Resting energy expenditure in the obese: A cross-validation and comparison of prediction equations

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ABSTRACT

Objective To examine the accuracy and precision of 12 equations or tables for predicting resting metabolic rate (RMR) in obese persons.
Design Observational (correlational) study.
Setting Obesity Research Center, St Luke's/Roosevelt Hospital, New York, NY.
Subjects/samples One hundred twenty-six (73 women, 53 men) healthy, obese subjects recruited through the Obesity Research Center's Weight Control Unit.
Measures RMR by indirect calorimetry. Weight and height were measured to the nearest 0.1 kg and to the nearest 1 cm.
Statistical analyses performed Bivariate regression of predicted RMR on measured RMR; paired t tests for the difference between means of predicted RMR and measured RMR.
Results Of the 12 prediction equations, 6 had intercepts or slopes that were significantly different from 0 and 1, respectively. With two exceptions, the equations accounted for between 56% and 63% of the variance in measured RMR. The Robertson and Reid (1952) equation and the Fleisch (1951) equation performed best with our obese sample.
Applications/conclusions The Robertson and Reid (1952) and the Fleisch (1951) equations are recommended for clinical use with obese patients. *J Am Diet Assoc. 1993; 93: 1031-1036.*

Obesity is a prevalent condition in the United States. Those who treat obese patients often need to establish their energy requirement. In the absence of equipment to perform calorimetry, the energy requirement is usually estimated using a two-stage calculation. First, resting or basal needs are estimated by means of a prediction equation. Second, the resting requirement is adjusted upward on the basis of an estimate of energy expended in physical activity.

Many equations and tables are available for predicting an individual's resting metabolic rate (RMR). Most of the equations were developed by using linear regression to fit functions according to sex, age, height, weight, and other readily available clinical indexes. However, these equations may be inaccurate for obese persons because they have, by definition, an inappropriately large adipose tissue compartment, and adipose tissue is thought to have a low metabolic rate per unit weight (1-3).

Little information is available on the accuracy of predicted RMR in healthy, obese subjects. Of 12 equations that we found in the literature (1,4-13), many were either developed using normal-weight subjects or did not report a separate analysis for the obese subsample. Several investigators who reported a separate analysis for obese subjects did not find the obese different from the nonobese (6-9). Two equations reported by Pavlou et al (14) were derived in an attempt to correct for obvious inaccuracies when existing RMR equations were applied to obese subjects, and one equation was derived by Bernstein et al from a sample of obese patients (1).

To our knowledge, no cross-validations and simultaneous comparisons of these equations on obese subjects have been reported, and few cross-validations have been done on normal-weight sample populations (exceptions are the studies of Mifflin

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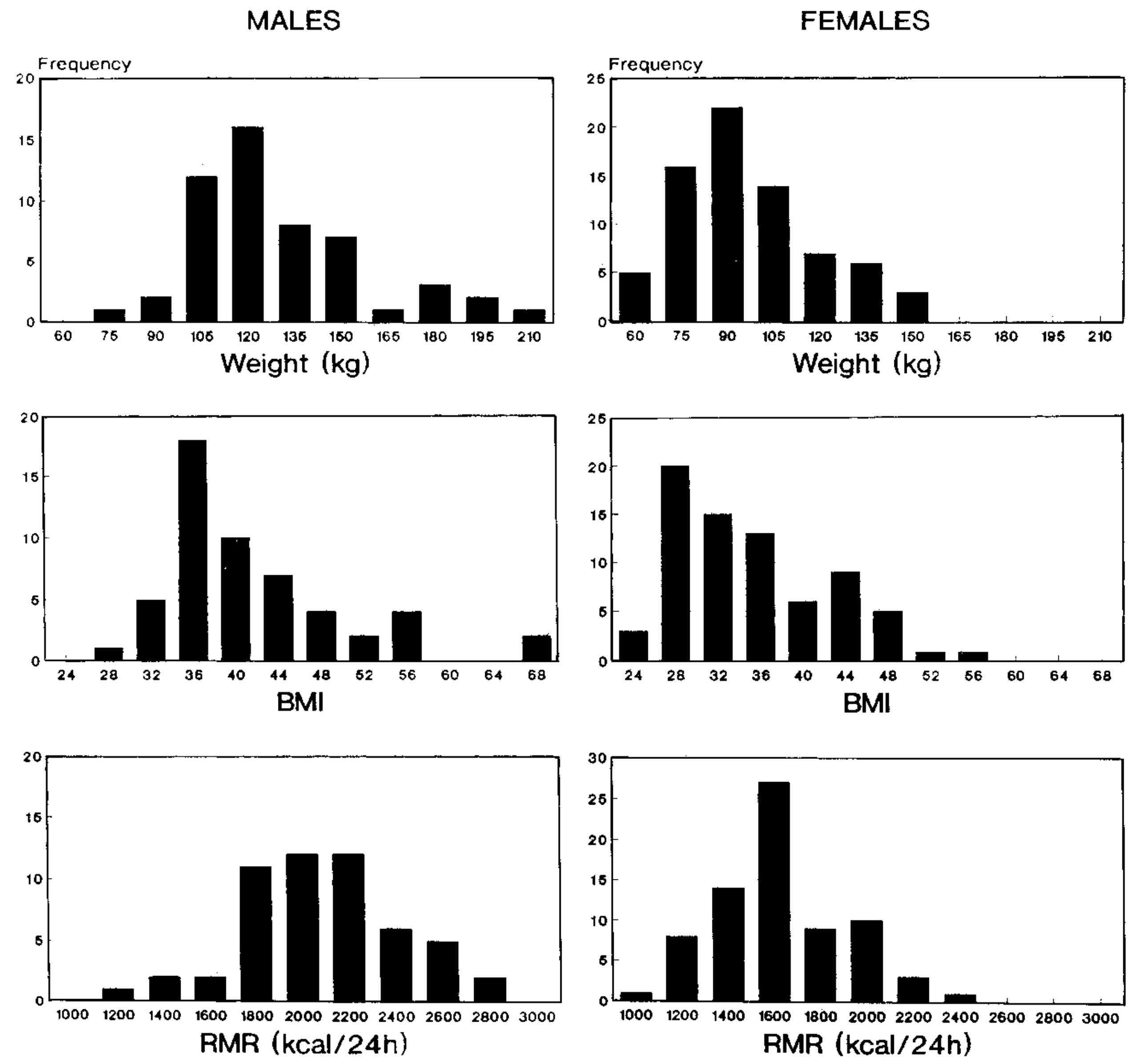

FIG 1. Distributions of weight, body mass index (BMI), and resting metabolic rate (RMR) for men and women in the study sample.

et al [7], Owen et al [8], and Owen et al [9]). To the degree that the sample population on which an equation is developed is small and the number of variables considered for inclusion is large, the opportunity for chance correlations to contribute to the prediction equation for RMR is greater. Thus, cross-validation may show the accuracy of these equations to be lower in samples other than the ones in which they were developed. This result is referred to as "shrinkage" (15). In addition, unappreciated differences in sample characteristics or in measurement methods among investigators may make equations developed for a particular site or sample unsuitable for others.

In this study, we examined the accuracy and precision of 12 published RMR prediction equations in a group of 126 healthy, obese subjects.

METHODS

Subjects

Outpatients more than 20% above desirable weight according to 1959 Metropolitan Life Insurance tables (16) were selected from among those who enrolled between 1984 and 1988 at the Obesity Research Center's Weight Control Unit at St Luke's/Roosevelt Hospital Center, New York, NY. At the time of enrollment, patients undergo a battery of tests, including a complete physical examination and blood biochemistry and thyroid hormone tests. The study population has been described elsewhere (1,17).

Subjects who were selected had no self-reported history of previous or present health problems that might affect metabolic rate and had no recent history of dieting or weight loss at the time of enrollment. Exclusion criteria included thyroid disorders, diabetes mellitus, and taking medications such as thyroid hormones, antihistamines, and certain antidepressants. Most of the 73 women and 54 men reported that their weight was stable or that they were gaining weight slowly. One large man whose RMR was more than 3 standard deviations (SDs) above the mean was excluded from analyses as an outlier, which left 53 men. Figure 1 shows weight, body mass index, and measured RMR distributions for the sample; the means ± SD for women and men, respectively, for each were as follows: weight = 96.7 ± 22.4 kg and 129.9 ± 27.7 kg; body mass index = 35.2 ± 7.2 and 41.5 ± 8.5; measured RMR = 1,626 ± 274 kcal/24 hour and 2,073 ± 328 kcal/24 hour. Mean age was 38.5 ± 11.4 years for women and 38.6 ± 10.6 years for men. Mean height was 165.3 ± 6.6 cm for women and 176.9 ± 7.7 cm for men.

Protocol
Subjects fasted overnight and arrived at the laboratory in the morning. Metabolic rates were measured by indirect calorimetry in a temperature-controlled, quiet room. Measurements were taken using a tightly applied face mask during a 15-minute period after a 12- to 14-hour fast and after a minimum of 30 minutes of rest. The equipment consisted of a Beckman OM-11 polarographic oxygen analyzer (Beckman, SensorMedics Corp, Anaheim, Calif) for measuring oxygen consumption, a Beckman LB-2 nondispersive infrared medical analyzer for measuring carbon dioxide production, and a Monro computer (Litton Business Systems, Orange, NJ) capable of printing out the analysis of the expired air and the calculated respiratory quotient. The mean within-individual SD for repeated RMR tests in our laboratory is 57 kcal/24 hours (error coefficient of variation = 3.8%).

Weight and height were measured to the nearest 0.1 kg and 0.1 cm. When weighed, subjects were dressed in underclothes and were not wearing shoes.

Equations and Statistical Analyses
Table 1 presents the 12 published equations examined in this study. The equation of Bernstein et al (1) was developed several years ago on a sample population from our center, although not on the same subjects who participated in this study. The James equation (6), adopted by the World Health Organization, is published with basal metabolic rate rather than RMR as the predicted variable. Even in that form the James equation tended to overestimate the metabolic rate, so no adjustment was made to convert basal metabolic rate to RMR.

We assessed the accuracy and precision of the 12 equations by comparing calculated vs measured RMRs. Specifically, we regressed measured RMRs on RMRs predicted from each of the published equations. For our comparisons, an equation is accurate to the degree that the resulting linear regression equation has an intercept of 0 and a slope of 1; that is, there is neither a constant bias in the estimate, nor a bias whose magnitude or direction depends on the value of the RMR. The equation is precise to the degree that it leaves little unexplained variance in the dependent variable (ie, $1-R^2$ approaches 0). Standard statistical tests were used to determine whether the intercept and slope were different from 0 and 1. The standard error of the estimate for each equation is the square root of $1-R^2$ multiplied by the SD of the measured RMR. Of the estimates, 68% will fall within 1 standard error of the measured value.

As a further test of the appropriateness of these equations for obese populations, the mean difference between measured and predicted RMR for each equation was evaluated by paired *t* tests.

Table 1
Equations for estimating resting metabolic rate (RMR) (kcal/24 hours)[a]

Reference	Equations
Bernstein et al (1)	W: 7.48(kg) − 0.42(cm) − 3.0(yr) + 844 M: 11.0(kg) + 10.2(cm) − 5.8(yr) − 1,032
Cunningham (4)	501.6 + 21.6(LBM); where for W: LBM = (69.8 − 0.26[kg] − 0.12[yr]) × kg/73.2 for M: LBM = (79.5 − 0.24[kg] − 0.15[yr]) × kg/73.2
Harris and Benedict (5)	W: 655 + 9.5(kg) + 1.9(cm) − 4.7(yr) M: 66 + 13.8(kg) + 5.0(cm) − 6.8(yr)
James (6)	W: 18 − 30 yr: 487 + 14.8(kg) 30 − 60 yr: 845 + 8.17(kg) >60 yr: 658 + 9.01(kg) M: 18 − 30 yr: 692 + 15.1(kg) 30 − 60 yr: 873 + 11.6(kg) >60 yr: 588 + 11.7(kg)
Mifflin et al (7)	W: 9.99(kg) + 6.25(cm) − 4.92(yr) − 161 M: 9.99(kg) + 6.25(cm) − 4.92(yr) + 5
Owen et al (8,9)	W: 795 + 7.18(kg) M: 879 + 10.2(kg)
Pavlou et al (14) (a) (b)	M: − 169.1 + 1.02(pRMR) M: 2089.7 − 8.17(cm) + 16.8(kg) − 8.9(yr) − 1.03(%AIBW)
Aub and Dubois (10)[c]	See tabled values in original reference.
Boothby et al (11)[c]	See tabled values in original reference.
Fleisch (12)[c]	See values in our Table 4.
Robertson and Reid (13)[c]	See values in our Table 3.

[a]Key: W = women; M = men; pRMR = predicted RMR by Harris and Benedict equation (5), %AIBW = percentage above ideal body weight, LBM = lean body mass. Most scientific calculators have an exponent function that can be used to calculate weight to the .425 power and height to the .725 power.
[c]Equation uses body surface area (BSA) and tabled values given in references. BSA (m^2) = .007184$(w)^{.425} \times h^{.725}$. RMR = BSA × 24 × tabled value.

Statistical analyses were carried out with SAS (1990, version 5.18, Statistical Analysis Systems, Carey, NC) and BMDP (1987, version 2, BioMedical Data Programs, Berkeley, Calif) statistical packages.

RESULTS
Table 2 presents the results of the regression analyses in this cross-validation.

For men, 6 of the 12 prediction equations had intercepts or slopes that were significantly different from 0 or 1, respectively. A significantly different intercept means that there is a constant error in predicted RMR of a magnitude independent of the predictor variable's value; a slope significantly different from 1 means that predicted RMRs deviate from measured RMRs by an amount that depends on the values of the predictor variables. Furthermore, the mean error (measured minus predicted RMR) of 8 of the 12 equations was negative and statistically significant ($P<.05$) by *t* test, which indicates that RMRs were overestimated in this sample. If the equation developed on a previous sample at this site by Bernstein et al (1) is excluded, 10 of 11 of the equations for men yield a negative mean error ($P<.001$ by sign test).

Table 2
Regression coefficients (±standard error), R^2, and mean error for resting metabolic rate equations from Table 1 applied to an obese sample population

Group and equation	Reference	Intercept	Slope	R^2	Mean error
Men					
Aub and Dubois	(10)	−227±265	1.02±.117	.59	−180**
Bernstein et al	(1)	655±160	.71±.079**	.60	87
Boothby et al	(11)	−186±239	1.01±.106	.63	−159**
Cunningham	(4)	−1,877±693**	1.80±.332*	.38	−9
Fleisch	(12)	−255±263	1.10±.124	.60	−37
Harris and Benedict	(5)	563±172**	.61±.068**	.60	−408**
James	(6)	378±185*	.70±.075**	.62	−359**
Mifflin et al	(7)	249±205	.83±.092	.60	−132**
Owen et al	(8,9)	194±245	.85±.110	.53	−132**
Pavlou et al (a)	(14)	663±160**	.60±.067**	.60	−289**
Pavlou et al (b)	(14)	727±162**	.56±.067**	.57	−321**
Robertson and Reid	(13)	−154±244	1.08±.118	.61	21
Women					
Aub and Dubois	(10)	−122±173	.99±.097	.59	−135**
Bernstein et al	(1)	−29±160	1.20±.115	.60	244**
Boothby et al	(11)	−43±168	.97±.098	.58	−87**
Cunningham	(4)	−1,565±330**	1.98±.205**	.56	18
Fleisch	(12)	−77±171	1.01±.101	.58	−56*
Harris and Benedict	(5)	97±147	.90±.085	.60	−81**
James	(6)	350±131**	.75±.075**	.57	−82**
Mifflin et al	(7)	310±128*	.80±.076**	.60	−23
Owen et al	(8,9)	−294±198	1.29±.132*	.57	137**
Robertson and Reid	(13)	−77±164	1.06±.101	.60	18

*$P<.05$.
**$P<.01$.

For women, 4 of the 10 equations had intercepts or slopes that differed significantly from 0 or 1. Seven of 10 had a significant mean error, and 6 of 9 (again, excluding the one previously developed at this site) gave a negative mean error, which indicates that the predicted RMR tended to be too high ($P=.26$). With only two exceptions, the equations accounted for between 56% and 63% of the variance in measured RMR. One of these exceptions, the Cunningham equation for men (4), fared poorly because of its method of estimating lean body mass from body weight and age. The other exception is the equation of Owen et al for men (8), which, in this sample, accounted for 53% of the variance.

DISCUSSION

Most published equations overestimated RMRs for the obese men in our sample. For the women, the trend was similar but not as strong. This difference in results may be a consequence of the greater obesity of the male sample whose mean body mass index was 41.5, compared with 35.2 for women. The correlations between estimated and measured values indicated that 30% to 40% of the variability in measured RMR remains unexplained by height, weight, age, and various transformations of these variables such as body surface area.

Several studies (7-9,18) have concluded that the Harris and Benedict equation (5), and possibly other older equations, overestimate RMR in healthy, normal men and women by about 5% to 15%. Our study shows that even recently developed equations are likely to err with obese subjects.

Only the Robertson and Reid equation (13) gave estimated RMR values that were not statistically different in mean, intercept, or slope from measured RMRs for both men and

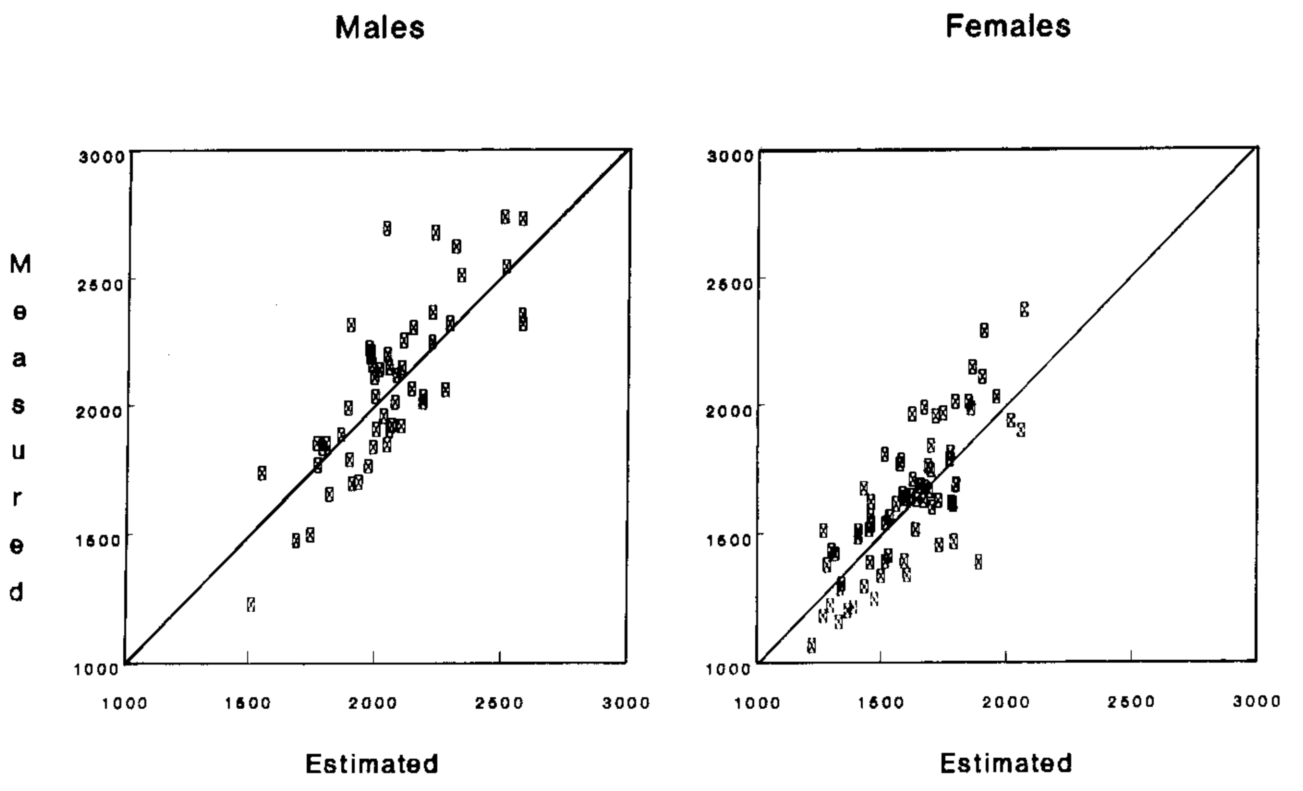

FIG 2. Comparison of measured and estimated resting metabolic rates (kilocalories per 24 hours). Identical values fall on the diagonal line.

women (Figure 2). The Fleisch equation (12) also did well, predicting RMR accurately for men and with only a small mean error for women. The size of the error for the female sample, 56 kcal/24 hours, although statistically significant, is hardly of clinical importance. The Fleisch equation was second only to the Robertson and Reid equation in accuracy for both men and women in our sample.

If, after excluding equations that showed statistically significant differences in slope or intercept, we rank equations according to the size of the mean error, the equations that use body surface area tended to do better than those that use multiple linear regression of weight, height, and age. The equations using body surface area constitute four of the five best equations for women and four of the six best for men. It is not clear why this should be the case, but one possibility is that the formula for the calculation of body surface area includes a power term, kilogram $^{.425}$. This term is a curvilinear function that increases at a decreasing rate, and it may approximate more closely the amount of fat-free mass with increasing body weight than do linear functions of weight.

Fat-free mass is the major determinant of RMR (2,3,19). Data from other samples at our site, and from other investigators (8), show that the percentage of fat tends to be larger for persons with greater body weights. That is, fat-free mass is likely to be 70% of the weight of a 70-kg person but 50% of the weight of a 120-kg person. An equation that multiplies weight by a fixed coefficient will fail to capture this curvilinear component. This suggests that investigators developing equations for use with a wide range of body weights should consider including power terms.

Another question that arises from the results of our study is why the Robertson and Reid equation (13) performed so well compared with other equations. A methodologic difference may be responsible. The protocol of Robertson and Reid (13) for determining RMR involved taking repeated measures until two successive values were within 5% of each other. This allowed subjects to become familiar with the measurement procedure and eliminated elevations in RMR caused by anxiety during testing. Thus, the measured RMR values used in developing the tables of Robertson and Reid were probably lower than those of other studies. This margin of difference may have been sufficient to make their equations more suitable for an obese sample than most other equations, which tended to overestimate RMR.

One puzzling aspect of our results is that the equation previously developed on a sample at this site did not fare particularly well. If between-site differences are responsible, in part, for decreased predictive power in a cross-validation, then one would expect the equation developed at this site to have an advantage. Keep in mind, however, that the selection criteria for the present sample were somewhat different from those for the previous sample. The previous sample included patients of all weights, whereas the present sample included only patients who were more than 20% above desirable weight. In addition, the previous sample excluded only patients who were taking thyroid or diabetes medication, whereas the present sample excluded subjects with any history or existing problems that might affect metabolic rate and with a recent history of dieting or weight loss. Prediction equations may be substantially in error if they are used to estimate energy requirements for persons with hypothyroid or hyperthyroid conditions or uncontrolled diabetes mellitus.

How much would estimates of RMR have been improved by measures of fat-free mass? Some investigators (20,21) have accounted for 67% to 82% of the variance in measured RMR with regression equations based on fat-free mass. A review of their work suggests that fat-free mass explains about 85% of the

Table 3
Kilocalories per square meter of body surface according to Robertson and Reid (13)

Age (y)	Men	Women
3	60.1	54.5
4	57.9	53.9
5	56.3	53.0
6	54.2	51.8
7	52.1	50.2
8	50.1	48.4
9	48.2	46.4
10	46.6	44.3
11	45.1	42.4
12	43.8	40.6
13	42.7	39.1
14	41.8	37.8
15	41.0	36.8
16	40.3	36.0
17	39.7	35.3
18	39.2	34.9
19	38.8	34.5
20	38.4	34.3
21	38.1	34.1
22	37.8	34.0
23	37.6	34.0
24	37.3	33.9
25	37.1	34.0
26	37.0	34.0
27	36.8	34.0
28	36.6	34.0
29	36.5	34.1
30	36.4	34.1
31	36.3	34.0
32	36.2	33.9
33	36.1	33.8
34	36.0	33.7
35	35.9	33.5
36	35.8	33.3
37	35.7	33.1
38	35.7	32.9
39	35.6	32.8
40	35.5	32.6
41–44	34.5	32.5
45–49	34.1	32.2
50–54	33.8	31.9
55–59	33.4	31.6
60–64	33.1	31.3
65–69	32.7	31.0
70–74	32.4	30.7
75 or more	32.0	...

Extracted from Robertson JD, Reid DD. Standards for the basal metabolism of normal people in Britain. *Lancet.* 1952; 1:943. Table III.

Table 4
Kilocalories per square meter of body surface according to Fleisch (12)

Age (y)	Men	Women
1	53.0	53.0
2	52.4	52.4
3	51.3	51.2
4	50.3	49.8
5	49.3	48.4
6	48.3	47.0
7	47.3	45.4
8	46.3	43.8
9	45.2	42.8
10	44.0	42.5
11	43.0	42.0
12	42.5	41.3
13	42.3	40.3
14	42.1	39.2
15	41.8	37.9
16	41.4	36.9
17	40.8	36.3
18	40.0	35.9
19	39.2	35.5
20	38.6	35.3
25	37.5	35.2
30	36.8	35.1
35	36.5	35.0
40	36.3	34.9
45	36.2	34.5
50	35.8	33.9
55	35.4	33.3
60	34.9	32.7
65	34.4	32.2
70	33.8	31.7
75	33.2	31.3
80	33.0	30.9

Extracted from Fleisch A. Le metabolisme basal standard et sa determinaton au moyen du "Metabocalculator". *Helv Med Acta.* 1951; 1:36-39. Tables 2 and 3.

variation in RMR (22). Others have found that fat-free mass accounted for only 55% to 60% of the variance, which is not substantially different from the amount accounted for by body weight alone (8). The answer depends, in part, on whether the question concerns an individual or a sample and on the ranges and distributions of the variables. If several persons have similar weights, heights, and ages, then knowledge of the amount of fat-free mass (assuming there is some variation among persons) would make a useful contribution. In the usual sample study, however, there was a large range in weight, height, and age; hence, a strong correlation exists between those variables and fat-free mass. In such a case, measures of fat-free mass may add relatively little to the accuracy of RMR estimates based on weight alone.

APPLICATIONS

Dietitians are frequently called on to estimate daily energy requirements when measurements of metabolic rate cannot be made. Most published equations for estimating RMR tend to give excessively high values for obese men and women. For adults who are more than 20% above desirable weight, or whose body mass index exceeds 28, we recommend the Robertson and Reid equation or the Fleisch equation, because they appear to offer the best estimates in an obese population. Of the estimates made with the Robertson and Reid equation, 68% were within 174 kcal (1 standard error of the estimate) of the measured value for women and within 203 kcal of the measured value for men. For the Fleisch equation, 1 standard error of the estimate was 178 kcal for women and 207 kcal for men. The tables needed to use these equations are presented here as Tables 3 and 4. ■

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