Quantification of bone mineral measured by single-energy computed tomography

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Twenty cadaver femoral condyles were examined with single-energy quantitated computed tomography (QCT), and the composition of the bone scanned was analyzed chemically. The calcium concentration correlated well with the QCT density ($r = 0.89, P < 0.001$). The highest correlation was recorded between the total calcium content in the scanned slices and the bone mass-related measures recorded by QCT ($r = 0.96, P < 0.001$). Single-energy computed tomography thus provides an accurate measure of total bone mineral content.

Computed tomography has been applied to bone mineral quantification in several research centers (Genant and Boyd 1977, Bentzen 1986). High correlations have been recorded between mechanical properties of bone and computed-tomography attenuation values (Bentzen et al. 1987, Alho et al. 1988). To reduce the main sources of errors, e.g., beam hardening and partial volume effect, the application of dual-energy computed tomography has been suggested (Genant and Boyd 1977, Adams et al. 1982). This study was undertaken to investigate the accuracy of single-energy computed tomography as a measure of bone mineral content.

Material and methods

Twenty cadaver femora (Table 1) were removed, stripped of soft tissue, and stored at –18 °C in sealed plastic bags between the experiments. Ten-millimeter-thick computed tomography slices were taken through the midcondylar area, and the scanned bone slices were marked. All the specimens were scanned with a GE 8800 (General Electric, Milwaukee, WI, USA) using 120 Kv, 100 mA single energy. All the quantitative computed tomography (QCT) recordings were done consecutively during 1 day without calibration phantoms, since the system is stable (Husby et al. 1989). In the QCT slices no distinction was made between cortical and cancellous bone. To exclude fat and other soft tissue, the lowest density limit was set to 50 CT number (CTno).

The mass-related measure (MRM) was derived from the equation: MRM (CTno) = mean density (CTno/cm^3) x CT volume (cm^3). The CT volume of each specimen was calculated by the computer with a lower threshold limit of 50 CTno, and represents the bone-matrix volume (total slice volume – soft tissue) used in the respective mass calculations. The 10-mm scanned condylar slices were marked exactly along the central laser tracer. In the frozen condition the slices were neatly cut with a band saw 5 mm to each side of the marked central line. To calculate the exact total volume of the scanned bone, each bone slice was weighed in air and suspended in distilled water on a microanalytic balance (Arnold 1960). The bone slices were dissolved in equal volumes of concentrated hydrochloric acid. The supernatant fat was pipetted off, and the remainder was diluted with deionized water. Total calcium (calcium mass of the slice) was measured in triplicate for each sample using an atomic absorption spectrophotometer (Perkin Elmer 1100) under standard conditions (Tietz 1970). The fat was dissolved and assayed for fat. It contained no detectable amounts of calcium. Pearson correlations and scatter plots were made between calcium concentration (calcium mass/volume) and QCT density, and calcium mass and MRM, respectively. Unweighted, least-squares, linear-regression analysis was performed when appropriate correlation coefficients and scatter plots were recorded.

Results

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Table 1. Descriptive statistics for 20 cadaveric femoral condyles used in the experiments. Mean *SD*

	Women (n 10)		Men (n 10)		All	
Age of specimen	77	*10*	71	*13*	74	*12*
Volume slice (ccm)	35	*6*	45	*4*	40	*7*
Fat (volume percent)	56	*10*	54	*6*	55	*9*
Calcium (mg/mL)	66	*13*	64	*14*	65	*13*
Calcium mass (mg)	2,405	*520*	2,917	*792*	2,661	*703*
QCT Density (CTno/ccm)	248	*61*	260	*64*	254	*61*
QCT mass value (CTno)	8,030	*2,362*	10,560	*4,037*	9,294	*3,470*

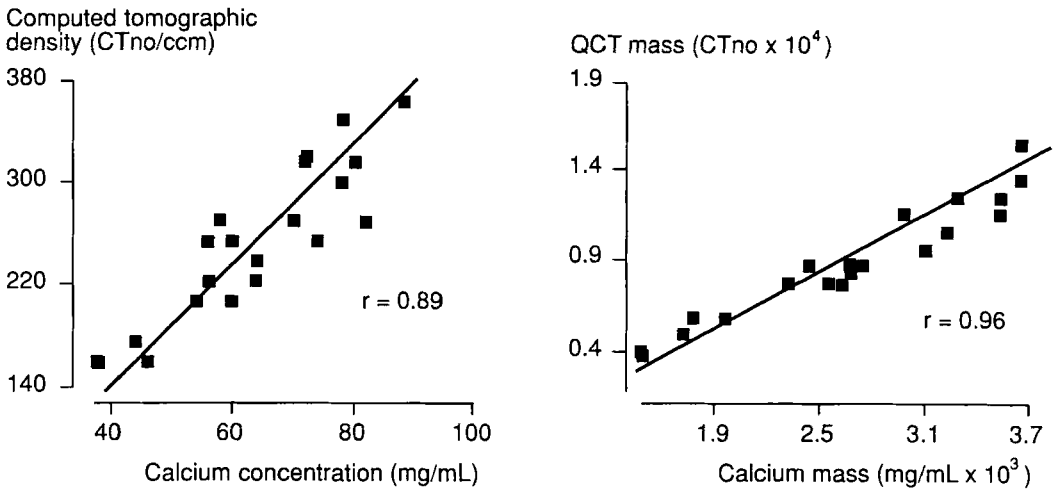

Figure 1. Scatter plots illustrating that the high correlation between calcium concentration and QCT density is enhanced when using mass values for both parameters.

Data were analyzed separately for the men and women, but the only noticable difference ($P < 0.001$, *t*-test) was found in volume, and therefore in calcium mass and QCT bone mass (Table 1). There was no correlation between the fat content and sex ($r = 0.14$). There were high correlations between QCT density measures and the calcium concentration ($r = 0.89$, $P < 0.001$). The highest correlation was recorded between the calcium mass value and the QCT bone-mass-related measure ($r = 0.96$, $P < 0.001$). Scatter plots were made between all the above parameters and fitted well into a linear regression model (Figure 1). Linear regression analyses yielded the following relationship:

Ca mass = 0.20 x MRM + 857;
Ca concentration = 0.20 x CT density + 15.0.

Discussion

We found a high correlation between QCT density and the calcium concentration of the femoral condyle, and even higher between the respective mass values. This may seem strange, but we want to emphasize that the CT volume is an approximation of the internal bone volume (bone-soft tissue), whereas the calcium mass is calculated from the physical volume of the slice. Our technique, by setting a lower threshold limit of 50 CTno for bone recordings, does not totally exclude the soft tissues. However, our approximation is based on empirical findings from pilot studies and avoids the problem of manual drawing of an area of interest, which would be even more sensitive to individual errors. There have been numerous reports of QCT of bone mineral content in vivo (Cann and Genant 1980, Isherwood 1976, Orphanoudakis et al. 1979). Relatively few in vitro studies have been made in which the QCT of bone mineral content has been compared with the direct chemical analysis. Reich et al. (1976) scanned cadaver tibiae and fibulae and measured the

amount of calcium in the scanned slices. A highly significant positive linear correlation was found. Similar findings are reported for the human tibia (Revak 1980) and in the long bones of dogs (Posner and Griffiths 1977). These studies have mainly concerned cortical bone, and the high order of correlation between computed tomography attenuation values and calcium concentration was to be expected because of the homogeneous structure of cortical compared with cancellous bone. Bradley (1978) assessed trabecular bone density in cadaveric lumbar vertebra by QCT and found a highly significant correlation between bone mineral content and QCT attenuation values. Genant and Boyd (1977) suggested that the presence of fat would modify the attenuation of trabecular bone, and that the dual energy technique would be needed to resolve this problem. Bone-mass determination has also been assessed from microradiographs by computer-assisted video densitometry (Strid and Kalebo 1988). The method seems convincing when applied to homogeneous cortical bone, but needs further investigation of the long bones of the appendicular skeleton including fat, cortical, and spongy bone. In contrast to these papers, our study took both spongy and cortical bone into account, setting the lowest attenuation threshold limit to 50 CTno to exclude the fat and soft tissue. This accords with other groups (Eriksson et al. 1988), who state that the combined recordings of both cortical and spongy bone are of interest when correlating the bone mineral content with mechanical properties. Reich et al. (1976) were also using the CT single-energy technique, and their report is in agreement with our findings. As earlier stated (Mazess 1983) dual-energy computed tomography increases the accuracy, but the precision may be reduced compared with single-energy computed tomography. Mechanical tests have shown that rotational and axial loading of the femur have the highest correlation with the QCT bone-mass-related measurements (Alho et al. 1988, Husby et al. 1989). Our present report also strongly suggests that the mass values of both QCT of bone and of bone-mineral content may be even more interesting than the plain density recordings.

Our study on cadavers demonstrates a linear relationship between bone-mineral content and the QCT of the bone. Whether or not this method is applicable to clinical use is yet to be shown. Present CT equipment has certain inherent difficulties, such as beam-hardening effect, partial volume effect, and patient-repositioning problems. Most scanners are now equipped with computer programs to perform first- and/or second-order bone corrections, which hopefully will reduce the beam-hardening effect. Our machine has such a program installed. The fast scanning time will help reduce patient-repositioning artefacts. We believe that single-energy QCT could provide a valuable and simple method for measurement of bone density and mass applicable to the appendicular and axial skeleton. The method is relevant to epidemiologic research on osteoporosis.

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