身體組成 —— 可測量些甚麼?

Body composition – what is measurable?

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In 1878 Behnke noted that 'nothing is measured with greater error than the human body'. Over the intervening period measurement techniques have been developed which range from the relatively simple anthropometric methods to those based on sophisticated radiation and nuclear physics technologies. Nevertheless, despite the undoubted progress, it is important that we ask ourselves whether Behnke's observation might still have some validity.

Many reviews have concentrated on the problems and limitations of given techniques with particular emphasis on achievable precision (because precision is easy to measure). However a straight-forward analysis of published data, especially of that relating to indirect techniques, shows that measurement precision is frequently small in magnitude compared to biological precision, the latter being simply a reflection of Nature's refusal to conform to imposed regression relationships. In this paper the body composition technologies are reviewed in the context of achievable accuracy and precision.

Introduction

In studies of body composition it is generally assumed that the important limitations of popular techniques such as skinfold anthropometry reside in the achievable experimental precision[1] and/or the accuracy of curve fitting procedures[2]. While such factors are in principle important, their effects can be masked by biological factors, and this is especially true where body compartments are estimated indirectly via predictor relationships derived from previously acquired data. In this paper error propagation is first reviewed in simple statistical terms, especially in relation to the part that biological factors might play in the precision and accuracy of indirect techniques. Precisions are then presented for a range of techniques for the principal body compartments, fat, water and protein as well as ratios such as total body water:fat-free mass (TBW:FFM) and total body protein:total body nitrogen (TBP:TBN).

Error propagation in indirect techniques

Predictor relationships are generally used to relate readily measurable quantities to body compartments which cannot easily be measured directly (in vivo), such as total body fat (TBF). In general terms indirect techniques of body composition are characterized by the measurement of a quantity, x, which is used to predict another quantity, y. Both x and y have at some stage in the development of the technique been measured and have been found to be crudely related. To simplify the argument let us suppose x is measured without random error and y with random error of standard deviation, S_m. If measured y is regressed against measured x then one can determine a residual standard deviation, S_r (usually referred to as the *standard error of the estimate)* which has two components, a measured component, S_m, and a biological component, S_b, such that

$$S_r^2 = S_b^2 + S_m^2 \qquad (1)$$

If the regression equation is then used to predict y from measurements of x alone, then the error in estimating measured y from measured x is given by

$$S^2 = S_r^2 \left[1 + \frac{1}{N} + \frac{(x_p - \bar{x})^2}{\sum (x_p - \bar{x})^2} \right] \qquad (2)$$

where x_p is a measured value of x and were $\bar{x}$ is the mean measured value of x for a set of measurements. Note that S^2 approaches S_r^2 if $N>>1$ and x_p is close to the mean. This is a familiar textbook formula which is used to determine the curved error lines characterizing linear regressions. However, as shown by Burkinshaw[3], the error in estimating the true value of y, S_T is given by

$$S_T^2 = S_r^2 - S_m^2 = S_b^2 \qquad (3)$$

so that errors in the measurement of the dependent variable, y, used to obtain the original regression equation do not propagate through to errors in the estimation of the true value of y. Indeed the error in predicting the true value of y depends only on the biological component of the residual error, providing x is measured without error. Note that if x is also measured with random error, as it usually is, then strictly speaking linear regression analysis is inappropriate and one needs to resort to factor analysis to get unbiased estimates of the slope and intercept of the relationship between the *true* values of measured quantities[4]. In this paper such refinements are ignored because the biological errors are generally large compared to measurement errors.

In any indirect body composition technique for a given

Table 1. Calculation of the biological component of the residual error in regressions of density versus log of sum of four skinfolds (biceps, triceps, subscapular and supra-iliac).

Subjects	Ages	Residual Errors (g cm^{-3})		
		Total[a]	Measurement[b]	Biological (S_b)
Males	20–29	0.0087	0.0020	0.0085
	40–49	0.0073	0.0020	0.0070
Females	20–29	0.0102	0.0020	0.0100
	40–49	0.0107	0.0020	0.0105

Data from [a] Durnin & Womersley[7].
[b] Buskirk[6].

subject one has no *a priori* knowledge of the biological error. Although it is systematic in origin, and therefore affects the accuracy of each individual estimate to an unknown extent, it also affects the precision of group means. It is frequently ignored probably because it does not affect the precision of the mean value derived from several measurements on the same individual.

Measurement of Total body fat

Historically TBF was first measured by densitometry and this has been generally regarded as the gold standard by which to compare other techniques. The densitometric technique depends on the fact that fat has a much lower density than other tissues and on the assumption that the FFM has a constant density. Any estimate of TBF by densitometry therefore depends on the biological variability of the density of the FFM and this has been estimated by Lohman[5] to amount to 0.0060 g cm^{-3} (SD). Buskirk[6] has also estimated the measurement precision to be of the order of 0.0020 g cm^{-3}, partly due to the difficulty in measuring residual lung volume. Another major limitation of densitometry is that it cannot usually be used on sick people. In any case one would expect greater variability in the density of the FFM especially in nutritionally depleted patients or those with disturbances in fluid balance.

Skinfold anthropometry is perhaps the most universally used technique because of its essential simplicity and low cost. It is a very good example of an indirect technique which depends on two assumptions, namely that the ratio of subcutaneous fat to total fat is constant and that measurements at a few selected sites are representative of total subcutaneous fat. The latter assumption is readily verified and leads to small errors but the former is known to be incorrect; even in normals the proportion of subcutaneous fat varies from 20% to 70% of TBF[5].

While many investigators have derived relationships between skinfolds and body density perhaps the best known is a study by Durnin and Womersley[7] who reported a general relationship of the form

$$D = C - m\log_{10} \Sigma_i S_i \qquad (4)$$

where S_i is the mean measured skinfold at site i and where C and m are age and sex-dependent parameters derived from the linear regressions. Durnin and Womersley[7] reported residual errors on these regressions, examples of which are shown in Table 1. Using Buskirk's figure for the measurement error on density (0.0020 g cm^{-3})[6] one can derive the biological component of the residual error shown in the right hand column of Table 1. In accordance with Equation 3 these residual errors can be used to derive the precision on groups of subjects as shown in Table 2, the right hand column of which shows the precision expressed in terms of percentages of the respective mean % fat values for a given age group (calculated via Siri's equation[8]).

Inspection of the regression relationships and Table 2 show that the percentage errors are worse for leaner people in contradiction to popular mythology[1]. It should be noted that the above analysis assumes that the experimental precision in measuring skinfolds does not affect the ultimate precision (because it is small compared to the biological component) and that the biological variability in the density of the FFM does not affect precision (which is of course untrue, but there will be covariance present). The true errors for skinfold anthropometry will therefore be somewhere between the values quoted in Table 2 and those derived by adding in quadrature the biological errors for densitometry (see Table 3).

Table 3. Comparison of precision achieved with several methods of measuring total body fat in normals.

Technique	Precision (cv)	Comments
Densitometry	8 – 17%	Calculated from Lohman[5]
Skinfold Anthropometry[a]	15 – 21%	Durnin & Womersley +Siri Equation
$^3H_20$, $^2H_20$ Dilution[b]	9%	M – TBW/0.73
IVNAA/$^3H_20$ Dilution[c]	6.5%	M – (TBW+TBP+TBM+TBG)
Dual Energy X-ray Analysis[d]	6 – 7%	from Heymsfield et al.[10]

[a] Excludes biological error inherent in Siri Equation.
[b] Assumes 1.5% random error in TBW and 1.5% biological error (SD) in the constant, 0.73.
[c] Based on random errors in TBW (1.5%), TBP (4.2%), TBM (10%) and TBG (20%)[11]. Biological variation in ratio of TBP:TBN not considered (see below).
[d] Value derived by assuming difference method has 7% error (SD) which can be subtracted in quadrature from residual error.

Other methods for measuring TBF include difference techniques based on dilution measurements of total body water, combinations of in vivo neutron activation analysis (IVNAA)

Table 2. Calculation of effects of biological component of residual error on prediction of total body fat.

Subjects	Ages	Mean sum of skinfolds (mm)	log sf	Density[a] (g cm^{-3})	%Fat[b]	Density[a] + RE Biol S_b (g cm^{-3})	%Fat[b]	% Error (SD)
Males	20–29	42	1.6232	1.0605	16.8	1.0687	13.2	21.4
	40–49	55	1.740	1.0402	25.9	1.0482	22.2	14.3
Females	20–29	66	1.8195	1.0294	30.8	1.0401	25.9	15.9
	40–49	78	1.892	1.0175	36.5	1.0280	31.5	13.7

[a] Calculation based on Durnin & Womersley regressions[7].
[b] Calculation via Siri Equation[8].

and dilution techniques, total body electrical conductivity[9] (and bioelectrical impedance analysis — BIA) as well as dual energy X-ray absorptiometry (DEXA)[10]. The typical precisions for three examples of these techniques are shown in Table 3, together with typical precisions for densitometry and skinfold anthropometry. At the present time the most precise technique, combined with minimum risk, non invasiveness and relatively small cost, appears to be DEXA.

In addition the accuracy of DEXA is not in principle affected by disease states; this also applies to the IVNAA/dilution techniques but the latter generally require higher radiation effective doses and greater levels of scientific expertise to conduct properly.

Although a relative newcomer to the field BIA is very much an indirect technique and will almost certainly be inaccurate in body composition studies of patients with nutritional or metabolic disorders.

Measurement of total body water and TBW:FFM

The measurement of TBW is most conveniently carried out by $^{3}H_2O$, $^{2}H_2O$ or ^{18}O dilution, all of which are direct methods for which the random error can readily be reduced to 1.5% or less. The most important systematic error is that due to exchange with non-aqueous hydrogen or oxygen reported by Schoeller et al[12] to amount to ~3% for tritium or deuterium and ~0.7% for ^{18}O. Other methods of measuring TBW (eg BIA)[9] are indirect and cannot be expected to approach the accuracy of simple dilution techniques.

Since the pioneering work of Moore[13] in the 1950s there has been a lot of interest in the hydration of the fat-free mass (TBW:FFM). Table 4 shows measured and predicted ranges for this ratio in normals estimated from measured body nitrogen (TBN) and tritium dilution[14].

Table 4. Ranges of TBW:FFM in normals[a].

	IVNAA/$^{3}H_2O$[a]	Anthropometry[b]
Measured range	0.69 – 0.76	0.65 – 0.80
Random error	1.2%[c]	4 – 5% (typical)
Predicted normal range	0.685 – 0.754[d]	

[a] TBW measured by $^{3}H_2O$ dilution, FFM by IVNAA and tritium dilution[14].

[b] TBW measured by $^{3}H_2O$ dilution, FFM by skinfold anthropometry.

[c] Largely from 4% random error in nitrogen (protein) measurement.

[d] Taking into account biological variability in the ratio of total body minerals to FFM.

Also shown in the right hand column is the measured range and precision where the FFM has been estimated by skinfold anthropometry[7]. One can readily verify that to have a value of 0.80 a normal average adult would need to have an excess of around 20 kg of water, a figure which even exceeds the typical water accumulation of septic shock syndrome patients at the end of their fluid sequestration phase[15]. This clearly demonstrates the limitation of the skinfold anthropometry technique for measurements of either TBF or FFM in individuals.

Total body protein and TBP:TBN

At the present time the only way to estimate TBP is by measuring TBN via IVNAA; over recent years the prompt gamma technique has been favoured over the delayed gamma method partly because of the low effective radiation dose of the former and partly because the major effects of body habitus are eliminated by simultaneously measuring body hydrogen[16]. Reported precisions for TBN can be as low as 1.6% (for 0.45 mSv effective dose)[17].

The technique is dependent on accurate phantom calibration with maximum systematic errors of better than 5% being readily achieved[18].

However, absolute estimates of TBP are dependent on the ratio TBP:TBN which is generally assumed to be 6.25. The achievable precision on estimates of TBP in any group of subjects (normals or patients) is dependent on the precision ascribed to the TBP:TBN ratio. Representative values of various proteins include 5.80 for collagen, 6.60 for actinomyosin and 7.29 for albumin. To the author's knowledge there has been no reported measurements of even the normal variation in the mean ratio, not to mention shifts occurring in depletive illness where selective loss of muscle tissue might be expected to reduce the ratio. However chemical measurements of both nitrogen and protein in two homogenized depleted cadavers[19] yielded values of TBP:TBN of 6.33 ± 0.19 (SEM) and 6.40 ± 0.22 (SEM), respectively with neither value being significantly different from 6.25.

Strictly speaking estimates of TBP from TBN constitute an indirect technique but at least in principle total nitrogen is measured and, on the basis of admittedly limited evidence, the ratio TBP:TBN is unlikely to depart much from 6.25, except perhaps for progressive depletive illness where serial measurements might be affected.

Conclusion

It is hoped that this paper has demonstrated the importance of understanding the biological errors inherent in indirect techniques. Though such errors are systematic and subject specific they affect the precision on group means. The term biological error is perhaps a misnomer since the biological component of the residual error is simply a reflection of Nature's refusal to conform to imposed regression relationships. Nevertheless the importance of these errors limits the use of techniques such as skinfold anthropometry to studies of very large groups of subjects (normals only). Certainly static or serial studies of individuals, whether normal or otherwise, should not be contemplated.

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