TEXTURE ANALYSIS OF RADIOGRAPHIC TRABECULAR PATTERNS IN DISUSE OSTEOPENIA

Kaufman, J.J., Mont, M.A., +Hakim, N., *Ohley, W., *Lundahl, T., Soifer, T.,
and Siffert, R.S., Mt. Sinai School of Med., New York, N.Y., *Univ. of
Rhode Island, Kingston, R.I., + Columbia University, New York, N.Y.

INTRODUCTION: Bone strength is determined by many factors including overall density, cortical thickness and trabecular architecture. Since the earliest changes in bone during osteoporosis occur in trabecular areas, we feel that radiographic images of those regions of bone contain diagnostically relevant information. Radiographic trabecular pattern changes have been studied by Singh [1] and others on a gross level and in a more quantitative manner by Rockoff [2] who analyzed angular orientations of normal and osteoporotic bone from computer digitized images. It is the objective of this study to further quantitate trabecular pattern changes of standard x-rays in a disuse osteopenic and bone reformation clinical situation. We employ digital image processing and texture analysis methods to extract features useful for monitoring changes that occur in trabecular patterns during degenerative bone diseases.

METHODS: X-rays of the os calcis of 5 patients who sustained an ankle fracture were analyzed. Each patient was treated by a period of plaster immobilization for several weeks to several months. The x-ray images of the calcanei at the time of fracture were considered the baseline for each patient and subsequent images were compared for trabecular pattern changes over a period of 1 month to 5 years post-fracture.

Analysis of the images was restricted to a standardized 2 cm^2 area encompassing most of the major compressive trabeculae of the calcaneus (Fig. 1). The x-ray images were digitized from a light box using a video camera interfaced to an IBM PC/AT computer using an analog to digital interface board (Imaging Technology, Woburn, MA) and image processing software (Werner Frei Associates, Santa Monica, CA), and were stored on disk for off-line processing and analysis. The images were histogram equalized to compensate for variations in grey level distribution. An aluminum calibration wedge was used in some of the radiographs to compensate for exposure artifacts and to investigate the sensitivity of the pattern recognition procedures employed to variations in radiographic procedure. The wedge also allows the incorporation of densitometric measurements into the feature space.

Several types of texture analysis were used to extract features from the trabecular images: (1) Classical Texture Analysis (run lengths, cooccurrences, 2-D Fourier transforms and variograms); (2) Fractal Analysis (one- and two-dimensional); (3) Structural Analysis (trabecular orientation and relative extrema density); and (4) Random Field Modeling (spatial autoregressive and Gauss-Markov). [3]

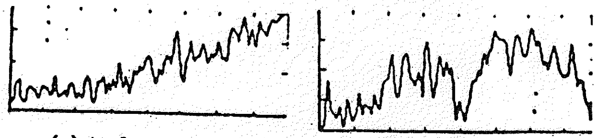
RESULTS: Some of the features obtained with the above techniques did not show a consistent correlation with the clinical history of the patients. However, there were three which did give good overall performance: run lengths, fractals and relative extrema density. Fractal results are being reported in a separate publication [4]. Relative extrema density curves are presented in Fig. 2 and correspond to the images of Fig. 1. Table I presents relative extrema data for three typical patients. Run length statistics (the ratio of long run emphasis to short run emphasis) at four different time points for the five patients in the study are plotted in Fig. 3.

DISCUSSION AND CONCLUSION: A consistent correlation was found between certain textural features (run lengths, relative extrema density, and fractals) derived from x-ray images and the associated clinical history of the patients. The measure of relative extrema density should be especially relevant to the diagnosis of degenerative bone diseases since it is a statistical representation of the trabecular bone spacing and density. These radiographic analyses may also have significance with respect to their ability to predict the overall biomechanical competence of trabecular bone [5]. The increase observed in the ratio of long run emphasis to short run emphasis may be a result of the general coarsening of the image which seems to take place in initial stages of bone loss. The grey level run length approach characterizes coarse textures as having many pixels in a constant grey tone run and fine textures as having few pixels in a constant grey tone run.

This study demonstrates that textural analysis of radiographic trabecular patterns can be employed to quantitate architectural changes under clinical circumstances of disuse osteopenia.

(a) At fracture (b) Five months post fracture

Figure 1: Digitized Image



(a) At fracture (b) Five months post fracture

Figure 2 Relative Extrema Curves

TABLE I: RELATIVE EXTREMA DATA

	MONTHS AFTER FRACTURE								
PATIENT	0	1	2	3	5	9	10	16	60
AM	27		23	21	23	21			
CF	31	22			22			27	
AS	23	21			19				18

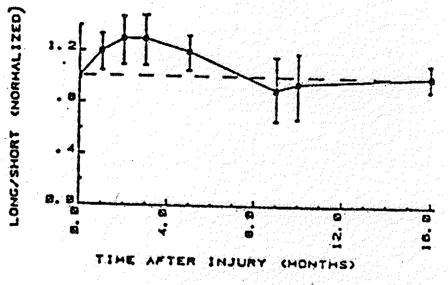


Figure 3: Run Length Statistics

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Jonathan J. Kaufman, Dept. of Orthopaedics, Mount Sinai School of Medicine, 1 Gustave L. Levy Place, New York, N.Y. 10029

DIGITAL IMAGE PROCESSING OF VERTEBRAL COMPUTED TOMOGRAPHY SCANS FOR MECHANICAL STRENGTH ESTIMATION

J.J. Kaufman, N. Hakim, P. Nasser, M. Mont, M. Klion, G. Herman, A.A. Pilla and R.S. Siffert
Department of Orthopaedics, Mount Sinai Medical Center, NY, NY
Department of Electrical Engineering, Columbia University, NY, NY

INTRODUCTION The accurate clinical assessment of fracture risk in osteoporotic patients is important for appropriate treatment to be instituted and the progress of therapy monitored. Currently, clinical evaluation relies primarily on bone mineral measurements such as quantitative computed tomography (QCT) of the spine. Although widely used, these density-based methods do not accurately discriminate between fracture and non-fracture populations: this may be due, in part, to the fact that density measurements do not contain information about the structure of trabecular bone. Architecture has been shown to be correlated with the incidence of vertebral compression fractures [1] and suggested as a major determinant of mechanical strength [2]. A previous study has demonstrated that changes in trabecular patterns in radiographs of human calcaneii with disuse osteopenia can be detected using digital image processing and texture analysis techniques [3]. The goal of the present study was to determine if the application of these techniques to conventional vertebral CT scans could be used to measure trabecular architecture and more accurately estimate <u>in vitro</u> mechanical strength compared to only QCT.

MATERIALS AND METHODS Twenty lumbar vertebrae were harvested from ten cadavera within twelve hours after death, and frozen at -20°C until needed. The donors' ages ranged from thirty to ninety-six years, with a mean of fifty-seven years. Three contiguous five millimeter CT scans of each vertebra were obtained (Model 9800, General Electric, Milwaukee, WI). The spines were immersed in a circular water bath and scanned with a hydroxyapatite phantom (courtesy of General Electric) for mineral equivalent calibration (mg/cc) of the CT numbers.

Digital processing of the CT images was performed using an IBM-PC/AT computer. The average mineral density (QCT) was obtained from analysis of the CT image corresponding to a 2 cm^2 central portion of the vertebra. Textural analysis using the relative extrema statistical approach [4] was performed on the same portion of the image. The QCT and textural statistics of each image of the three-image set were averaged to obtain the final estimate of bone mineral density and architecture for each vertebra.

A two cm cube of trabecular bone was cut from the central part of each vertebra using a Buehler Isomet circular saw under constant irrigation. The cube corresponded to the vertebral portion from which QCT and textural statistics were obtained. A uniaxial compressive load was applied to each specimen at a constant deformation rate of 0.085 mm/sec with an Instron (Canton, MA) machine. The stress versus strain curve was obtained and the maximum compressive stress recorded.

RESULTS AND DISCUSSION The values obtained for QCT ranged from 19 mg/cc for a 96 year old female to 192 mg/cc for a 42 year old male. A log-log plot of maximum stress versus QCT value and a best-fit power law relationship ($R^2 = 0.91$, $p < 0.001$) are shown in Fig. 1. A semilog plot of maximum stress versus mean extrema spacing and a best-fit exponential relationship ($R^2 = 0.39$, $p < 0.005$) are shown in Fig. 2. Using both QCT and mean extrema spacing in a multivariate regression for maximum stress did not result in a significant ($p > 0.40$) reduction in mean squared error.

DISCUSSION AND CONCLUSION A significant relationship was found between mean extrema spacing and the log of maximum stress. This architectural feature did not, however, increase the accuracy of estimation of stength over that obtained by using QCT alone. Further investigations are ongoing to develop more sensitive textural measures of trabecular architecture. A study of the textural features of sagittal CT vertebral scans is also being performed to assess their correlation with mechanical strength, since these views may be more indicative of structural changes [5]. It will also be important to understand more fully the relationship between trabecular architecture and strength, and how this structure manifests itself as textural information in CT images. The results presented imply that digital image processing and texture analysis has potential for assessing mechanical strength of bone and together with QCT could be used for accurate and non-invasive prediction of fracture risk.

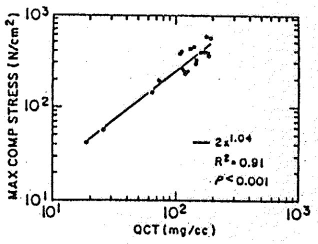

Fig.1: Log-log plot of strength vs QCT.

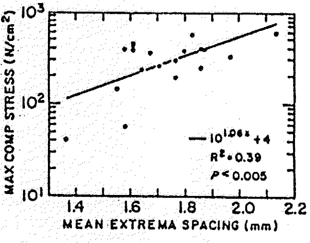

Fig.2: Log-linear plot of strength vs mean spacing.

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TEXTURE ANALYSIS OF VERTEBRAL COMPUTED TOMOGRAPHY SCANS IMPROVE TRABECULAR STRENGTH ESTIMATION

J.J. Kaufman, P. Nasser, M. Mont, N. Hakim, A.A. Pilla and R.S. Siffert
Department of Orthopaedics, Mount Sinai School of Medicine, NY

INTRODUCTION: The ability to assess bone strength is important for accurately diagnosing osteoporosis and monitoring the course of treatment. Present techniques rely primarily on the measurement of bone mineral density, determined, for example, by quantitative computed tomography (QCT), and provide a reasonable estimate of bone strength and fracture risk. There are other factors which must be taken into account, such as bone architecture and quality. The relationship between bone mass, trabecular architecture and bone strength is examined in this paper. Kleerekoper [1] examining the relationship between trabecular architecture measured histologically and bone strength, showed certain architectural features are better correlated with strength than bone density. We have demonstrated that architectural changes in plain radiographs of trabecular bone can be quantified in a disuse human model [2]. We have also shown that transverse computed tomographic (CT) images of vertebral specimens provide limited architectural information related to bone strength [3]. The purpose of the present work was to further develop digital image processing-based methods for assessing trabecular architecture from radiographic images of bone, and to establish radiographic architectural measures closely related to bone strength.

MATERIALS AND METHODS: Thirty lumbar vertebrae were harvested from ten cadavera within twelve hours after death, and frozen at -20°C until needed. The donors' ages ranged from thirty to ninety-six years, with a mean of fifty-seven years. Three contiguous five millimeter transverse CT scans of each vertebrae were obtained (Model 9800, General Electric, Milwaukee, WI). Sagittal CT's were also obtained for one vertebrae from each cadaver using a 1.5 mm scan. The spines were immersed in a circular water bath and scanned with a hydroxyapatite phantom (courtesy of General Electric) for mineral equivalent calibration (mg/cc) of the CT numbers. Digital processing of the CT images was performed using an IBM-PC/AT computer. The average mineral densities (QCT) were obtained from analysis of the transverse and sagittal CT images corresponding to 2 cm square central transverse and sagittal portions, respectively, of the vertebrae. Trabecular architecture was quantified by textural analysis of the sagittal CT scans. Run length textural statistics [4] measured the relative degree of coarseness or fineness of the CT image. The relative asymmetry or anisotropy of the image in the horizontal and vertical directions was characterized by the respective ratio of run length statistics, and measured by the relative asymmetry index α. For mechanical testing, 2 cm cubes of trabecular bone were cut from the central part of each of 20 vertebrae, using a Buehler Isomet circular saw under constant irrigation. The cube corresponded to the vertebral portion from which QCT values were obtained. A uniaxial compressive load was applied to each specimen at a constant deformation rate of 0.085 mm/sec with an Instron (Canton, MA) machine. The stress versus strain curve was obtained and the maximum compressive stress recorded. The 10 sagittally scanned vertebral specimens were not mechanically tested.

RESULTS: The values obtained for QCT ranged from 19 mg/cc for a 96 year old female to 192 mg/cc for a 42 year old male. The QCT values for the transverse and sagittal vertebral images of the same vertebra were highly correlated (r=0.92). A log-log plot of maximum stress versus transverse QCT value and a best fit power law relationship (R^2=0.91, $p<0.001$) is shown in Fig.1. The relationship between asymmetry index α and compressive strength of the adjacent vertebra is shown in Fig.2. The Table shows results for a matched (age/sex) pair which relate asymmetry, mass, and strength.

DISCUSSION AND CONCLUSION: The results show a high correlation of trabecular bone mineral density with compressive strength. However, the data also shows several examples in which bone with less mineral mass is stronger than bone with more mineral mass; therefore, other factors are involved. In this work, we assumed the ultimate compressive stress of a vertebra can be estimated by the strength of an adjacent vertebra. The asymmetry index α appears to be a discriminating factor for strength estimation under this assumption. The matched pair result (Table) suggests bone density and asymmetry index can, together, serve as more accurate predictors of bone strength than bone mass alone. In conclusion, more accurate assessments of *in vivo* bone strength and fracture risk should be possible by using architectural information in radiographic images of trabecular bone.

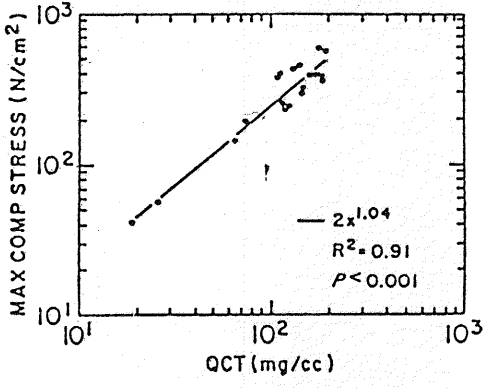

Fig. 1: Vertebral Compressive Strength vs QCT

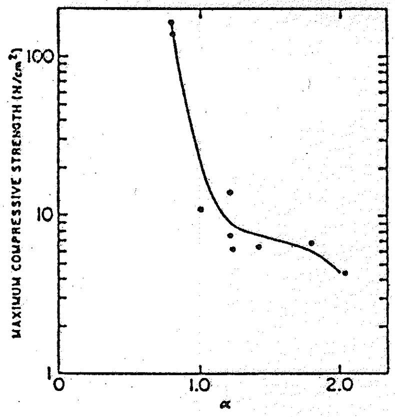

Fig. 2: Vertebral Compressive Strength vs. Asymmetry Index α

TABLE

SEX/AGE	QCT (mg/cc)	α	STRENGTH (kg)
M/56	127	1.2	168
M/56	145	3.0	141

ACKNOWLEDGEMENTS: The authors gratefully acknowledge C.E. Cann and W.C. Hayes for their helpful suggestions, D. Bigler, A. Jackson, M. Figueiredo for their assistance.

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VERTEBRAL CT IMAGE SEGMENTATION FOR TRABECULAR ARCHITECTURE ASSESSMENT

J.J. Kaufman, J. el-Batal, M. Figueiredo, P. Nasser, M. Mont, A.A. Pilla and R.S. Siffert

Department of Orthopaedics, Mount Sinai School of Medicine, New York, NY 10029.

INTRODUCTION: The accurate clinical assessment of bone strength and fracture risk is important for management of bone loss diseases such as osteoporosis. Current techniques which include quantitative computed tomography (QCT) rely primarily on mass measurement for assessing bone mechanical integrity. These methods do not, however, always provide reliable estimates of bone strength and fracture risk. One reason is trabecular bone architecture, which is not identified in mass measurements, can also be an important factor contributing to bone strength. We have previously applied digital image processing and texture analysis techniques to both plain radiographs and vertebral CT scans for quantifying trabecular architecture [1-3]. The purpose of the present study is to further elucidate the relationship between trabecular bone strength and CT derived architectural features.

MATERIAL AND METHODS: Thirty lumbar vertebrae were harvested from seven cadavera within twelve hours after death, and frozen at -20°C until needed. The donors' ages ranged from thirty to ninety-six years, with a mean of fifty-seven years. Three contiguous five millimeter transverse CT scans of each vertebrae were obtained (Model 9800, General Electric, Milwaukee, WI). Sagittal CT's were also obtained for one vertebrae from each cadaver using a 1.5mm scan. The spines were immersed in a circular water bath and scanned with a hydroxyapatite phantom (courtesy of General Electric) for mineral equivalent calibration (mg/cc) of the CT numbers. Digital processing of the CT images was performed using am IBM-PC/AT computer. The average mineral densities (QCT) were obtained from analysis of the transverse and sagittal CT images corresponding to 2cm square central transverse and sagittal portions, respectively, of the vertebrae. A digital segmentation algorithm designed specifically for vertebral trabecular bone was developed and applied to the sagittal CT images. The algorithm uses matching templates and local thresholding to create a binary image which retains trabecular thickness in contrast to more common line tracing algorithms. The segmented sagittal CT images were analyzed using the fabric asymmetry index (FAI) which is closely related to the fabric ellipsoid described by Cowin [4]. It is defined as the ratio of the maximum to minimum value of the mean intercept length, which for vertebral specimens corresponds approximately to vertical (0°) and horizontal (90°) directions, respectively. For mechanical testing, 2cm cubes of trabecular bone were cut from the central portion of each of 20 vertebrae, using a Buehler Isomet circular saw under constant irrigation. The cube corresponded to the vertebral portion from which QCT and FAI values were obtained. A uniaxial compressive load was applied to each specimen at a constant deformation rate of 0.085 mm/sec with an Instron machine. The stress versus strain curve was obtained and the maximum compressive stress recorded. The seven sagittally scanned vertebral specimens were not mechanically tested.

RESULTS: A binary segmented image of a sagittal vertebral CT and a graph of mean intercept length versus angle are illustrated in figures 1 and 2, respectively. The table presents FAI, QCT, and maximum compressive strength values of the adjacent vertebra for nine vertebral specimens. Regression analysis of QCT versus maximum strength has been previously presented [3] and resulted in a linear relationship (R^2=0.91). A multivariate regression for the nine specimens using both QCT and FAI to predict strength did improve the regression fit, but was not statistically significant.

DISCUSSION AND CONCLUSION: Architecture of bone is an important factor contributing to its strength. Although histomorphometric analysis can be used in basic studies to explore the relationship between mass, architecture and strength, we have analyzed architecture using a fabric measure (FAI) from sagittal CT images. The small number of samples in our study made it difficult to establish statistical significance with respect to improvement in mean squared regression error. However, the non-invasive approach developed here, which utilizes a binary segmentation algorithm, provides a method for non-invasive assessment of trabecular architecture. This should lead eventually to more accurate clinical assessment of fracture risk.

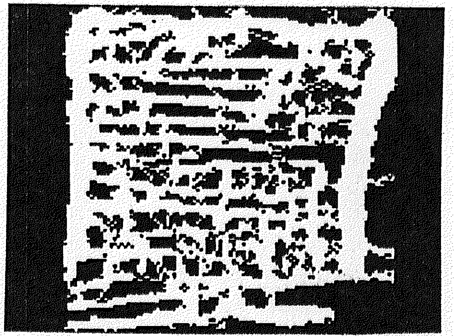

Figure 1. Binary segmented vertebral CT.

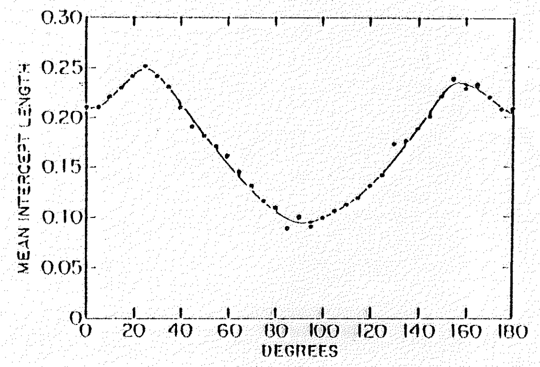

Figure 2. Mean intercept length vs. angle for segmented CT.

TABLE

Max. Comp. Strength	QCT	FAI
61	70	1.5
64	120	3.8
128	115	1.7
133	160	2.7
142	160	2.3
156	170	2.6
168	138	2.6

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QUANTITATIVE ANALYSIS OF TRABECULAR ARCHITECTURE IN PLAIN RADIOGRAPHS OF THE HUMAN OS CALCIS

RS Siffert, G. Luo+, JJ Kaufman and SC Cowin+

The Mount Sinai School of Medicine, New York, NY
+Dept. of Mechanical Engineering, City College (CUNY), New York, NY.

INTRODUCTION: The accurate clinical assessment of bone strength and fracture risk is important for management of bone loss diseases such as osteoporosis. Current techniques such as dual energy x-ray absorptiometry (DEXA) provide accurate estimates of bone mass, but do not always provide reliable estimates of bone strength and fracture risk. One reason is that trabecular architecture, which is not identified in mass measurements, can also be an important factor contributing to bone strength. The primary objective of the present study was to determine if quantitative measurements of trabecular architecture as represented by mean intercept length (MIL) or fabric, and a new feature, known as covariance, could be evaluated from plain radiographs. Another related objective was to compare these x-ray derived architectural features with those evaluated from the actual underlying trabecular structure.

MATERIAL AND METHODS: Six human os calci were obtained from subjects of unknown age and sex, and for which all soft tissue was removed previously. Plain radiographs were acquired of each calcaneus in the lateral view. The radiographs were then digitized into 512x480 pixels 8-bit digital images through use of a PC computer and video acquistion software and hardware [1]. An approximately 16 mm x 16 mm rectangular region from the superior-posterior portion of the os calci was used for evaluating the architectural features. A local thresholding procedure was implemented to produce a binary image which was then analyzed with fabric and covariance measures at 10° increments. For the fabric analysis, the length (F1) and orientation (O) of the major axis together with the MIL value (F2) orthogonal to the major axis was recorded. For the covariance analysis, the largest value (C1) and its angular orientation (O) together with the covariance value (C2) orthogonal to the major orientation was recorded. Following this, two of the os calci were cut in half with a band-saw in the sagittal plane. One half of each of the two os calci was sanded smooth, and then each of the two surfaces was lightly coated with black ink, to enhance the contrast between the trabeculae and marrow spaces. They were then digitized as before, and identically processed except that a global thresholding technique was used. The fabric and covariance data for the two bone slices were also recorded.

RESULTS: The covariance data for os calcis #2 is shown in polar form in Fig. 1, for both the radiographic derived and bone slice data. As may be seen, there is a close correspondence in overall shape and orientation. The Table provides the results from the radiographic images for all the samples, as well as the corresponding slice data for samples 1 and 2. As may be seen for these two samples, the covariance data for the radiographs and slices are oriented identically at 10 and 20 degrees for the two samples, respectively. The actual values for the fabric and covariance data are not equal for the radiographs and slices; however, the ratios of the two orthogonal covariance values are close, being 0.88 and 0.87 for sample #1 and 0.78 and 0.83 for sample #2 for the slice and radiographic images, respectively.

DISCUSSION AND CONCLUSION: Estimating fracture risk and bone strength in osteoporotic patients is an important clinical problem. Using bone mass alone is suboptimal but no other means currently exists for assessing bone integrity in vivo. Fabric is one measure of trabecular architecture which has been shown, after mass, to be the most important feature related to bone strength. Whereas mass accounts for approximately 65 percent of the variation in observed bone strength, fabric can explain approximately an additional 20-25 percent [2]. Currently, no non-invasive technique exists for clinically evaluating trabecular architecture. We have demonstrated that architectural measurements based on fabric and covariance can be made from standard radiographs of the os calcis. Although these radiographs were of in vitro samples, similar quality images can be made clinically [1]. We have also employed a new feature, namely the covariance function, as another means to assess structure. It is not yet known what the relationship of covariance is to the biomechanical properties of bone, but it has found use in characterizing a wide range of porous structures [3]. Finally, we have shown that structural features measured from plain radiographs are closely related to those made on individual bone slices. Future studies will examine these relationships in more detail, in efforts towards incorporating radiographic based architectural information into clinical assessments of bone strength and fracture risk.

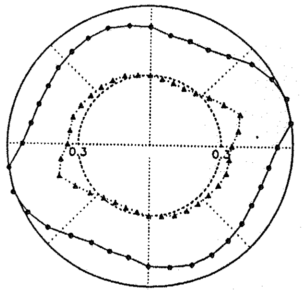

Fig. 1 Covariance data (Sample #2) for slice (triangles) and radiograph (dots).

TABLE

Sample #	MIL (F1 F2 O)	Covariance (C1 C2 O)
1,slice	2.1 1.4 15°	0.40 0.35 10°
1,radiograph	1.8 1.4 10°	0.55 0.48 10°
2,slice	2.6 1.7 15°	0.40 0.31 20°
2,radiograph	2.0 1.6 15°	0.58 0.48 20°
3,radiograph	2.3 1.5 15°	0.52 0.44 28°
4,radiograph	2.4 1.5 15°	0.53 0.43 15°
5,radiograph	2.2 1.5 15°	0.53 0.41 15°
6,radiograph	2.3 1.7 15°	0.53 0.45 20°

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FULL Name, Address, Phone, Fax, and E-Mail Numbers of Corresponding Author:

Robert S. Siffert, M.D., Box 1188, Department of Orthopaedics, Mount Sinai Medical Center, NY, NY 10029. Voice:212-241-7741 Fax:212-427-0208.

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