Review

Comparison of Predictive Equations for Resting Metabolic Rate in Healthy Nonobese and Obese Adults: A Systematic Review

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ABSTRACT

Background An assessment of energy needs is a necessary component in the development and evaluation of a nutrition care plan. The metabolic rate can be measured or estimated by equations, but estimation is by far the more common method. However, predictive equations might generate errors large enough to impact outcome. Therefore, a systematic review of the literature was undertaken to document the accuracy of predictive equations preliminary to deciding on the imperative to measure metabolic rate.

Methods As part of a larger project to determine the role of indirect calorimetry in clinical practice, an evidence team identified published articles that examined the validity of various predictive equations for resting metabolic rate (RMR) in nonobese and obese people and also in individuals of various ethnic and age groups. Articles were accepted based on defined criteria and abstracted using evidence analysis tools developed by the American Dietetic Association. Because these equations are applied by dietetics practitioners to individuals, a key inclusion criterion was research reports of individual data. The evidence was systematically evaluated, and a conclusion statement and grade were developed.

Results Four prediction equations were identified as the most commonly used in clinical practice (Harris-Benedict, Mifflin-St Jeor, Owen, and World Health Organization/Food and Agriculture Organization/United Nations University [WHO/FAO/UNU]). Of these equations, the Mifflin-St Jeor equation was the most reliable, predicting RMR within 10% of measured in more nonobese and obese individuals than any other equation, and it also had the narrowest error range. No validation work concentrating on individual errors was found for the WHO/FAO/UNU equation. Older adults and US-residing ethnic minorities were underrepresented both in the development of predictive equations and in validation studies.

Conclusions The Mifflin-St Jeor equation is more likely than the other equations tested to estimate RMR to within 10% of that measured, but noteworthy errors and limitations exist when it is applied to individuals and possibly when it is generalized to certain age and ethnic groups. RMR estimation errors would be eliminated by valid measurement of RMR with indirect calorimetry, using an evidence-based protocol to minimize measurement error. The Expert Panel advises clinical judgment regarding when to accept estimated RMR using predictive equations in any given individual. Indirect calorimetry may be an important tool when, in the judgment of the clinician, the predictive methods fail an individual in a clinically relevant way. For members of groups that are greatly underrepresented by existing validation studies of predictive equations, a high level of suspicion regarding the accuracy of the equations is warranted.

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An accurate assessment of energy needs is necessary to complete individual nutrition assessments and to determine the effectiveness of planned nutrition interventions. With a few extreme exceptions, the resting metabolic rate (RMR) is by far the largest single component of total daily caloric expenditure, and calorimetry is among the most accurate methods for determining RMR in various states of health and disease. Direct calorimeters and respiratory chambers have been in existence since the late 19th and early 20th centuries, but such devices were and remain primarily research tools (1). Hence, calculation by mathematical equations, developed from direct or indirect calorimetry measures, was adopted as the major method of determining energy needs in individuals.

Since the 1970s, portable indirect calorimeters for measurement of gas exchange and RMR have been available clinically. These devices are accurate to within 5% (2), although accurate measures require attention to client-specific (fasting, exercise, resting, comfort) and machine-specific (calibration, steady state, adequate test time) conditions for test accuracy. The evidence behind these indirect calorimetry conditions was also addressed by the same evidence panel, and will be published separately. Although indirect calorimetry has had a high clinical profile, the expense of the calorimeters, the time needed to accomplish a measurement, and the need for trained personnel to run the tests have prevented widespread use of indirect calorimetry for individual patients, especially outside the critical care arena (3). Predictive equations therefore remain the order of the day in dietetics practice for most clinic and inpatient care.

Statistical laws are such that predictive regression equations work best in groups of people. When regression equations are applied to an individual (as in clinical and research usage of RMR equations), significant error can occur. Furthermore, if the individual does not share important characteristics with the group of people from whom the equation was developed (for RMR these would include age, sex, body composition, and possibly ethnicity), the chance for clinically important error increases.

The coming availability of relatively inexpensive, quick, and user-friendly portable calorimeters carries the potential for broad application of indirect calorimetry in dietetics practice. To assess the potential role of wide use of indirect calorimetry in place of predictive equations in the non–intensive care unit clinical setting, a review of the literature describing the strengths and limits of predictive methods for RMR and the consequences/outcomes related to erroneous caloric assessment was deemed necessary by the American Dietetic Association (ADA). The strength of predictive equations in acutely ill patients and outcomes associated with measurement of RMR were not included in the current article, because these topics will be covered by disease-specific expert panels under other evidence-based guidelines supported by ADA.

METHODS

A group of evidence analysts and clinical and research experts was convened by ADA to determine according to the literature what role indirect calorimetry should play in clinical care. The panel of experts was drawn from clinical and/or research areas including nutrition support, geriatrics, obesity, and oncology. The evidence analysts were registered dietitians with rigorous training in the evidence analysis process.

The project format was to pose questions that related indirect calorimetry to clinical practice. Three broad questions were delineated by this team. The current review is documentation of the first question, "Which predictive methods of RMR work the best, and how accurate are they for an individual?" The second broad question is, "What are the best evidence-based methods to use in measuring RMR by indirect calorimetry?" This question was addressed by the current evidence panel, and will be reported in a separate publication. A third question evaluated the outcomes associated with indirect calorimetry measurement, and will be reported by disease-specific evidence panels.

The evidence analysts searched the literature, systematically abstracted articles pertinent to these questions, and assigned a quality grade to each article (Figure 1) (4,5). The expert panel guided the evidence analysis process by clarifying the primary questions to be addressed, supplying references pertinent to the analysis beyond those that appeared in the literature search, evaluating the annotated lists of included and excluded articles, and developing by consensus a scientifically sound conclusion statement. Each statement was graded on the strength of the supporting data (Figure 2) (5,6).

Refinement of the Question

Because RMR might vary according to differences in body composition, age, or ethnicity, subquestions regarding the validity of predictive equations in healthy nonobese adults, obese adults, older individuals, and ethnic groups were delineated. The questions were modified according to the suggested question framework advocated by the Agency for Healthcare Research and Quality (7).

Healthy subjects were defined as those who did not have a disease that might have impact on RMR, such as thyroid disease or diabetes mellitus, and were not taking medications known to affect RMR. Validation studies typically assured these criteria by medical examinations, health surveys, or self-report as a component of the study procedures. In two cases, only the healthy control subjects (and not the clinical patients) were used for the current article. Disease-specific evidence panels will consider indirect calorimetry data in ill patients for addition to medical nutrition therapy protocols in the future. Obesity was considered an accepted disease state, provided the individuals measured did not also have thyroid disease, diabetes, or medications impacting RMR.

For this systematic review, the definition of obesity was by body mass index category as outlined by the National Heart, Lung, and Blood Institute (8). The investigators of original articles, however, often described body weight status in terms of percent ideal body weight or percent reference weight, with obesity defined as weight greater than 120% of reference weight. A few described obesity in terms of percent body fat by hydrodensitometry or dual absorptiometry. Because the primary data were usually not available for recalculation of body mass index, individuals defined as obese by these older criteria were accepted as obese by our evidence analysis. When investigators reported their data combining all weight categories, lean to obese, the studies were accepted but not reported as describing either nonobese or obese subjects because broad weight ranges would be reflected in the prediction estimation errors. Trials accepted for inclusion in the evidence analysis reported measured weight, and all studies reported height with 11 not describing height measurement details.

Literature Search and Data Collection

An independent researcher completed search strategies that were general (to optimize sensitivity) and targeted (to optimize specificity). Medical Subject Heading search

Ten research design areas evaluated before assigning a quality rating are:

1. Clear research question
2. Absence of bias in subject selection
3. Comparable groups after randomization
4. Description of withdrawal method
5. Absence of subject, clinical, and/or investigator indirect calorimetry measurement bias
6. Interventions clearly described
7. Outcomes stated, with valid and reliable measurement

Valid and reliable indirect calorimetry protocol measurement techniques that had to be described before receiving a "yes" to this research design area:

   a. Machine calibration
   b. 20 to 30 minutes rest before measurement if traveling to a measurement center
   c. Discuss procedures prior to single measurements (subject training)
   d. Steady state (predetermined group mean covariance, elimination of erratic measurements, and/or ongoing acceptable monitoring)
   e. Measurement length
   f. Exercise restrictions in healthy adults the day prior to measurements or description of sedentary lifestyle in healthy adults or identifying movement restrictions in critically ill patients
   g. Fasting

8. Appropriate statistical treatment
9. Conclusions supported by results
10. Funding bias unlikely

Three quality ratings available and assigned using the following criteria are:

Quality rating: "−"
Indicated that majority of research design and implementation criteria had not been met, and questions suggested limited research rigor.

Quality rating: "∅"
Indicated that the research design and implementation was not exceptionally strong or did not achieve indirect calorimetry protocol adherence or had risks that would bias measurement accuracy.

Quality rating: "+"
Indicated that all key research design issues (ie, 2, 3, 6, and 7) and at least one other area were appropriately handled.

Figure 1. Research design quality rating checklist.

Grade I: Good—The evidence consists of results from studies of strong design for answering the question addressed. The results are both clinically important and consistent with minor exceptions at most. The results are free of serious doubts about generalizability, bias, and flaws in research design. Studies with negative results have sufficiently large sample sizes to have adequate statistical power.

Grade II: Fair—The evidence consists of results from studies of strong design answering the question addressed, but there is uncertainty attached to the conclusion because of inconsistencies among the results from different studies or because of doubts about generalizability, limited number of studies, bias, research design flaws, or adequacy of sample size. Alternatively, the evidence consists solely of results from weaker designs for the questions addressed, but the results have been confirmed in separate studies and are consistent with minor exceptions at most.

Grade III: Limited—The evidence consists of results from a limited number of studies of weak design for answering the questions addressed. Evidence from studies of strong design is either unavailable because no studies of strong design have been done or because the studies that have been done are inconclusive due to lack of generalizability, bias, design flaws, or inadequate sample sizes.

Grade IV: Expert Opinion Only—The support of the conclusion consists solely of the statement of informed medical commentators based on their clinical experience, unsubstantiated by the results of any research studies, or only has the support of narrative reviews.

Figure 2. Definitions of grades for conclusion statements (6).

terms of "indirect calorimetry and energy metabolism" or "calorimetry and basal metabolic rate" in the National Library of Medicine's PubMed database were used. Additional search strategies within PubMed included free-text of "energy metabolism," "resting metabolic rate," "resting energy metabolism," "resting energy expenditure" and "Harris-Benedict." Limitations placed on initial search strategies included publication dates ranging from January 1, 1980, to March 01, 2003, English language, adults (19 years and older), and human subjects. The literature

1. Primary research design (randomized clinical trial, cohort, cross-sectional repeated measures crossover).
2. Individual errors rather than or in addition to group means reported.
3. Studies applying Bland Altman or root mean squared error analysis, analysis of variance, or group mean errors with 95% confidence intervals were also abstracted and considered as supportive data when assigning a grade level to predictive equation conclusion statements, but these were subservient to measures of individual variation.
4. Sample size at least 10 per groups with clear description of the subject population under study.
5. Dropout rate <20%.
6. Only the most recent report was used, when multiple publications of the same data were found by the same authors.
7. Tracer or euglycemic clamp methodologies were not employed.

Figure 3. Inclusion criteria for accepting a published article as pertinent to the question.

search yielded 1,868 citations for the entire project. Additional searches in the Cumulative Index to Nursing & Allied Health Literature (1981 to 2003) and Excerpta Medica Database (limited, 1999 to 2003) databases were added. Nutrition journals representing clinical nutrition or critical care settings were hand or electronically searched. After sorting through the citation titles, approximately 300 were found that pertained to the RMR prediction question. Based on designated inclusion criteria (Figure 3), 38 articles were considered in the conclusion statement development.

In the results that follow, prediction accuracy is defined as the percentage of individuals in the study group whose RMR was predicted to within ±10% of measured RMR. This error limit on prediction accuracy was accepted empirically as being consistent with calorimetry measurement errors of 5% or less (2). All other predictions were considered errors, and these errors are reported as percentages of subjects whose RMR was underestimated and overestimated. Additionally, to clarify the extent and clinical risk of prediction inaccuracy in any given individual, the maximal underestimation and maximal overestimation are reported. Because group mean data mask larger individual errors and also are not applicable to practice decisions for individual subjects, group mean data were not used to determine the conclusion statements. An extreme example of how group means may mask individual errors would be an equation in which the prediction is 100% of measured, but 50% of individual measurements were 500 kcal below the group mean and 50% were 500 kcal above the group mean. The predictive equation would seem strong by group mean analysis, although 500-kcal errors would have clinical importance if applied to caloric delivery. When investigators of studies did not report individual data points, or analyze the data in terms of agreement with the measure (as predictions within 10% of measured), we could not evaluate the real extent of error that would be obtained from the estimate.

RESULTS

Of the many equations developed for prediction of RMR in general populations, four were identified as commonly used and therefore clinically relevant for application to individuals. The four predictive equations (Figure 4) were those developed by Harris and Benedict (10), Owen (11,12), World Health Organization/Food and Agriculture Organization/United Nations University WHO/FAO/UNU (13), and Mifflin-St Jeor (14).

Healthy, Nonobese Individual Adults

Mifflin-St Jeor. The Mifflin-St Jeor equation was derived from a sample of 498 normal-weight, overweight, obese, and severely obese individuals ages 19 to 78 (44.5±14.1) years (14). The racial composition of the sample was not specified, and the representation of older adults (75 to 84 years) was limited. Very few oldest old (>80 years) individuals were measured.

The Mifflin-St Jeor equation performed the best of the four predictive equations evaluated. The 10 validation studies considered in evaluating the Mifflin-St Jeor equation are presented in Figure 5. In a high-quality study of 83 nonobese adults ages 18 to 78 years using the Mifflin-St Jeor equation, in 82% of the cases the prediction was ±10% of measured RMR, with errors evenly distributed between underestimation and overestimation. Maximal underestimation error was 18%, and maximal overestimation error was 15% of measured RMR (18).

Harris-Benedict. The Harris-Benedict equation was developed using predominantly normal-weight white men (n=136) ages 16 to 63 years (mean=27±9) and women (n=103) ages 15 to 74 (mean=31±14) in studies conducted over a time frame of about 1907 to 1917 (10). Although literature descriptions identify the Harris-Benedict formula as representing basal metabolic rate, in truth, the measures were taken under resting and not basal conditions.

Because it is the oldest of the equations still in clinical use, the Harris-Benedict equation has undergone the most extensive validation, and the 25 studies evaluated are listed in Figure 6 (see pages 781 through 783). With the Harris-Benedict equations, accurate prediction of RMR across all validation studies occurred in 45% to 80% of individuals (11,12,18,27), and overestimates occurred more frequently than underestimates.

Owen. The Owen equation for men was based on a sample size of 60 subjects, ages 18 to 82 years (mean=38±15.6), including 24 nonobese, 11 obese, and five extremely obese individuals (11). The women's equation was developed from a sample of 44 women ages 18 to 65 years (mean=35±12) years, and included all weight classifications (12). One subject was underweight, 23 were normal weight, four were overweight, 10 were obese, and six were extremely obese. Eight of the women were trained athletes, but these women were not included in the calculation of the equation. No old or oldest old women were included, and the oldest old men were underrepresented. The ethnic composition of the women's study was not reported, but the men's sample included white, black, and Asian people.

The 13 validation studies included in the evaluation of the Owen equations are listed in Figure 7. In a validation

- Mifflin-St Jeor, 1990 (14)
  - Men: $RMR^{a}=9.99\times weight+6.25\times height-4.92\times age+5$.
  - Women: $RMR=9.99\times weight+6.25\times height-4.92\times age-161$.
- Harris Benedict, 1919 (10)
  - Men: $RMR=66.47+13.75\times weight+5.0\times height-6.75\times age$.
  - Women: $RMR=665.09+9.56\times weight+1.84\times height-4.67\times age$.
- Owen, 1986-87 (11,12)
  - Men: $RMR=879+10.2\times weight$.
  - Women: $RMR=795+7.18\times weight$.
- WHO/FAO/UNU[b], 1985 (13)
  - Weight only:

Age (y)	
Men	
18-30	$15.3\times weight+679$
31-60	$11.6\times weight+879$
>60	$13.5\times weight+487$
Women	
18-30	$14.7\times weight+496$
31-60	$8.7\times weight+829$
>60	$10.5\times weight+596$

  - Weight and height (m):

Age (y)	
Men	
18-30	$15.4\times weight-27\times height+717$
31-60	$11.3\times weight+16\times height+901$
>60	$8.8\times weight+1,128\times height-1,071$
Women	
18-30	$13.3\times weight+334\times height+35$
31-60	$8.7\times weight-25\times height+865$
>60	$9.2\times weight+637\times height-302$

Figure 4. Predictive equations selected for validation study comparisons. [a]RMR=resting metabolic rate in kcal/day. [b]WHO/FAO/UNU=World Health Organization/Food and Agricultural Organization/United Nations University. All equations use weight in kilograms, height in centimeters (except WHO/FAO/UNU, which uses height in meters), and age in years.

study of strong design, the Owen equation predicted within ±10% measured RMR in 73% of individuals (18). Underestimates occurred 21% and overestimates 6% of the time. The maximal underestimation was 24% and maximal overestimation was 28% of measured RMR (18).

World Health Organization/Food and Agriculture Organization/United Nations University. The WHO/FAO/UNU equations were developed using data from Schofield, Schofield, and James (13,36-38), mostly derived from young European military and police recruits, including 2,279 men and 247 women with 45% of Italian descent (36-39). The age range of the study sample was 19 to 82 years; hence, the oldest old population was minimally represented. Two equations were developed, the first using weight only and the second including weight and height. In all subsequent validation work done with the WHO/FAO/UNU equation, group mean but not individual prediction accuracy was reported. Therefore, we could not evaluate the accuracy of the WHO/FAO/UNU equation for individual prediction of caloric need on the same basis that the other equations were evaluated.

Obese but otherwise Healthy Individual Adults

For obese adults, the accuracy rate of all predictive equations decreased compared with the nonobese adults, and the range of individual errors increased. This trend was less prominent in the Mifflin-St Jeor equation than it was in any other equation.

Mifflin-St Jeor. In one validation study of strong design, 70% of obese subjects were predicted accurately by the Mifflin-St Jeor equation, as compared with 82% in nonobese subjects in the same study (18). Underestimates occurred more commonly than overestimates. The maximum underestimate was 20%, and the maximum overestimate was 15% of measured RMR (18).

Harris-Benedict. The Harris-Benedict equation prediction was accurate in 38% to 64% of obese people (11,12,18,28,30). This predictability level decreased to 26% when an adjusted body weight was used in the equation (18). Overestimation errors were reported more commonly than underestimation errors in all trials. Maximal individual errors were 35% of measured RMR underestimation using current body weight (28) and 42% using adjusted body weight (18). Maximal overestimation individual errors were 43% of measured RMR using current body weight (27) and 25% of measured RMR using adjusted body weight (18). Of note, use of an adjusted body weight in the Harris-Benedict equation reduced the risk of overestimating RMR, but it drastically increased the maximum underestimation error. The expert panel therefore concluded that the Harris-Benedict equation for en-

Author, year (reference number)	Subject age,[a] number of subjects, sex	Weight class, percent body fat or NHLBI[b] BMI[c] category and range[a]	Study quality[d]	Calorimetry method criteria met (missing techniques)	Accurate prediction[e]	Inaccurate prediction[f]	Maximal errors[g]
Arciero and colleagues, 1993 (15)	50-78 y 89 M[h]	Lean to obese: 8%-33% body fat	∅	No (calibration, steady state)	NA[i]	NA	18% underestimate to 5% overestimate
Arciero and colleagues, 1993 (16)	50-81 y 75 F[j]	Lean to obese: 20%-43% body fat	∅	No (calibration, steady state)	NA	NA	31% underestimate to 7% overestimate
DeLorenzo and colleagues, 2001 (17)	18-59 y 127 M 193 F	Lean to obese: M: 18-59 F: 19-39	+	Yes	NA	NA	NA
Frankenfield and colleagues,[d] 2003 (18)	20-78 y 130 M, F 83 nonobese 47 obese	Nonobese: 16-30 Obese: 31-99	+	Yes	Nonobese: 82% within 10% of measured RMR[k] Obese: 70% within 10% of measured RMR	Nonobese: 8% underestimated to 10% overestimated Obese: 21% underestimated to 9% overestimated	Nonobese: 18% underestimate to 15% overestimate Obese: 20% underestimate to 15% overestimate
Garrel and colleagues, 1996 (19)	18-33 y 67 M, F	Nonobese: 20.1-25.6	−	Yes	Unclear	NA	NA
Heshka and colleagues, 1993 (9)	29-49 y 53 M	Overweight to obese: 28-56	∅	No (calibration, training, steady state, exercise)	NA	NA	NA
Heshka and colleagues, 1993 (9)	27-50 y 73 F	Nonobese to obese: 24-56	∅	No (calibration, training, steady state, exercise)	NA	NA	NA
Liu and colleagues, 1993 (20)	29-59 y 223 M, F	Nonobese: 19-25	∅	No (calibration)	NA	NA	NA
Scalfi and colleagues, 1993 (21)	18-32 y 74 F	Lean to overweight: 19-29 Obese: 30-42	+	Yes	NA	NA	NA
Siervo and colleagues, 2003 (22)	18-31 y 157 F	Nonobese: 21-25 Overweight: 26-29 Obese: 31-39	+	Yes	NA	NA	NA
Taafe and colleagues, 1995 (23)	60-82 y 116 F	Nonobese to obese: 19-39	+	Yes	NA	NA	NA

[a] Range established from mean±1 standard deviation.
[b] NHLBI=National Heart, Lung, and Blood Institute.
[c] BMI=body mass index; calculated as kg/m^2.
[d] Quality ratings: "−"=indicated that majority of research design and implementation criteria had not been met and questions suggested limited research rigor; "∅"=indicated that the research design and implementation was not exceptionally strong or did not achieve indirect calorimetry protocol adherence or had risks that would bias measurement accuracy; "+"=indicated that all key research design issues (ie, 2, 3, 6, and 7 in Figure 1) and at least one other area were appropriately handled.
[e] Percentage of all subjects whose resting metabolic rate predicted by the Mifflin-St Jeor equation was within 90% to 110% of measured resting metabolic rate.
[f] Percentage of all subjects whose predicted resting metabolic rate by Mifflin-St Jeor equation was <90% or >110% measured.
[g] The lowest and highest prediction as a percent of measured resting metabolic rate.
[h] M=male.
[i] NA=not applicable.
[j] F=female.
[k] RMR=resting metabolic rate.

Figure 5. Mifflin-St Jeor nonobese and obese validation studies used to evaluate the Mifflin-St Jeor prediction equation.

Author, year (reference number)	Subject age,[a] number of subjects, sex	Weight class, percent body fat or NHLBI[b] BMI[c] category and range[a]	Study quality[d]	Calorimetry method criteria met (missing techniques)	Accurate prediction[e]	Inaccurate prediction[f]	Maximal errors[g]
Arciero and colleagues, 1993 (15)	50-78 y 89 M[h]	Nonobese to obese: 8%-33% body fat	∅	No (calibration, steady state)	NA[i]	NA	Lean to obese: 19% underestimate to 9% overestimate
Arciero and colleagues, 1993 (16)	50-81 y 75 F[j]	Nonobese to obese: 20%-43% body fat	∅	No (calibration, steady state)	NA	NA	Lean to obese: 27% underestimate to 12% overestimate
Case and colleagues, 1997 (24)	21-33 y 89 F	Nonobese: 17-29	∅	No (length)	NA	NA	NA
Clark and colleagues, 1991 (25)	18-33 y 29 M	Nonobese: 18-30	∅	Yes	NA	NA	NA
Daly and colleagues, 1985 (26)	22-52 y 35 M (Emory) 24-35 y 24 M (Sloan-Kettering) 29-53 y 39 F (Emory) 23-34 y 29 F (Sloan-Kettering)	Nonobese: M: 95%-122% ideal body weight (Emory) 95%-117% ideal body weight (Sloan-Kettering) F: 92%-123% ideal body weight (Emory) 86%-117% ideal body weight (Sloan-Kettering)	∅	No (training, length, exercise)	NA	NA	NA
DeLorenzo and colleagues, 2001 (17)	18-59 y 127 M 193 F	Nonobese to obese: M: 18-59 F: 19-39	+	Yes	NA	NA	NA
Feurer and colleagues, 1984 (27) Healthy controls only	21-32 y 20 M 22-30 y 52 F	Nonobese: M: 94%-117% ideal body weight F: 95%-113% ideal body weight	−	No (exercise, fast)	Nonobese: 80%-81% within 10% of measured RMR[k]	Nonobese: 0% underestimated to 10% overestimated	Nonobese: M: 10% underestimate to 19% overestimate; F: 6% underestimate to 18% overestimate
Feurer and colleagues, 1983 (28)	26-47 y 18 M 32-46 y 94 F	Obese: M: 176%-246% ideal body weight F: 178%-264% ideal body weight	∅	No (fast)	Obese: 39% within 10% of measured RMR	Obese: 9% underestimated to 52% overestimated	Obese: 65% underestimate to 43% overestimate
Forman and colleagues, 1998 (29)	Black, African 33-35 y 25 F White 32-34 y 22 F	Obese: black, African 35-37 White 34-38	∅	No (calibration)	NA	NA	NA

(*continued*)

Author, year (reference number)	Subject age,[a] number of subjects, sex	Weight class, percent body fat or NHLBI[b] BMI[c] category and range[a]	Study quality[d]	Calorimetry method criteria met (missing techniques)	Accurate prediction[e]	Inaccurate prediction[f]	Maximal errors[g]
Foster and colleagues, 1988 (30)	32-52 y 80 F	Obese: 32-46	∅	No (exercise, fast)	Obese: 59% within 10% of measured RMR	Obese: 21% underestimated to 20% overestimated	NA
Frankenfield and colleagues, 2003 (18)	20-78 y 130 M, F 83 nonobese 47 obese	Nonobese: 16-30 Obese: 31-99	+	Yes	Nonobese: 69% within 10% of measured RMR	Nonobese: 4% underestimated to 27% overestimated	Nonobese: 15% underestimate to 20% overestimate
					Obese: 64% within 10% of measured RMR	Obese: 6% underestimated to 30% overestimated	Obese: 28% underestimate to 28% overestimate
Fredrix and colleagues, 1990 (31)	55-71 y 18 M 59-73 y 22 F	Lean to obese: 24-29 23-33	∅	No (training, steady state)	NA	NA	NA
Garrel and colleagues, 1996 (19)	18-33 y 67 M, F	Nonobese: 20-26	−	Yes	NA	NA	NA
Heshka and colleagues, 1993 (9)	29-49 y 53 M	Overweight to obese: 28-56	∅	No (calibration, training, steady state, exercise)	NA	NA	NA
Heshka and colleagues, 1993 (9)	27-50 y 73 F	Nonobese to obese: 24-56	∅	No (calibration, training, steady state, exercise)	NA	NA	NA
Hirano and colleagues, 2001 (32)	19-38 y 19 F	Overweight to obese: 26-59	+	Yes	NA	NA	NA
Liu and colleagues, 1993 (20)	29-59 y 223 M, F	Nonobese: 19-25	∅	No (calibration)	NA	NA	NA
Mifflin-St Jeor and colleagues, 1990 (14)	19-76 y 498 M, F	Nonobese to obese: 19-42	+	Yes	NA	NA	NA
Owen and colleagues, 1987 (11)	18-82 y 60 M	Nonobese: 20.4-29.9 Obese: 30.4-60.5	+	Yes	Nonobese: 68% within 10% of measured RMR Obese: 38% within 10% of measured RMR	Nonobese: 2% underestimated to 30% overestimated Obese: 6% underestimated to 56% overestimated	Nonobese: 23% underestimate to 39% overestimate Obese: 25% underestimate to 38% overestimate

(*continued*)

Author, year (reference number)	Subject age,[a] number of subjects, sex	Weight class, percent body fat or NHLBI[b] BMI[c] category and range[a]	Study quality[d]	Calorimetry method criteria met (missing techniques)	Accurate prediction[e]	Inaccurate prediction[f]	Maximal errors[g]
Owen and colleagues, 1986 (12)	18-65 y 44 F	Nonobese: 18.2-29.3 Obese: 18-50	+	Yes	Nonobese: 45% Obese: 38% within 10% of measured RMR	Nonobese: 0% underestimated to 55% overestimated Obese: 0% underestimated to 62% overestimated	Nonobese: 7% under to 42% overestimate Obese: 7% under to 35% overestimate
Pavlou and colleagues, 1986 (33)	30-60 y 31 M	Nonobese to obese: 25%-48% fat mass	+	Yes	Nonobese to obese: 64% within 10% of measured RMR	Nonobese to obese: 0% underestimated to 36% overestimated	Nonobese to obese: 19% underestimate to 35% overestimate
Scalfi and colleagues, 1993 (21)	18-32 y 104 F 74 Nonobese 30 Obese	Nonobese: 19-29 Obese: 30-42	+	Yes	NA	NA	NA
Siervo and colleagues, 2003 (22)	18-31 y 157 F	Nonobese:[b] 21-25 Overweight:[b] 26-29 Obese: 31-39	+	Yes	NA	NA	NA
Taaffe and colleagues, 1995 (23)	60-82 y 116 F	Nonobese to obese: 19-39	+	Yes	NA	NA	NA
van der Ploeg and colleagues, 2002 (34)	31-59 y 41 M	Nonobese to obese: 20-32	+	Yes	NA	NA	NA
Vermeij and colleagues, 1990 (35) Healthy controls only	22-48 y 50 sex not reported	Not reported	−	No (exercise, fast)	NA	NA	20% underestimate to 20% overestimate

[a]Range established from mean±1 standard deviation.
[b]NHLBI=National Heart, Lung, and Blood Institute.
[c]BMI=body mass index; calculated as kg/m^2.
[d]Quality ratings: "−"=indicated that majority of research design and implementation criteria had not been met and questions suggested limited research rigor; "∅"=indicated that the research design and implementation was not exceptionally strong or did not achieve indirect calorimetry protocol adherence or had risks that would bias measurement accuracy; "+"=indicated that all key research design issues (ie, 2, 3, 6, and 7 in Figure 1) and at least one other area were appropriately handled.
[e]Percentage of all subjects whose resting metabolic rate predicted by the Mifflin-St Jeor equation was within 90% to 110% of measured resting metabolic rate.
[f]Percentage of all subjects whose predicted resting metabolic rate by the Mifflin-St Jeor equation was <90% or >110% measured.
[g]The lowest and highest prediction as a percent of measured resting metabolic rate.
[h]M=male.
[i]NA=not applicable.
[j]F=female.
[k]RMR=resting metabolic rate.

Figure 6. Harris-Benedict nonobese and obese adults: List of studies used in the energy estimation equation and selected characteristics using actual body weight.

Author, year (reference number)	Subject age,[a] number of subjects, sex	Weight class, percent body fat or NHLBI[b] BMI[c] category and range	Study quality[d]	Calorimetry method criteria met (missing techniques)	Accurate prediction[e]	Inaccurate prediction[f]	Maximal errors[g]
Arciero and colleagues, 1993 (15)	50-81 y 75 F[h]	Nonobese to obese: 20%-43% body fat	∅	No (calibration, steady state)	NA[i]	NA	27% underestimate to 12% overestimate
Clark and Hoffer, 1991 (25)	18-33 y 29 M[j]	Nonobese: 18-30	∅	Yes	NA	NA	NA
DeLorenzo and colleagues, 2001 (17)	18-59 y 127 M 193 F	Nonobese to obese: M: 18-59 F: 19-39	+	Yes	NA	NA	NA
Frankenfield and colleagues, 2003 (18)	20-78 y 83 M, F	Nonobese: 16-30 Obese: 31-99	+	Yes	Nonobese: 73% within 10% of measured RMR[k] Obese: 51% within 10% of measured RMR	Nonobese: 21% underestimated to 6% overestimated Obese: 43% underestimated to 6% overestimated	Nonobese: 24% underestimate to 28% overestimate Obese: 37% underestimate to 15% overestimate
Fredrix and colleagues, 1990 (31)	55-71 y 18 M 59-73 y 22 F	Nonobese: M: 24-29 F: 23-33	∅	No (training, steady state)	NA	NA	NA
Garrel and colleagues, 1996 (19)	18-33 y 67 M, F	Nonobese: 20-26	–	Yes	Nonobese: 80% within 10% of measured RMR	NA	NA
Heshka and colleagues, 1993 (9)	27-50 y 73 F	Nonobese to obese: 24-56	∅	No (calibration, steady state, training, exercise)	NA	NA	NA
Heshka and colleagues, 1993 (9)	29-49 y 53 M	Overweight to obese: 28-56	∅	No (calibration, steady state, training, exercise)	NA	NA	NA
Liu and colleagues, 1993 (20)	29-59 y 223 M, F	Nonobese: 19-25	∅	No (calibration)	NA	NA	NA
Mifflin-St Jeor and colleagues, 1990 (14)	19-76 y 498 M, F	Nonobese to obese: 19-42	+	Yes	NA	NA	NA
Scalfi and colleagues, 1993 (21)	18-32 y 74 F	Nonobese: 19-29 Obese: 30-42	+	Yes	NA	NA	NA
Siervo and colleagues, 2003 (22)	18-31 y 157 F	Nonobese: 21-25 Overweight: 26-29 Obese: 31-39	+	Yes	NA	NA	NA

(*continued*)

Author, year (reference number)	Subject age,[a] number of subjects, sex	Weight class, percent body fat or NHLBI[b] BMI[c] category and range	Study quality[d]	Calorimetry method criteria met (missing techniques)	Accurate prediction[e]	Inaccurate prediction[f]	Maximal errors[g]
Taaffe and colleagues, 1995 (23)	60-82 y 116 F	Nonobese to obese: 19-39	+	Yes	NA	NA	NA

[a]Range established from mean±1 standard deviation.
[b]NHLBI=National Heart, Lung, and Blood Institute.
[c]Body mass index; calculated as kg/m^2.
[d]Quality ratings: "−"=indicated that majority of research design and implementation criteria had not been met and questions suggested limited research rigor; "∅"=indicated that the research design and implementation was not exceptionally strong or did not achieve indirect calorimetry protocol adherence or had risks that would bias measurement accuracy; "+"=indicated that all key research design issues (ie, 2, 3, 6, and 7 in Figure 1) and at least one other area were appropriately handled.
[e]Percentage of all subjects whose resting metabolic rate predicted by the Mifflin-St Jeor equation was within 90% to 110% of measured resting metabolic rate.
[f]Percentage of all subjects whose predicted resting metabolic rate by the Mifflin-St Jeor equation was <90% or >110% measured.
[g]The lowest and highest prediction as a percent of measured resting metabolic rate.
[h]F=female.
[i]NA=not applicable.
[j]M=male.
[k]RMR=resting metabolic rate.

Figure 7. Owen nonobese and obese validation studies used in the energy estimation equation.

ergy expenditure prediction in obese subjects, particularly with an adjusted body weight, should be avoided.

Owen. The Owen equation predicted RMR within 10% of measured in 51% of obese individuals (18). The errors were distributed as 43% underestimates and 6% overestimates. The maximum underestimation was 37%, and the maximum overestimation was 15% of measured RMR (18). In a subset of individuals with severe obesity, the Owen equation only predicted within 10% accuracy in 33% of subjects, with underestimation being the predominant error (60% of subjects) (18). The Owen equation is not suitable for prediction of RMR in obese individuals.

World Health Organization/Food and Agriculture Organization/United Nations University. Neither individual nor group mean prediction accuracy was reported in obese individuals for the WHO/FAO/UNU equation. No conclusion statement regarding the accuracy of this equation in individuals can be offered. A summary of the conclusion statements and grades for all equations in nonobese and obese individuals is given in Figure 8.

Older Adults

Predictive equations generally have not performed well in elderly individuals, but only limited trials are available, and the age range generally covers 50 to 84 years with minimal representation of subjects over 80 years. No validation studies in elderly subjects reported the percentage of individuals predicted within 10% of measured RMR for any equation. Maximal underestimations up to 18% and overestimations of 5% were reported for the Mifflin-St Jeor equation in elderly men (15), and maximal underestimations of 31% and overestimations of 7% of measured RMR for elderly women (16). Note that the maximal overestimations reported in these studies are within the 10% limit defining accuracy in the current review.

For the Harris-Benedict equation in elderly men, maximal underestimations were 19% and overestimations were 9% of measured RMR (15). For women, the maximum underestimation was 27% and the maximum overestimation was 12% of measured RMR (16). There are insufficient studies to describe the oldest old.

For the Owen equation in elderly women, maximal underestimations were 27% of measured RMR, whereas maximal overestimations were up to 12% (16). Very few oldest old women were measured.

The WHO/FAO/UNU equation in older adults produced a maximal underestimation of 17% and maximal overestimation of 7% of measured RMR in men (15), and underestimation of 8% and overestimation of 12% of measured RMR in women (16).

The limited data on elderly subjects are summarized in Figure 8. Whereas the narrowest margins of error are with WHO/FAO/UNU, no validation studies in overweight or obese individuals have been reported, which is a limitation for application to elderly individuals in the United States. No one equation can be recommended because of the limited data, but the Mifflin-St Jeor equation might be considered for the sake of consistency with

Equation	Nonobese, 20-82 y, BMI[a]=18.5-29.9	Obese, 20-82 y, BMI >30	Older adults, 60-82 y, nonobese and obese
Mifflin-St Jeor	82% of estimates are accurate; errors evenly distributed between underestimation and overestimation (18) *Error range:* Maximal underestimation by 18% to overestimation by 15% (Grade II)[b]	70% of estimates are accurate; errors tend to be underestimates (18) *Error range:* Maximal underestimation by 20% to overestimation by 15% (Grade II)	*Accuracy within 10% not available* *Error range:* Underestimation by 18% to overestimation by 5% in men (15); underestimation by 31% to overestimation by 7% in women (16) (Grade III)
Harris-Benedict Actual body weight	45%-81% of estimates are accurate; errors tend to be overestimates (11-12, 18,27) *Error range:* Maximal underestimation by 23% to overestimation by 42% (Grade I)	38%-64% of estimates are accurate; errors tend to be overestimates (11-12,18, 28,30) *Error range:* Maximal underestimation by 35% to overestimation by 43% of measured (Grade I)	*Accuracy within 10% not available* *Error range:* Underestimation by 19% to overestimation by 9% in men (15); underestimation by 27% to overestimation by 12% in women (16) (Grade III)
Harris-Benedict Adjusted body weight (ABW)[c]	Not applicable	26% of estimates are accurate; errors tend to be underestimates (18) *Error range:* Maximal underestimation by 42% to overestimation by 25% (Grade II)	Individual prediction accuracy using adjusted body weight is not reported for older adults in any of the evaluated studies
Owen	73% of estimates are accurate; errors tend to be underestimates (18) *Error range:* Maximal underestimation by 24% to overestimation by 28% (Grade II)	51% of estimates are accurate; errors tend to be underestimates (18) *Error range:* Maximal underestimation by 37% to overestimation by 15% (Grade II)	*Accuracy within 10% not available* *Error range:* There is no individual error range for men; in white women, maximal underestimation by 27% to overestimation by 12% (16) (Grade III)
WHO/FAO/UNU[d]	Individual prediction accuracy is not reported for nonobese adults in any of the evaluated studies	Individual prediction accuracy is not reported for obese adults in any of the evaluated studies	*Accuracy within 10% not available* *Error range:* Maximal underestimation by 17% to overestimation by 7% in men (15); maximal underestimation by 8% to overestimation by 12% in women (16) (Grade III)

[a]BMI=body mass index; calculated as kg/m^2.
[b]See Figure 2 for description of conclusion grades.
[c]ABW=[(adjusted body wt−ideal wt)×0.25]+ideal weight.
[d]WHO/FAO/UNU=World Health Organization/Food and Agriculture Organization/United Nations University.

Figure 8. Conclusion statements and accuracy of resting metabolic rate measurement vs estimations.

the recommendation for nonobese and obese people given earlier.

US-Residing Ethnic Groups

In the literature search, no validation studies of RMR-predictive equations reporting individual errors were found in typical US ethnic groups of adults. Studies in obese black women were limited (29). The Mifflin-St Jeor and Owen equations have not been validated for prediction accuracy to US-residing ethnic groups of black, Asian or Pacific Islander, American Indian, Alaskan Native, or Hispanic populations. No recommendation for a prediction equation can be made at this time.

DISCUSSION

A systematic review of the RMR literature was necessary to guide the decisions on estimation vs measurement of RMR in practice, and to equip dietetics professionals with the most up-to-date evidence of what is known and what is not known about how RMR is assessed. For decades, dietetics professionals have relied on predictive equations of RMR as the foundation for the energy prescription of their care plans. Because there was no realistic alternative, reliance on equations has continued despite some recognition that the error rate of the equations when applied to individuals might be unacceptably high (19).

With the marketing of highly portable, inexpensive indirect calorimetry devices, a revolutionary change in how clinical nutrition is practiced may be emerging. As portable indirect calorimeters are purchased by health care and sports facilities and by individuals, dietetics professionals may be called on to address questions about the devices themselves, whether they will improve care, and whether current predictive methods are strong enough to rely on without measuring RMR. Before such potential changes occur, ADA determined that a systematic review of the literature was necessary to inform clinicians on the strengths and weaknesses of predictive equations for RMR.

The current systematic review has focused on RMR prediction in individuals rather than groups because that is how the equations are applied in practice. Although the requirement to consider data reported on individuals eliminated studies that presented only group mean data, this decision ensured that the research most applicable to practice was highlighted. Although these studies used rigorous research methods and thus were accepted for consideration, their data reporting did not permit comparison with measurements from individual subjects. This systematic review has not included equations for ill people because other evidence-based protocol development teams will be grappling with those equations. It is reasonable to presume, however, that the current review results would apply to any chronic disease that does not increase RMR (eg, hypertension, diabetes). Obesity as a disease is included in the results of this review.

Expert panel members systematically evaluated evidence on the question of how accurately prediction equations actually describe measured RMR. The panel found that in healthy nonobese and obese individuals, the performance of the commonly applied Harris-Benedict equation is surpassed by the Mifflin-St Jeor equation in terms of both accuracy rate and lower magnitude of error. However, the Mifflin-St Jeor equation still carries a clinically relevant error rate (20%) relative to actual measurement of RMR that cannot be distinguished without measurement.

LIMITATIONS

Several limitations in the use of predictive equations in nonobese and obese individuals were identified. First, in populations in which validation work was performed, error rates were not negligible, and there was no clinical feature that identified the individuals in whom the prediction was inaccurate. This factor underscores the need to use clinical judgment when determining whether to use a predictive equation or to measure RMR.

Second, there are significant segments of the US population in whom the predictive equations have not been validated. Such groups include elderly subjects and various nonwhite ethnic groups. Although older adults (ages 60 to 84 years) were often included in validation studies, they were rarely the focus of a validation study, and in no case were individual accuracy rates among members of older age groups reported. The number of data points reported for individuals in the oldest old age group (those over 80 years) was too minimal to consider separately.

Although lean body mass is reduced and physical activity is limited frequently in aging, they are largely under the control of the individual (maintenance of physical activity leading to preservation of lean body mass) and therefore are not inevitable. Great heterogeneity is thus introduced into body composition and function within groups of aging people. Additionally, chronic illness becomes a more common feature with age. Variation in body composition and the presence of chronic illness can alter the expected relationship between body size and RMR and make prediction of RMR difficult in elderly subjects. These realities suggest that well-controlled studies of RMR would be invaluable in planning for nutritional care of these individuals.

Third, although RMR data in various ethnic groups have been collected, they have not been used to evaluate predictive equations of RMR in individuals, and so these studies could not be used to evaluate predictive accuracy. The predictive equations in most common use today were developed predominantly from white individuals, so applicability to various nonwhite ethnic groups is a pertinent clinical and research question. Because validation studies of predictive equations are lacking in nonwhite racial/ethnic groups, applicability of the equations in these groups should be questioned. In a narrative review, 10 of 15 studies indicated that African-American women have lower mean RMR, adjusted to lean body mass, than white women, with differences of up to 15% (274 kcal/day) (40). Other investigators have linked the reduced weight loss during dietary interventions to lower RMR in African-American women (41-43), and differences in energy expenditure gene expression have been documented (44). Clearly, we cannot assume that RMR is a universal physical measure, regardless of genetics or body composition. These realities suggest that well-controlled studies of RMR in various ethnic groups in the United States are needed in planning for nutritional care of these individuals. To satisfy the age problem discussed above, such studies would have to be stratified by age in racial and ethnic groups.

The importance of accurate RMR prediction lies in the fact that energy imbalance results in weight loss or weight gain, factors that may lead to significant morbidity and mortality. Medical management of weight loss or weight gain focuses on restoration of energy balance. Such restoration can be difficult because of the complex interaction of the components of energy expenditure (resting metabolic rate, activity energy expenditure, thermic effect of feeding), calorie availability, and consumption (which is often a behavioral question). Measurement of RMR may help the practitioner and client to set attainable goals or to visualize the limits that must be placed on energy intake, thereby improving the success rate of weight management, but because energy balance is such a complex system, outcomes research addressing the value of indirect calorimetry in successful weight management is necessary before measurement of RMR becomes a standard of care. For the time being, it remains up to the individual practitioner whether and under what conditions measurement or prediction of RMR should be used.

CONCLUSIONS

Current calculation methods for estimating RMR have clinically important limitations, including undetectable differences from measured RMR, lower accuracy rates in obesity, and gaps in our knowledge of how the equations work in various ethnic groups and elderly subjects. The expert panel members believe that the data exist to address the age and ethnic questions, and urge the owners of these data to publish validation studies of the equations for these groups, focusing on individual errors.

Indirect calorimetry may be a vital tool for dietetics professionals to use in providing the most effective care to their clients. There is an urgent need to perform studies comparing measured and predicted RMR with outcomes of interest (eg, compliance with medical nutrition therapy, weight change, better blood glucose control, reduced need for medications, fewer hospitalizations, and shorter length of hospital stay). In the meantime, the best recommendation the expert panel can make is for practitioners to use clinical judgment to discern the best method to determine energy requirements. If a prediction formula is used, the Mifflin-St Jeor equation is recommended based on this systematic review of the literature. However, the use of indirect calorimetry to measure RMR provides the most accurate assessment of nutritional needs. This review will be updated as new research becomes available.

This article shows the use of an evidence-based approach and describes the results of evidence analysis using ADA's method. This article provides the synopsis of the evidence analysis of RMR prediction in a usable form for the dietetics practitioner.

Many dietetics practitioners were taught to use various formulas as the basis for energy predictions. Although these equations are widely cited in textbooks and software, when the data are analyzed, it is clear that the practitioner should become aware of the limitations in the use of these equations. Clinical judgment must be used to determine what level of nutrition care should be based on these estimates. Consideration of the magnitude and types of errors will lead to a clinical decision of whether an accurate metabolic rate by measurement is required to provide nutrition care adequately.

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