Volume 7 Supplement 2 December 1992

ISSN: 0884-0431

THE AMERICAN SOCIETY FOR BONE AND MINERAL RESEARCH
·1977·

Journal of Bone and Mineral Research

The Official Journal of
the American Society for Bone and Mineral Research

Functional Regulation of Bone Cell Biology by Mechanical Factors

Proceedings of a Workshop organized on behalf of the
European Calcified Tissue Society by
Austrian Society for Bone and Mineral Research
Ludwig Boltzmann-Institute for Osteology, Hanusch-Hospital

Editors: E.H. Burger and K. Klaushofer
Associate Editors: P.H. Stern and S.B. Arnaud

Sponsored by
Allgemaine Unfallversicharungsanstalt, Wien
European Space Agency

Mary Ann Liebert, Inc. publishers

JOURNAL OF BONE AND MINERAL RESEARCH

The Official Journal of the American Society for Bone and Mineral Research

Journal of Bone and Mineral Research is cosponsored by the National Osteoporosis Foundation

GENERAL INFORMATION

JOURNAL OF BONE AND MINERAL RESEARCH provides a forum for papers dealing with all areas of metabolic bone diseases and reports on the increasingly large body of research in this area.

JOURNAL OF BONE AND MINERAL RESEARCH (ISSN: 0884-0431) is published monthly for $276 by Mary Ann Liebert, Inc., 1651 Third Avenue, New York, NY 10128. Second-class postage paid at New York, NY, and at additional mailing offices.

Postmaster: Send address changes to *JOURNAL OF BONE AND MINERAL RESEARCH* c/o Subscription Department, Mary Ann Liebert, Inc., publishers, 1651 Third Avenue, New York, NY 10128.

JOURNAL OF BONE AND MINERAL RESEARCH is published by Mary Ann Liebert, Inc.

Subscriptions should be addressed to the Publisher and are payable in advance. Rates for subscriptions are $276 per volume of 12 issues in the United States and Possessions and $326 elsewhere. Subscriptions begin with the first issue of the current volume.

Reprints, except special orders of 100 or more, are available from the authors.

Information for Manuscript Submission is given on the inside back cover of this issue.

Business communications should be addressed to the Publisher.

Advertising inquiries from within the United States or Canada should be addressed to Mary Ann Liebert, Inc., 1651 Third Avenue, New York, NY 10128. Advertising inquiries from Europe and elsewhere should be addressed to Hilary Turnbull, imPress, 2 Penrith Avenue, Glasgow G46 6LU, Scotland; Telephone: 44 41 620 0106; Fax: 44 41 620 0055.

Manuscripts should be directed to the Editor: Lawrence G. Raisz, M.D., Head, Division of Endocrinology and Metabolism, The University of Connecticut Health Center, School of Medicine, Farmington, CT 06030.

All authored papers and editorial news and comments, opinions, findings, conclusions, or recommendations in the *JOURNAL OF BONE AND MINERAL RESEARCH* are those of the author(s), and do not necessarily reflect the views of the journal and its publisher, nor does their publication in the *JOURNAL OF BONE AND MINERAL RESEARCH* imply any endorsement.

JOURNAL OF BONE AND MINERAL RESEARCH is indexed in *Index Medicus, Current Contents/Life Science, Excerpta Medica, Cambridge Scientific Abstracts, Chemical Abstracts, Reference Update, Science Citation Index,* and *Nuclear Medicine Literature Updating and Indexing Service.*

JOURNAL OF BONE AND MINERAL RESEARCH is a **Journal Club™** selection.

Mary Ann Liebert, Inc. publishers

JOURNAL OF BONE AND MINERAL RESEARCH

VOLUME 7 | SUPPLEMENT 2 | DECEMBER 1992

Proceedings of the European Calcified Tissue Workshop
Functional Regulation of Bone Cell Biology by Mechanical Factors
Vienna, Austria
March 14, 1991
Editors: Elisabeth H. Burger, Ph.D. and Klaus Klaushofer, M.D.
Associate Editors: Paula H. Stern, Ph.D. and Sara B. Arnaud, M.D.

JOURNAL OF BONE AND MINERAL RESEARCH
Volume 7, Supplement 2, 1992
Mary Ann Liebert, Inc., Publishers

Demonstration of Subchondral Bone Density Patterns by Three-Dimensional CT Osteoabsorptiometry as a Noninvasive Method for In Vivo Assessment of Individual Long-Term Stresses in Joints

MAGDALENA MÜLLER-GERBL,[1] REINHARD PUTZ,[1] and ROLF KENN[2]

ABSTRACT

Since the work of Pauwels and his successors, it has been possible to use the distribution of subchondral bone density within a joint surface as a metric parameter that can reflect the principal long-term stress acting upon a joint. However, the x-ray densitometry method he employed cannot be applied to living people. A procedure was therefore developed whereby CT osteoabsorptiometry (CT OAM), based on the use of computed tomography, allows the distribution pattern of the density to be demonstrated in living subjects. This method has now been further developed, so that the form of the individual joint surfaces can be included by means of a three-dimensional reconstruction program. This method is presented here. In addition, selected representative examples of various joints from normal people, athletes, and patients are used to demonstrate the use of CT OAM. In these examples from living subjects, regularly occurring, reproducible distribution patterns of subchondral bone density can be recorded, reflecting changes in mechanical stresses on a joint (increased stress, reduced stress, and disorders of joint mechanics). CT osteoabsorptiometry is demonstrated as a suitable noninvasive technique for investigating the individual long-term stresses (loading history) acting on a living joint.

INTRODUCTION

THE MAGNITUDE OF LOAD acting locally is without doubt a decisive factor in the regulation of bone density, particularly in regions adjacent to joints (e.g., Refs. 1–3). Furthermore, certain sports, or a gain in weight, lead to a general increase in bone density,[4–8] whereas weight loss or a decrease in physical activity (e.g., immobilization or bed rest) leads to extensive osteoporosis.[9–11]

Investigations carried out by Pauwels[1,12] showed that the distribution of the principal resultant stress in a joint surface is related to that of the bone density. This relationship, which is true for both spongy and subchondral bone, led him to speak of a *verkörpertes Spannungsfeld* (materialized field of stress) in the subchondral lamellae. Further investigations by Kummer,[13] Knief,[14] and Amtmann[15] confirmed the high correlation between the degree of x-ray absorption (taken as a measure of bone density) and the distribution of stress as demonstrated in the photoelastic stress model. This endorsed Wolff's hypothesis[2] that bone adapts to functional necessity by a remodeling process, thus reflecting the distribution of the resultant force acting on it. A photographic procedure estimating the density distribution from an x-ray picture was introduced by Konermann[16] and further developed and refined by Schleicher et al.[17] It is today regarded as an established method of x-ray densitometry.

All these methods that demonstrate the density distribution over the subchondral joint surface suffer from a disadvantage, however. They are applicable only to thin sections and therefore cannot be used in a living subject.

Since information about the distribution of bone density

[1]Anatomische Anstalt der Ludwig-Maximilians-Universität München, Germany.
[2]Radiologische Abteilung der Chirurgischen Klinik Innenstadt der Ludwig-Maximilians-Universität München, Germany.

is of great diagnostic value for evaluation of the mechanical condition of individual joints, we used computed tomography (CT) to develop a procedure (CT osteoabsorptiometry (CT OAM)[18] that allows calculation of the area distribution of the subchondral bone density of a joint by computed tomography in the living subject. Thus, both the course of normal adaptation in the mechanics of a joint, as well as pathologic aberrations, can be monitored.

This article describes a further development of the original method[18] by which the subchondral pattern of mineralization within individual types of joint surfaces can be documented. Selected examples of various joints were used to demonstrate the pattern of mineralization in normal subjects, athletes, and patients and to illustrate the possibilities of the CT OAM technique.

MATERIAL AND METHODS

CT data sets with a section thickness of 2–4 mm from the persons listed in Table 1 provided the basis for arriving at the osteoabsorptiometric values.

TABLE 1. JOINTS UNDER INVESTIGATION BY CT OAM

Joint and number of persons	*Age (years)*
Hip joint	
20 healthy persons	18–90
Shoulder joint	
20 healthy persons	22–86
11 male gymnasts[a]	16–29
1 patient with dislocation[b]	45
Femoropatellar joint	
20 healthy persons	25–72
1 patient with poliomyelitis[c]	36

[a]Highly trained athletes who had pursued an intensive training program for 10 years.

[b]Male patient with traumatic dislocation of the shoulder joint whose humerus had remained unreduced for 3 months.

[c]Male patient with a history of childhood poliomyelitis whose left leg was able to bear only about 10% of the normal load.

CT osteoabsorptiometry

Values on the Hounsfield (HU) density scale were calculated with the EVADOS radiotherapy planing computer (Siemens, Erlangen, Germany) used in x-ray therapy (Fig. 1).[18] Conversion into the SIDOS-TELE format allowed calculation of geographic differences in density. These resulting images were then further processed by image-analyzing methods, and a false-color scheme was used to visualize regions of equal density.

To obtain a projection of the subchondral density onto the joint surface, the density values of single sections were measured at a predetermined depth of 1.5 mm and the results were transferred to a contour map of the joint, so that comparative analysis of the distribution of material over the entire joint surface became possible.

CT OAM by three-dimensional reconstruction

A further development of the method (Fig. 2) was achieved by introduction of a CT program for three-dimensional reconstruction, by means of which the density distribution of the subchondral mineralization was obtained in the computed tomogram itself. With this program, it was possible to reconstruct the joint surface itself, as well as the various density zones separately. An image-analyzing system was then able to provide a false color scheme demonstration of the density grades and their superimposition.

RESULTS

Hip joint

In young people, the maximal density is always localized in the ventral and dorsal regions of the socket. Density charts of the elderly, on the other hand, usually show a maximum in the central part of the facies lunata of the acetabulum (Fig. 3). The corresponding conventional anteroposterior (AP) x-rays, however, show in both cases the same shape for the subchondral layer (Fig. 4).

Shoulder joint

In young people, the zone of greatest density is found to be ventral and dorsal. In the elderly, however, it lies in the central region of the glenoid cavity (Fig. 5a and b).

The density in the glenoid cavity of gymnasts is markedly higher compared to nonathletes and is localized over a wide central area (Fig. 5c).

The patient with a long-term unreduced traumatic dislocation revealed a distinctly lower degree of mineralization throughout the joint (Fig. 5d).

Femoropatellar joint

In normal subjects there is a patellar maximum in the proximal part of the lateral joint facet (Fig. 6a). In the patient with poliomyelitis the regions of maximum density were in the correct position in both knees. However, the affected knee showed much lower mineralization than the nonaffected knee (Fig. 6b and c).

DISCUSSION

Our investigations have shown that the articular surfaces, at least of the larger joints, manifest a regularly occurring, reproducible distribution pattern of subchondral bone density, which can be made visible by means of CT osteoabsorptiometry. The surface representation of the density distribution makes it possible to estimate the individual distribution of material easily and quickly and thus provides information about the individual loading history of the joint. The advantages offered by the new procedure,

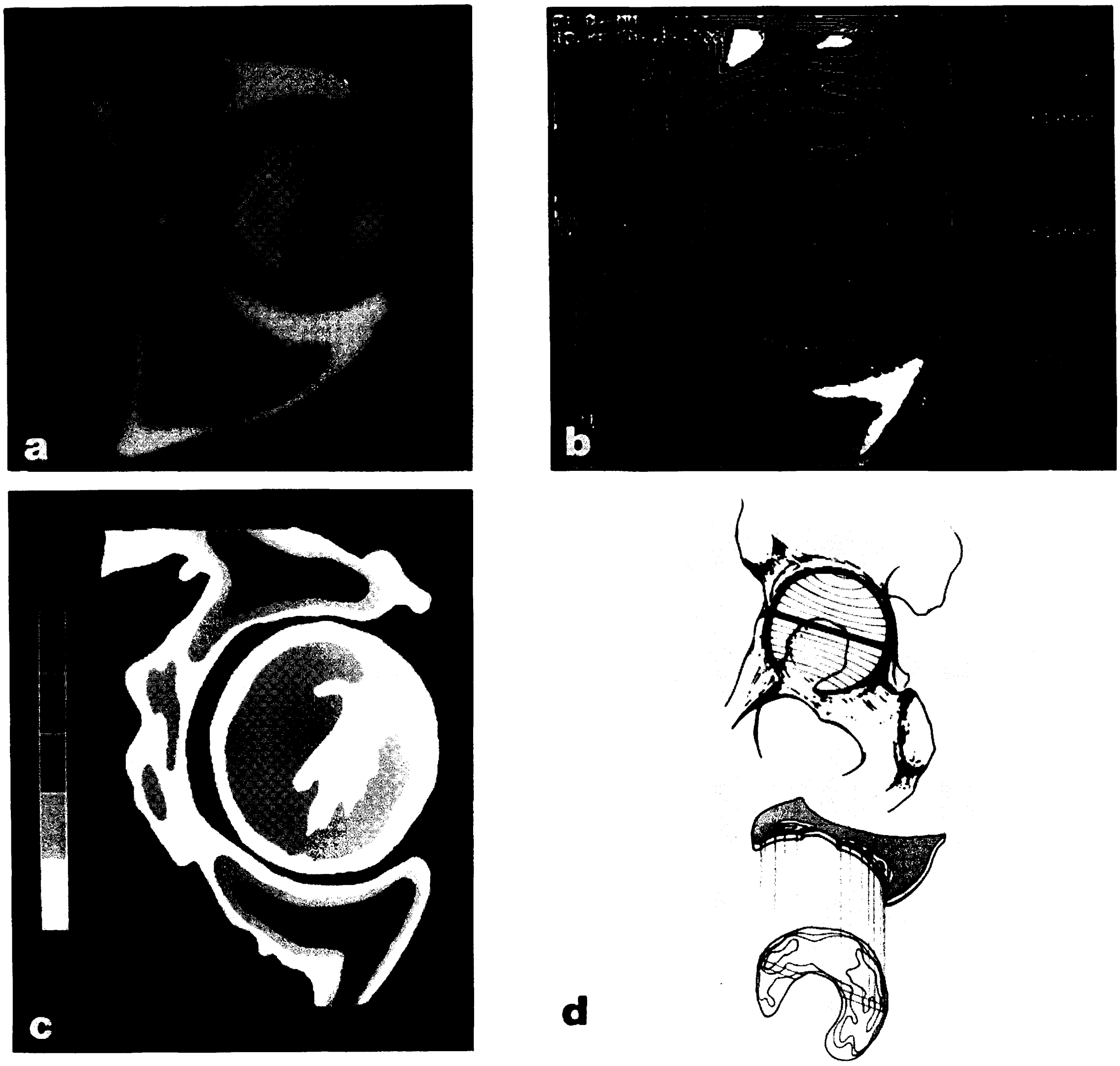

FIG. 1. CT osteoabsorptiometry of a right hip joint. (a) Axial CT section. (b) Isodensities in subchondral region of the acetabulum and femoral head. (c) Diagram of the articular surfaces of the hip joint showing regions of different density (copied from false color display). (d) Method of producing density maps from single sections.

which employs three-dimensional reconstruction, are that the accurate projection of the subchondral density onto the individual shape of each joint surface is now possible and can, additionally, be done in a much shorter time compared with the former method.

The impact of CT OAM is particularly well demonstrated by the acetabulum. Although the subchondral sclerosis in both the AP x-rays shown in Fig. 4 exhibits the same form ("sourcil"), the CT OAM reveals fundamentally different distribution patterns. This makes it clear that summation x-rays do not allow a differentiated localization of density differences within a joint surface to be elicited. Our new method permits information to be obtained not only in the frontal plane but also in the sagittal plane. For other joint surfaces, such as the glenoid cavity or the patella, information about the density distribution can be obtained only by means of CT OAM.

Comparison of the results obtained from the glenoid cavity in young and old normal subjects points to an age-dependent variation in the morphologic and mechanical conditions of the shoulder joint, thus adding to our earlier studies on elderly dissecting room cadavers,[19] in which a central maximum for mineralization was found. This age dependence of mineralization corresponds to findings in the acetabulum of the hip joint. The body of this joint shows an incongruence,[20,21] which tends to disappear with increasing age. Investigations of the contact surfaces in young people revealed corresponding contact zones in the anterior and posterior regions of the socket, whereas in older people these are central.

The age dependence of the morphologic findings also shows that the mechanics of a joint are largely determined by age changes. Therefore, the morphologic findings obtained from a particular group cannot be applied to other

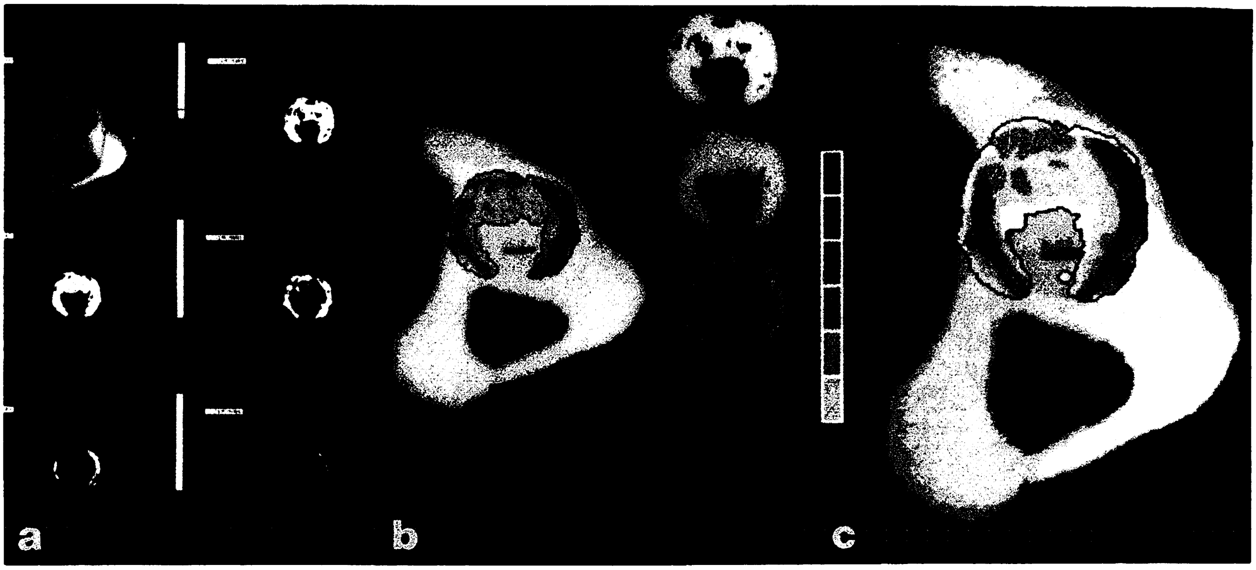

FIG. 2. Three-dimensional CT osteoabsorptiometry of a left hip joint by three-dimensional reconstruction. (a) The whole hip bone and the different density zones resulting from the three-dimensional reconstruction (seen from lateral). (b) Method of producing density maps in a false color display. (c) Resulting image.

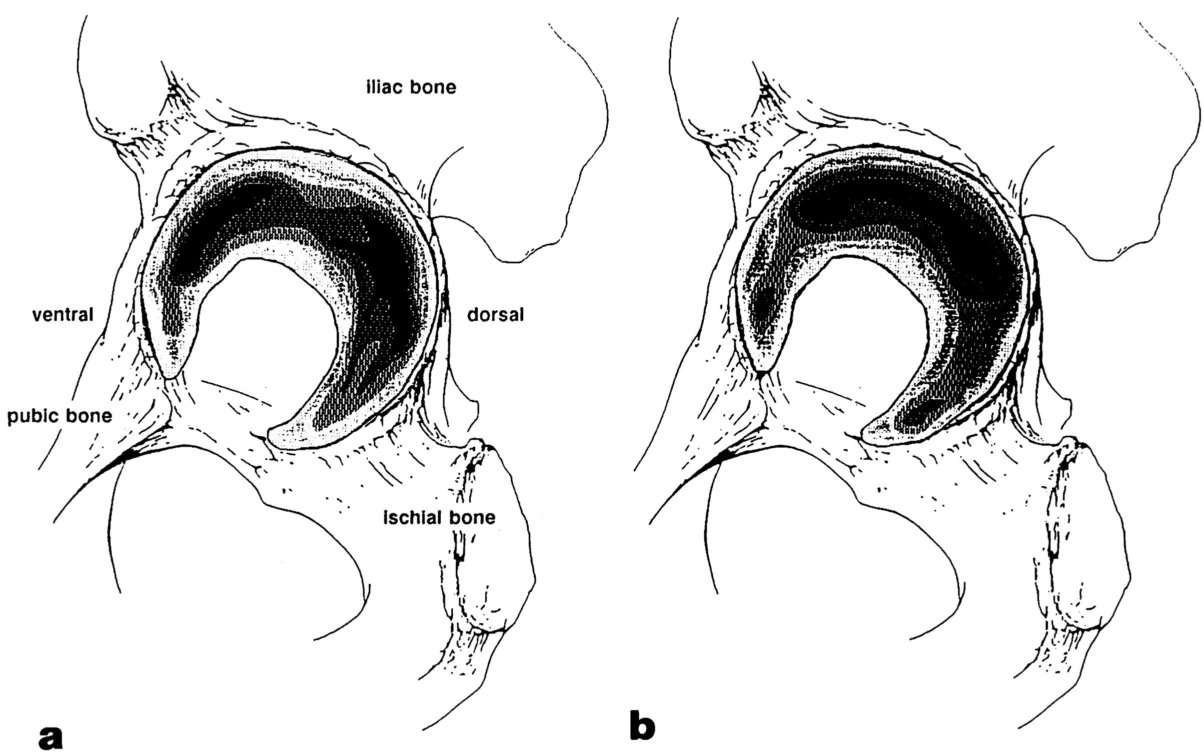

FIG. 3. Density maps of the entire lunate facet of the hip joint (seen from lateral) of (a) an 18-year-old girl: the zones of highest density are found ventrally and dorsally; and (b) a 68-year-old woman: the maximum is localized in the central part of the acetabulum.

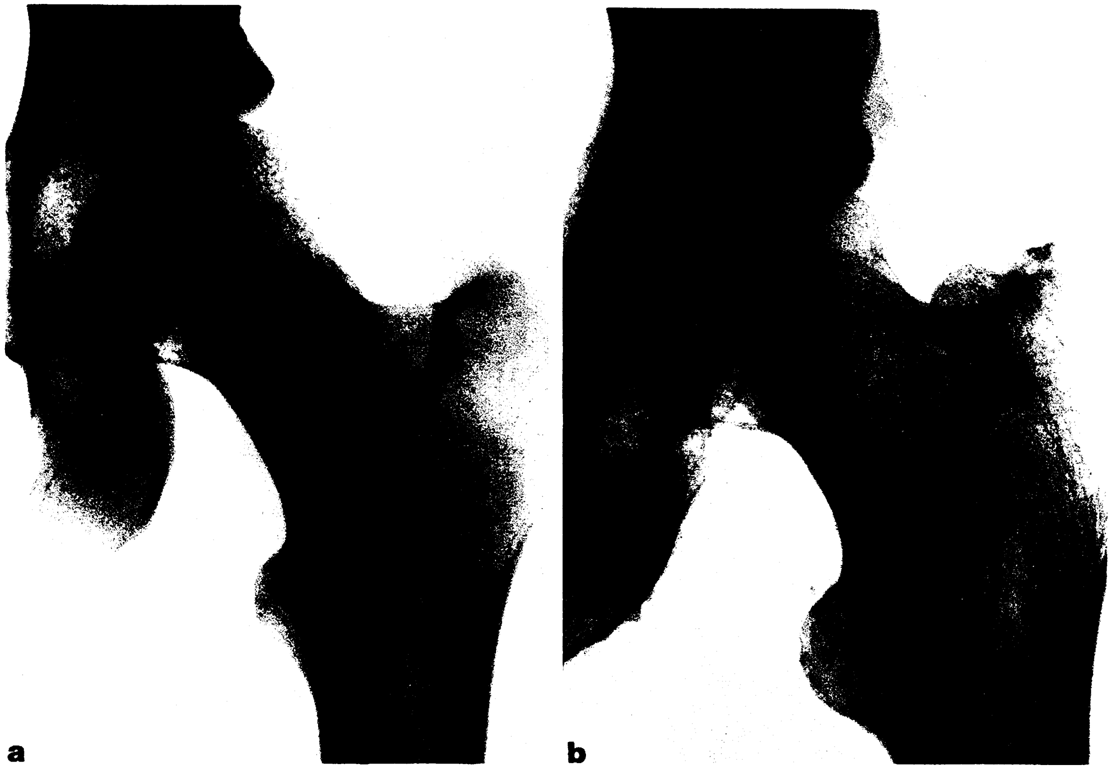

FIG. 4. AP x-rays of the hip joint of the same persons as in Fig. 3. Despite the different density patterns by CT OAM, the shape of the subchondral layer of the acetabulum (arrows) show no difference in both x-rays: (a) 18-year-old girl; (b) 68-year-old woman.

age groups, and an age dependence that is of therapeutic value may emerge. Furthermore, these data may be important for the design of prostheses.

In accordance with the interdependence already mentioned, continual remodeling changes in bone take place and constitute an adaptive reaction to each mechanical situation of the joint. Increased loading leads to increase in bone density,[4-8] reduced loading to bone resorption.[9-11] This is very clearly supported by the findings in the socket of the shoulder joint in gymnasts, as shown by density values, which are markedly higher than in normal subjects. It is well known that, in ring gymnasts, the body weight may during certain practice phases undergo a fivefold increase. This is confirmed by the investigations of Bodem et al.,[22] which offer a clear explanation for the increased mineralization. High, intermittently appearing resultant forces in a joint lead to the appearance of repeated peak pressure points in the central region of the socket, which thus becomes excessively in demand as a contact area. This can be seen as a biologic stimulus, leading to an increase in the mineralization in the region.

Decreased mineralization as the result of reduced demand was apparent in the patient in whom a dislocated shoulder joint remained reduced for 3 months. The patient with poliomyelitis also reflected the failure to use his left leg fully by showing a marked reduction in the mineralization of the patella on the paralyzed side. These examples are regarded as representing the final situation of increased or decreased stress acting over a long period of time but do not provide information on the temporal course of the density changes themselves.

The regular occurring, reproducible distribution patterns of subchondral mineralization appearing in the articular surfaces of large joints are an expression of each mechanical situation, revealed as remodeling changes in the bone and reflecting the loading history.

It must be expressly emphasized that the methods we report do not deal with the calculation of absolute values but are much more concerned with demonstrating differences in relative concentration within a joint surface. In contrast to the usual methods of CT densitometry used for the diagnosis of osteoporosis, CT osteoabsorptiometry, because of various radiologic effects (partial volume effect and beam hardening), can only be used with reproducible results on the subchondral bony lamellae or on compact bone.[18] To obtain objectively quantified density values available over a period of time, quantitative dual-energy computed tomography (QDECT) must be used or the measurements compared with a reference phantom control.

An important question arising in connection with these distribution patterns is whether changes in bone mass density (physical density) as a whole are being demonstrated, or merely differences in the degree of mineralization. In a comparative investigation employing quantitative dual-energy computed tomography with basis material decomposition,[23] it was possible to show that the distribution of

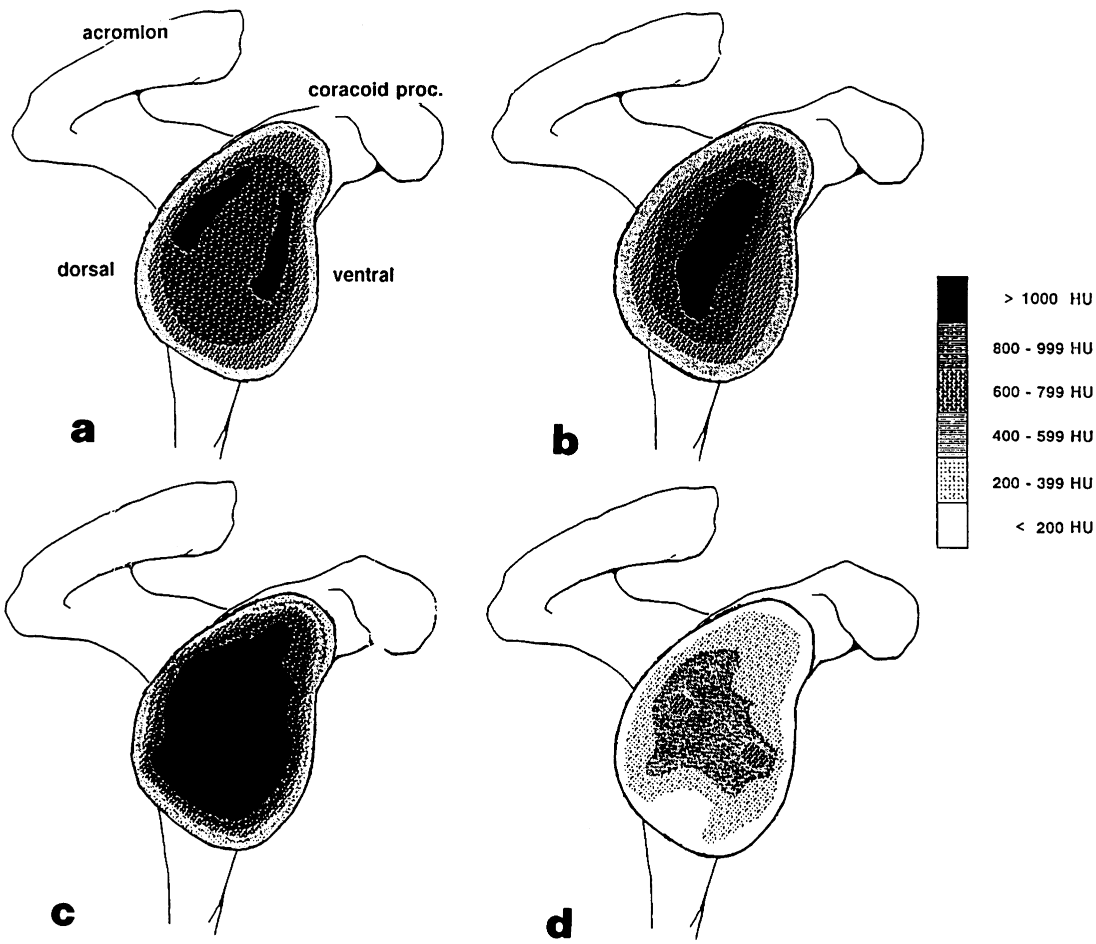

FIG. 5. Density maps of the glenoid cavity of the shoulder joint (lateral view) of (a) a 36-year-old healthy man: zone of greatest density is found to be ventral and dorsal; (b) a 78-year-old healthy man: the maximum lies in the central region of the glenoid cavity; (c) a 23-year-old gynmast: the overall density is markedly increased and localized over a wide central area; and (d) a 45-year-old male patient with traumatic dislocation without reduction of the humerus for 3 months. This density pattern revealed a clearly lower degree of mineralization throughout the joint.

mineralized tissue within a joint surface can be demonstrated by CT OAM.

Any possible correlation of these patterns of mineralization with the mechanical properties of bones—strength or stiffness, for example—remains to be tested.

The diagnostic value of the method can only be assessed during further prospective studies with carefully chosen patient and control groups. This is also true for the time needed for adaptation to changes in the mechanical stress to occur.

CLINICAL RELEVANCE

Our findings show that CT osteoabsorptiometry offers a wide range of applications. It can be employed for diagnostic purposes to gain information about the individual mechanical situation of a joint. It also provides a procedure for use in basic clinical research, since it is a noninvasive technique that does not unreasonably burden the patient.

In our opinion, this method can be used in those areas of medical practice dealing with sport or in industry, where heavy demands are made upon the joints, for the early detection of altered loading conditions. This methodology may be useful in following the clinical course of patients with mild to moderate osteoarthrosis.

The value of CT OAM for biomechanics lies in its ability to demonstrate the morphologic counterpart of the long-term stress acting on a joint in the living subject and also to follow the mechanical changes that take place in the course of a lifetime. For example, CT OAM can be used to

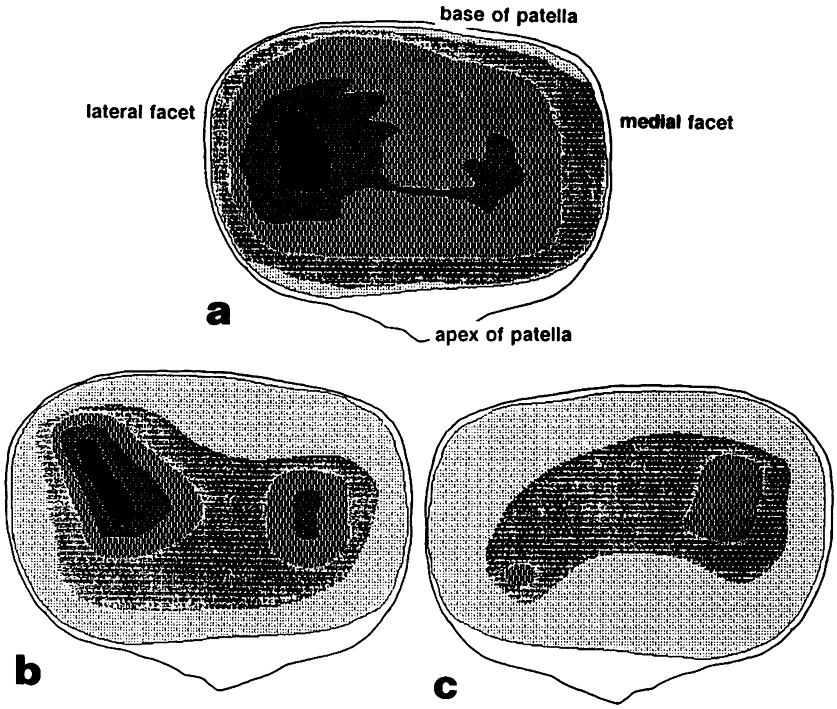

FIG. 6. Posterior view of articular surface of patella showing the subchondral density distribution of (a) a 46-year-old healthy man (right knee): the maximum is in the proximal part of the lateral joint facet; (b) a 36-year-old man with a history of childhood poliomyelitis (right, nonaffected knee); and (c) the left knee of the same patient (affected leg). The regions of maximum density lay in the same position on both sides, but the mineralization is generally lower on the affected side.

monitor the resultant changes in mechanical force distribution pre- and postoperatively in correction operations, such as femoral, supracondylar femoral, or high tibial osteotomy. At present it is not possible to display the progress of stress distribution in the bone surrounding a total joint prosthesis, because our technique cannot be used in the presence of metallic devices since they produce artefacts leading to false density values.

ACKNOWLEDGMENT

The authors would like to thank Dr. F. Eckstein for submitting Fig. 6.

REFERENCES

1. Pauwels F 1965 Gesammelte Abhandlungen zur Biomechanik des Bewegungsapparates. Springer, Berlin.
2. Wolff J 1892 Das Gesetz der Transformation der Knochen. Verlag A. Hirschwald, Berlin.
3. Roux W 1895 Gesammelte Abhandlungen über Entwicklungsmechanik der Organismen I und II. Engelmann, Leipzig.
4. Jones H, Priest J, Hayes W, Tichenor C, Nagel D 1977 Humeral hypertrophy in response to exercise. J Bone Joint Surg [Am] **59**:204–208.
5. Nilsson B, Westlin N 1971 Bone density in athletes. Clin Orthop **77**:179–182.
6. Chamay A, Tschantz P 1972 Mechanical influences in bone remodelling. Experimental research on Wolff's law. J Biomechan **5**:173–180.
7. Woo S, Kuei S, Amiel D, Gomez M, Hayes W, White F, Akeson W 1981 The effect of prolonged physical training on the properties of long bone: A study of Wolff's law. J Bone Joint Surg [Am] **63**:780–787.
8. Martin R, Albright J, Clarke W, Niffenegger J 1980 Load-carrying effects on the adult beagle tibia. Sports Exerc **13**: 343–349.
9. Issekutz B, Blizzard J, Birkhead N, Rodahl K 1966 Effect of prolonged bed rest on urinary calcium output. J Appl Physiol **21**:1013–1020.
10. Donaldson C, Hulley S, Vogel J, Hattner R, Bayers J, McMillan D 1970 Effects of prolonged bed rest on bone mineral. Metabolism **19**:1071–1084.
11. Whedon D 1984 Disuse osteoporosis: Physiologic aspects. Calcif Tissue Int **36**:146–150.
12. Pauwels F 1980 Biomechanics of the Locomotor Apparatus. Springer, Berlin.
13. Kummer B 1962 Funktioneller Bau und funktionelle Anpassung des Knochens. Anat Anz **111**:261–293.
14. Knief JJ 1967 Materialverteilung und Beanspruchungsverteilung im coxalen Femurende: Densitometrische und spannungsoptische Untersuchungen. Z Anat Entw.-gesch **126**:81–116.
15. Amtmann E 1971 Mechanical stress, functional adaption and the variation-structure of the femur diaphysis. Ergebn. Anat. Entw.-gesch, Vol. 44, Part 3. Springer, Berlin.
16. Konermann H 1971 Quantitative Bestimmung der Materialverteilung nach Röntgenbildern des Knochens mit einer

neuen photographischen Methode. Z Anat **134**:13–48.
17. Schleicher A, Tillmann B, Zilles K 1980 Quantitative analysis of x-ray images with a television image analyser. Microsc Acta **83**:189–196.
18. Müller-Gerbl M, Putz R, Hodapp N, Schulte E, Wimmer B 1989 Computed tomography-osteoabsorptiometry for assessing the density distribution of subchondral bone as a measure of long-term mechanical adaptation in individual joints. Skeletal Radiol **18**:507–512.
19. Müller-Gerbl M, Putz R, Hodapp N, Schulte E, Wimmer B 1990 Computed tomography-osteoabsorptiometry: A method of assessing the mechanical condition of the major joints in a living subject. Clin Biomech **5**:193–198.
20. Bullough P, Goodfellow J, Greenwald AS, O'Connor J 1968 Incongruent surfaces in the human hip joint. Nature **217**: 1290.
21. Bullough P, Goodfellow J, O'Connor J 1973 The relationship between degenerative changes and load-bearing in the human hip. J Bone Joint Surg [Br] **55**:746–758.
22. Bodem F, Brussatis F, Menke W 1984 Zur theoretischen Biomechanik des Schultergelenkes: Die Entstehung gewöhnlicher und aussergewöhnlicher mechanischer Belastungen des glenohumeralen Gelenkknorpels. In: Refior HJ, Plitz W, Jäger M, Hackenbroch MH (eds) Biomechanik der gesunden und kranken Schulter. Thieme, Stuttgart, pp 82–87.
23. Müller-Gerbl M, Hodapp N, Reinbold WD, Putz R 1991 Can CT osteoabsorptiometry be used to display the distribution of subchondral mineralisation? (abstract) Calcif Tissue Int. Suppl **48**:68.

Address reprint requests to:
Dr. M. Müller-Gerbl
Anatomische Anstalt
Pettenkoferstr. 11
D-8000 Mñchen 2, Germany