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Computed tomography-osteoabsorptiometry for assessing the density distribution of subchondral bone as a measure of long-term mechanical adaptation in individual joints

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Abstract. To estimate subchondral mineralisation patterns which represent the long-term loading history of individual joints, a method has been developed employing computed tomography (CT) which permits repeated examination of living joints. The method was tested on 5 knee, 3 sacroiliac, 3 ankle and 5 shoulder joints and then investigated with X-ray densitometry. A CT absorptiometric presentation and maps of the area distribution of the subchondral bone density areas were derived using an image analyser. Comparison of the results from both X-ray densitometry and CT-absorptiometry revealed almost identical pictures of distribution of the subchondral bone density. The method may be used to examine subchondral mineralisation as a measure of the mechanical adaptability of joints in the living subject.

Key words: Computed tomography-osteoabsorptiometry – Subchondral bone density – Biomechanics – Functional adaptation – X-ray densitometry

In certain joints of the human body, the surface distribution of the average effective load on that joint is related quantitatively to the distribution of the subchondral mineralisation, and this has been most often confirmed in the hip-joint [8, 13, 15, 17]. One long-established method of assessing the distribution of stress over a joint surface employs X-ray densitometry, whereby the density distribution of the subchondral bone may be measured in thin sections. The most commonly used procedure is that described by Schleicher and his co-workers in 1980 [20], in which the radiographs are scanned mechanically and resolved into pixels, and for each of these the degree of exposure measured with an image analyser. The theoretical basis for this procedure has been described by several authors [2, 5, 6, 9], who have been able to show that the density distribution of the subchondral bone (recorded on the film as different degrees of absorption of the X-ray beam) can be correlated with the distribution of stress over the joint surface, as demonstrated in the 'photoelastic model'. For this reason, Pauwels [17] spoke of the varying degrees of mineralisation of a joint surface as a *"verkörpertes Spannungsfeld"* (materialised field of stress).

X-ray densitometry, however, can only be used on films made from sections of anatomical specimens. We here present a way of using computed tomography (CT) to measure the density distribution of subchondral mineralisation in the living subject. In addition, we aim to establish to what extent the results of CT and X-ray densitometry agree with one another. Finally, the clinical relevance of this new method of CT osteoabsorptiometry is discussed.

Material and methods

The work was carried out on 5 knee, 3 sacroiliac, 5 shoulder, and 3 ankle joints taken from bodies in the dissecting rooms of the Anatomisches Institut, Freiburg; these had been embalmed in 4% formalin. Both procedures (normal X-ray densitometry and X-ray CT absorptiometry) were used on all these specimens.

Computed tomography-osteoabsorptiometry

Computed tomography exposures of all specimens were first made at section intervals of 2 mm with a SOMATOM DR-H computer tomograph. The densitometric values of the CT scans were obtained in arbitrarily chosen Hounsfield units. The scans

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were processed in a Siemens EVADOS radiotherapy planning computer, using the two software packages EVA1 and SIDOS-TELE 9.4 D.

The first step involves the processing of the individual scans with the EVA1 program, whereby the part of the joint surface to be examined is enlarged until it fills the entire screen (Fig. 1A). The resolution of the image depends upon the original magnification and was found to lie between 0.25 and 0.8 mm. Resolution at right angles to this plane corresponds to the section thickness, i.e., 2 mm.

Conversion into the SIDOS-TELE format follows. This software package calculates the frequency distribution of the density values and displays them as the columns of a histogram. The SIDOS-TELE software is used to evaluate "isodensities": contour lines which separate regions of greater density from those of lesser density (Fig. 1B). Regions including fewer than 21 pixels are ignored, so that, with the resolution employed, only those with a final area between 3 and 12 mm^2 are displayed. We recognise the following six density zones <249 HU, 250–499 HU, 500–649 HU, 650–799 HU, 800–999 HU and >1000 HU, making five different isodensities available.

The resulting picture is then subjected to image analysis, being first of all read into an IBAS 2000 (ZEISS, Oberkochen) computer, capable of presenting the different areas of equal density as a false colour display. Each region, separated from the next by the limiting isodensities, thus appears in its own colour (Fig. 1C). In order to arrive at the absorption pattern over the entire joint surface, the classified Hounsfield values were, in each CT section, calculated along a line 1.5 mm below the joint surface and displayed as a two-dimensional surface map (Fig. 2).

X-ray densitometry

All the specimens were finally sawn into parallel sections 2 mm thick and subjected to contact photography with the apparatus used for routine detection of breast tumours (17 keV photons). The radiographs were standardized using an aluminium alloy calibration wedge placed on each film adjacent to the bone sections to be evaluated. Using a camera, these X-ray films were then fed into a computer and digitised [20]. By assigning a particular colour to each of these values, it is possible to obtain pictures in which regions of equal density are represented by the same colour. A superficial display of the density distribution over the whole articular surface was achieved in the way previously described for CT-absorptiometry.

The correlation between Hounsfield calibration and the optical density of the X-ray densitometry was calculated as follows: Records of the same sections were taken for both methods. The Hounsfield values in the CT slices and optical density values in the X-rays were measured over corresponding areas and submitted to linear regression analysis. The correlation coefficient was 0.92. The relationship obtained was used as a standard for all other pairs of specimens.

Results

A glance at the CT scan and X-ray film of the same section suggests the almost identical patterns of density distribution produced by the two methods (Fig. 3A, B). Systematic comparison of corresponding pictures of each section shows that an average of 82% of identical pixels are, with six selected density levels, grouped about the same co-

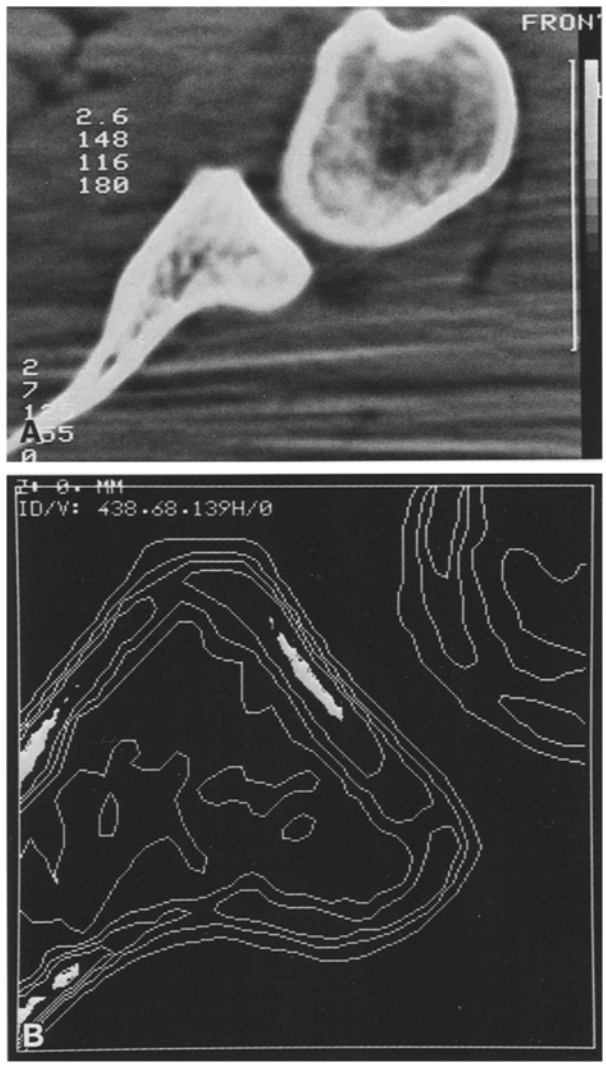

Fig. 1A–C. CT absorptiometry of right shoulder-joint. **A** Axial CT section. **B** Isodensities in subchondral region of glenoid cavity and head of humerus. **C** Diagram of glenoid cavity showing regions of different density (copied from false-colour display)

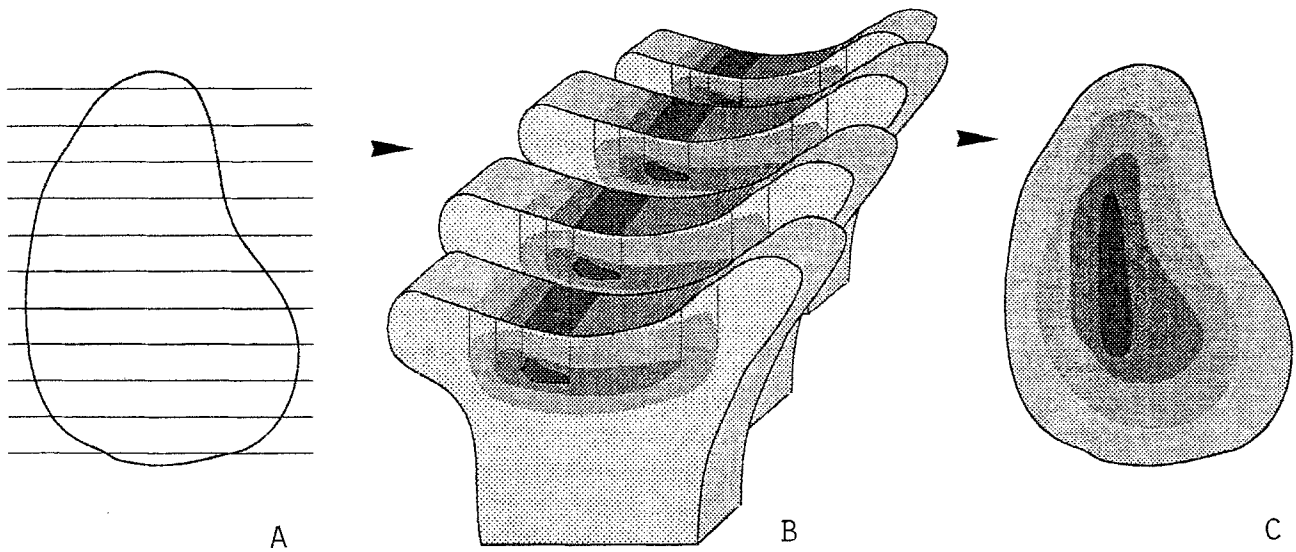

Fig. 2A–C. Method of producing density maps from single sections. **A** Section planes projected onto surface of the glenoid cavity. **B** Density distribution of the individual sections projected onto the surface. **C** Area distribution of subchondral bone density (density map) over the joint surface

ordinates in the object image. In our series, 8% deviated by a single colour step, and 10% by two or more such steps. Naturally, the examination of the maps of a whole joint surface allows a much better comparison between the two methods than is possible with the sections alone. Figure 4A, B shows the surface display of the subchondral absorption pattern of the surfaces of the femoropatellar joint, calculated first with CT and then with X-ray densitometry from the same specimens. Figure 5A, B is a similar representation of the glenoid fossa. The density maps obtained with the two different methods can hardly be distinguished from one another. Equally satisfactory agreement was found in all 16 specimens examined.

Discussion

Our results have clearly demonstrated that CT-osteoabsorptiometry and X-ray densitometry lead to exactly the same result. However, although the result may be the same, the striking difference is that

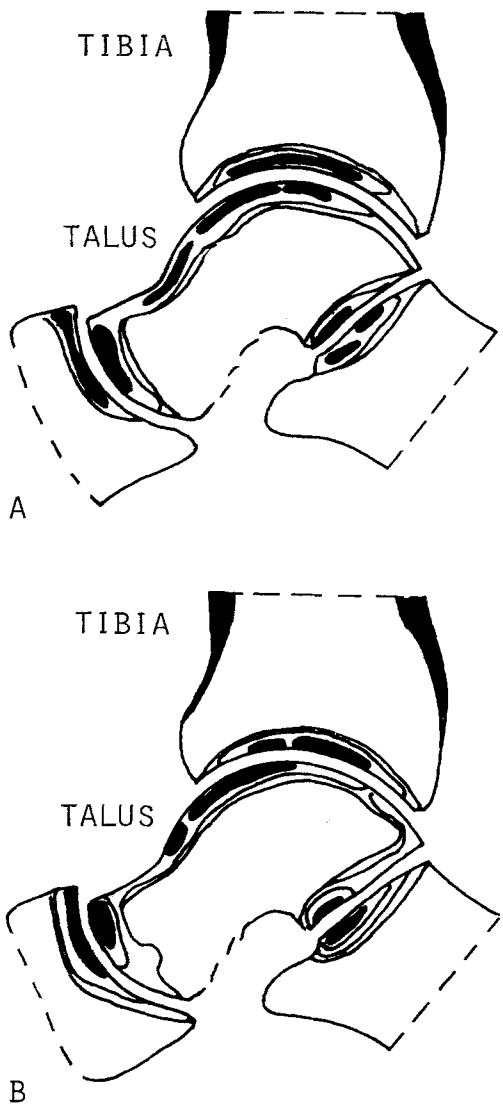

Fig. 3A and B. Density of the subchondral mineralisation in corresponding sections of the ankle joint. Zone of highest density *black* (copied from false-colour display). **A** Results obtained with X-ray densitometry. **B** Results obtained with CT absorptiometry

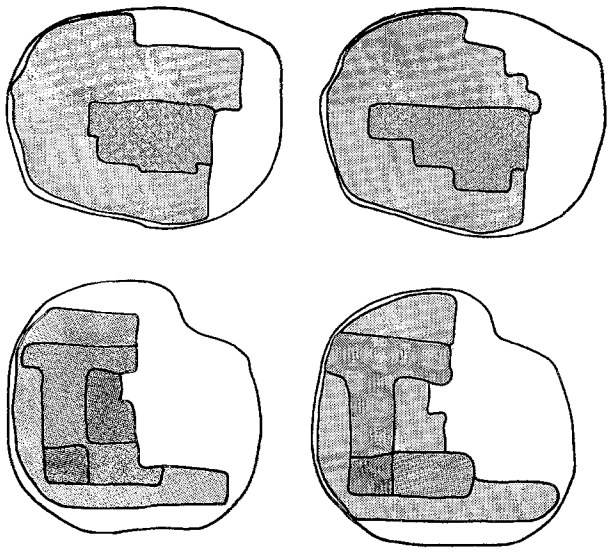

Fig. 4A and B. Density distribution map made with the IBAS 2000. Patellar (*above*) and femoral articular surfaces of femoropatellar joint showing surface distribution of the subchondral mineralisation in 5 steps between 250–1100 HU (copied from false-colour display). **A** Results obtained with X-ray densitometry. **B** Results obtained with CT absorptiometry

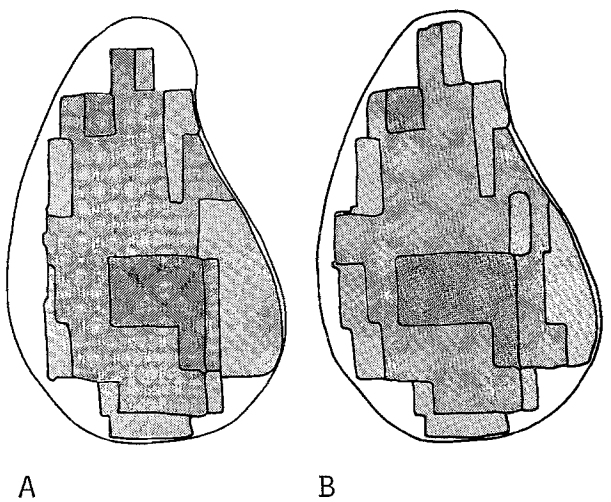

Fig. 5A and B. Density distribution map made with the IBAS 2000. Lateral view of a right glenoid cavity showing surface distribution of subchondral mineralisation (copied from a false-colour display). **A** Results obtained with X-ray densitometry. **B** Results obtained with CT absorptiometry

the former method can be used on the living subject.

In considering possible sources of error, it must be recalled that this is a method of arriving at the relative absorption in different parts of the subchondral area of the articular surface; that is to say, it is concerned with localisation of maximal

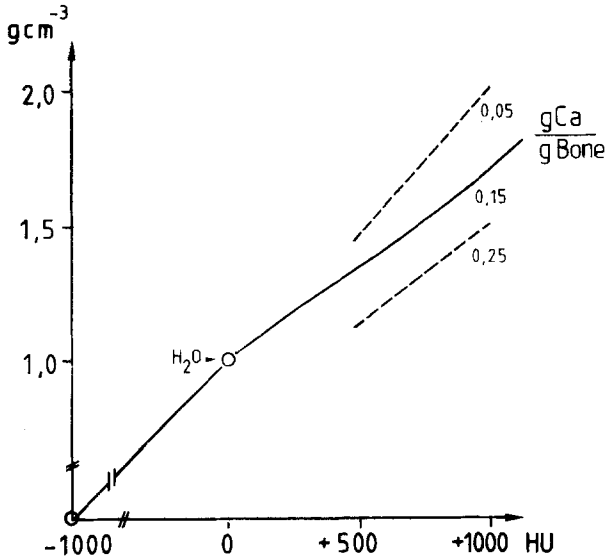

Fig. 6. Empirical relationship between values in Hounsfield units (HU) and physical density [21]

and minimal values, and not with the determination of absolute density, which is the aim of CT bone mineralisation measurement.

The following are possible sources of error:

1. The partial volume effect. This is reduced by avoiding tangential sections which run through regions where the density gradient is steep.

2. The calibration tolerance of CT. Internal calibration of the scanner against air was carried out prior to each measurement. Control measurements made with a reference standard showed a maximum variation of about ± 4 HU, which for our purposes can be neglected.

3. Beam hardening. The principal effect of beam hardening can be compensated for by calibration against water. Deviations in the deeper regions of the subchondral bone, such as are used in this method, amount to about 4% [7]. This therefore can also be neglected.

4. Errors due to the superimposition of materials with different Z values, in this case mineral salts, connective tissue, and fat. Optical density differences in X-ray densitometry, like the HU values in CT, depend upon the linear attenuation coefficient, which itself depends on the mass density, the photon energy, and the atomic number Z of the material involved. In the case of the polychromatic X-rays normally employed in CT, a complicated superimposition of several interaction effects occurs, so that there is no unique correlation between the density and the HU value (Fig. 6) [19].

For a mean photon energy value of 70 KeV (as is found in our CT), separation into components – mineral and non-mineral – provides a sufficient approximation. The variation in the Hounsfield values is expressed by the equation $HU = -1000 (1 - c_1 - 1.59c_2)$ [18]. C_1 represents the non-mineral and C_2 the mineral content in g/cm^3. The ratio of the mass attenuation coefficients of hydroxyapatite and water is 1.59. The mineral component therefore contributes about 1.6 times more to the HU value than the other components, and this effect is enhanced by the ratio of about 3 between the density of the mineral and that of the other components. It follows that the greater part of the HU distribution is due to the effect of the mineral salt concentration, although the other constituents cannot be ignored.

We can therefore claim that this method has reliable correlation between the effective load and the HU distribution, that is to say, the distribution of absorption of the x-rays used. This, as has already been pointed out, is of great importance. A more detailed investigation of the correlation between effective load and mineral content alone, employing dual energy quantitative computed tomography (DEQCT) [1, 3, 4], has already been started. The surface display of the density distribution suggested here makes rapid and simple assessment of the loading history of any one particular joint possible. Maximum density corresponds to a point of maximum strain. In bone, permanent alterations of structure remain as witness to the passing demands made upon a joint. An increased load produces an increase in density; a reduction of the load leads to bone resorption.

During the life of a joint the effective load acting on it can change, either because of an increase or decrease in movement, or because of such altered mechanical circumstances as follow, for example, a badly reduced fracture or a correction osteotomy. The temporarily modified mechanical situation is then reflected in the changing picture of the density of the articular cartilage as it becomes adapted to the altered circumstances.

Möllers et al. [12] carried out an investigation into the distribution of the subchondral bone density at the lower end of the radius, using X-ray densitometry on postmortem bone sections, both from normal subjects and from those with a history of a badly reduced Colles' fracture. The distribution of substance in the normal radii showed a typical pattern of distribution which was markedly different from the density distribution in the abnormal bones. This pattern – very unlike that of the healthy radius – must be interpreted as the result of an alteration in the effective strain acting upon the distal surface of the radius (with an increase in the load on its dorsal part), and may well account for the frequently experienced pain and the danger of future osteoarthrosis. Murphy et al. [14] investigated the adaptive changes in a femur 6 years after the implantation of an Austin Moore prosthesis. Regions of strain due to loading of the femoral head and greater trochanter are abnormally high immediately after implantation, particularly in the neighbourhood of the calcar femoris. However, 6 years later the strain distribution of the load was completely normal, owing to a subsequent increase in both the area and density of the bone.

The distribution pattern of strain in a joint is altered by either partial or total meniscectomy [10] as the pattern of mineralisation adapts itself to the new demands. This was shown to be the case by Odgaard et al. [16], and a comparison of the distribution pattern before and after the operation confirms the different extents of the increase in strain on the proximal articular surface of the tibia which follow partial and total removal of the meniscus. Differences in the degree of mineralisation of a joint are also found in diseases which are not of mechanical origin. Steiger et al. [21] investigated patients with rheumatoid arthritis and at intervals measured the mean mineral content of the bone in grams per cubic centimetres. They also measured the 'compact bone parameter'. This parameter specifies the amount of tissue in which the density exceeds 0.8 g/cc as a measure of bone-density distribution. They were able to record significant differences in the degree of mineralisation even in the absence of observable radiological changes. By means of a three-dimensional demonstration, they were also able to show that the changes occur predominantly in the subchondral bone. Unlike us, however, they did not concern themselves with differences in the position of the maximum values within the bony lamellae.

It is, of course, essential to emphasise the limited accuracy of the values obtained by the method described here, which are only able to reflect the relative differences of concentration within the joint surface. To obtain quantitatively absolute values for the density, it is necessary to use the dual energy method [1, 3, 4], or to take measurements against a "reference phantom" [3, 4, 11].

Our results have demonstrated that CT absorptiometry has many practical applications. It can be used diagnostically to obtain information about the mechanical status of a joint, and also to assess progress following an operation or injury which

may have altered the mechanical circumstances of a joint. In addition, it constitutes a method which can be used in basic clinical research, is not invasive and does not overtax the patient. A further great advantage of the method is that it can be used to investigate both normal subjects and selected samples of people who, either because they take part in a particular sport or for other reasons, are subjected to unusually heavy stress.

We believe this method can be used by specialists in Sport or Industrial Medicine when investigating situations which make great demands on the joints, and enable them to prevent damage. Furthermore, because of the ubiquity of CT apparatus, its use need not be limited to single cases.

In summary we claim that CT-osteoabsorptiometry, taking into account certain sources of error, provides a method of estimating the mineralisation pattern of a joint surface. Thus a method is available which allows the adaptive capacity of an individual joint to be assessed in the living subject, and enables progressive observations to be made after a joint has been subjected to abnormal mechanical conditions such as occur, for example, following a correction osteotomy.

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