British Journal of Nutrition (1993), **69**, 631–644

New and simple equations to estimate the energy and fat contents and energy density of humans in sickness and health

BY JOHN F. SUTCLIFFE[1], GRANT S. KNIGHT[2], JAIME C. PINILLA[3] AND GRAHAM L. HILL[2]

[1] *Department of Nuclear Medicine, Leeds General Infirmary, Great George Street, Leeds LS1 3EX*
[2] *Department of Surgery, University of Auckland School of Medicine, Park Road, Auckland, New Zealand*
[3] *Department of Surgery, Saskatoon University Hospital, University of Saskatchewan School of Medicine, Saskatoon S7N 0X0, Canada*

(*Received 5 March 1991 – Accepted 4 June 1992*)

Two formulas were derived to estimate the energy content of the human body which use only body mass, total body water by ^3H_2O dilution space and body minerals assessed by anthropometry. The formulas were tested in a body composition database of 561 patients and 151 normal volunteers using established metabolizable energy values for protein, fat and glycogen. Total body protein was determined by *in vivo* neutron activation analysis (IVNAA), body water by dilution of tritium and body minerals from skeletal frame size. Body glycogen was assumed to be 14·6% of the mineral component. Body fat was obtained by difference, body mass less the sum of water, protein, minerals and glycogen. The standard deviation in the estimate of body energy content was 30 MJ or 4·1% of the energy content of reference man. Two formulas for body energy content were derived by regression with body mass, total body water and body minerals or height. Two formulas for energy density and formulas for percentage body fat were similarly derived.

Body energy content: Human subjects

The measurement of the energy content of the human body is of fundamental importance in the care of patients with abnormalities of nutrition and metabolism.

Chemical energy is stored in the body in the bonding of C to itself and to H, and it is through the oxidation of the hydrocarbon content of protein, fat and glycogen that energy is released (Blaxter, 1989). It has therefore been suggested that changes in the energy content of the body could be deduced from measured C balance (Kinney & Moore, 1956) and apparatus using the technique of *in vivo* neutron activation analysis (IVNAA) has been developed in a few centres (Kyere *et al.* 1982; Kehayias *et al.* 1987) to measure total body C (TBC). However, the energy equivalents of C are different in protein, fat and glycogen and, therefore, estimation of total body energy content from TBC is not precise.

The metabolizable energy values of endogenous protein, fat and glycogen have been determined recently (Livesey & Elia, 1988) to be 19·68 MJ/kg (4·70 kcal/g), 39·5 MJ/kg (9·44 kcal/g) and 17·5 MJ/kg (4·18 kcal/g) respectively. When the masses of these three substances in the body are known, total energy content (E; MJ) can be calculated from the equation:

$$E = 19{\cdot}68 \times TBP + 39{\cdot}5 \times TBF + 17{\cdot}5 \times TBG, \qquad (1)$$

where TBP, TBF and TBG are the amounts (kg) of protein, fat and glycogen respectively. The energy content of a 70 kg reference man (ICRP, 1975), comprising 11·3 kg protein, 12·5 kg fat and 0·5 kg glycogen, is 725 MJ or 10·36 MJ/kg body mass.

Since fat is the major energy store of the body, hydrodensitometry has been used as the 'gold standard' method for measuring the fat proportion of the body, assuming the densities of the fat and fat-free components to be 900 and 1100 kg/m^3 respectively (Siri, 1961). The method has been refined (Garrow *et al.* 1979) to use incomplete immersion in water, with head and lung volume being determined from air displacement. Short-term changes in body mass, volume and water content can be used to deduce changes in body protein and fat (Murgatroyd & Coward, 1989) assuming a constant mineral component and the densities of water, protein and fat to be 993, 1340 and 900 kg/m^3 respectively. Thus, energy and N balance studies can be performed in the interim and other methods of body composition measurement evaluated against the refined hydrodensitometry method (Jebb *et al.* 1991).

Hydrodensitometry is not practicable in the clinical situation, particularly with patients who may be immobile or have attached therapeutic or life-support equipment. Hence, other (simpler) methods to assess body composition have been devised. Skinfold anthropometry to measure body fat (Durnin & Womersley, 1974) requires manipulative skill and can be systematically in error in extremes of depletion and obesity. Infra-red reflectance with subcutaneous fat over the biceps muscle (Conway & Norris, 1987) has recently been found to correlate well with total body fat. Bioelectrical impedance analysis (BIA) to measure body water (Lukaski *et al.* 1985) also requires skill on the part of the operator to reduce errors, and further development, perhaps at different frequencies, will be necessary before this simple technique can produce reliable and accurate measurements of water space. Likewise electrical conductivity induced by an enclosing radiofrequency coil to measure total body water (TBW) will require further evaluation (Van Loan & Mayclin, 1987; Chadwick & Saunders, 1990).

Recent advances in dual-energy X-ray absorptiometry (DEXA) (Mazess *et al.* 1990) to differentiate soft tissue into its lean and fat components in addition to accurate measurements of bone mineral density may permit body composition assessment to become widely available. This method, however, cannot differentiate the protein and water components of lean soft tissue for which a constant proportion must be assumed, and may give erroneous estimates of body fat in the extremely obese. Magnetic resonance imaging (MRI) may also permit the estimate of the magnitude and disposition of fat and fat-free body components, but cost precludes this from being commonly available at present.

The amount of protein in the body can be measured directly by IVNAA and TBW by dilution of tritium-labelled water. If total body minerals (TBM) and TBG are estimated by skeletal anthropometry then TBF can be estimated by subtracting the sum of TBW, TBP, TBM and TBG from total body mass (WT) (Beddoe *et al.* 1984; Knight *et al.* 1986):

$$\mathrm{TBF} = \mathrm{WT}-(\mathrm{TBW}+\mathrm{TBP}+\mathrm{TBM}+\mathrm{TBG}). \tag{2}$$

This technique may be useful for healthy subjects and for patients of abnormal body composition.

Few centres have IVNAA facilities necessary to measure either TBP or TBC. Therefore, starting from equation 1, we have derived several formulas which can be used to estimate E from much simpler and more widely available measurements; E′ is the approximate estimate of body energy content whilst E is the exact value.

Derivation of formulas

If TBF is eliminated between equations 1 and 2, E can be expressed as:

$$\begin{aligned} \mathrm{E} &= 19{\cdot}68\times\mathrm{TBP}+39{\cdot}5\times(\mathrm{WT}-(\mathrm{TBW}+\mathrm{TBP}+\mathrm{TBM}+\mathrm{TBG}))+17{\cdot}5\times\mathrm{TBG}, \\ &= 39{\cdot}5\times(\mathrm{WT}-\mathrm{TBW}-\mathrm{TBM})-19{\cdot}82\times\mathrm{TBP}-22{\cdot}0\times\mathrm{TBG}. \end{aligned} \tag{3}$$

Of the quantities on the right-hand side of equation 3, WT can be measured in any hospital with high precision and accuracy and TBW can be measured by dilution of isotopically labelled water in many centres specializing in the investigation and treatment of nutritional disorders. TBM can be estimated with sufficient accuracy by skeletal anthropometry (Beddoe *et al.* 1984). TBG may be related to TBM or TBW but contributes only a minor term in the calculation of E (1·5% in reference man; ICRP, 1975) which may not be significant within the errors of measurement of other body components. In the present work, TBG has been assumed to be equal to 0·1463 × TBM (TBG 0·0091 × fat-free mass (FFM), TBM 0·0622 × FFM; Beddoe *et al.* 1984) whereupon equation 3 becomes:

$$E = 39{\cdot}5 \times (WT - TBW) - 19{\cdot}82 \times TBP - 42{\cdot}72 \times TBM. \qquad (4)$$

The remaining problem then is to find some simple relationship between TBP and other quantities that are easily measured. TBP can be estimated by regression *v.* body mass, water and minerals.

Derivation of TBP and E from hydration of the FFM. One method by which TBP may be estimated is from the hydration of the FFM, h. This has a value of approximately 73% in the healthy population, but varies from 82% in extreme hydration (sepsis) to 69% in the other extreme of dehydration (Sheng & Huggins, 1979). Thus:

$$\begin{aligned} h &= TBW/(WT - TBF), \\ &= TBW/(TBW + TBP + TBM + TBG), \qquad (5) \end{aligned}$$

from which:

$$TBP = TBW \times (1/h - 1) - TBM - TBG. \qquad (6)$$

Assuming the relationship between TBG and TBM given earlier (in the derivation of equation 4), E is given by:

$$E = 39{\cdot}5 \times WT - (39{\cdot}5 + 19{\cdot}82 \times (1/h - 1)) \times TBW - 20{\cdot}0 \times TBM. \qquad (7)$$

Assuming normal hydration of the FFM (h 0·73), the equation for E becomes:

$$E' = 39{\cdot}5 \times WT - 46{\cdot}83 \times TBW - 20{\cdot}00 \times TBM. \qquad (8)$$

The coefficient for the term in TBW may vary from 48·4 MJ/kg (h 0·69) to 43·9 MJ/kg (h 0·82).

Derivation of E assuming a direct relationship between TBP and TBW. TBP correlates positively with TBW and, therefore, it is reasonable to derive an equation for E assuming a fixed relationship between TBP and TBW. If it is assumed that TBP = TBW/3·7 (TBM 0·0622 × FFM, TBG 0·0091 × FFM (Beddoe *et al.* 1984), TBW 0·731 × FFM) equation 4 becomes:

$$E' = 39{\cdot}5 \times WT - 44{\cdot}86 \times TBW - 42{\cdot}72 \times TBM. \qquad (9)$$

METHODS

Body composition data and their energy equivalents have been analysed. These comprised measurements of total body protein, water, minerals and glycogen in 561 surgical patients and 151 normal volunteers. The patients (269 female, 292 male) had a mean age of 54 (SD 18) years with a range of 14–92 years. The normal volunteers (eighty-one female, seventy male) had a mean age of 38 (SD 15) years ranging from 19 to 82 years. Informed consent was obtained before each measurement. The research programme was approved by the hospital ethical committee. The characteristics of the populations studied are shown in Table 1.

Of the patients, 161 were diagnosed with cancer, forty-three with Crohn's disease, sixty-three with ulcerative colitis, eleven with peptic ulcers, twenty with intestinal obstructions, seventeen with fistulas, twenty-three pancreatitis, twenty-six on continuous ambulatory peritoneal dialysis (CAPD), eleven with diverticular diseases, thirty-two with cholelithiasis, five trauma patients and the remainder with miscellaneous diagnoses.

Table 1. *Characteristics of the populations studied*

(Mean values and standard deviations)

	Mean	SD	Range
Male patients (*n* 292)			
Body mass (WT) (kg)	68·1	14·6	32·1–117·2
TBW (kg)	40·4	7·6	19·7–76·5
TBP (kg)	9·8	2·2	3·7–18·5
TBF (kg)	14·0	8·2	0·5–50·3
TBM (kg)	3·46	0·52	1·97–5·0
Height (m)	1·73	0·07	1·49–1·95
Age (years)	54·2	16·9	15–92
E (MJ)	754·7	347·7	179–2268
E/WT (MJ/kg)	10·69	3·28	3·54–22·91
Female patients (*n* 269)			
WT (kg)	58·2	14·7	28·3–111·4
TBW (kg)	30·0	6·4	16·3–64·4
TBP (kg)	6·8	1·9	1·5–14·6
TBF (kg)	18·4	8·9	1·8–54·9
TBM (kg)	2·71	0·46	1·83–4·6
Height (m)	1·60	0·07	1·39–1·79
Age (years)	54·0	19·3	14–92
E (MJ)	866	370·8	192·7–2345
E/WT (MJ/kg)	14·39	3·47	5·08–22·2
Normal males (*n* 70)			
WT (kg)	76·3	10·3	58·2–97·2
TBW (kg)	44·7	6·7	32·8–63·0
TBP (kg)	12·7	2·1	7·4–18·5
TBF (kg)	14·9	7·1	2·1–31·1
TBM (kg)	3·45	0·47	2·39–4·38
Height (m)	1·76	0·07	1·61–1·96
Age (years)	41·2	15·7	20–82
E (MJ)	848·3	294	291·2–1534
E/WT (MJ/kg)	10·98	3·0	4·21–17·3
Normal females (*n* 81)			
WT (kg)	62·4	9·9	45·9–115·3
TBW (kg)	32·7	4·1	24·9–45·6
TBP (kg)	8·5	1·4	5·2–12·9
TBF (kg)	18·1	6·8	3·5–53·8
TBM (kg)	2·71	0·40	1·87–4·0
Height (m)	1·65	0·06	1·45–1·80
Age (years)	36·6	14·5	19–81
E (MJ)	888·2	277·1	291·5–2374
E/WT (MJ/kg)	14·04	2·40	4·98–20·59

TBW, TBP, TBF, TBM, total body water, protein, fat and minerals respectively; E, total body energy content.

The method of determining the size of the body compartments has been described previously (Beddoe *et al.* 1984). TBP was calculated from total body N, which is measured relative to body H by the prompt gamma ray emission resulting from the capture of thermal neutrons by these elements. The use of H as an internal standard (Vartsky *et al.* 1979) greatly reduces the dependence of the gamma ray emission from N, in relation to its abundance, on body habitus, and also permits information obtained from scanning a major proportion of the body to be applied to the whole body. In the Auckland IVNAA facility the subject's torso and thighs were scanned. Total body H is the sum of the H content of TBW, TBP, TBF and TBG. Local non-association of N with H does not significantly change the whole body N:H value.

The reproducibility of the estimate of TBP was measured by twenty repeated scans of an anthropomorphic phantom containing physiological concentrations of the major body elements, as a solution of urea, glycerol and water. These measurements were carried out over a period of 2–3 d, and the sequence of measurements was repeated at intervals of several months. No significant changes were observed in the reproducibility of measurement of protein over the intervening periods. This was 0·48 kg (SD; 4·2% of protein in reference man (ICRP, 1975)). After changes were made to the neutron shielding of the gamma detectors in 1987, the precision of the estimate of protein was improved to 0·30 kg (SD; 2·6% of protein in reference man). An analysis of two human cadavers (Knight *et al.* 1986) gave excellent agreement in the measurement of body N between chemical and neutron activation analyses, to within 40 g (2·7%) in one and 4 g (0·6%) in the other. The measurement of body protein from N:H is not greatly dependent on the magnitude of other body components (e.g. TBW, TBF) and only small errors result from the assumption that H comprises 10% of body mass (Vartsky *et al.* 1979).

TBW was measured by ^3H_2O dilution, injecting 100 μCi (3·7 MBq) of tritium and giving a total dose of 0·2 mSv. The precision of the method was estimated to be 0·63 kg (SD; 1·5% of water in reference man) from random errors in weighing syringes, dilution of stock solution, pipetting, and statistics of counting tritium activity in standards and samples. This error is likely to exceed the amount of non-aqueous H exchange in most subjects (Culebras & Moore, 1977).

TBM were estimated from skeletal anthropometry, applying a regression equation relating mineral content to the size of the skeletal frame. This equation, given below, was derived from the measurements of fifty normal volunteers (Beddoe *et al.* 1984) in which the mineral content was assessed assuming that minerals formed the same proportion of the FFM as in reference man. It is of the form:

$$\text{TBM (kg)} = 0{\cdot}116 + 0{\cdot}0000267 \times \text{height} \times \text{biacromial diameter (cm)} \times \text{mediastinal thickness (cm)}. \quad (10)$$

The precision of this estimate is assumed to be 0·36 kg (SD; 10% of minerals in reference man (Beddoe *et al.* 1984)). In the analysis of the cadavers (Knight *et al.* 1986) the estimate of minerals was within 20 g of the chemical measurement in one and overestimated by 0·7 kg (40%) in the other.

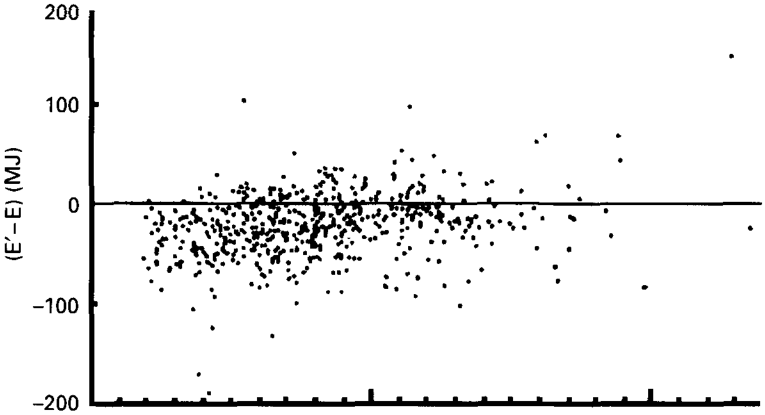
TBG is assumed to be 14·6% of the mineral compartment and has a precision of estimate assumed to be 0·1 kg (SD; 20% of reference man (Beddoe *et al.* 1984)). In both cadavers this estimate based on skeletal frame size was 0·3 kg above the analysed value, which is to be expected considering postmortem degradation of glycogen.

TBF was estimated as the difference between WT and the sum of TBW, TBP, TBM and TBG. The precision of the estimate is 0·8 kg (SD; 6·4% of fat in reference man), and is most affected by the measurement of TBW. This error is derived as the square root of the sum of variances in the other body compartments and the measurement of body mass. In the analyses of the cadavers the difference estimates relative to chemical measurements of fat were high by 0·23 kg in the first and low by 0·94 kg in the second.

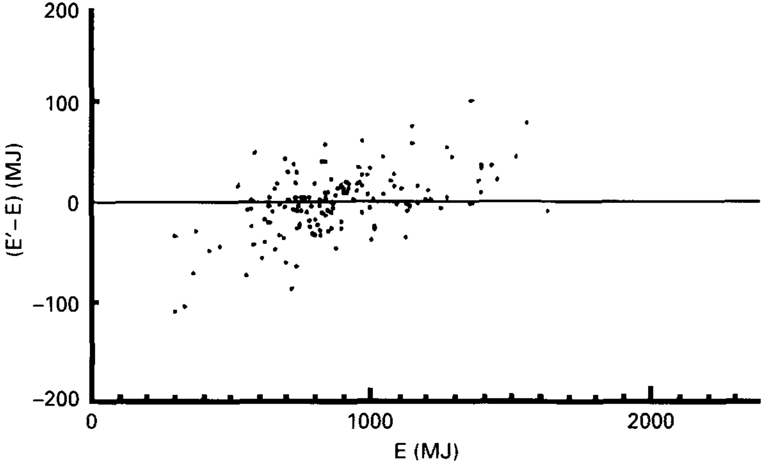
The precision of the estimate of E from body stores of protein, fat (by difference) and glycogen (from TBM; equation 1) was 29·9 MJ (SD), based on the square root of the sum of the variances in the estimate of each body compartment and taking account of errors in weighing the subject and recent improvements in the IVNAA measurement of body N.

RESULTS

Assessment of E assuming constant hydration of the FFM. The hydration of the FFM in patients was found to be slightly dependent on WT and TBM ($r - 0{\cdot}19$ and $r - 0{\cdot}22$, $P < 0{\cdot}0005$) and less dependent on TBW (r 0·10, $0{\cdot}01 > P > 0{\cdot}005$) by covariate analysis. In



(a) Patients



(b) Normal subjects

Fig. 1. The error in the estimate of total body energy (E′) as a function of body energy content (E) in 561 patients and 151 normal subjects, in which total body protein is derived from the assumption that the hydration of the fat-free mass is 73% (E′ is the approximate estimate of body energy content given by equation 8).
(a) Patients:

$$(E' - E) = 0{\cdot}0254 \ (\text{SD } 0{\cdot}0037) \times E - 42{\cdot}37 \ (\text{SD } 3{\cdot}36),$$

SD about the regression line 30·9 MJ, r 0·286.
(b) Normal subjects:

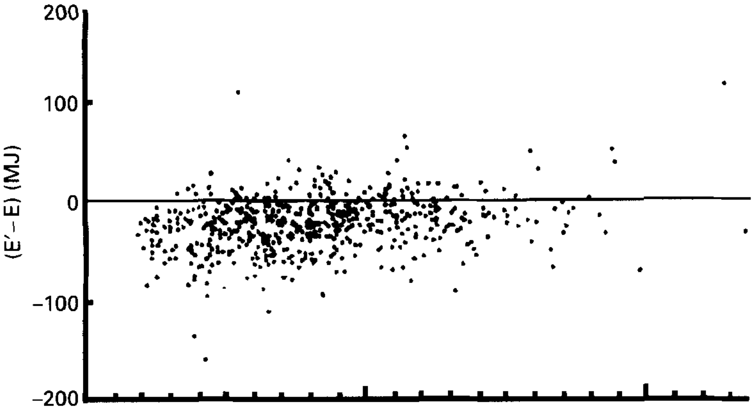
$$(E' - E) = 0{\cdot}0546 \ (\text{SD } 0{\cdot}0091) \times E - 49{\cdot}38 \ (\text{SD } 8{\cdot}45),$$

SD about the regression line 27·7 MJ, r 0·49.

normal subjects there was a similar small dependence of the hydration of the FFM on WT (r – 0·3, $P < 0{\cdot}0005$) but less dependence on TBW and TBM (r 0·05, $0{\cdot}3 > P > 0{\cdot}25$ and r – 0·16, $0{\cdot}05 > P > 0{\cdot}025$). It has a mean in patients of h 0·747 (SD 0·026) and in normal subjects of h 0·731 (SD 0·022).

Fig. 1 (a and b) shows the error in the estimate of E using equation 8 where a constant value for the hydration of the FFM is assumed to derive TBP.

Assessment of E assuming TBP is proportional to TBW. Fig. 2 (a and b) shows a plot of the error in the estimate of E using equation 9 where TBP is assumed to be proportional to TBW. Mean differences and residual standard deviations are shown in Table 2.


(a) Patients

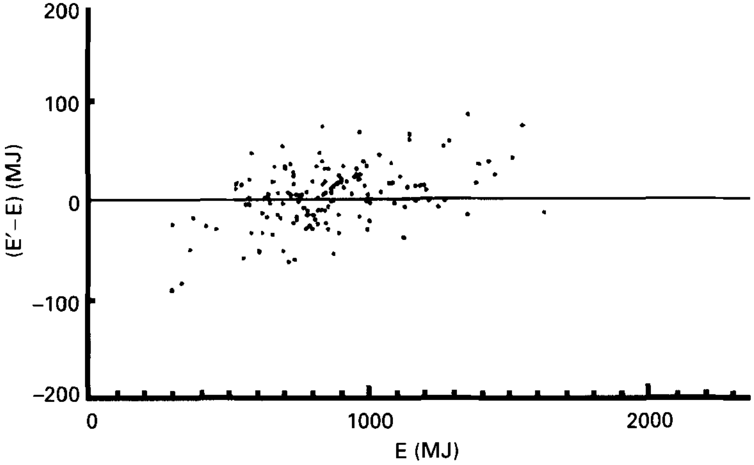

(b) Normal subjects

Fig. 2. The error in the estimate of total body energy (E′) as a function of body energy content (E) in 561 patients and 151 normal subjects, in which total body protein (TBP) is derived from the assumption of proportionality to body water (TBW; TBP = TBW/3·7); E′ is the approximate estimate of body energy content given by equation 9).

(a) Patients:

$$(E' - E) = 0{\cdot}193\ (\text{SD } 0{\cdot}0032) \times E - 38{\cdot}62\ (\text{SD } 2{\cdot}87),$$

SD about the regression line 26·64 MJ, *r* 0·255.

(b) Normal subjects:

$$(E' - E) = 0{\cdot}041\ (\text{SD } 0{\cdot}0085) \times E - 32{\cdot}11\ (\text{SD } 7{\cdot}85),$$

SD about the regression line 27·13 MJ, *r* 0·396.

Multiple regression analysis for E

The relationships which best-fit E to WT, TBW and TBM or height (HT; m) in the combined populations of patients and normal subjects are:

$$E' = 38{\cdot}23 \times \text{WT} - 43{\cdot}06 \times \text{TBW} - 40{\cdot}66 \times \text{TBM} + 28{\cdot}54, \qquad (11)$$

$$E' = 37{\cdot}47 \times \text{WT} - 42{\cdot}52 \times \text{TBW} - 248{\cdot}4 \times \text{HT} + 348{\cdot}8. \qquad (12)$$

Table 2. *The residual standard deviation* (RSD) *and mean difference* (*MD*) *in the estimate of body energy content* (*E′*) *in the combined populations of patients and normal subjects**

Equation no.	Regression equation	MD (MJ)	RSD (MJ)
8	$E' = 39{\cdot}5 \times WT - 46{\cdot}83 \times TBW - 20{\cdot}0 \times TBM$	−17·21	37·42
9	$E' = 39{\cdot}5 \times WT - 44{\cdot}86 \times TBW - 42{\cdot}72 \times TBM$	−17·09	34·59
11	$E' = 38{\cdot}23 \times WT - 43{\cdot}06 \times TBW - 40{\cdot}66 \times TBM + 28{\cdot}54$		27·83
	Patients only using equation 11	−5·3	25·7
	Normals only using equation 11	19·7	26·9
	Patients only:†		
	$E' = 38{\cdot}60 \times WT - 42{\cdot}63 \times TBW - 51{\cdot}45 \times TBM + 28{\cdot}74$	0	25·2
	Normals only†:		
	$E' = 37{\cdot}47 \times WT - 43{\cdot}24 \times TBW - 33{\cdot}54 \times TBM + 46{\cdot}07$	0	25·8
12	$E' = 37{\cdot}47 \times WT - 42{\cdot}52 \times TBW - 248{\cdot}4 \times HT + 348{\cdot}8$	0	25·89
	Patients only using equation 12	−2·6	25·6
	Normals only using equation 12	9·7	24·7
	Patients only†:		
	$E' = 37{\cdot}54 \times WT - 42{\cdot}35 \times TBW - 240{\cdot}8 \times HT + 328{\cdot}5$	0	25·44
	Normals only†:		
	$E' = 37{\cdot}07 \times WT - 43{\cdot}11 \times TBW - 234{\cdot}6 \times HT + 365{\cdot}1$	0	23·26

WT, body mass; TBW, total body water; TBM, total body minerals; HT, height.

* For details of subjects, see Table 1 and p. 633.

† Regression equations derived in separate populations.

Mean differences in each population and residual standard deviations are shown in Table 2. Additional regression equations derived separately in the patient and normal populations are also shown in Table 2. Fig. 3 (a and b) shows a plot of the error in the estimate of E (E′) as a function of E using equation 12.

The Quetelet's Index as a predictor of TBF

Blaxter (1989) gives predictor equations for the Quetelet's index, or percentage fat per unit WT, in terms of WT/HT^2 (kg/m^2):

$$\text{for men: percentage fat} = 1{\cdot}28 \times WT/HT^2 - 10{\cdot}1, \tag{13a}$$

$$\text{for women: percentage fat} = 1{\cdot}48 \times WT/HT^2 - 7{\cdot}0. \tag{13b}$$

No information is given by Blaxter (1989) about the populations in which these equations were derived and the method used to determine TBF. The error in the estimate of percentage fat using these equations for the populations studied in Auckland showed a significant dependence on percentage fat ($r - 0{\cdot}68$ in patients and $r - 0{\cdot}78$ in normal subjects). Regression analysis of the body composition data yielded the following equations:

$$\text{male patients: percentage fat} = 2{\cdot}244 \times WT/(HT)^2 - 35{\cdot}8, \tag{13c}$$

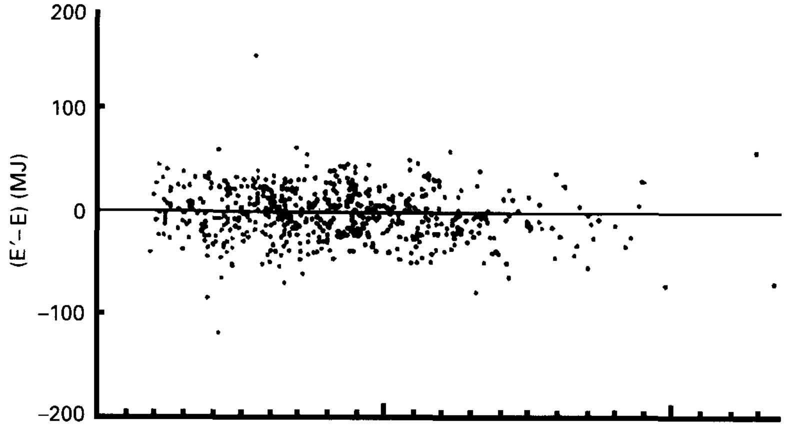
$$\text{female patients: percentage fat} = 2{\cdot}044 \times WT/(HT)^2 - 10{\cdot}5, \tag{13d}$$

$$\text{normal males: percentage fat} = 1{\cdot}962 \times WT/(HT)^2 - 34{\cdot}0, \tag{13e}$$

$$\text{normal females: percentage fat} = 2{\cdot}670 \times WT/(HT)^2 - 27{\cdot}7, \tag{13f}$$

for which the standard deviation is 9·8 and 10·4% in male and female patients and 9·6 and

(a) Patients



(b) Normal subjects

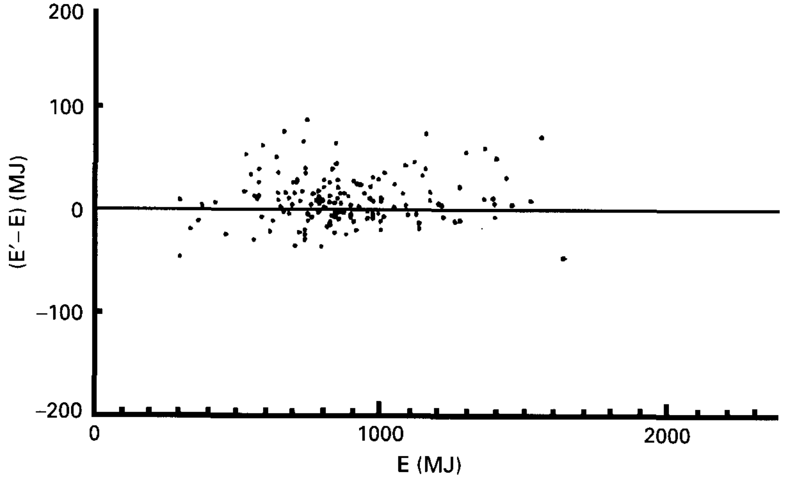


Fig. 3. The error in the estimate of total body energy (E') as a function of body energy content (E) in 561 patients and 151 normal subjects, in which E' is the approximate estimate of E derived from the multiple regression equation 12,

$$E' = 37{\cdot}465 \times \mathrm{WT} - 42{\cdot}517 \times \mathrm{TBW} - 248{\cdot}4 \times \mathrm{HT} + 348{\cdot}8,$$

where WT is body mass, TBW is total body water, HT is height.
(a) Patients:

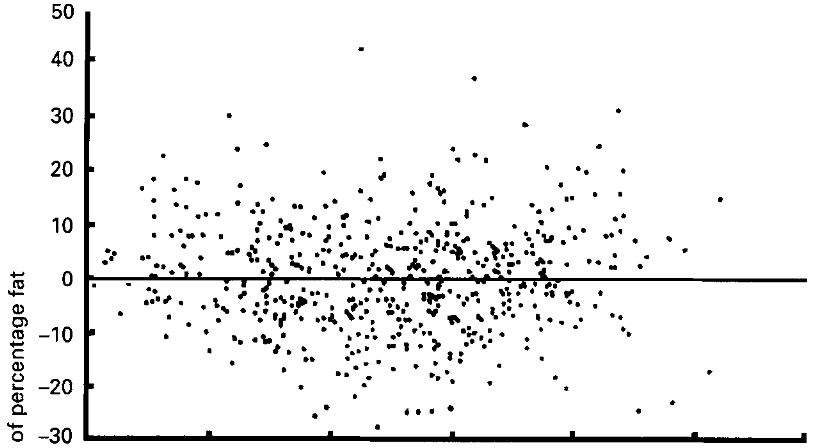
$$(E' - E) = -0{\cdot}0081\ (\textsc{sd}\ 0{\cdot}003) \times E + 4{\cdot}05\ (\textsc{sd}\ 2{\cdot}66),$$

SD about the regression line 25·4 MJ, *r* −0·116, mean difference −2·6 MJ, SD about mean 25·6 MJ.
(b) Normal subjects:

$$(E' - E) = 0{\cdot}0028\ (\textsc{sd}\ 0{\cdot}0071) \times E + 7{\cdot}23\ (\textsc{sd}\ 6{\cdot}55),$$

SD about the regression line 24·66 MJ, *r* 0·0325, mean difference 9·7 MJ, SD about mean 24·7 MJ.

(a) Patients



(b) Normal subjects

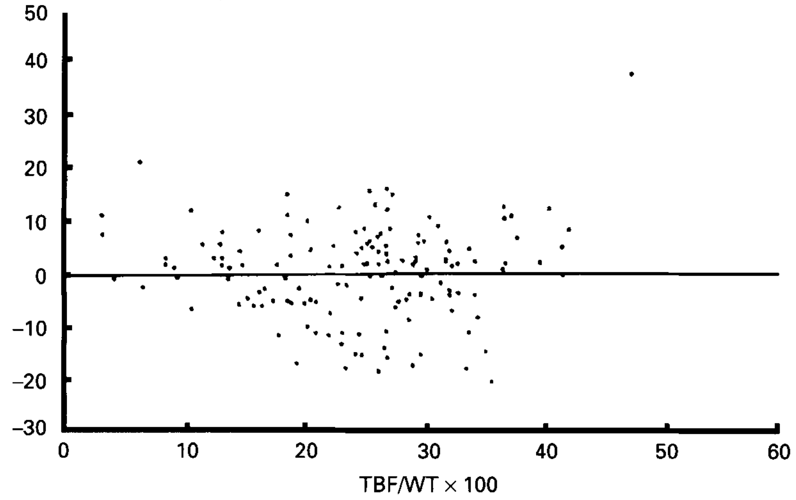


Fig. 4. The error in the estimate of the percentage of body fat (TBF) using the Quetelet's index (body mass (WT)/height (HT)^2) in 561 patients and 151 normal subjects.

Male patients: $\%(\text{TBF}/\text{WT}) = 2{\cdot}244 \times (\text{WT}/\text{HT}^2) - 35{\cdot}8$.
Female patients: $\%(\text{TBF}/\text{WT}) = 2{\cdot}044 \times (\text{WT}/\text{HT}^2) - 10{\cdot}5$.
Normal males: $\%(\text{TBF}/\text{WT}) = 1{\cdot}962 \times (\text{WT}/\text{HT}^2) - 34{\cdot}0$.
Normal females: $\%(\text{TBF}/\text{WT}) = 2{\cdot}670 \times (\text{WT}/\text{HT}^2) - 27{\cdot}7$.

(a) Patients:

$$\%\text{ error} = 0\ (\text{SD } 0{\cdot}040) \times (\text{TBF}/\text{WT} \times 100) + 0{\cdot}0001\ (\text{SD } 1{\cdot}10),$$

SD about regression line 9·4%, $r - 3{\cdot}3 \times 10^{-6}$.
(b) Normal subjects:

$$\%\text{ error} = 0\ (\text{SD } 0{\cdot}085) \times (\text{TBF}/\text{WT} \times 100) + 0{\cdot}0001\ (\text{SD } 1{\cdot}62),$$

SD about regression line 8·4%, $r\ 1{\cdot}5 \times 10^{-6}$.

Table 3. *The residual standard deviation* (RSD) *and mean differences* (*MD*) *in the estimate of energy density* (*E*′) *in the combined populations of patients and normal subjects**

Equation no.	Regression equation	MD (MJ/kg)	RSD (MJ/kg)
14	$E'/WT = 38{\cdot}02-(43{\cdot}14\times TBW+36{\cdot}63\times TBM-32{\cdot}25)/WT$		0·435
	Patients only using equation 14	−0·07	0·42
	Normals only using equation 14	0·26	0·38
	Patients only†:		
	$E'/WT = 38{\cdot}40-(42{\cdot}89\times TBW+45{\cdot}32\times TBM-30{\cdot}82)/WT$	0	0·419
	Normals only†:		
	$E'/WT = 37{\cdot}13-(43{\cdot}10\times TBW+28{\cdot}73\times TBM-49{\cdot}51)/WT$	0	0·375
15	$E'/WT = 37{\cdot}35-(42{\cdot}63\times TBW+216{\cdot}3\times HT-306{\cdot}1)/WT$		0·414
	Patients only using equation 15	−0·034	0·42
	Normals only using equation 15	0·13	0·35
	Patients only†:		
	$E'/WT = 37{\cdot}45-(42{\cdot}56\times TBW+208{\cdot}7\times HT-287{\cdot}6)/WT$	0	0·424
	Normals only†:		
	$E'/WT = 36{\cdot}90-(42{\cdot}90\times TBW+230{\cdot}2\times HT-361{\cdot}1)/WT$	0	0·332
	E′ from equation 12 divided by WT:		
12	$E'/WT = 37{\cdot}47-(42{\cdot}52\times TBW+248{\cdot}4\times HT-348{\cdot}8)/WT$	0	0·416

WT, body mass; TBW, total body water; TBM, total body minerals; HT, height.

* For details of subjects, see Table 1 and p. 633.

† Regression equations derived in separate populations.

8·3% in normal males and females respectively. Fig. 4 (a and b) shows a plot of the error in the estimate of percentage fat using equations 13 (c–f).

Multiple regression for energy density

The relationships which best-fit energy density to the TBW:WT, TBM:WT and HT(m):WT values in the combined populations of patients and normal subjects are:

$$E'/WT = 38{\cdot}02-43{\cdot}14\times TBW/WT-36{\cdot}63\times TBM/WT+32{\cdot}25/WT, \qquad (14)$$

$$E'/WT = 37{\cdot}35-42{\cdot}63\times TBW/WT-216{\cdot}3\times HT/WT+306{\cdot}1/WT, \qquad (15)$$

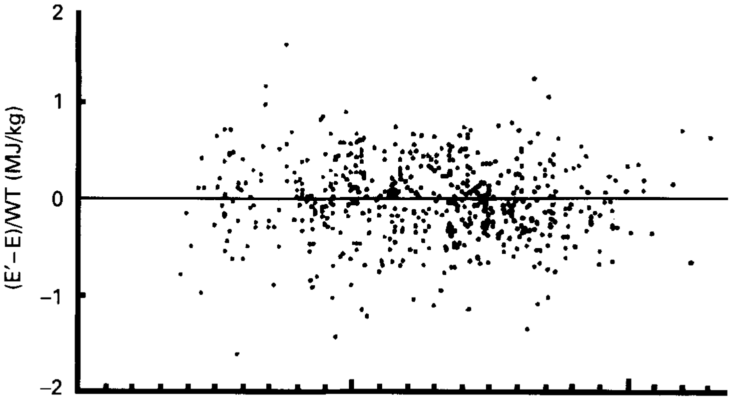
Mean differences in each population and residual standard deviations are shown in Table 3. Additional regression equations for energy density derived in the patient and normal populations separately are also shown in the table. Fig. 5 (a and b) shows a plot of the error in the estimate of energy density using equation 15.

DISCUSSION

The measurement of the energy content of the human body is of great importance to human biology and particularly for studies of patients with wasting disease and obesity. At present most centres estimate body fat and lean tissue stores by anthropometry, total body electrical conductivity (TOBEC), BIA or DEXA. Each of these estimates is subject to errors such that some methods are not yet appropriate for observing small changes in individuals (Cohn, 1985; Jebb *et al.* 1991).

In a five-component model of the composition of the body, where energy is stored in three components, it seems reasonable that E could be estimated from the difference between WT and the other two, and that TBM could be related to HT. WT and HT are obtained easily and accurately. The estimation of TBM from anthropometry of the

(a) Patients



(b) Normal subjects

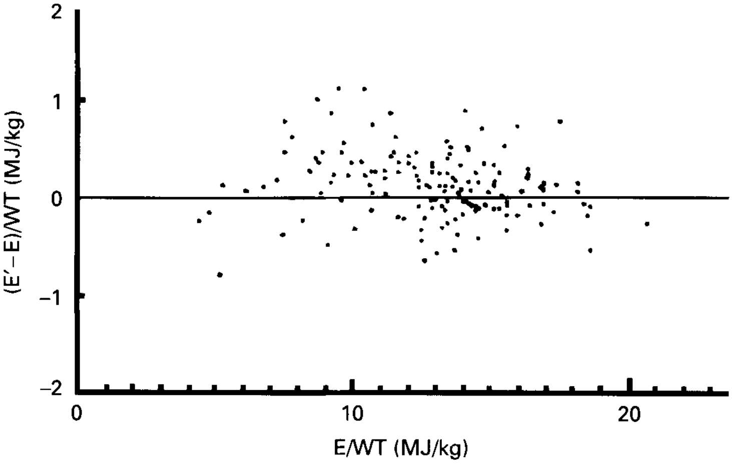


Fig. 5. The error in the estimate of total body energy (E)/body mass (WT) as a function of energy density (MJ/kg) in 561 patients and 151 normal subjects, in which the approximate estimate of E (E′)/WT is derived from the multiple regression equation 15:

$$E'/WT = 37{\cdot}35 - 42{\cdot}63 \times TBW/WT - 216{\cdot}3 \times HT/WT + 306{\cdot}1/WT,$$

where TBW is total body water, HT is height.
(a) Patients:

$$(E' - E)/WT = -0{\cdot}0119 \text{ (SD } 0{\cdot}0047) \times E/WT + 0{\cdot}117 \text{ (SD } 0{\cdot}062),$$

SD about regression line 0·422 MJ/kg, r–0·107, mean difference –0·0345 MJ/kg, SD about mean 0·425 MJ/kg.
(b) Normal subjects:

$$(E' - E)/WT = -0{\cdot}0198 \text{ (SD } 0{\cdot}0092) \times E/WT + 0{\cdot}381 \text{ (SD } 0{\cdot}121),$$

SD about regression line 0·340 MJ/kg, r–0·176, mean difference 0·127 MJ/kg, SD about mean 0·345 MJ/kg.

skeleton cannot take account of osteoporosis, which may result, therefore, in a systematic overestimate of E in these individuals. It is, however, the accurate measurement of TBW that limits the accuracy of this simple method to assess E. TBW can be measured accurately and precisely in many centres by tritium dilution, though with an experimental error likely to exceed the amount of non-aqueous exchange of H.

The DEXA technique presently can estimate fat and lean mass with a reproducibility of 1 and 0·8 kg respectively (Mazess *et al.* 1990), but some doubts exist concerning the accuracy of these soft tissue measurements. It is probable that many centres will derive their own regression equations to relate percentage fat measured by DEXA to WT/HT^2. Although DEXA facilities are now increasingly available in hospitals to monitor osteoporosis and other skeletal disorders, BIA is likely to become more widespread because of its low cost, convenience and non-invasiveness.

The error in the estimate of TBW, lean and fat mass by BIA presently precludes its use for accurate assessment of E (Jebb *et al.* 1991), but further development of the technique may improve its precision and accuracy. In particular, multifrequency BIA measurements offer the possibility of dividing the water space into its intracellular and extracellular components (Segal *et al.* 1991) and perhaps eliminate the significant error due to the positioning of contact electrodes.

It is evident that the regression equations for E or energy density that substitute HT for TBM are slightly superior in their fit to the body composition data. Also HT is more easily measured than TBM. In the application of regression equation 12 to calculate E (or equation 15 to calculate energy density) in other populations, it is possible that the errors in the estimate will be larger than those in the population from which these equations were derived. The standard deviation in E', however, is likely to be no greater than 30 MJ (equivalent to 0·8 kg fat) if the errors in measurement of WT, TBW and TBM or HT do not exceed those reported here. Short-term changes in E exceeding 43 MJ (equivalent to 1·1 kg fat) could be estimated from changes in WT and TBW only.

The authors would like to acknowledge Dr A. H. Beddoe and Mr H. Zuidmeer for the design and construction of the Auckland IVNAA facility, and the measurement of body composition in many patients and normal volunteers: Mr P. Murphy for his compilation of the database; and Dr L. Burkinshaw for useful discussions and statistical advice. The research is supported by the Medical Research Council of New Zealand and Travenol Laboratories, New Zealand, Ltd.

REFERENCES

Beddoe, A. H., Streat, S. J. & Hill, G. L. (1984). Evaluation of an in-vivo prompt gamma neutron activation facility for body composition studies in critically ill intensive care patients: results on 41 normals. *Metabolism* **33**, 270–280.

Blaxter, K. L. (1989). *Energy Metabolism in Animals and Man.* Cambridge: University Press.

Chadwick, P. J. & Saunders, N. H. (1990). TRIM, an electromagnetic body composition analyser. In *Advances in Body Composition Studies*, pp. 387–390 [S. Yasumura, J. E. Harrison, K. G. McNeill, A. D. Woodhead and F. A. Dilmanian, editors]. New York: Plenum Press.

Cohn, S. (1985). How valid are bioelectric impedance measurements in body composition studies? *American Journal of Clinical Nutrition* **42**, 889–890.

Conway, J. M. & Norris, K. H. (1987). Noninvasive body composition in humans by near infrared interactance. In *Proceedings of an International Symposium on In-vivo Body Composition Studies*, Brookhaven, New York. *IPSM Publication* no. 3, pp. 163–170 [K. J. Ellis, S. Yasumura and W. D. Morgan, editors]. London: IPSM.

Culebras, J. M. & Moore, F. D. (1977). Total body water and exchangeable hydrogen. 1. Theoretical calculation of nonaqueous exchangeable hydrogen in man. *American Journal of Physiology* **232**, R54–R59.

Durnin, J. V. G. & Womersley, J. (1974). Body fat assessment from total body density and its estimate from skinfold thicknesses: measurements on 481 men and women aged from 16 to 72 years. *British Journal of Nutrition* **32**, 77–87.

Garrow, J. S., Stalley, S., Diethelm, R., Pittet, P., Hesp, R. & Halliday, D. (1979). A new method for measuring the body density of obese adults, *British Journal of Nutrition* **42**, 173–183.

ICRP (1975). *Report of the Task Group on Reference Man: Anatomical, Physiological and Metabolic Characteristics. ICRP Report* no. 23. Oxford: Pergamon Press.

Jebb, S. A., Coward, W. A., Murgatroyd, P. R., Goldberg, G. R. & Prentice, A. M. (1991). In-vivo measurement of changes in body composition: validation against 12d continuous whole-body calorimetry. *Proceedings of the Nutrition Society* **50**, 37A.

Kehayias, J. J., Ellis, K. J., Cohn, S. H., Yasumura, S. & Weinlein, J. H. (1987). Use of a pulsed neutron generator for in-vivo measurement of body carbon. In *Proceedings of an International Symposium on In-vivo Body Composition Studies*, Brookhaven, New York. *IPSM Publication* no. 3, pp. 427–435 [K. J. Ellis, S. Yasumura and W. D. Morgan, editors]. London: IPSM.

Kinney, J. M. & Moore, F. D. (1956). Carbon balance: a clinical approach to energy exchange. *Surgery* **40**, 16–26.

Knight, G. S., Beddoe, A. H., Streat, S. J. & Hill, G. L. (1986). Body composition of two human cadavers by neutron activation and chemical analysis. *American Journal of Physiology* **250**, E179–E185.

Kyere, K., Oldroyd, B., Oxby, C. B., Burkinshaw, L., Ellis, R. E. & Hill, G. L. (1982). The feasibility of measuring total body carbon by counting neutron inelastic scatter gamma rays. *Physics in Medicine and Biology* **27**, 805–817.

Livesey, G. & Elia, M. (1988). Estimation of energy expenditure, net carbohydrate utilisation and net fat oxidation and synthesis by indirect calorimetry: evaluation of errors with special reference to the detailed composition of fuels. *American Journal of Clinical Nutrition* **47**, 608–628.

Lukaski, H. C., Johnson, P. E., Bolonchuk, W. W. & Lykken, G. I. (1985). Assessment of fat-free mass using bioelectrical impedance measurement of the human body. *American Journal of Clinical Nutrition* **41**, 810–817.

Mazess, R. B., Barden, H. S., Bisek, J. P. & Hanson, J. (1990). Dual energy X-ray absorptiometry for total body and regional bone mineral and soft tissue composition. *American Journal of Clinical Nutrition* **51**, 1106–1112.

Murgatroyd, P. R. & Coward, W. A. (1989). An improved method for estimating changes in whole body fat and protein mass in man. *British Journal of Nutrition* **62**, 311–314.

Segal, K. R., Burastero, S., Chun, A., Coronel, P., Pierson, R. N. & Wang, J. (1991). Estimation of extracellular and total body water by multifrequency bioelectrical impedance measurement. *American Journal of Clinical Nutrition* **54**, 26–29.

Sheng, H. P. & Huggins, R. A. (1979). A review of body composition studies with emphasis on total body water and fat. *American Journal of Clinical Nutrition* **32**, 630–647.

Siri, W. E. (1961). Body composition from fluid spaces and density: analysis of methods. In *Techniques for Measuring Body Composition*, pp. 223–244 [J. Bosek and A. Henschel, editors]. Washington, DC: National Academy of Sciences.

Van Loan, M. & Mayclin, P. (1987). A new TOBEC instrument and procedure for the assessment of body composition: use of Fourier coefficients to predict lean body mass and total body water. *American Journal of Clinical Nutrition* **45**, 131–137.

Vartsky, D., Preswich, W. V., Thomas, B. J., Dabek, J. T., Chettle, D. R., Fremlin, J. H. & Stammers, K. (1979). The use of body hydrogen as an internal standard in the measurement of nitrogen by prompt neutron capture gamma rays. *Journal of Radioanalytical Chemistry* **48**, 243–252.

Printed in Great Britain