# Body composition by dual-energy X-ray absorptiometry — a review of the technology

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This paper begins with a fundamental description of the dual-energy X-ray absorpiometry (DXA) technique for measurement of bone mineral. It describes how, in extending the technique to do accurate assessment of body fat and lean, it is important that material standards for fat and lean exist, and that a suitable model for fat distribution in the body be developed.

The computational steps employed in DXA and in the familiar underwater weighing (UWW) technique are compared and contrasted. Experimental data on over 350 human subjects shows that the percent fat results of DXA and UWW do not agree. However when both methods are used to determine body tissue density, there is good agreement. The authors suggest that the discrepancy may lie with the equations that are used in UWW to compute % fat from body density.

## Introduction

The technique of X-ray absorptiometry was developed originally for measurement of bone mineral content. However from the beginning it has been known that the X-ray attenuation data can provide information on the fat/lean composition of soft tissue as a byproduct of the bone mineral measurement. Makers of bone densitometry equipment have for years provided software which gives fat/lean results, but only recently have they taken a more careful look at the accuracy of these soft tissue results[1].

Nearly all of the many techniques for estimating body composition are indirect measurements. That is, they measure some physical property of the body which is related to body composition, and then make use of the assumed constancy of the relationship to calculate composition. DXA is no exception. Table 1 shows these relationships for a number of common body fat measurement techniques. Note that DXA is sensitive primarily to the higher atomic number elements which are present as electrolytes in the body, specifically in tissues of the lean compartment.

## DXA fundamentals

Figure 1 is a schematic diagram of the Norland DXA scanner, but it illustrates the fundamental components and functions common to all DXA systems. There is an X-ray source with a collimator to direct a beam of X-rays through the body of the subject. There is an X-ray detector system which is capable of measuring the intensity of the X-ray beam which has passed through the body of the subject, the measurement being made at two distinct X-ray energies. Finally, there is a motorized drive system which can move the X-ray beam in a scanning pattern over the subject's body (indicated in the figure by arrows denoting motion). The net result of the scan is that a measurement is made of the attenuation of the X-ray beam, at two energies, at every point in the scanned area.

Figure 2 (a) and (b) illustrate how the DXA scan produces an image of the body. Arrows A and B in (a) denote two typical X-ray beam locations at which attenuation measurements

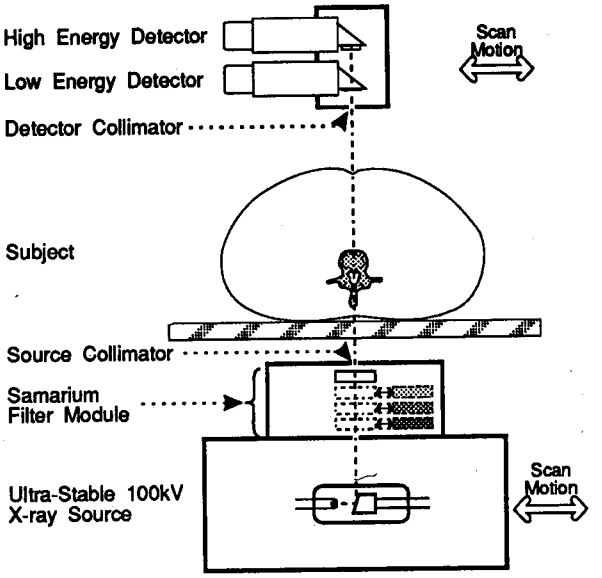


Figure 1. Diagram of a typical DXA scanner. © Russell H. Nord, 1993. Used with permission.

are made. These measurements are analysed for bone mineral content to produce picture elements (pixels) A and B in (b). A typical scan image is made up of thousands of such pixels.

The physics behind the use of two X-ray energies to separate different materials has been discussed in the literature[2]. What is important to know for the present discussion is that it is possible to differentiate two, and only two, dissimilar materials using multiple X-ray energies.

The components of the body can be grouped into three classes with respect of their X-ray attenuation properties: bone mineral, fat (lipid), and lean (nonfat soft tissue). The X-ray properties of these materials are dissimilar primarily because of their differing proportions of high atomic number

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Table 1. Physical properties measured and assumptions made in several methods of total body fat determination.

| Technique | Directly-measured property | Key to applicability |
|---|---|---|
| Underwater weighing (hydrostatic weighing). | Total body tissue density. | Fat has lower mass density (0.9g/cm$^3$) than non-fat (1.1g/cm$^3$). |
| Neutron activation analysis (NAA) | Total amount of N in body. | Fat contains no N, while protein s and amino acids of lean compartment contain a rather fixed fraction. |
| Total body potassium (TBK). | Total amount of radio-active K-40 in body. | Fat is potassium-free. Lean compartment contains a rather constant fraction of potassium and thus of potassium-40. |
| Bio-impedance analysis (BIA). | Electrical impedance of body between left hand and right foot. | Fat is basically non-conductive, whereas the water and electrolytes of the lean compartment are highly conductive. |
| Skinfolds. | Thickness of subcutaneous fat layer at specific locations. | There is a correlation between amount of subcutaneous fat (thickness) and total body fat content. |
| Dual-energy X-ray absorptiometry (DXA). | Relative attenuation of two energies in X-ray beam. | The ratio of the attenuations at two X-ray energies is different for high atomic number elements which are present as electrolytes only in lean compartment tissue. |

elements. Bone mineral contains a large percentage of calcium and phosphorus, whereas soft tissue is composed nearly completely of hydrogen, carbon and oxygen. However, there is a slight difference between the lean and fat components of soft tissue, since the lean compartment components contain traces of potassium, chlorine, sulfur and calcium, primarily as electrolytes. The fat compartment contains none.

How then is it possible to independently measure these three compartments in the human body? The DXA technique gets around the limitation of two materials by making use of the fact that bone mineral in the body is concentrated in dense local regions (bones). Thus it is possible to sort the pixels into those which contain bone and those which do not, and to analyse the two types differently. The no-bone pixels (such as A in Fig. 2) are analysed for fat and lean as the two materials. The bone-containing pixels (such as B in the figure) are analysed for bone and soft tissue as the two materials. The specific mix of fat and lean that is treated as 'soft tissue' in the bone pixels must be somehow estimated, since it cannot be measured. It is not the same for all subjects since people vary so much in fat/lean ratio. In DXA regional scans, such as of the lumbar spine, the soft tissue 'hidden' by the bone (indicated by diagonal hatching in Fig. 2 (a)) is assumed to be the same composition as the surrounding soft tissue which can be measured. This is a reasonable assumption for such a regional scan, as can be seen in Fig. 2 (a). The fat and lean distribution (sketched from an actual CT image) is such that, between the vertical dashed lines defining the scan region, all X-ray beam lines will pass through an approximately equal proportion of fat and lean.

**Extension of DXA to whole body fat/lean measurement**

We have seen that it is necessary to estimate the soft tissue composition when analysing a DXA scan for bone mineral content. However, only a rough estimate of composition is needed in order to measure bone mineral to an acceptable accuracy. In order to obtain good accuracy for whole body fat and lean, it has been necessary to refine the DXA technology in two areas.

One such area of refinement is in calibration standards for fat and lean. In order to compute fat/lean composition from X-ray properties of the soft tissue, it is necessary to know the X-ray properties of fat and lean themselves. In order to measure such properties, it is necessary to have material standards. The authors have proposed such standards[3], which have been adopted and used in the body composition software of two DXA manufacturers (Norland and Hologic), and have been favourably reviewed by at least one independent researcher.[4]

The existence of fat and lean material standards allowed DXA instruments to be accurately calibrated for individual pixels. However, the assessment of fat and lean in the whole body required yet another vital step: the selection of a suitable fat distribution model. This is a second area which has been carefully refined in the latest round of DXA body composition software development.

What is a fat distribution model and why is it important? In the regional spine scan discussed in the previous section, it was assumed that the composition of the soft tissue was the same everywhere. That assumption might be called the uniform fat distribution model. To understand why a better model is needed, let us take another look at Fig. 2 (a). A whole body scan includes all of the soft tissue, not just the central portion as in a spine measurement. The fact that the fat is concentrated in the outer layers of the body make the uniform distribution model a poor approximation.

Note that, in general, the closer the scanning X-ray beam gets to the bone, the greater is the proportion of lean to fat tissue. This increase in lean proportion closer to bones is generally true in the body, because most musculature is next to bones and much fat is subcutaneous. We can quantify the fat distribution in a meaningful way by organizing the soft tissue region of the DXA scan into 'shells', as shown in (c). Shell 1 consists of all the pixels which lie directly adjacent to the bone, shell 2 consists of all pixels adjacent to shell 1, shell 3 is next, and so forth, out to the edge of the body. From the known general distribution of muscle and fat, we would expect that the fat proportion in the shells would increase as

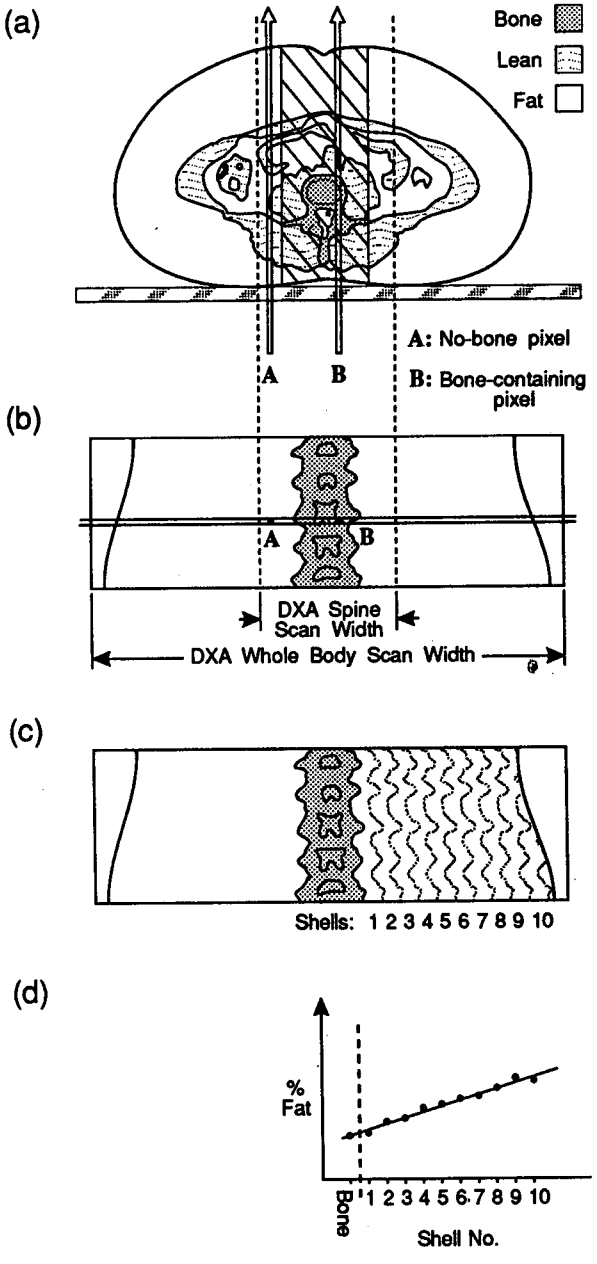


Figure 2. (a). Cross section of body in the lumbar spine region; (b) DXA scan image of lumbar spine region; (c) DXA spine scan with soft tissue shells defined; (d) Hypothetical body fat distribution. © Russell H. Nord, 1993. Used with permission.

the shell number increases, somewhat as is shown in (d). We can envision applying a linear regression to the points, then extrapolating the resulting line to estimate the %FAT of the tissue over and under the bone. We might call this a linear fat distribution model.

Figure 3 is a plot of actual fat distribution data from scans of several people. Note that although the curves are at different levels and have different slopes, they have in common that they are reasonably linear nearest the bone. We have examined such curves for scores of individuals and have found this characteristic to be the norm. On the basis of this data, Norland has chosen to use a weighted linear distribution model, with the shells nearer the bone weighted more heavily in the regression.

**Evaluation of DXA results**

There is a tendency among body composition researchers to evaluate the results of a new method of fat/lean determination

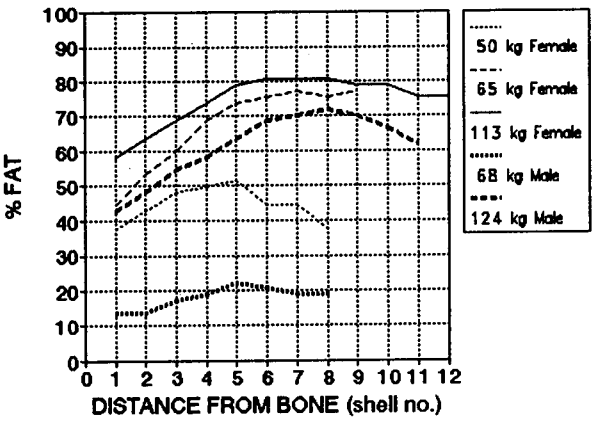


Figure 3. Actual *in vivo* body fat distribution. Shells are 13 mm thick. St Luke's Hospital data[5].

by comparing results with those of UWW. In effect UWW is often considered to be the gold standard. On the other hand, there are a number of people in body composition who question the accuracy of UWW results, and some seem eager to embrace DXA as 'the new gold standard'.

Which technique is correct? Both involve assumptions which may be imperfect, and both require parameters in their computations which may not be completely accurate. So we suggest that neither has yet justified the 'gold' designation.

The two charts of Fig. 4 show the flow of data in the two techniques, and we can use them to better understand how to best compare and evaluate the results of each. In these charts, the boxes indicate the data that is being processed to ultimately produce a %FAT result. The circles represent computations, where the data is processed into another form. The dotted arrows show the principles, equations, and required parameters which enter into each computation.

Consider first the UWW chart. The primary input data are the weights of the subject, in air and in water. The first computation (process 1) is simply the use of Archimedes' principle to compute the average density of the subject's body. Of courser this average density includes the gases contained in the body, and so a correction must be made (process 2). Residual lung volume is measured using nitrogen dilution or some other technique, and abdominal gas is usually estimated. The result is the average density of the tissues of the body. Finally, the percent fat (%FAT) is computed from this average tissue density by means of the Siri or Brozek equation.

On the DXA chart, the primary input data are the X-ray attenuations at every point in the scan. In the Norland system these are used to compute the equivalent aluminum and acrylic masses at each point (process 4). This is an intermediate 'basis set' which is characteristic of DXA's ability to view things as being composed of two materials. The aluminum/acrylic values are then converted to the bone/soft tissue basis set (process 5) or to the fat/lean basis set (process 6), depending on whether or not bone is present. The conversion from one basis set to another requires knowledge of the materials' X-ray properties, thus standards for bone, fat and lean enter into the computations (processes 5 and 6). (Note: Norland DXA instruments make use of the aluminum/acrylic intermediate step; other manufacturers may convert attenuations directly to bone/soft tissue or to fat/lean. There is no difference in the end).

As we have seen in the previous section, in order to quan-

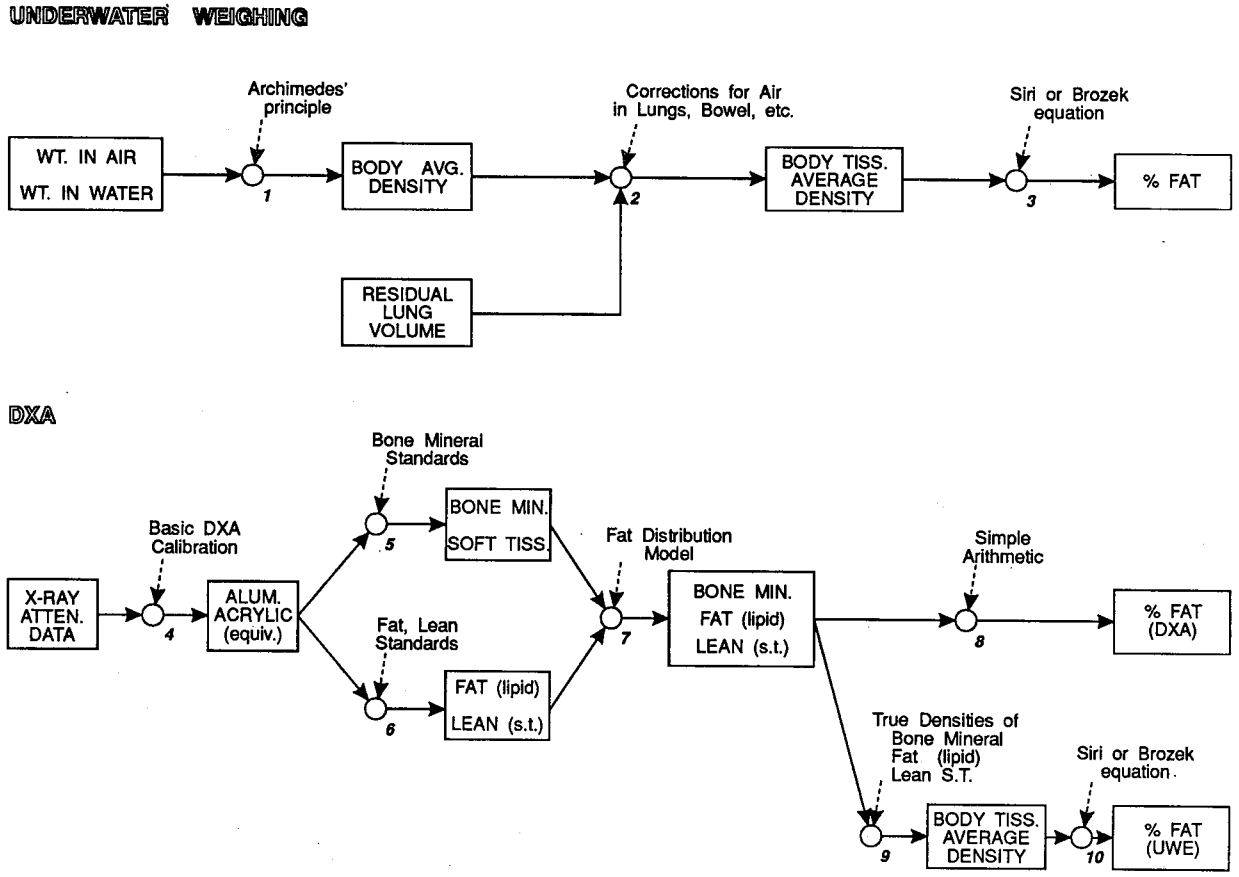


Figure 4. Flow and processing of data in Underwater Weighing and in DXA body fat determination. ©Russell H. Nord, 1993. Used with permission.

tify the composition of the soft tissue which is 'hidden' by bone, we must make use of a fat distribution model (process 7). This process gives us the total body masses of bone mineral, fat (lipid) and lean (soft tissue). At this point there are two ways by which %FAT can be calculated:

- Knowing the masses of the three compartments — bone, fat and lean — use simple arithmetic to calculate fat mass as a percentage of the total mass (process 8).
- Knowing the masses of the three compartments, and using the physical densities of these materials, calculate the average tissue density (process 9). Then use the Siri or Brozek equation to compute % fat (process 10).

Of these two calculations, the first is certainly simpler and more straightforward. It also avoids a known error in the Siri and Brozek equations due to the assumption that bone mass will be a fixed fraction of total nonfat mass. Unfortunately this straightforward DXA calculation does not give %FAT results which agree with UWW. Figure 5 shows the results obtained by UWW and by DXA on over 200 human subjects measured at two different centres[5,6]. The regression slope of 0.84 indicates a fairly large disagreement between the two methods.

Which technique contains the error and where does the error enter in? A review of Fig. 4 reveals that there is an earlier point in the two computation processes at which a comparison can be made. Note that both methods give a value for

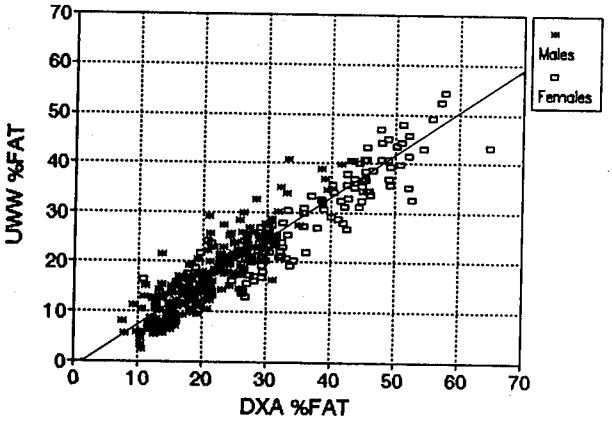


Figure 5. *In vivo* Percent Fat — comparison of two methods. Regression: UWW%FAT = 0.843 * DXA%FAT – 1.1. Data from St Luke's Hospital[5] and the University of Wisconsin[6].

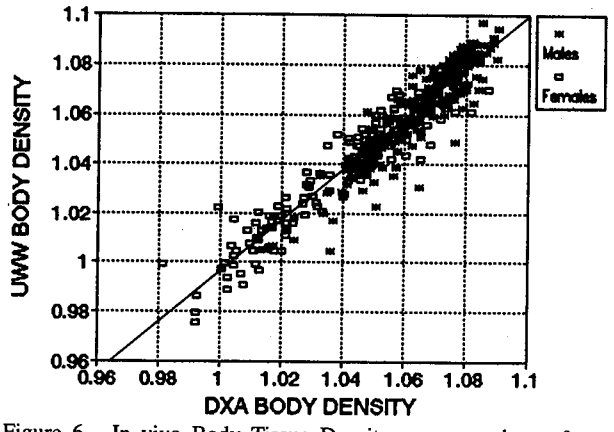


Figure 6. In vivo Body Tissue Density — comparison of two methods. Regression: UWW Density = 1.028 * DXA Density – 0.032. Data from St Luke's Hospital[5] and the University of Wisconsin[6].

total body average tissue density (in UWW, following process 2; in DXA, following process 9). The determination of body average density by UWW is a simple physical measurement complicated only by the need to measure body gases. We can therefore expect the UWW average tissue density to be correct.

But average tissue densities by the two methods agree rather well, as shown in Fig. 6, using exactly the same human population as in Fig. 5. At the middle of the range the two methods differ by only 0.003 g/cm$^3$, which is 0.2% of the midrange value.

## Conclusion

We have seen that the physics behind the DXA measurement of body fat is quite different from that of UWW. And we have seen that experimentally the percent fat values obtained by the two methods on the same group of people differ considerably. However, the two methods have been found to agree very well in their measures of body tissue density.

We suggest that perhaps the discrepancy is in the currently used Brozek and Siri equations. We suggest that the principal assumptions used in the derivation of these equations, such as density of lean tissue and fraction of bone mineral in the lean compartment, be critically re-examined.

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