# Mass Estimates by Computed Tomography:
## Physical Density from CT Numbers

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**The premise is suggested that attenuation in CT scanning should be expressed in terms of physical density rather than CT numbers. A simple experiment was performed to establish a calibration curve of physical density vs. CT number which, within the constraints of beam hardening and other sources of CT number variation and drift, is unique to the specific scanner being calibrated. By expressing attenuation values in terms of physical density, the mass in grams of any organ or tumor can be calculated in vivo, from its volume determined also by CT. As an example, density of bone becomes additional information with any CT scan done for another purpose that includes plane(s) across a skeletal structure.**

A recent article has described how computed tomography (CT) can be used to achieve reasonable volume estimates of irregularly-shaped anatomic structures [1]. Computer software interfaces can use, for example, a Simpson's rule principle to achieve an accuracy within $\pm$ 10% of directly measured volumes. If the physical density were known, then mass (volume $\times$ physical density) could be calculated. Currently, one property of physical density, attenuation of x-rays, is expressed by CT numbers.

The concept of CT numbers is relatively simple. For each given pixel, the CT computer determines a relative linear attenuation coefficient, $\mu$, then normalizes this number to the reference material, water. This result is multiplied by a magnifying constant K to get a product, the CT number. Dense (compact) bone is assigned a CT number value equal to the integer +K and air is assigned the integral value −K. The CT number is $K([\mu - \mu_w]/\mu_w)$, where K = a magnifying constant, which depends on the make of CT scanner, $\mu$ = linear attenuation coefficient of pixel being observed, and $\mu_w$ = linear attenuation coefficient of water. The attenuation coefficient, $\mu$, is related to the various interactions that determine its value, according to the formula [2]: $\mu = \rho N_g[\sigma_R(Z_R, E) + \sigma_{p.e.}(Z_{p.e.}, E) + \sigma_c(E) + \sigma_\pi(Z_\pi, E)]$, where Z = effective atomic number for coherent ($Z_R$), photoelectric ($Z_{p.e.}$), or pair-production ($Z_\pi$) interactions, E = photon energy, $\rho$ = physical density (g/cm$^3$), $N_g$ = electron mass density (electrons/g), $\sigma_R$ = cross section for coherent interactions per electron (cm$^2$/electron), $\sigma_{p.e.}$ = cross section for photoelectric interactions per electron (cm$^2$/electron), $\sigma_c$ = cross section for Compton interactions per electron (cm$^2$/electron), $\sigma_\pi$ = cross section for pair-production interactions per electron (cm$^2$/electron), and $\sigma$(Z, E) = cross section as a function of Z and E.

Of course, at photon energies used by a CT scanner, $\sigma_\pi$ and $\sigma_R$ make very little contribution to $\mu$ [3]. The product $\rho N_g$ is the number of electrons per cubic centimeter and is called the electron density, $N_e$. Note that $\mu$, and therefore the CT number, can be regarded as a function of physical density $\rho$ or electron density $N_e$.

In 1975 at the Hospital of the University of Pennsylvania, Phelps et al. [3] developed the correlation of CT numbers with electron density, physical density, and effective atomic number for an EMI scanner operated at 120 kVp. They showed that excellent correlation exists betwen CT numbers and electron density, indicating

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TABLE 1: **Known Masses and Densities**

| | Density (g/cm³) | CT No. | Standard Deviation | |
|---|---|---|---|---|
| | | | CT No. | % |
| Pine | 0.367 | −659.2 | 3.63 | 0.55 |
| Mahogany | 0.512 | −513.4 | 13.60 | 2.65 |
| Poplar | 0.540 | −496.5 | 1.76 | 0.35 |
| Maple | 0.693 | −360.8 | 1.36 | 0.37 |
| Ash | 0.788 | −251.8 | 2.93 | 1.16 |
| Teak | 0.798 | −242.7 | 1.89 | 0.78 |
| Water | 1.000 | −5.5 | 0.52 | 9.50 |
| Graphite A | 1.678 | +424.3 | 1.36 | 0.32 |
| Mean standard deviation | | | | 1.96 |

the major role of Compton interactions in CT imaging. The plot of the cube of the effective atomic number reflected the role of photoelectric interactions and gave the poorest correlation. Their study also demonstrated the very good correlation that exists (and would be expected from the above equations) between CT numbers and physical density (g/cm³). What they did not recognize, or at least did not describe, was that they had created a calibration curve for their particular EMI scanner. To the extent established by the limited experiment described below, for every CT number obtained from a properly calibrated scanner, there exists a unique corresponding value of physical density.

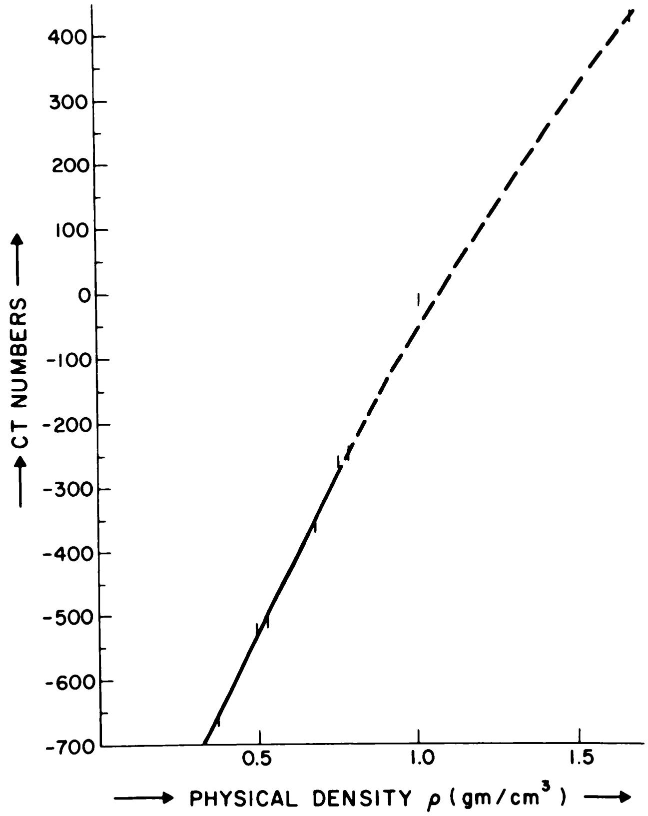


Fig. 1.—Calibration curve for Ohio-Nuclear 2010 CT scanner.

## Materials and Methods

An experiment was designed to use an Ohio-Nuclear 2010 CT scanner to directly estimate the physical density and weight (mass in grams) of any in vivo structure with definable boundaries. To eliminate the effect of the previously described ±10% inaccuracy in measuring irregular volumes, seven standard geometric shapes were machined and precisely measured. Specifically, the phantoms were simple rectangular parallelepipeds of about 2 × 2 × 6 inches (about 5 × 5 × 15.2 cm) with an approximate volume of 24 cubic inches (about 393 cm³). Six of the seven blocks were made from various types of woods, from lightweight pine to heavy teak, and a seventh was made from graphite. A physiologic spread of densities was expected from scanning these organic materials. Water was later scanned as a control.

After accurate weighing and measuring, the true physical density of each block was calculated simply by dividing the mass in grams, obtained with a balance-beam laboratory scale, by the caliper-measured volume in cubic centimeters (table 1). Each block was then scanned lengthwise using about 16 cuts each 10 mm thick, each with a 10-mm incremental table movement. Machine settings were 120 kVp and 200 mAs (4 sec at 50 mA). At each scan level, a circular area of interest was designated to occupy about 75% of the central cross-sectional area of the square cross-section in order to minimize pixel averaging at the edges. The CT number of each cross-section was recorded, and the values for the two end scans were discarded, again to minimize the pixel averaging effect at the wood-air interface. The 13 or 14 other CT number values were combined into a simple average (table 1). The values from table 1 were then plotted on linear graph paper to create a calibration curve plot of physical density vs. CT number, specifically for one standard Ohio-Nuclear 2010 unit (fig. 1).

To check the validity of the calibration curve shown in figure 1, four different precisely-machined blocks of known volume were scanned as density unknowns. The CT numbers were recorded and averaged as before. The average CT number for each block was then used with the calibration curve to obtain an estimate of the density of the material (table 2). The blocks were then weighed, and with their caliper-measured volumes known, an actual physical density was obtained for each block (table 2).

## Results

The calibration curve for one Ohio-Nuclear 2010 unit (fig. 1) is roughly linear for CT numbers of −700 to −100 (densities of 0.33–0.95 g/cm³); above −100, the plot becomes slightly nonlinear, with a gentle curve toward density. The deviation of water values from the relative linearity of the other data points has been explained in detail elsewhere [3] and is attributed to the relatively high effective atomic number of water. From this curve, the physical density of an unknown object can be obtained simply by scanning it with the Ohio Nuclear 2010 unit and extrapolating from its CT numbers. In this experiment, the density of the unknown blocks obtained by CT differed from the actual density obtained with balance scales and calipers by 0.8%.

Since the "weight" of an object is simply the product of its volume (cm³) times its physical density (g/cm³), an unknown object can be weighed in vivo simply by using CT volume-

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TABLE 2: **Unknown Masses and Densities**

| | Density Estimate from Calibration Curve (g/cm³) | True Density (g/cm³) | Mass Estimate from Calibration Curve (g) | True Mass (g) | Errors in Estimates* Density/Mass (%) |
|---|---|---|---|---|---|
| Walnut | 0.54 | 0.547 | 213.0 | 215.0 | 1.2/0.94 |
| Oak | 0.72 | 0.724 | 279.1 | 284.7 | 0.5/1.99 |
| Frozen meat | 1.02 | 1.015 | 390.2 | 408.2 | 0.3/4.50 |
| Graphite B | 1.66 | 1.680 | 669.2 | 660.9 | 1.2/1.20 |
| Mean error | | | | | 0.8/2.16 |

* The percentage of error in density (mean = 0.8%) was calculated from the actual caliper-measured volumes of the blocks, and therefore represents the error inherent in the calibration curve. The percentage of error in the mass (mean = 2.16%) uses CT-measured volumes of the blocks, and therefore also incorporates an additional volume-measurement error. The difference in these two errors (mean = 1.4%) represents the error in CT volume estimates for the simple geometry of a rectangular parallelepiped.

estimating techniques [1]. In this instance, caliper-measured volumes multiplied by CT-determined physical density gave a very good estimate (±0.8%) of the mass of the object. If we measure an unknown object in vivo, where irregular volumes are measured [1] with accuracy of ±10.00%, the errors in volume and density estimation combine so that the predicted error of the mass estimate is ±10.03%. That is, the combined error will be attributed almost exclusively to the error in volume measurement. Furthermore, if the greater accuracies (±4.95%) reported by Breiman et al. [4] are consistently obtainable, this error can be further reduced. Incidentally, the volumes of the blocks in the current study were calculated from their CT images using a hand-operated cursor and standard Ohio-Nuclear software to measure the dimensions of the blocks. Due to the precise geometric shape of the blocks, Simpson's rule approximations were unnecessary, and an average volume error of 1.4% was achieved.

## Discussion

A recent article has pointed out the unreliability of CT numbers as absolute values [5]. CT numbers may vary significantly, even between two scanners of the same manufacture and model. This range of CT numbers for a given tissue type may be largely the result of scanner performance variations. Furthermore, beam hardening of a polychromatic x-ray spectrum as it passes through the body may be another significant perturbation. The creation of a calibration curve similar to figure 1 for each scanner by using a universal set of phantoms would at least quantify, and possibly minimize or eliminate, inter- and intrascanner variations. If necessary, calibration phantom(s) could be included in the field with the patient during actual scanning. In a sense, all scanners would finally learn to speak the same language and would remember that language from day to day. It is important to recognize that no new complicating factors are introduced by speaking in terms of physical density rather than CT numbers. If further experimentation should uncover factors that occasionally reduce the accuracy of CT estimates of physical density, they almost certainly will be the same inaccuracies that we currently accept every day when we use "Hounsfield units."

In the context of physical density instead of CT numbers as a scanner language, several advantages are obvious. The surgeon and the pathologist usually think in terms of mass and physical density whether dealing with an anatomic or neoplastic mass. For example, the size of the prostate and thyroid are traditionally expressed in terms of grams in the literature. The firmness or softness of a tumor, to the extent that these factors are involved in degree of differentiation and/or necrosis, as well as the general cystic or solid nature of the lesion, are more comprehensively expressed to the nonradiologist in terms of physical density than in terms of CT number.

One of the most promising and convenient of the outcomes of density calibration of a scanner would be automatic access to osteodensitometry values for any CT scan that includes planes across a skeletal structure. It has already been established [6] that calcium concentration (mg/cm³) of vertebra, femur, tibia, or other bony structures can be measured by this technique. To obtain highly accurate values, it may be necessary to scan $K_2HOP_4$ solution(s) or other bonelike calibration phantom(s) concurrently with the bones being measured [7]. Quantification of osteopenia for several conditions (e.g., renal failure, disuse, Paget disease, postmenopause, steroid therapy) is described in the referenced articles [6, 7]. The value of CT measurements of lung density is also described [8]. CT quantification of the exact density-based calcium content of a lung nodule may yield a precise interscanner physical density number that can be used to differentiate benign from malignant lung nodules.

If density differences do happen to exist between two tumor types, the radiologist's in vivo scanning might be compared with surgical and autopsy specimens to refine the CT criteria that address subsequent presurgical or premortem differential diagnoses. Few pathology laboratories have their own CT scanner, but they all have weighing scales to check the mass of a specimen and a bucket to use the Archimedean technique in measuring the water-displacement volume.

Linear attenuation coefficients for various body tissues, fluids, and tumors have already been measured [9] and remain too foreign a concept for general application by pathologists and surgeons. Normal ranges of "weights" (grams) for various organs have also been tabulated for different ages [10]. The mass of any given irregularly-shaped organ can theoretically

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be obtained in vivo with an accuracy of ±10.03% using a CT scanner. A series of CT values could then, for example, be compared with those found at autopsy. Postmortem changes probably cause significant variance in mass. Accordingly, CT may be a better estimate of antemortem tumor and/or organ mass than autopsy.

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## REFERENCES

1. Brenner DE, Whitley NO, Houk TL, et al. Volume determinations in computerized tomography. *JAMA* **1982**;247:1299-1302
2. Geise RA, McCullough EC. The use of CT scanners in megavoltage photon-beam therapy planning. *Radiology* **1977**;124:133-141
3. Phelps ME, Gado MH, Hoffman EJ. Correlation of effective atomic number and electron density with attenuation coefficients measured with polychromatic x rays. *Radiology* **1975**;117:585-588
4. Breiman RS, Beck JW, Korobkin M, et al. Volume determinations using computed tomography. *AJR* **1982**;138:329-333
5. Levi C, Gray JE, McCullough EC, Hattery RR. The unreliability of CT numbers as absolute values. *AJR* **1982**;139:443-447
6. Bradley JG, Huang HK, Ledley RS. Evaluation of calcium concentration in bones from CT scans. *Radiology* **1978**;128:103-107
7. Revak CS. Mineral content of cortical bone measured by computed tomography. *CT* **1980**;4:342-350
8. Wegner OH, Koeppe P, Oeser H. Measurement of lung density by CT. *CT* **1978**;2:263-273
9. Phelps ME, Hoffman EJ, Ter-Pogossian MM. Attenuation coefficients of various body tissue, fluids, and lesions at photon energies of 18 to 136 keV. *Radiology* **1975**;117:573-583
10. Boyd E. Growth including reproduction and morphological development. In: Altman, Dittmer, eds. *Biological handbooks*. Washington: Federation of American Societies for Experimental Biology, **1962**:346-348