Prediction of Vertebral Body Compressive Fracture using Quantitative Computed Tomography*†‡

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ABSTRACT: We performed quantitative computed tomography *in vitro* on the first and third lumbar vertebrae in human cadavera using a dibasic potassium phosphate phantom for calibration. The quantitative computed-tomography numbers exhibited a significant positive correlation ($R^2 = 0.89$, $p < 0.0001$) with direct measurements of the apparent density of the vertebral trabecular bone. We also conducted uniaxial compression tests to failure of the vertebral bodies after removal of the posterior elements, and found that vertebral compressive strength was also correlated at a high level of significance ($R^2 = 0.82$, $p < 0.0001$) with direct measurement of the trabecular apparent density. These findings suggested the possibility that the quantitative computed-tomography values might be directly predictive of vertebral compressive strength. However, when we correlated the quantitative computed-tomography values directly with vertebral compressive strength, the results ($R^2 = 0.46$, $p < 0.061$) were suggestive but not quite significant. All vertebral bodies failed by compression of the end-plate, suggesting only a modest structural role for the cortical shell under these loading conditions. This was confirmed by comparing the compressive load to failure of twenty additional pairs of vertebrae that were tested with and without an intact vertebral cortex. Removal of the cortex was associated with approximately 10 per cent reduction in vertebral load to failure.

CLINICAL RELEVANCE: Although our findings were only suggestive of a correlation between quantitative computed tomography and vertebral compressive strength, the strong correlation between each of these variables and the apparent trabecular density supports the assertion that quantitative computed tomography should be investigated clinically as a predictor of risk of vertebral fracture.

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Osteoporosis is a skeletal condition that is characterized by a reduction in bone volume and an increased vulnerability to fracture, particularly of the femoral neck and vertebrae[2,14,23,26]. The frequency of osteoporosis is well recognized, with 50 per cent of women who are forty-five years old or older exhibiting radiographic evidence of osteoporosis of the lumbar spine[25]. Basic research on osteoporosis has been focused primarily on the cellular and metabolic mechanisms of the disease[2,14,26] and on the development of non-invasive techniques to measure bone mass for diagnosis and evaluation of treatment[13,16]. However, it is bone fracture that represents the overriding clinical consequence of osteoporosis, with an estimated four million people in the United States having osteoporosis that is severe enough to result in vertebral fracture[25]. Despite this, the biomechanical aspects of the disease have received little attention and the available diagnostic tools have not been reliable in predicting the risk of fracture. As a result, the decision to use therapeutic modalities such as estrogen and fluoride, which are associated with significant risks, is made without the benefit of accurate predictors of fracture[3,9,37,38].

In recent years, both dual-energy absorptiometry[30,31] and quantitative computed tomography[5,18,35] have been investigated as a means for non-invasive quantitative determination of bone mineral of the spine. It appears that there are advantages and disadvantages for both techniques. Values for the bone-mineral content of the lumbar vertebrae as measured by dual-energy absorptiometry in *in vitro* testing have been shown to correlate with the ultimate compressive strength of vertebral bodies ($R^2 = 0.73$)[21]. However, the use of this technique in a clinical setting is complicated by the fact that it provides an integral measure of spinal bone-mineral content. Thus, the measurement includes contributions from both cortical and trabecular bone of the vertebral body and from the posterior elements. On the assumption that the vertebral cortex makes a major structural contribution to the strength of the vertebral body[39], proponents of dual-energy absorptiometry claim its integral nature as an advantage of the technique. However, elderly patients with osteoporosis often exhibit end-plate sclerosis, osteophyte formation, articular facet hypertrophy, and vascular calcification[10], and these changes can be expected to make uncertain contributions to vertebral strength. Thus, the positive contribution to the over-all density measurement due to the mineral content associated with these changes may

TABLE IV

CHANGE IN THE CURVES OF MORE THAN FIVE DEGREES BETWEEN THE INITIAL EXAMINATION AND FOLLOW-UP ACCORDING TO AGE AND SEX *(No. of Curves)*

Age	Regressed	Improved	Altered	Unchanged	Deteriorated	Total
6 to 10 yrs.						
M	17 (21%)	5 (6%)	16 (20%)	41 (50%)	3 (4%)	82
F	30 (33%)	6 (7%)	20 (22%)	31 (34%)	5 (5%)	92
11 to 15 yrs.						
M	5 (9%)	8 (14%)	8 (14%)	34 (61%)	1 (2%)	56
F	4 (7%)	6 (11%)	10 (18%)	30 (55%)	5 (9%)	55
Total	56 (20%)	25 (9%)	54 (19%)	136 (48%)	14 (5%)	285

lished in 1983, and although dozens of scoliosis patients had been registered for admission in the years prior to that date, we now see only two or three new patients with a severe deformity each month.

In the screening program that we have described, we found only two patients who had a scoliosis of more than 50 degrees. Therefore, if one were to define the prevalence of scoliosis in schoolchildren as being 1 or 2 per cent or more, without further explanation, it would not be meaningful.

All would agree that a 20-degree scoliosis in an immature individual constitutes a clinical problem regarding therapy. Its prevalence in our series of schoolchildren was very low — 1.4 per 1000 (0.1 per cent). If one proposes that curves of more than 10 degrees need therapeutic measures to prevent deterioration, and that they should be kept under observation, the prevalence in our series rises to 2.4 per cent. However, since only 49 per cent of the curves were true scoliosis (that is, prone to increase), the actual prevalence becomes 1.2 per cent. According to our data the probability of a 5 to 9-degree curve being true scoliosis is no less than for a curve in the range of 10 to 19 degrees. Therefore, there is no reason to neglect children with a smaller curve. If we use 5 degrees as the criterion for diagnosis, the prevalence of scoliosis reaches 6.6 per cent in the total series, but since only 54 per cent of the curves were true scoliosis, the actual prevalence was 3.6 per cent. So high a prevalence should probably be considered a screening prevalence rather than an actual prevalence. In the vast majority of the 3.6 per cent, a deformity of more than 20 degrees will not develop and the child will not have a clinical problem or require therapy.

According to our data, the prevalence of scoliosis in the six to thirteen-year age group was not significantly different from that in the total sample. From this one may infer that, while there is an annual increment of curves, there must be a corresponding number of curves that regress, except in the age group of fourteen years and older. It is because of this age group that the balance is upset and a peak of prevalence occurs.

Some screening programs deal only with children between the ages of eleven and thirteen. However, in our series the ten curves that exceeded 20 degrees were distributed evenly among nearly all of the age groups from seven to fifteen years. We therefore suggest that screening programs include children of all ages older than seven, but focus on children who are older than eleven and especially on those who are older than fourteen.

In our series girls showed only a slightly larger prevalence of scoliosis. This is in accordance with our experience in treating inpatients and outpatients with scoliosis. Although in a few reports in the English literature the facts were similar to ours, in most other studies the prevalence of idiopathic scoliosis in girls was stated to be three to five times higher than in boys. We do not know whether our results represent the general condition in China. If so, the most probable explanation for this difference would be genetic.

Of the children who initially had positive physical findings but in whom no curve was seen on roentgenograms, we chose thirty-one at random for repeat roentgenographic examination one year later. In the second examination, eight of the children were seen to have a scoliosis of 5 to 7 degrees. One possible explanation for this is that some children with positive physical findings may have intermittent postural malalignment that manifests itself in some roentgenographic examinations but not in others. This may serve to emphasize the need for repeated roentgenographic examination for accurate diagnosis and for the exclusion of false-positive findings.

As the bending test is quite reliable, it may be used as the only technique for follow-up of children with stable curves, as seen on two sequential roentgenographic examinations, in whom the curve does not approach 20 degrees.

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overshadow the contribution of the negative changes occurring in the trabecular bone of the vertebral bodies and thus lead to an overestimation of vertebral strength.

Quantitative computed tomography appears to be well suited for quantitative mineral measurements of the lumbar spine, as it is able to separate the trabecular bone of the vertebral bodies from the cortical shell and posterior elements[7,8,16-18,20,41]. However, there are inherent limitations and uncertainties in the determination of quantitative bone density by computed tomography. Using single-energy scans, the presence of unknown and variable quantities of fat may lead to erroneous values[17,18]. In addition, because of edge artefacts, partial volume effects, and pixel-size limitations, computed tomography scanners were unable to provide accurate quantitative values for the bone mass of the vertebral cortical shell. This implies that only the properties of the central trabecular region are available to quantify the properties of the vertebral body.

Our purpose in this study was to investigate the accuracy of computed tomography for measuring the apparent density of vertebral trabecular bone and to determine whether non-invasive techniques can be used to identify vertebrae that are at risk for the development of spontaneous compression fractures. We therefore had to address some additional problems involved in relating the vertebral quantitative computed-tomography values to the fracture characteristics of the vertebral body. First, there is the fact that the accuracy of computed tomography numbers has seldom been evaluated against physical parameters, such as ash weight[34] or apparent density[33], which best correlate with the mechanical properties of bone[11,12]. Second, the vertebral body represents a complex arrangement of both cortical and trabecular bone. The structural capacity of the vertebral body therefore may be a function of the mechanical properties of the cortical and trabecular bone, of their geometric arrangement, and of the magnitudes and directions of the applied loads. Thus, the relationship between non-invasive measures of bone density and the strength of the vertebral body complex is by no means straightforward.

The relative structural contributions of the cortical shell and the trabecular bone are important considerations in the prediction of vertebral body strength. It seems that the region of the vertebra that supports the largest portion of the total load should provide the clearest indication of the strength of the vertebral body. However, investigations of the distribution of vertebral body load have resulted in considerable controversy[5,6,15,39]. In one of these studies, Rockoff et al.[39] reported that the cortex contributes 45 to 75 per cent of the peak strength of the vertebral body under compressive load. Given the limitations of the measurements of the cortical shell by computed tomography, this would suggest possible difficulties in relating quantitative computed tomography to vertebral strength. Several earlier studies, however, suggested that the contribution of the central trabecular region is more significant than that of the cortical shell[5,6].

Our approach to establishing a relation between quantitative computed-tomography measurements and vertebral body strength therefore focused on two main issues. First, we had to show that calibrated computed-tomography measurements correlated with the apparent density of the central trabecular region of the vertebral body. Second, it was necessary to demonstrate that the apparent density of the central trabecular region could be used to predict the failure strength of the vertebral body. These results, verified by additional experiments confirming the relative contribution of the vertebral cortical shell, could then be used to formulate a relationship between quantitative computed-tomography measurements and the strength of the vertebral body.

Materials and Methods

Twenty-six intact human lumbar spines were harvested from cadavera within twelve hours after death. The donors' ages ranged from sixty-three to ninety-nine years, with a mean of seventy-eight years. Documentation of age, sex, and cause of death was obtained, and specimens were discarded if there was a history of spinal surgery, metastatic cancer, or diseases affecting bone mineralization. The first and third lumbar vertebrae were designated as the vertebral bodies to be tested, with the end-plates and discs immediately above and below them to be incorporated in the mechanical testing procedures. Forty vertebrae were suitable for study. The spines were double-wrapped in plastic and frozen at −20 degrees Celsius until they were needed. Biplane radiographs of all spines were made to rule out unsuspected destructive spinal disease.

Quantitative Computed Tomography and Measurements of Vertebral Strength

Eight vertebral bodies were examined by quantitative computed tomography (model 8800, General Electric, Milwaukee, Wisconsin), with the spine immersed in a water bath to improve imaging geometry and more closely approximate a physiological situation. A phantom with separate chambers filled with water, ethyl alcohol, and known concentrations (five, ten, twenty, and thirty grams per cent) of dibasic potassium phosphate was used to calibrate against scanner drift[17,18]. The phantom and spine were positioned so that each scan slice included all chambers of the phantom. A computerized radiograph was used to center the first scan inferior to the superior end-plate of each target vertebra, being careful to exclude the end-plate. Contiguous five-millimeter scans (three or four per vertebra) were made caudally until the inferior end-plate was reached. For the central scan, computed tomography values (Hounsfield units) were obtained from each chamber of the phantom and from six pre-selected locations within the vertebral body (Fig. 1). An average computed-tomography value was also determined for the central trabecular bone of each of the eight vertebrae by using the cursor to outline the entire central trabecular region, positioned approximately two pixels from the vertebral cortex and from the entrance of the basivertebral vein. For each scan slice, the values for water and solutions of dibasic potassium phosphate were plotted and found to fall on a straight line. Using this slope and

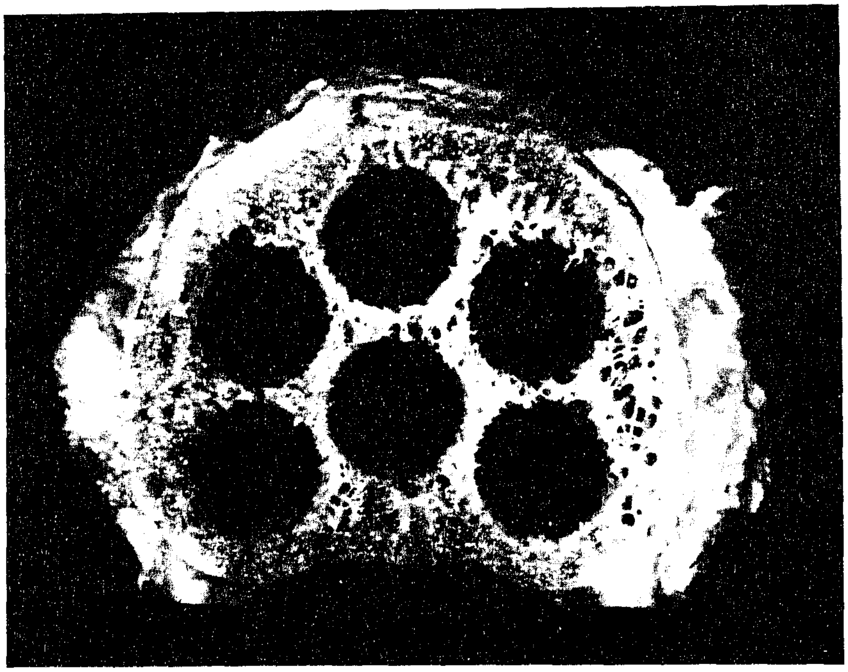

FIG. 1

Location of test specimens within a vertebral body for direct determination of apparent density and trabecular compressive strength, and also for previous measurements of quantitative computed-tomography values.

intercept to provide a baseline correction, a computed tomography value for each measurement from the vertebral body was then calculated[17].

For mechanical testing, the posterior elements were removed from the sixteen vertebrae by division of the pedicles. The end-plates above and below the target vertebrae were embedded in the test rig so that load was applied perpendicular to the end-plates. Uniaxial compressive loads were applied using an electrohydraulic materials-testing machine (model 1331, Instron, Canton, Massachusetts 02021) at a constant deformation rate of 0.1 millimeter per second. Testing was discontinued immediately when there was an abrupt change in the slope of the load deformation curve.

After testing, the discs were removed and the end-plates of the target vertebrae were examined for fracture. All dimensions of the vertebrae were checked using a vernier caliper. After removal of the end-plates, the vertebral body was machined under continuous irrigation to form six cylinders of trabecular bone. The cylinders measured 9.5 millimeters in diameter and nine to thirteen millimeters in height, and were located in the six trabecular regions for which local computed-tomography values had been determined. After removal of the marrow by a Water-Pik, hydrated weights of these specimens were determined on an analytical balance and the apparent density was calculated[11,12]. Forty-eight cylindrical specimens were available for comparing quantitative computed-tomography values and direct measurements of apparent density. For the eight vertebrae for which quantitative computed-tomography data were available and for the eight additional vertebrae, an average central-trabecular apparent density was also obtained by averaging the direct measurements of apparent density at the six locations.

Contribution of the Cortical Shell to Vertebral Strength

The relative contribution of the cortical shell and trabecular bone to the strength of the vertebral body was assessed using forty first and third lumbar vertebrae: twenty from the experiments just described and twenty additional vertebrae excised from ten additional spines. The forty vertebrae were divided into two groups of specimen pairs. To

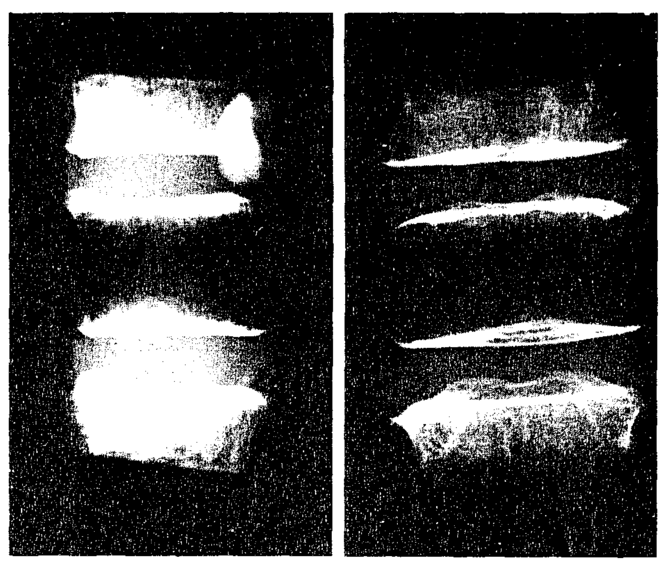

FIG. 2-A FIG. 2-B

Figs. 2-A and 2-B: Radiographs of a vertebral body after removal of the cortex by manual sanding. The cortices of the proximal and distal half-vertebrae are intact.

Fig. 2-A: Anteroposterior radiograph.

Fig. 2-B: Lateral radiograph.

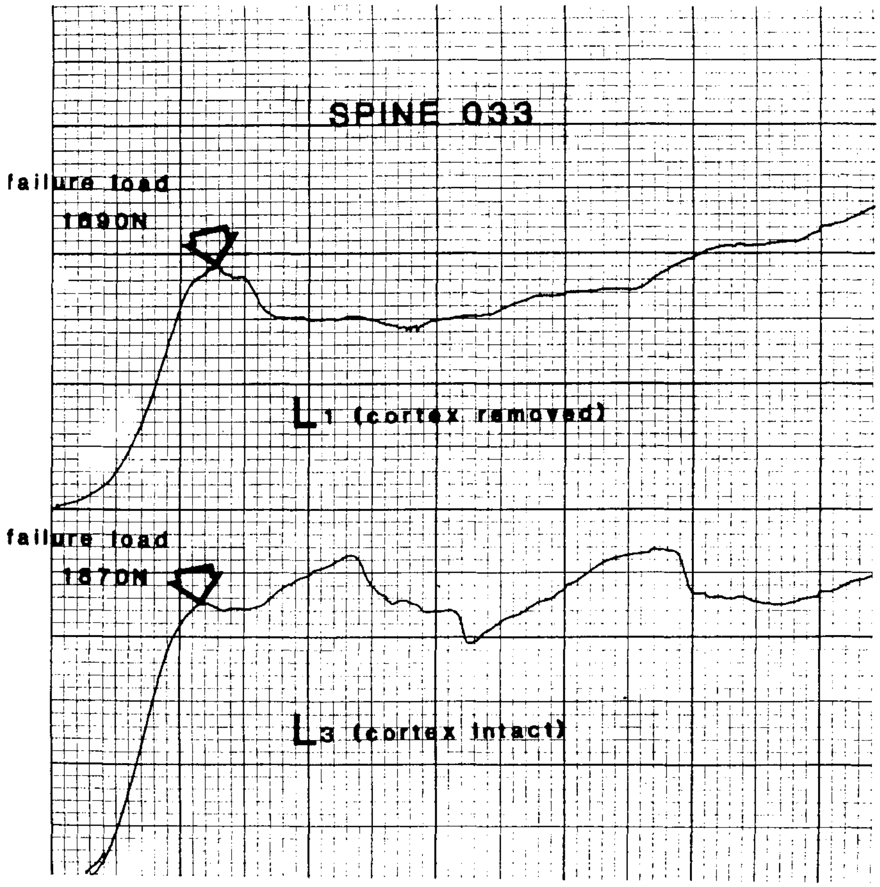

FIG. 3

Representative load-deformation curve of the first lumbar vertebral body (with cortex removed) and the third lumbar vertebral body (with cortex intact) from the same spine. In these experiments on the structural contribution of the vertebral cortex, compressive testing was continued beyond initial failure of the end-plates (noted by the arrows). For the experiments comparing quantitative computed tomography and density with compressive strength, testing was discontinued when the end-plate fractured.

determine if the compressive failure loads of the first and third lumbar vertebrae from the same spine were similar, the first and third lumbar vertebrae from ten spines were prepared, mounted, and mechanically tested as already described. The entire cortex of the first lumbar vertebra from the remaining ten spines was removed by careful manual sanding, with frequent use of the Water-Pik to prevent inadvertent damage to the underlying trabecular bone (Figs. 2-A and 2-B). Attempted removal of the cortex using power instruments invariably destroyed some of the trabecular bone and created localized stress concentrations. The importance of the cortex to the vertebral body was assessed by comparing the difference in strength of the first and third lumbar vertebrae for the ten spines with the cortex intact with the difference in strength of the first and third lumbar vertebrae for the ten spines from which the cortex of the first lumbar vertebra had been removed (Fig. 3).

Results

Vertebral Compressive Strength Compared with Apparent Density and Quantitative Computed Tomography

Computed tomography provided a very accurate quantitative measurement of the apparent density of vertebral trabecular bone. Once the computed tomography values were corrected by using the reference calibration scale (water and dibasic potassium phosphate), there was a highly significant positive correlation ($R^2 = 0.89$, $p < 0.0001$) between the Hounsfield number and the directly measured apparent density of the marrow-free trabecular cylinders (Fig. 4). However, these calibration procedures were found to be essential. Despite frequent internal calibrations of the scanner so that the value of water was set at zero, we found variations from scan to scan for the density of water of as many as ten Hounsfield units.

Our previous studies[11,12] have shown that the compressive strength of trabecular bone is a power law function of the density of the specimen, with an exponent of approximately 2.0 for specimens exhibiting a wide range of apparent densities. These findings suggested that the compressive strength (vertebral load to failure divided by area) of the vertebral body should be approximately proportional to the square of the trabecular apparent density. To test this hypothesis, we measured load to failure for sixteen vertebrae, defining failure as the maximum load prior to the abrupt change in the slope of the load deformation curve. Direct measurements of central trabecular apparent density were available for all sixteen specimens. Average quantitative computed-tomography values were available for eight

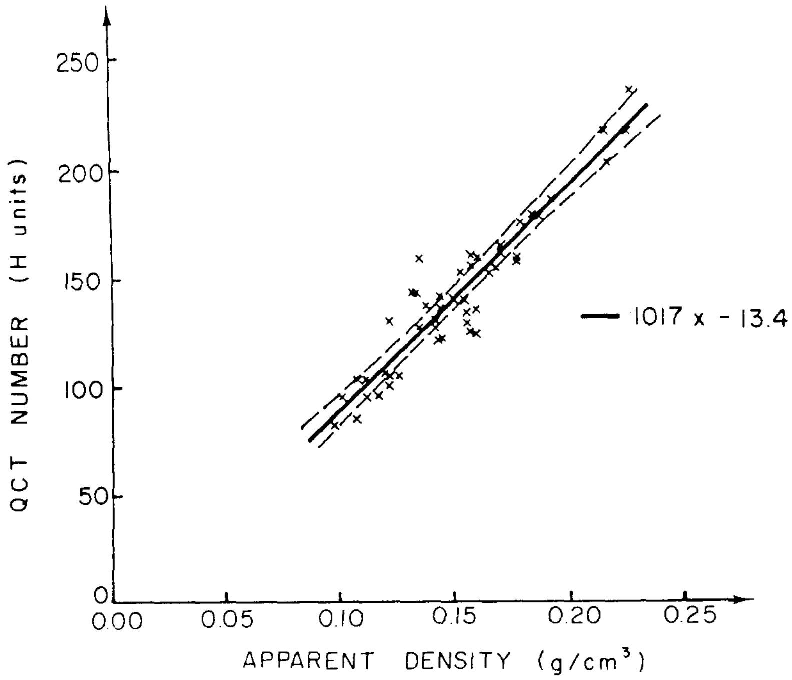

FIG. 4

Correlation between corrected quantitative computed-tomography (QCT) number and apparent density of forty-eight vertebral trabecular-bone plugs ($R^2 = 0.89$, $p < 0.0001$). The equation of the best-fit linear regression and its 95 per cent confidence-interval bands are shown. The standard deviation of the linear regression is 11.7 Hounsfield units.

of the vertebrae. All of the sixteen vertebrae failed by end-plate fracture (nine superior and seven inferior end-plates). There was no visible disruption of the trabecular bone within the vertebral body that would affect the measurement of its apparent density or mechanical properties.

A log-log plot of vertebral compressive strength (load to failure divided by area) against average central apparent density (Fig. 5) resulted in a highly significant correlation ($R^2 = 0.82$, $p < 0.0001$) for a best-fit power law relationship with an exponent of 2.26 ± 0.35 (95 per cent confi-

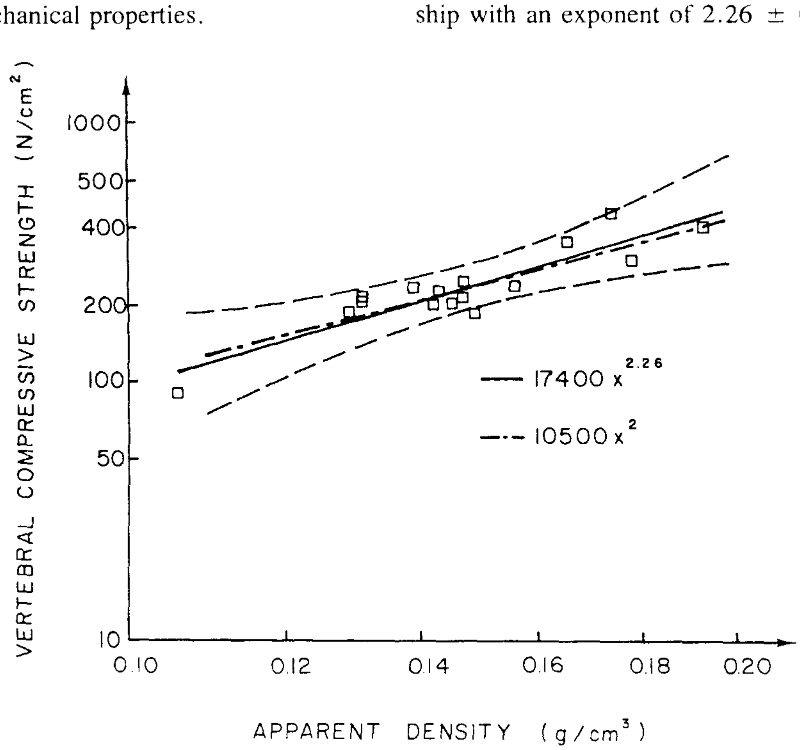

FIG. 5

Log-log plot of vertebral compressive strength (failure load/area) versus average values for the directly measured trabecular apparent densities of sixteen vertebral specimens. A best-fit power law curve, shown as a solid line, has an exponent of 2.26 ± 0.35 (95 per cent confidence interval) and an $R^2 = 0.82$ with $p < 0.0001$ (solid line). This exponent does not differ significantly from the squared relationship, shown as a broken line, which was the expected finding based on previous studies[11,12]. Also shown (top and bottom broken lines) is the 95 per cent confidence band for the 2.26 power law curve.

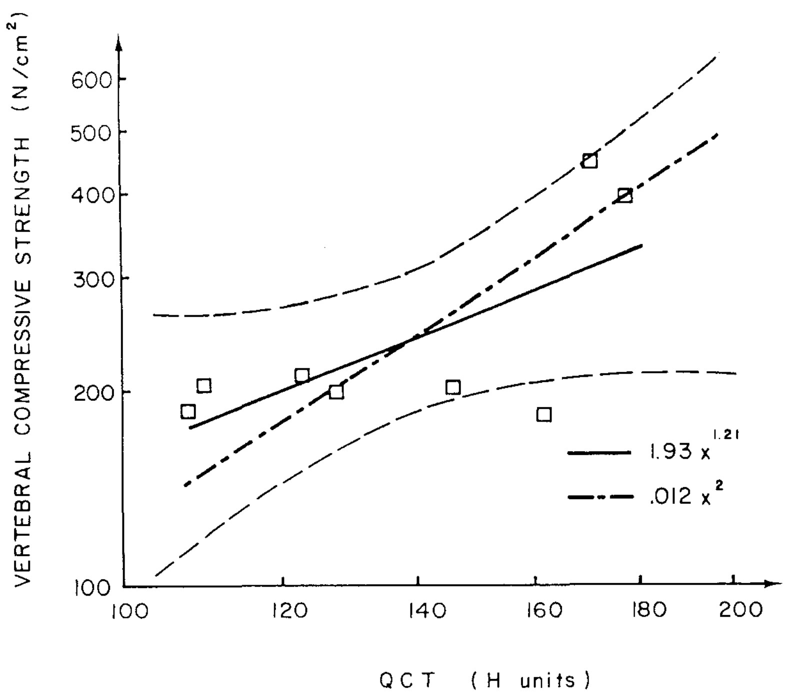

FIG. 6

Log-log plot of vertebral compressive strength versus quantitative computed-tomography (QCT) value for eight vertebral specimens. The best-fit power law relationship has an exponent of 1.21 ± 1.29 (95 per cent confidence interval) and an R^2 = 0.47 with p = 0.061 (solid line). The power law based on a squared relationship (broken line) between strength and quantitative computed tomography falls within the 95 per cent confidence bands of the best-fit regression (top and bottom broken lines).

dence interval). As shown in Figure 5, this confidence interval on the exponent of the power law relationship between strength and density encompasses the value of two for the exponent suggested by previous studies[11,12]. A log-log plot (Fig. 6) of vertebral compressive strength against the average quantitative computed-tomography value (for the eight specimens for which such data were available) results in a correlation coefficient, R^2, of 0.47 and a significance level of p = 0.061. The best-fit power law relationship had an exponent of 1.21 ± 1.29 (95 per cent confidence interval).

Structural Contribution of the Cortical Shell

The cortical shell was found to contribute very little to the over-all strength of the vertebral body under these test conditions. For vertebral bodies that were tested intact, the average load to failure for the first lumbar vertebra (ten specimens) was 3160 ± 424 newtons, and for the third lumbar vertebra (ten specimens) it was 3385 ± 485 newtons. Thus, with the vertebral cortex intact, the average load to failure of the first lumbar vertebra was approximately 6 per cent less than that of the third lumbar vertebra. In the ten additional spines, for first lumbar vertebrae tested without cortex, the average load to failure was 2771 ± 360 newtons. For these ten spines, the average load to failure for the third lumbar vertebral body was again determined with the cortex intact and was found to be 3176 ± 301 newtons. A grouped comparison showed that the two groups of intact third lumbar vertebrae were not significantly different ($p > 0.05$), indicating that the two groups of vertebral specimens could be considered as samples from the same population. In the second set of ten spines, the mean difference in strength between the third lumbar vertebra and the first (without cortex) was 14.4 per cent. When this difference is compared by a grouped t test with the percentage difference in strength of the first and third lumbar vertebrae for the ten spines with an intact cortex of the first lumbar vertebra, this difference is significant ($p < 0.05$).

Discussion

These results suggest the possibility of a simple non-invasive method for predicting the risk of vertebral fracture *in vivo*. With appropriate calibration procedures, the corrected computed-tomography numbers provide a highly accurate determination of vertebral trabecular apparent densities. The accuracy of single-energy computed-tomography scanning as a measure of physical parameters such as ash weight or osseous apparent density has been controversial[19,30]. Early studies, often without an appropriate calibration procedure and using patients with a wide range of ages and severity of osteoporosis, reported computed tomography errors of as much as 30 per cent[7,27]. Our results more closely approach those of Genant et al.[18,19] and of Rohloff et al.[40], who reported computed tomography errors of 5 to 8 per cent. This also compares favorably with the figure of approximately 10 per cent reported for spinal specimens analyzed by dual-energy absorptiometry[29].

It is important to note that the quantitative computed-tomography scans were conducted with the marrow *in situ* and that the direct measurements of apparent density were made on bone specimens after removal of the marrow. It is widely recognized that the vertebral body contains hemapoietic marrow (soft tissue), fat, and bone in varying concentrations. Because the density of fat is less than that of soft tissue, it reduces the measured computed-tomography number of the spine by about twelve Hounsfield units per 10 per cent fat by weight[17]. Dual-energy computed-tomography techniques can improve the accuracy of this measurement, thus reducing the magnitude of error but at the expense of a considerable loss in precision[18]. In our study, a single regression equation adequately related computed tomography numbers and apparent density for all of the tested vertebral bodies. This suggests that the fat content of the marrow did not vary sufficiently to affect this relationship. The biological range of the fat content of marrow, by volume, of 12 to 73 per cent[30] appears to be an overestimation of the true variability in the fat content within the vertebrae of our subject population. Within a population group of limited age span, fat-induced inaccuracy does not appear to be significant, and it may therefore be possible to use single-energy computed-tomography scanning without having to resort to dual-energy measurements. Further studies are underway to assess whether computed tomography numbers and apparent density can be related by a single regression equation for a population with a wide range of ages. Attempts to obtain accurate quantitative computed-tomography values for the vertebral cortex and end-plates were unsuccessful but apparently are unnecessary to provide reliable predictors of load to failure under these *in vitro* test conditions.

The failure test of the vertebral bodies was conducted in uniaxial compression in order to provide more reproducible loading conditions and because fractures of the lumbar vertebrae in patients with osteoporosis frequently reflect this failure mode. By leaving the disc and both end-plates of the vertebrae attached, there was a more physiological load transmission to the target vertebral end-plate[22]. Removal of the posterior elements by division of the pedicles was done so that pure uniaxial compression was applied to the end-plates. This model should provide low estimates of the strength of the intact vertebra, since in compression from zero to 57 per cent of the load is carried by the posterior elements[1,28,32,36]. However, in uniaxial compression, most load is carried by the vertebral body in the lumbar region of the spine, and thus our *in vitro* test method may well be an adequate representation of this *in vivo* condition. Future studies with the posterior elements left intact and the spine subjected to a flexion load will help clarify the influence of the posterior elements and loading conditions on load to failure.

Our power law relationships between direct measures of central trabecular apparent density and vertebral compressive strength (Fig. 6) suggest the possibility of developing non-invasive predictors of the risk of vertebral fracture that may be suitable for clinical use. However, on the basis of eight specimens, we were unable to demonstrate statistically significant predictions of vertebral compressive strength from average quantitative computed-tomography values. We expect that this predictive capability would be improved for a larger sample, especially in light of the highly significant correlations between vertebral compressive strength and direct measures of vertebral trabecular apparent density. For these sixteen specimens, the exponent of the power law relationship was not significantly different from 2.0, as was predicted from our previous studies[11,12]. This finding further indicates that axial compressive stresses in the interior trabecular bone are the most important feature of vertebral loading in compression. We did not have to resort to more sophisticated representations of vertebral loading[4,24,39] to represent the relative contributions of cortical and trabecular bone. It is also possible that the predictions of vertebral compressive strength directly from quantitative computed-tomography data would be improved by accounting for these effects as well as for the non-uniform distribution of central trabecular density.

Results comparing the relative contribution of the cortical shell and the central trabeculae to the vertebral load to failure also suggest that the role of the central trabeculae is most important in uniaxial compressive loading. The reduction of strength of approximately 10 per cent when the cortex is removed, although a statistically significant reduction, is much less than the 40 to 75 per cent reduction reported by Rockoff et al.[39]. This may be a consequence of different methods of preparation and testing. The vertebral bodies used in the study of Rockoff et al. were soaked in ethanol before testing, and this may have resulted in alterations of the failure properties of the trabecular bone. The peak load in their study was estimated to occur at the first sign of deviation from non-linearity of the steepest slope of the load deformation curve. Our load deformation curves showed that the peak loads as determined by the criteria of Rockoff et al. had a variable relationship to our vertebral load to failure. In addition, in our hands, removal of the cortical shell using a high-speed circular hand-saw (as reported by Rockoff et al.) invariably damaged the underlying trabecular bone and caused localized stress concentrations, which may have influenced the earlier conclusions. Our results indicate that, when subjected to uniaxial compression at a slow deformation rate, the cortex of the lumbar vertebra contributes little to the yield strength of the vertebral body. Thus, one of the advantages claimed for spinal dual-energy absorptiometry — that it provides an integrated measure of both cortical and trabecular contributions to mineral content — does not seem to be important based on the relative biomechanical contributions of these regions. Instead, it appears to be sufficient to distinguish between cortical and trabecular components and then to determine the apparent density and compressive strength of the central trabecular bone. Using the simple relationships established here, quantitative computed-tomography measurements seem to be well suited for this purpose.

In summary, our results show that, with appropriate calibration, single-energy quantitative computed tomography can be used with precision to predict the local apparent density of vertebral trabecular bone. The presence of variable fat content does not appear to compromise this relationship significantly. Direct measures of the average apparent density of the interior trabecular bone can also be used to predict the load to failure of vertebral bodies under these *in vitro* test conditions ($R^2 = 0.82$, $p < 0.0001$). Because of the small number of specimens included, we were unable to demonstrate significant correlations at the $p = 0.05$ level between vertebral compressive strength and average quantitative computed-tomography number ($R^2 = 0.47$, $p = 0.061$).

It also remains to be demonstrated from retrospective or prospective clinical studies whether these predictors of risk of fracture will provide a useful tool for identifying individual patients who are at increased risk for spontaneous vertebral fractures.

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Chondrosarcoma in Maffucci's Syndrome*

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ABSTRACT: **Nine patients with Maffucci's syndrome were seen at our institution; chondrosarcoma developed in five. On the basis of the cases of these patients and those reported in the English literature since 1973, we determined that the incidence of chondrosarcoma in patients with Maffucci's syndrome is 17.8 per cent.**

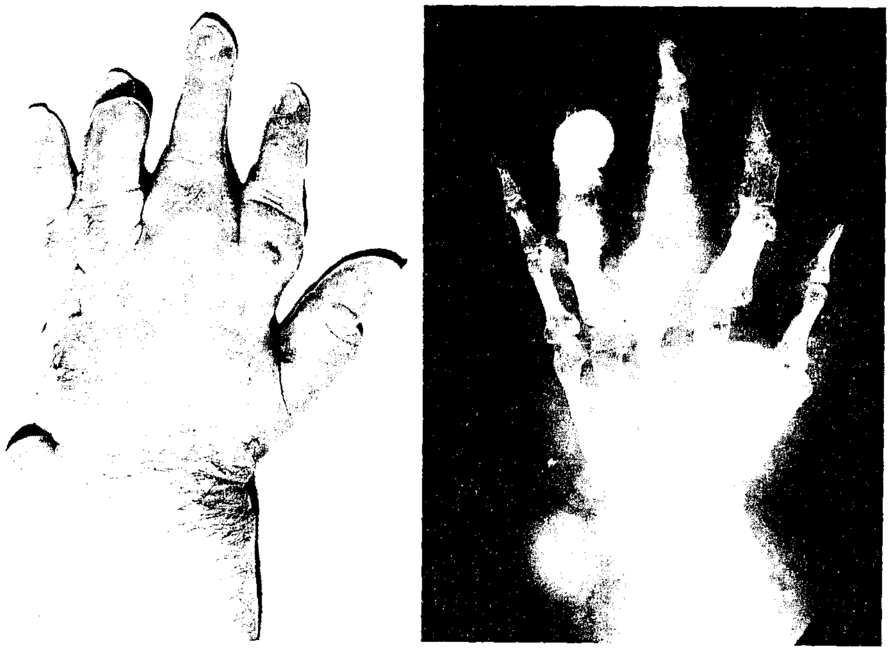

FIG. 1

Case 1. Marked deformity of the hand of a patient with Maffucci's syndrome. Note the calcified phleboliths within several of the soft-tissue hemangiomas.

Maffucci's syndrome is an uncommon congenital mesodermal dysplasia that is characterized by multiple enchondromas and soft-tissue hemangiomas. The syndrome causes varying degrees of disability, but malignant transformation in the cartilage is the most severe complication. In the decade after the extensive review of Maffucci's syndrome by Lewis and Ketcham, in which sixteen cases of chondrosarcoma were cited, only two cases of chondrosarcoma complicating Maffucci's syndrome were reported[2,7]. In our own center, chondrosarcoma developed in five of nine patients with Maffucci's syndrome.

Observations

We reviewed the cases of all 245 patients whose records were coded for multiple chondromas, Maffucci's syndrome, or Ollier's disease in the Mayo Clinic Department of Medical Statistics since 1951. The nine who fulfilled the criteria

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