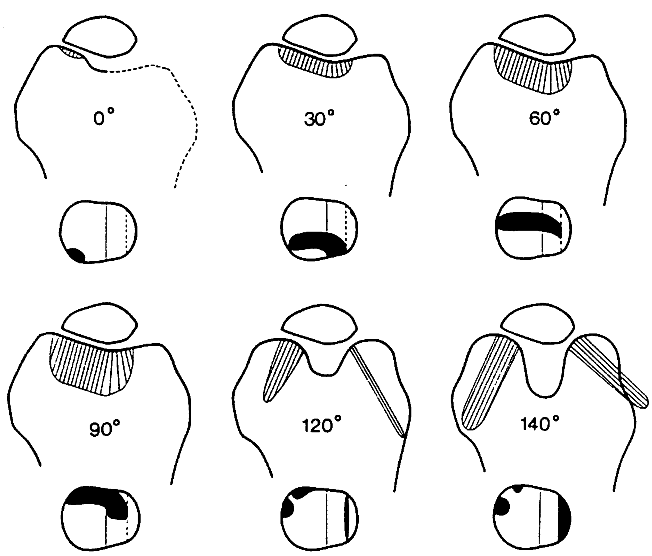


Fig. 8
Distribution of stress in the femoropatellar-joint based on the contact areas determined by Hehne (1983) and the joint forces calculated by Maquet (1976)

Distribution des contraintes sur l'articulation fémoro-patellaire, basée sur les aires de contact déterminées par Hehne (1983) et les forces articulaires calculées par Maquet (1976)

sity at the secondary ridge (Fig. 7a). This is not seen in patients with central damage to the tissue (Fig. 7b). The single example of a patient with medial degeneration reveals significantly reduced mineralisation of the joint (Fig. 7c), whereas in a patient with lateral degeneration bone density is raised to a remarkable extent (Fig. 7d).

Discussion

Subchondral mineralisation

CT osteoabsorptiometry gives a picture of the mineralisation in the arthroscopy patients which agrees well with information obtained from the anatomical specimens [5], and makes it possible to take similar measurements in the living subject. Taking into consideration the contact areas described in the literature [11] one can interpret the density maxima in the proximal part of the lateral facet as the expression of more frequent contact under intensive loading. Whereas the proximal lateral facet is in contact in all positions of the knee-joint greater than 60°, medially there is a changeover from the paramedian segment (90°) across the secondary ridge (120°) to the "odd facet" (140°). Taking into account the significant increase in force exerted by the quadriceps as flexion increases [16], the finding of higher mineralisation in the proximal part of the lateral facet and a lower density medially and distally becomes plausible (Fig. 8). In this way, the density distribution can be explained in terms of the principal stress [22] or the "loading history" of a joint [3], which makes it possible to infer the long-term distribution of load from the pattern of mineralisation. The situation in the patient with poliomyelitis confirms that the degree of mineralisation is determined by the magnitude of the mechanical stress acting on the joint, and that the bone reacts with atrophy or hypertrophy to changes in the mechanical environment, as was suggested by Kummer [15]. These findings are also in agreement with the observations of Müller Gerbl et al [20], who were able to show that, following a corrective osteotomy at the knee joint, the density of the tibial plateau at first decreases, probably due to a decrease in activity of the patient. About one year later the distribution pattern has changed in comparison with the preoperative situation, indicating a more central position of the resultant joint force. The slightly higher bone density found in the younger age group may be attributed to the greater physical activity of these people, which is also suggested by the more striking extension of the highly mineralised regions towards the secondary ridge in the younger subjects. These findings suggest that information on the distribution of the subchondral mineralisation and the position of the maxima is obtainable with CT-OAM and that the method allows a quantitative assessment of the degree of mineralisation of the joint to be made. It is also clear that, compared with the conventional AP, lateral or tangential radiograph, the method provides a great deal more information on the overall biomechanical conditions of an individual joint.

Cartilage degeneration

The localisation of the cartilage degeneration agrees with that reported in the literature. The damage associated with the "odd facet", which is more common than lateral lesions [4, 9] is frequently found in young people [6]. Lesions of the lateral facet [8] predominantly appear, however, with advancing age [33].

Comparison of subchondral mineralisation with cartilage degeneration

The greater degree of mineralisation of the lateral facet suggests that the cartilage degeneration found there may be due to intense and prolonged stress acting on this region of the joint. A similar conclusion followed the clinical and radiological investigations of Ficat et al [7] and Ficat and Hungerford [8], who described a "lateral hyperpression-syndrome" in the patella. They attributed this pathological entity to functional dominance of the lateral retinaculum, due to imbalance between the action of the vastus lateralis and medialis. It has also been demonstrated in animals that, following a proximal tibial osteotomy, the mechanical overloading of a single joint compartment can induce degenerative changes [10], and that these are associated with increased density of the subchondral bone [35]. Radin et al [29] put forward the theory that the initial step towards arthrosis may be caused by stiffening of the subchondral bone due to microfractures and microcallus formation. This is supposed to lead to excessive mechanical demands being made upon the overlying cartilage. The similarity of the observed mineralisation pattern with the distribution of stiffness (determined by means of compression tests) in the subchondral bone of the human patella [32] and the high correlation between CT measurements of the density of the subchondral bone and its mechanical stiffness [12], suggest a connection between an increase in density and stiffening. The degeneration of the articular cartilage over the highly mineralised lateral patellar facet may therefore indeed be due to an increase in stiffness of its subchondral bone. The high percentage of degenerate cartilage, however, localised over slightly mineralised subchondral bone particularly found over the medial facet, is difficult to reconcile with the mechanism described above. Abernethy et al [1] and Radin and Rose [30] further developed the theory mentioned above and suggested that the initiation of cartilage degeneration might rather be due to "stiffness gradients" in the subchondral bone. They hypothesised that the articular cartilage is submitted to significant vertical shear forces at boundary regions between more and less elastic bone. The assumption that gradients in the stiffness of the subchondral bone can damage cartilage in this way agrees very well with our finding of steep density gradients in the periphery of the patella. This concerns particularly the medial facet, where there is a strong tendency towards early degeneration. It is also true that the medial facet is subjected to high stress peaks when the knee is fully flexed [11, 34], and animal experiments have shown that short peaks of transarticular loading may result in degeneration of the cartilage [31]. As may be concluded from the low degree of mineralisation of the medial facet, these peaks do not occur very often. The presence of high stress peaks in a part of the joint which is otherwise not subjected to heavy loading could in our opinion bring about an unsatisfactory mechanical environment, in which the joint may not be able to adapt functionally to such mechanical demands, for example by increasing the thickness of the articular cartilage [14]. This is in agreement with our own findings [5], in which we were able to show that cartilage is usually thicker in the lateral part of the femoropatellar joint than in the medial. The low density and considerable elasticity [1] of the underlying subchondral bone may account for the fact that the lesions on the medial side are only slightly progressive; in other words, not very likely to lead to the more severe forms of cartilage degeneration. According to Goodfellow et al [9] softening of the articular cartilage in this region may even be considered as a normal variant in adolescents. The more progressive nature of cartilage degeneration over regions of highly mineralised areas, on the other hand, may be due to the greater stiffness of the subchondral bone and its reduced capacity for shock absorption [23, 24, 30]. This might also account for the fact that the milder forms of chondromalacia patellae are much more common on the medial side of the joint [4, 21], while the more severe examples of femoropatellar arthrosis are almost exclusively lateral [8, 13]. The findings in the arthroscopy patients confirm these conclusions. We regard the marked island-shaped increases in density near the secondary ridge in the group without degeneration of the patellar cartilage as a result of the "point-like" opposition of the patellae to the femur at 120° of flexion [11, 34]. The relatively high density here suggests that these people frequently bend their knees. Since this secondary maximum is not found in patients with central cartilage degeneration, it is plausible that there exists a different mechanical enviroment in this group. It is possible that less frequent full flexion contributes to degeneration of the articular cartilage due to a relative lack of intermittent pressure. This is in accordance with the finding of Alexander [2] that there is a positive correlation failure to take advantage of the full range of physiological movement available at a joint and its susceptibility to osteoarthritis. Comparing the patients with severe medial and lateral cartilage degeneration suggests that the less than average mineralisation in the case of medial cartilage damage may be the result of too few general mechanical demands made on the joint, and the very high degree of mineralisation in the case of lateral damage the result of excessive use.

We conclude from these findings that the subchondral mineralisation assessed by means of CT osteoabsorptiometry provides relevant data on the mechanics of a joint, and that it may give some insight into the pathogenesis of cartilage degeneration which cannot be provided by the conventional radiological techniques. We believe that the gain in information on the mechanical condition of an individual joint justify applying this method now to the femoropatellar joint in clinical practice.

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