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DXA 與水下重量 —— 優點與缺點的比較

# Dual-energy X-ray absorptiometry vs underwater weighing — comparison of strengths and weaknesses

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This paper discusses a number of strengths and weaknesses of two methods for determination of body fat, Dual-energy X-ray Absorptiometry (DXA) and underwater weighing (UWW). Several error sources are theoretically quantified. One source of error in the UWW method, variation in bone mass fraction, is examined using data gathered on 219 human subjects who were measured by both methods. The experimental data show the expected linear form but do not exactly match the theoretical curves, indicating that all error sources are not completely understood. The data suggest a possible error in the Brozek equation which is commonly used to compute % fat in UWW.

## Introduction

Underwater weighing (UWW) has been an accepted method of determining the fat content of the human body for many years. Dual-energy X-ray absorptiometry (DXA) is a relatively new method for determining the bone mineral content and also the fat content of the body. Each of these techniques has its own inherent strengths and weaknesses, due to the quite different physics behind them. Table 1 lists the strengths and weaknesses of the two methods in a number of areas. In areas where it is possible to theoretically quantify the errors to which each method is subject, plots comparing these errors are provided.

Table 1. Strengths and weaknesses of two methods for *in vivo* determination of body fat percent.

| Method | Strengths | Weaknesses |
|---|---|---|
| Underwater Weighing. | Insensitive to fat distribution.<br>No radiation exposure. | Accurate estimate of body gas required.<br>Affected by abnormal hydration.<br>Affected by non-standard bone mass.<br>No absolute verification of accuracy. |
| DXA. | Insensitive to body gas.<br>Insensitive to hydration state.<br>Useable on nearly all subjects. | Affected by varying fat distribution.<br>Slight radiation exposure.<br>No absolute verification of accuracy. |

## Sensitivity to body gas

Gases contained within the body contribute to buoyancy, and their effect must be compensated in order to obtain an accurate measure of the density of body tissues in UWW. Residual lung volume (RLV) must be measured, while abdominal gas is normally simply estimated. Any error made in measuring or estimating these gas volume will affect the corrected body density value and will thus result in an error in %FAT.

The X-ray beam in DXA is unaffected by gases, whether inside the body or outside, so there is no sensitivity to body gases. Figure 1 shows the sensitivity of UWW to errors in determining RLV in a typical subject (55 kg, 35% fat, 2000 ml RLV).

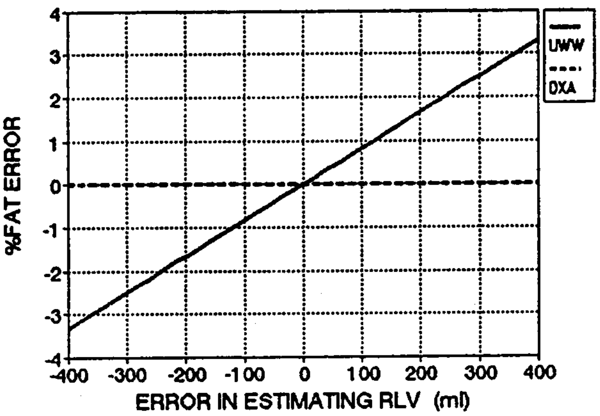


Figure 1. Theoretical error in percent fat as a function of error in estimating residual lung volume (for typical subject of 55 kg, 35% fat, 2000 ml RLV).

## Sensitivity to hydration state

Although water is a major constituent of the lean (nonfat) compartment, both UWW and DXA assume it to be present as a fixed fraction of the lean mass. Deviations from this fixed fraction confound both measurements, but to different extents. UWW evaluates a material by its mass density. In the Brozek equation[1], fat is assumed to have a density of 0.889 g/cm$^3$ and nonfat or lean 1.103 g/cm$^3$. Any intermediate density is evaluated as a combination of the two. Water, with a density of 1.0 g/cm$^3$, is evaluated as 43% fat.

DXA evaluates a material by its X-ray attenuation properties. It is not possible here to enumerate those properties, but the fact is that pure water looks like 9% fat to DXA[2]. However, water is never present in large quantities in the body in pure form; it exists as serum, lymph, or interstitial

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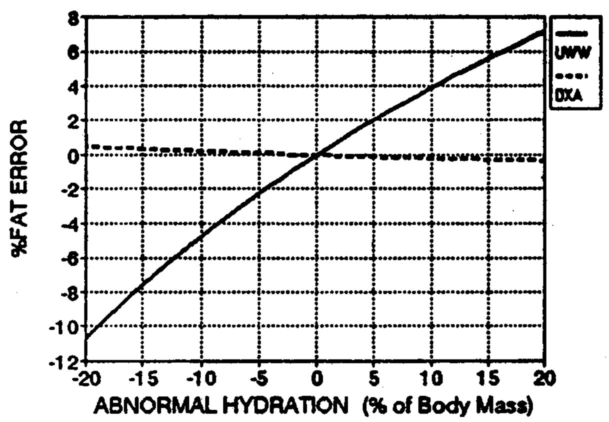


Figure 2. Theoretical error in percent fat as a function of hydration state of subject (for typical subject of 55 kg, 35% fat).

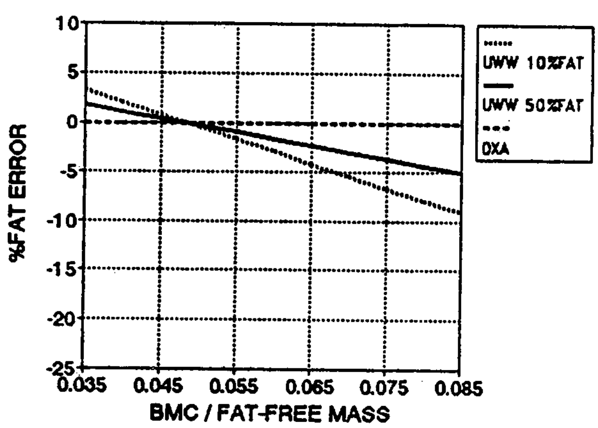


Figure 3. Theoretical error in percent fat as a function of bone mass fraction of total nonfat mass (for typical subject of 55 kg).

fluid, and as such contains various salts in solution. It is the presence of high atomic number elements such as sodium, chlorine, potassium, etc, which make lean tissue 'look lean' to the DXA system. Using published concentrations for interstitial fluid[3], we calculated that water in such form would look like –2% fat to DXA.

Figure 2 shows the relative effects of adding or subtracting water, as interstitial fluid, to or from a typical subject of 35% fat. The fluid, which belongs in the lean compartment, appears to add or subtract an amount of fat, as described above, producing an error in the %FAT value which can be calculated.

### Sensitivity to bone mass

The standard equations used in UWW assume that bone mineral, which has a relatively high density, will be a fixed fraction of the lean compartment. Any deviation from this fraction in an individual will result in an error. Since DXA is able to measure bone mineral mass independently, there is no similar error in DXA.

We estimated the bone mass fraction error by calculating the change in body density which would occur in a test subject if a certain amount of lean soft tissue were replaced by an equal mass of bone mineral of higher density. Figure 3 shows the resulting error in computed %FAT for typical subjects. The UWW %FAT error is zero at 4.8% because that is the ratio of bone mineral content to fat-free mass (BMC/FFM) assumed by Brozek[1].

### Sensitivity to fat distribution

In the DXA method, it is assumed that a particular model of fat distribution will adequately represent each subject. A companion paper discusses the need for such a model[4]. If a given subject's actual fat distribution deviates from the assumed model, there may be an error in computing both bone mineral content and fat/lean composition. The amount of this error is beyond the scope of this work.

In the UWW method, fat and lean contribute to buoyancy regardless of their distribution, so there is no similar error.

### Radiation exposure

The DXA measurement requires that the subject receives a small amount of X-ray exposure. A total body DXA scan will typically give the X-ray dose of less than 0.1 millirems, regardless of which manufacturer's instrument is used.

There is no X-ray exposure in UWW.

### Applicability to all subjects

UWW requires that subjects be able and willing to be completely submerged in water while exhaling rather forcibly. Obviously the method is ill suited for subjects who are sick, infirm, unconscious or afraid of water.

DXA requires only that subjects be able to lie still on the scanner table for a period of about 15 minutes, while breathing normally.

### Verification of accuracy

A weakness of both methods is the lack of any tests which verify accuracy absolutely. Such a study would require knowing the exact fat content of the test subjects, who would have to be live adult humans. Since the only known way to determine fat content accurately is by chemical analysis of all body tissues, this study is unlikely to be done. Use of cadavers, animals, or phantoms all have potential problems which make them inaccurate or unreliable.

### Experimental results

Experimental checks of the theoretical error estimates are difficult because of lack of knowledge of the correct body fat in human subjects and of the magnitude of the confounding factor (such as hydration state). However in the case of the bone mass fraction error, the DXA measurement provides a measure of the confounding factor and also a measure of body fat percent which is expected to be free of this error. In the process of calibrating Norland's DXA body composition software, both DXA and UWW measurements were made on a large number of volunteer subjects. The measurements were made at two sites, the Body Composition Unit at St Luke's Hospital in New York City[5], and the Department of Sports Medicine at the University of Wisconsin at Madison[6]. The DXA scans provide independent measurements of bone mineral mass (BMC) and non-bone lean mass (LEAN) as well as fat mass (FAT) from which we could calculate the true bone mass fraction for each subject. The difference between percent fat by UWW and by DXA for 219 adult subjects is plotted versus the ratio of BMC to fat-free mass in Figure 4. Compare this plot with the theoretical plot of Figure 3.

The experimental data are essentially linear in distribution, and the regression line crosses the zero error axis at approximately the expected value of BMC/FFM, the 4.8% used in the development of the Brozek equation[1]. The fact that the slope of the regression line is greater than expected may be an indication of yet another dependency on bone mass in one of

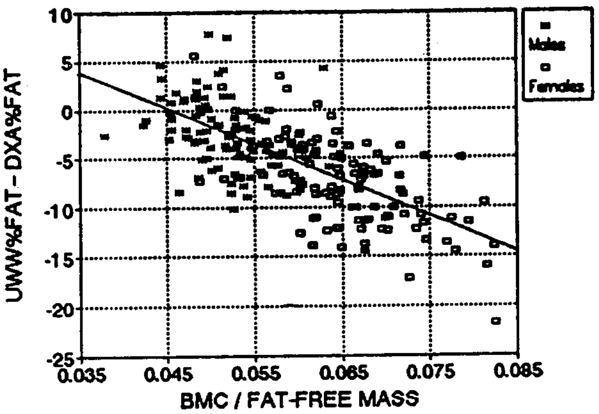


Figure 4. Experimental difference between UWW and DXA percent fat measurements on bone mass fraction.

the techniques, although at present we do not know what it is.

It is interesting to note from the data of Figure 4 that the mean value of BMC/FFM for this population is not 4.8% as given by Brozek, and that there is a significant difference in the mean value of men and women. The mean values we obtained for BMC/FFM are 5.2% for men, and 6.5% for women.

## Conclusion

The DXA technology has several important advantages over the UWW method in determination of total body fat percent. DXA is insensitive or less sensitive to several physiological variables which can confound the UWW measurement.

In view of the difference between our experimental values for bone mass fraction and those previously accepted, we suggest a need for re-examination of the equations used in the UWW method.

## References


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