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ORIGINAL ARTICLE

S. Milz · F. Eckstein · R. Putz

The thickness of the subchondral plate and its correlation with the thickness of the uncalcified articular cartilage in the human patella

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Abstract The regional thickness distributions of the subchondral plate and the unmineralized part of the articular cartilage were morphometrically determined in normal human patellae, and the correlation coefficient for each specimen calculated from the paired measurements. For this purpose the patellae were embedded in methyl methacrylate and cut as serial sections, which were assessed with a Vidas image-analyzing system (Kontron). The values obtained were used to reconstruct the individual and average thickness distributions and to calculate the correlation coefficients for each subject. Both the thickness of the subchondral plate and that of the cartilage revealed regular distributions which, however, followed different patterns. Central regions with maximum values from which the thickness decreased concentrically towards the periphery were found in both. However, the distribution patterns of the unmineralized cartilage and the subchondral plate could be clearly distinguished, both by the position of the maxima and by the arrangement of the isocrassids (contour lines of equal thickness). The thicknesses of the two tissues showed a correlation between 0.38 and 0.82 (mean 0.6). We attribute this to their different reactions to the type of stress acting upon them. It appears that the thickness of the subchondral plate is principally determined by stresses acting over a longer period of time with low frequency, whereas the thickness of the articular cartilage seems to be a response to intermittent dynamic stresses of a higher frequency.

Key words Subchondral bone · Cartilage thickness · Functional adaptation · Morphometry · Methyl methacrylate

S. Milz (✉) · F. Eckstein · R. Putz
Anatomische Anstalt, Lehrstuhl I, Pettenkoferstr. 11, D-80336 München, Germany,
Tel.: 089/5160 4811 or 4844; Fax.: 089/5160 4802

Introduction

The theory that the tissues of the passive locomotor system functionally adapt to long-term mechanical stress has been repeatedly reformulated (Wolff 1892; Kummer 1962; Pauwels 1965, 1980; Beaupre et al. 1990). It is well established that the thickness of cortical bone (Carter 1984) as well as the density of cancellous bone (Fyhrie and Carter 1986; Carter 1987) reflect the sum of the mechanical stimuli received (loading history), and that both will be remodeled towards an optimized distribution of strain-energy-density (Fyhrie and Carter 1986; Huiskes et al. 1987). A similar interpretation has been adopted for the articular cartilage (Oberländer 1977; Kurrat and Oberländer 1978, 1981; Müller-Gerbl et al. 1987; Putz et al. 1987; Eckstein et al. 1992), its regional thickness being assumed to adapt to the load supported during joint function.

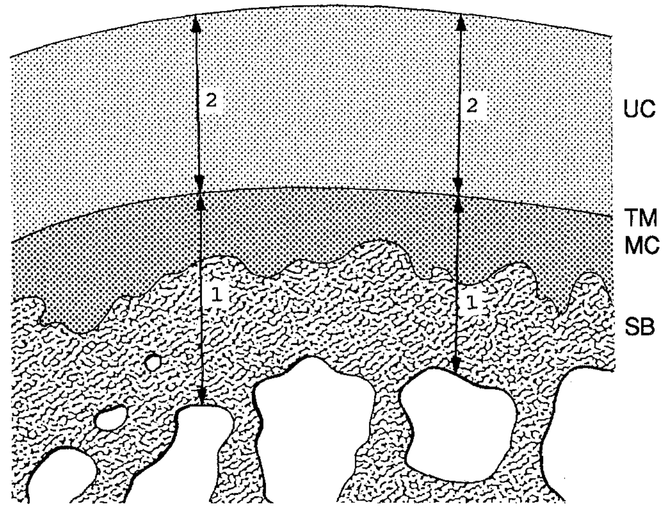
The subchondral bone, however, has so far received less attention. X-ray densitometric (Tillmann 1971, 1978; Oberländer 1973) and CT-osteoabsorptiometric studies (Müller-Gerbl et al. 1989, 1992; Eckstein et al. 1992, 1993) indicate that the distribution of the radiological density within the subchondral bone reflects the long-term stress distribution throughout the articular surface. Until now, however, there has been hardly any work on the thickness distribution of the subchondral plate, a structure which includes the mineralized layer of the articular cartilage and the immediately underlying hoirzontal plate of bone (Milz and Putz 1994). The correlation between the thickness of the subchondral plate and the covering articular cartilage has not yet been studied. The objectives of this investigation were therefore to assess the thickness of the subchondral plate and its correlation with that of the covering unmineralized articular cartilage. The human patella was chosen since it is physiologically subjected to a high degree of mechanical stress (Hehne 1983, 1990) and has the thickest cartilage found in any human joint (Fick 1910). It is therefore to be expected that significant differences in the thickness of the subchondral plate and the overlying unmineralized cartilage will be easily recognizable in the joint surfaces.

Materials and methods

Eleven formalin-fixed human patellae (from ten individuals aged 44–91 years; six male, four female) were selected from a pool of 160 knee joints from dissecting-room subjects. These were the only specimens showing no signs of macroscopic cartilaginous damage. The corresponding portion of the articular surface of the femur also showed no signs of cartilage damage. After block-embedding of the patellae, the sections were again examined and no cartilaginous lesions detected.

The specimens were dehydrated in ascending concentrations of alcohol, the fat removed in acetone and each whole specimen embedded in methyl methacrylate. These blocks were then cut using a saw microtome (Leitz) with a diamond blade. After the position of the bone in its clear methacrylate block had been determined, 500-μm transverse sections were cut at intervals of 3400 μm in ten of the specimens. The remaining specimen was cut into 100-μm sections, and these were used for contact radiography before being subjected to histological examination. The sections were stained using the method of Laczko-Levai (1975) and with Picrofuchsin–van Gieson.

In ten specimens the thickness of the subchondral plate and that of the uncalcified articular cartilage (Fig. 1a) were measured at identical locations on each 500-μm section (Fig. 1b). In cases where fewer than eight points were found (peripheral regions of very small patellae), zero values were alloted to the points lying outside the joint surface. Seven sections from each specimen were examined, so that a total of 56 measuring points were obtained. These points form a rectangular grid which allows the values of different patellae to be compared. The measurements were carried out with a Vidas image analysing system (Kontron, IPS 10) to which a Leitz stereo dissection microscope (M420) had been connected. All values were stored in a database, and the surface distribution of both parameters was reconstructed and plotted by means of a computer programme called Gnuplot (Computer Solutions, D-85567 Grafing, Germany). Contour lines of equal thickness ("isocrassids") were used to give a cartographic presentation of both parameters, at intervals of 300 μm for the subchondral plate and 500 μm for the uncalcified cartilage. Equally orientated plots were obtained for each single patella and for the mean values of all specimens in order to arrive at the average distribution pattern. The correlation coefficient between the thickness of the subchondral plate and that of the uncalcified cartilage was calculated for each patella from the 56 pairs of measurements.



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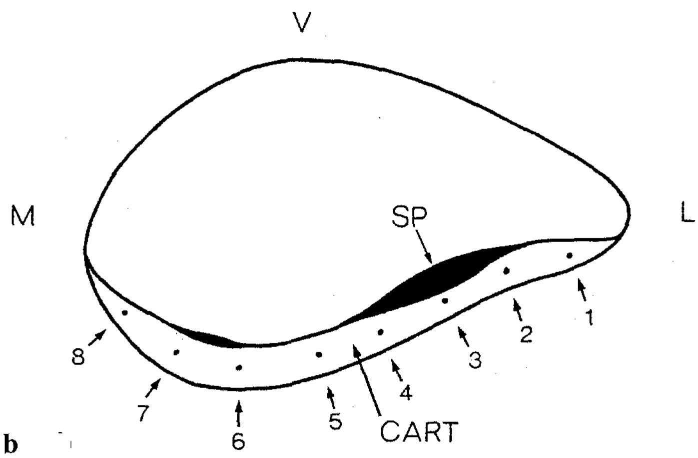


b

Fig. 1a, b **a** Diagram showing layers of articular surface and parameters measured at different measuring points (*UC* unmineralized cartilage, *MC* mineralized cartilage, *SB* subchondral bone, *TM* tidemark, *1* thickness of subchondral plate, *2* thickness of cartilage). **b** Arrangement of the measuring points throughout a single section (*SP* subchondral plate, *CART* cartilage)

Table 1 Human patellae: maximum and minimum thickness of the SP (in units of 100 μm)

Case no., side	Max	Min
1, L	13.79	1.23
2, R	20.90	1.6
3, R	13.6	1.79
4, L	15.1	1.6
5, R	9.27	1.28
6, R	17.59	1.63
7, L	12.33	0.88
8, L	15	1.47
9, L	13.93	1.08
10, R	13.16	1.1

Results

Subchondral plate

The thickness of the subchondral plate generally ranged from 100 μm to 1000 μm, although, in the region of the lateral facet, values of over 2000 μm were occasionally recorded (Table 1). In the course of taking the measurements no multiple tidemarks were detected. The regional distribution of the thickness was found to follow a regular pattern, consisting of a predominant maximum in the middle of the lateral facet. In some cases this principal maximum had two or more peaks. Apart from that there was often a secondary maximum of an island-like thickening in the region of the medial secondary ridge. The thickness values here were usually lower than they were laterally. From these two previously described maxima the thickness fell off, at first steeply and then more gently, towards the periphery. The single thickness stages were more or less concentrically arranged, the transition from one to another being not sudden but continuous. This can also be clearly seen in the histological preparations (Fig. 2). The lowest values were found at the edges

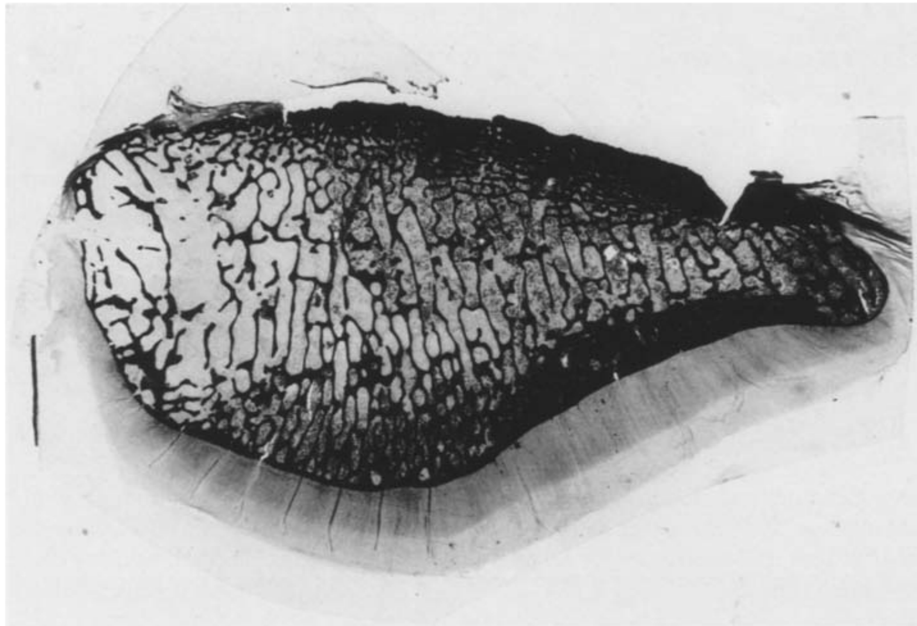
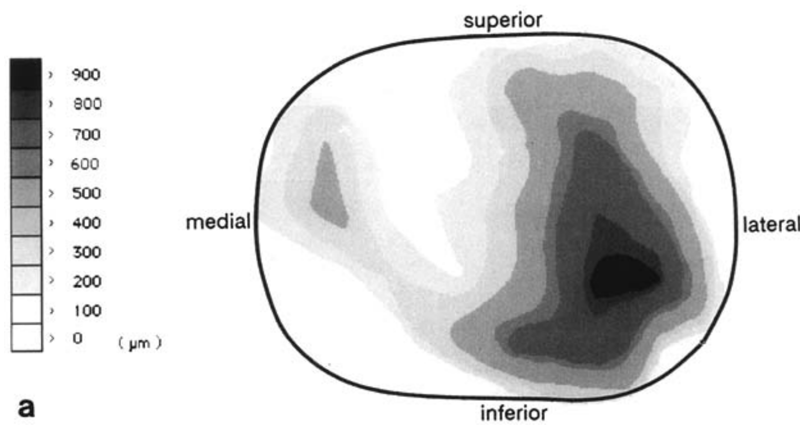


Fig. 2 Transverse section through human patella (Picrofuchsin–van Gieson). The differences between the thickness of the subchondral plate and that of the overlying cartilage ar clearly seen (See also **Fig. 1b**)



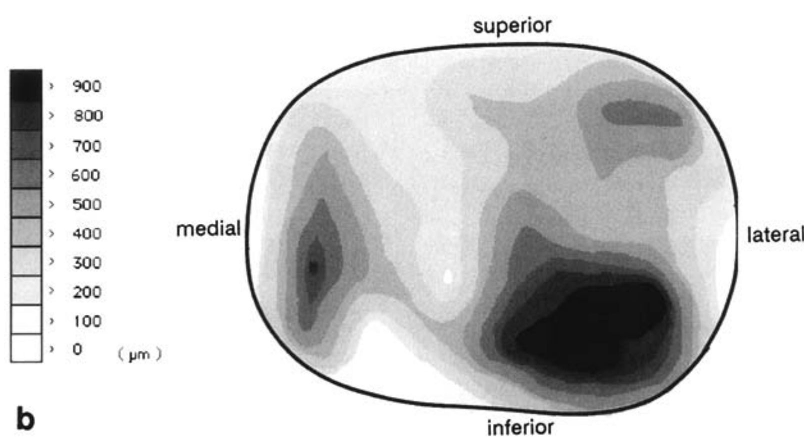


Fig. 3a, b Variation in the individual distributions of the subchondral plate thickness in two specimens: **a** specimen 1, **b** specimen 8

of the articular surface of the patella, where the thickness was reduced to about 100–160 μm (Table 1).

Comparing the distribution patterns of the 10 individual knees revealed some differences (Fig. 3a, b). However, a basic pattern following the description above was a constant feature, and this is outlined in the average distribution (Fig. 4). In this distribution the varying shapes and arrangements of the individual maxima resulted in

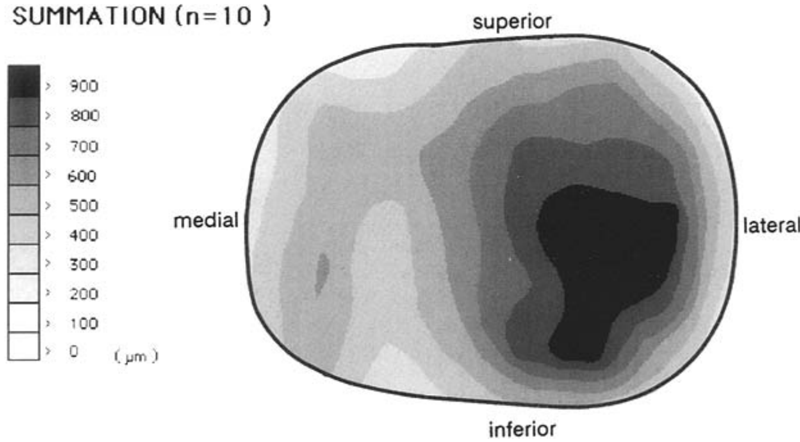


Fig. 4 Average thickness distribution of the subchondral plate of the human patella (n=10)

an extension and flattening of the averaged maxima in the medial and lateral facets. In most of the individual distribution patterns these appeared to have steeper sides and higher peaks.

Correlation of the thickness of the subchondral plate with the thickness of the uncalcified articular cartilage

The thickness of the articular cartilage reached its greatest value of up to 5 mm in the middle of the lateral facet and at the principal ridge (Table 2). From there it decreased concentrically towards the periphery. As in the case of the subchondral plate, the resulting isocrassid pattern revealed a basic regularity. At the periphery, the thickness of the cartilage amounted to between 120 µm and 1900 µm (Table 2). At the edges of the articular surface the cartilage usually came to an end with a steep decline, but sometimes also faded away without any sharp boundary into the fibers of the joint capsule.

Unlike that of the subchondral plate, the thickness of the cartilage usually showed wider extension of the thicker regions in a medial to lateral direction. In spite of the interindividual differences (Fig. 5a, b), the cartilage thickness also revealed a general background pattern, as is clearly shown by its average distribution (Fig. 6). When the distribution patterns of the cartilage thickness were compared with those of the subchondral plate, subjective evaluation showed that the basic arrangements of the isocrassids were clearly different. Direct comparison of the thickness of the subchondral plate with the unmineralized cartilage at identical measuring points revealed correlation coefficients between 0.38 and 0.82, the mean of ten values being 0.6 (Table 3, Fig. 7).

Table 2 Human patellae: maximum and minimum thickness of the cartilage (in units of 100 µm)

Case no., side	Max	Min
1, L	51.5	9.9
2, R	52.4	16.4
3, R	31.9	5,6
4, L	41	18.7
5, R	29.15	4.78
6, R	36.4	7.6
7, L	29.6	1.95
8, L	25.25	1.28
9, L	48.5	13.91
10, R	47.61	6.4

Discussion

Material and methods

With regard to the selection of the specimens, it is important to consider how far the parameters investigated are influenced by the age of the subject. For the patella it has been reported that subjects older than 50 years, particularly if female, show a significant decrease in cartilage thickness if specimens with cartilage degeneration are included (Meachim et al. 1977). However, selecting shoulder-joint specimens without cartilage lesions, Meachim (1971) reported that age has no influence on the average thickness of the unmineralized cartilage.

None of the 11 specimens which were selected out of a group of 160 knee joints and investigated in this study showed cartilage degeneration, either on naked-eye inspection or under dissection microscope control. We therefore think that, in spite of the very frequent age-related arthritic lesions which affect the patellar cartilage, these specimens were suitable for the investigation of the thickness of the subchondral plate and its correlation with that of the thickness of the unmineralized cartilage.

In order to be able to make a simultaneous assessment of both regional thickness distributions in one and the same specimen, embedding in methyl methacrylate and cutting with a high-precision saw microtome was considered necessary. It is essential if a locally accurate reconstruction of both sets of values is to be obtained. In our experience, the fixation (formalin and alcohol) and embedding procedure brings about a shrinkage artifact which particularly affects the hydrated, unmineralized cartilage. The data reported in the literature for highly hydrated soft tissues (Burkhardt 1966; Burck 1969; Romeis 1980) suggest that the measured thickness of fixed and embedded unmineralized cartilage is about 15–20% less than that of the fresh material. However, we

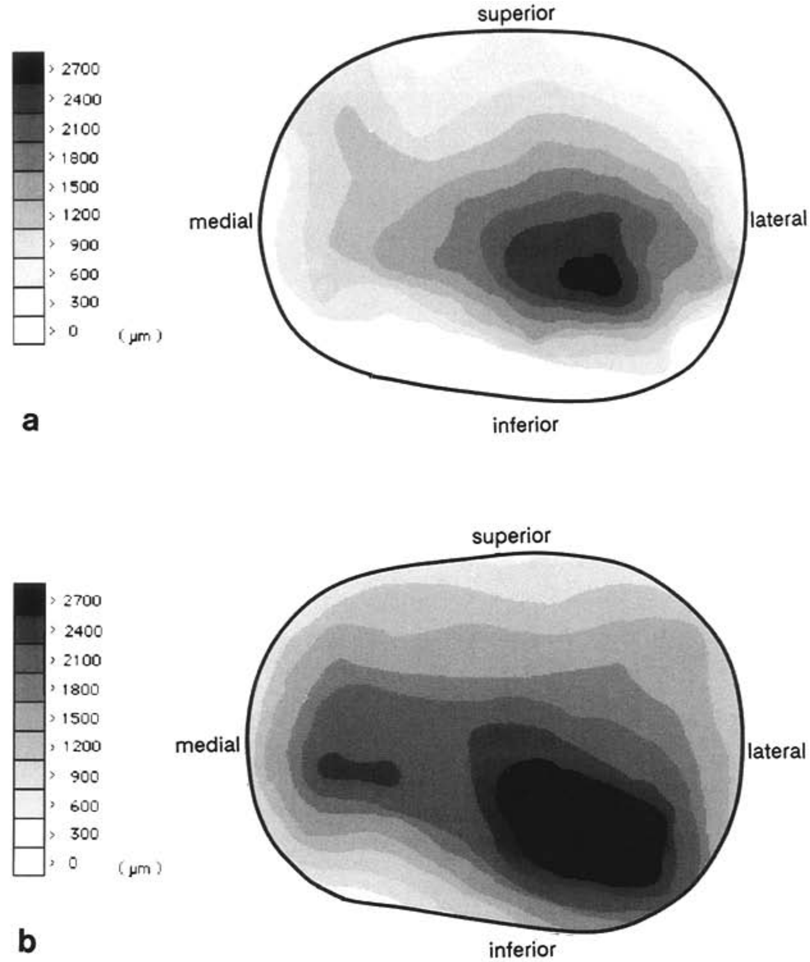


Fig. 5a, b Variation in the individual distributions of the cartilage thickness in two specimens. **a** Specimen No 1, **b** specimen No 8

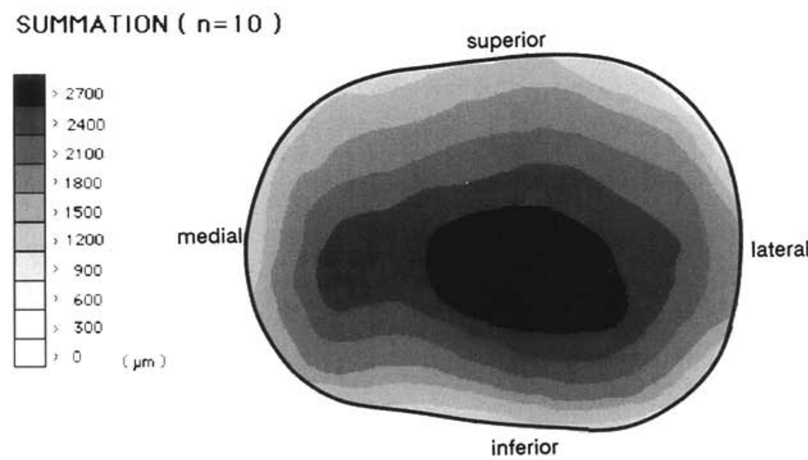


Fig. 6 Average thickness distribution of the cartilage of the human patella (n=10)

assumed that the shrinkage of the hyaline cartilage was everywhere uniform. Such an assumption is plausible, since the arrangement of the collagen fibers in the cartilaginous matrix of joints of this size is essentially independent of the locality. The same applies to the ratio between the fibers and the remaining matrix, except at the very periphery, where the fiber component seems to be somewhat greater. The glycosaminoglycan content differs between the various layers of the cartilage (Bayliss et al. 1983), but does not show major regional differences throughout the articular surface as a whole (Ficat and Maroudas 1975). This also supports our assumption that the shrinkage of the unmineralized cartilage is uniform over the whole of the joint surface.

Table 3 Correlation between the thickness of the cartilage and the thickness of the subchondral plate

Case no., side	Sex	*r*
1, L	Male	0.67
2, R	Male	0.52
3, R	Male	0.66
4, L	Male	0.38
5, R	Female	0.42
6, R	Male	0.63
7, L	Female	0.53
8, L	Male	0.82
9, L	Female	0.67
10, R	Female	0.62

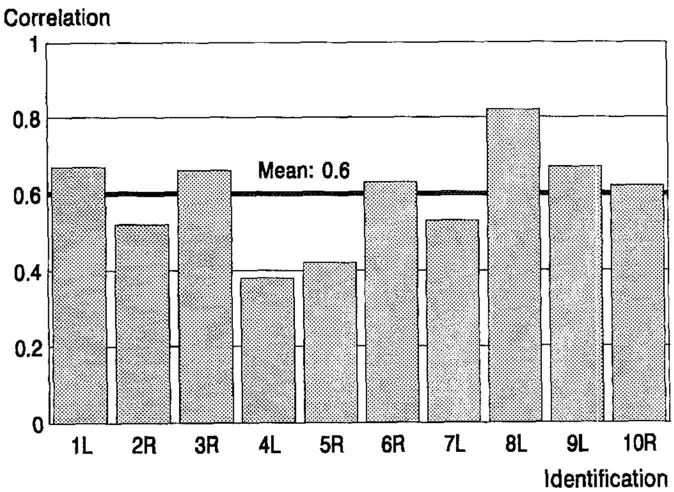


Fig. 7 Correlation between the thickness of the cartilage and the subchondral plate in 10 normal patellae

So far as the subchondral plate is concerned, there is no reason to suppose that it undergoes any significant shrinkage or swelling. Due to the high content of hydroxyapatite, which is responsible for its mechanical stability, it is extremely likely that the values measured are the same as those that would have been measured before fixation and embedding. If one assumes a largely uniform shrinkage of the unmineralized cartilage and no shrinkage of the subchondral plate, there should be no influence on the correlation coefficient due to fixation and embedding. An assessment of the correlation between the two parameters therefore seems acceptable, and in our opinion these conclusions can even be applied to the living subject.

The method employed for the reconstruction of the average distribution can only lead to a characteristic pattern if a regular individual distribution exists. The individual differences are then smoothed out and the general regularity of the arrangement of the isocrassids is more strongly underlined. Should no regular distribution exist, the individual distributions would instead be arbitrarily neutralized by opposing random patterns, with the result that no recognizably regular order would appear in the average distribution. This is clearly not the case here.

The shape of a distribution pattern depends on the location of the measuring points in the individual sections, and on the distance between one section and another. Possible inaccuracies when marking the measuring points on the section, or when setting the advancement of the saw blade between cuttings, can therefore lead to a distortion of the pattern derived therefrom. It is realistic to assume that the departure of the measuring points from the ideal position on a section was not more than 500 μm, and between the sections not more than 300 μm. These values apply to the worst case, with an estimated inaccuracy of about 8–10% for the input of the saw advancement and for the positioning of the measuring points. Since great care was taken with the latter, no significant distortion is to be expected in the resultant graphic reconstruction.

Thickness of the subchondral plate

The earliest measured values of the "pressure reception plate" (Druckaufnahmeplatte) for various bones were recorded by Roux (1896). He reported an almost uniform value of 1 mm in the patella. Our results are in complete disagreement with these figures. In no way can the subchondral plate of this bone be said to show a uniform thickness distribution, but rather a complex pattern of varying, concentrically arranged, thickness intervals.

If one compares the pattern of the thickness distribution of the subchondral plate with other morphological parameters, such as the surface density of the subarticular bone (Pedley and Meachim 1979), or the radiological density of the subchondral bone, determined either by X-ray densitometry (Tillmann and Brade 1980; Hehne 1983) or by CT-osteoabsorptiometry (Eckstein et al. 1992, 1993), one finds a general agreement about the position of the principal and subsidiary maxima. There is also a striking similarity in the arrangement of the isocrassids of the subchondral plate and the isodensities for the distribution of subchondral mineralisation (Eckstein et al. 1992, 1993). We therefore suggest that the regional differences in thickness of the subchondral plate are responsible for the differences in density of the subchondral bone estabished by X-ray densitometry and by CT-osteoabsorptiometry.

If the thickness distribution of the subchondral plate is related to the retropatellar pressure distribution at different angles of flexion (Ahmed et al. 1983; Hehne 1983, 1990; Hille et al. 1985; Hefzy and Yang 1993; Marder et al. 1993), obvious similarities between these patterns are revealed. The location of the pressure maxima can explain the thickness maxima of the subchondral plate in the lateral facet. The latter are interpreted as the result of a frequent involvement of joint contact under heavy loading. The less uniformly moulded secondary thickness maxima of the medial facet are possibly due to infrequent but important local loading at higher degrees of knee flexion (Wiberg 1941; Hehne 1983, 1990). However, Hefzy and Yang (1993) report that the pressure here is always less than on the lateral side.

The regional thickness distribution of the subchondral plate may therefore be interpreted as a morphological response to the local long-term stress, and therefore represents a summation of the pressure patterns corresponding to different angles of flexion (loading history).

Recent investigations indicate that osteocytes may function as "sensory organs" to mechanical stimuli (Skerry et al. 1989; Marotti et al. 1992; Lanyon 1993) and take part in coordinating the activity of osteoblasts and osteoclasts (Palumbo et al. 1990; Rodan 1992). However, exactly how the mechanical stimulus is translated into a cellular response, and how this response influences the thickness of the tissue, are still unknown.

Correlation with the thickness of the uncalcified articular cartilage

The findings on the regional distribution of the cartilage thickness itself are in agreement with those of Putz et al. (1987) and Eckstein et al. (1992), but not with those of Marar et al. (1975) or Hehne (1983), who described the thickness maxima as lying in the medial facet.

In agreement with our own conclusions about the subchondral plate, previous investigators have interpreted cartilage thickness as being adapted to the local mechanical stress (Oberländer 1977; Kurrat and Oberländer 1978, 1981; Müller-Gerbl et al. 1987; Putz et al. 1987; Eckstein et al. 1992).

If one compares the varying pressure distribution over the retropatellar joint surface at different angles of flexion (see especially Ahmed et al. 1983; Hehne 1983, 1990) with the thickness distribution of the unmineralized articular cartilage, a close correspondence only exists at mid-flexion, ca. 60° (Ahmed et al. 1983). It is in this position that, according to Goldstein et al. (1986) the greatest intermittent stress acts upon the patellar joint surface.

Whereas many studies have interpreted subchondral bone density or cartilage thickness in terms of local mechanical stress (Oberländer 1977; Kurrat and Oberländer 1978, 1981; Müller-Gerbl et al. 1987; Putz et al. 1987; Eckstein et al. 1992), few have directly compared both parameters. Correlation coefficients very similar to ours, relating the distributions of subchondral X-ray density (as measured in intervals of Hounsfield units) to cartilage thickness, have been reported by Eckstein et al. (1992). Our study also confirms that the thickness of the uncalcified cartilage and that of the subchondral plate yield low correlations, even if precisely corresponding measuring points are determined and both structures are assessed in terms of equal measuring units.

A much higher correlation (range: 0.60–0.96) has been determined for the thicknesses of the unmineralized and the mineralized articular cartilage (Müller-Gerbl et al. 1987) which constitutes part of the subchondral plate. It must therefore be the subchondral bone lamella itself (and not the unmineralized cartilage) which is responsible for the different distribution patterns of these parameters. These different patterns therefore suggest that different mechanical factors may influence the functional response of cartilage and subchondral bone.

Interpretation

During longitudinal cyclic loading of a joint, intermittent stress occurs at its articular surface and brings about a short term increase in the local hydrostatic pressure of the tissue. We suggest that the growth and preservation of the cartilage are determined by these intermittent stimuli, which, in the patella, are predominant in mid-flexion – during walking, for instance, or climbing stairs. This interpretation is supported by the results reported by Sah et al. (1989), Hall et al. (1991) and Parkkinen et al. (1993), who were able to demonstrate the stimulating effect of oscillating stresses on the metabolism of chondrocytes. Static stresses, on the other hand, have been shown to have an inhibiting effect on the synthetic activity of cartilage cells (Gray et al. 1988).

A certain minimally spaced variability of the stress is certainly also required to induce bone remodeling, and a purely static stress has been shown to have a minimal stimulating effect (Lanyon and Rubin 1984; Rubin and Lanyon 1987). However, it appears that the thickness of the subchondral plate is related more particularly to the mechanical conditions of the joint, which can be characterized as longer lasting, infrequently changing mechanical stresses. In contrast to the unmineralized cartilage, we regard the subchondral plate as responding predominantly to stresses oscillating with a very low frequency and acting over a longer period of time. We therefore suggest that, as in the tibial head (Milz and Putz 1994), the thickness distribution of the subchondral plate provides information about the individual "semistatic" loading history of the joint. We conclude that functional adaptation takes place in both the uncalcified cartilage and the subchondral plate zone. However, so far as local remodeling is concerned, these tissues appear to react quite differently to the various aspects of the same mechanical environment.

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