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エネルギーを知る·運動を知る—その関係と仕組みを学ぶ—4

基礎代謝の推定式について

Human Energy

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エネルギー必要量は，栄養管理を行う際，まず最初に検討する項目とされている．エネルギー必要量は総エネルギー消費量から算出され，健康な成人の場合，総エネルギー消費量のうち平均して約60％を基礎代謝量が占めている．基礎代謝量を実際に測定するのは必ずしも現実的ではないことから，基礎代謝量の推定式から算出する場合が多い．

本稿では，主な基礎代謝量の推定式の特徴，さまざまな対象集団における推定誤差，エネルギー必要量の算出について解説する．

エネルギー必要量

エネルギー必要量は，個人および集団の食事を計画する際にはじめに決定される．消費したエネルギーに相当する分だけ摂取しないと，体重が変化することになる．そのため，体重を変える必要のない健康な成人の場合，エネルギー必要量は総エネルギー消費量に等しい．この考え方は，健康な人のみでなく有疾患者にも適用できる．

日本人の食事摂取基準（2010年版）[1]における推定エネルギー必要量は，体重変化の必要ない健康な成人の場合，基礎代謝量に身体活動レベルを乗じて求める．一方，有疾患者においては，Harris-Benedictの式[2]から基礎代謝量を求め，これに活動係数と傷害係数〔injury factor：ストレス係数（stress factor/index）とも呼ばれる〕を乗じてエネルギー必要量を決定する方法がよく用いられている．井上[3]によれば，この方法が「もっとも理論的な方法である」と認識され使われるようになったのは日本静脈経腸栄養学会のtotal nutritional therapy（TNT）プロジェクトによるものであるとしている．

このTNTプロジェクトとは，米国のアボットインターナショナルがFederation Latino-americana de nutricion Parenteral Y Enteral（FELANPE：ラテンアメリカ静脈経腸栄養学会）と提携して開発した栄養教育プログラムで，栄養療法の世界的標準として全世界に広げることを目的としたものである．そこでは，**表1**に示すようにHarris-Benedict式を用いて基礎代謝量を求め，これに活動係数と傷害係数を乗じてエネルギー必要量を求める方法が紹介されている．この方法が，TNT受講者の増加とともに，わが国におけるエネルギー必要量決定の「標準」であるかのように認識されるようになってきたようである．しかし，なぜ基礎代謝量の推定にHarris-Benedict式を用いることになったかは定かではない．

また，国際的な栄養療法のガイドラインであるAmerican Society for Parenteral and Enteral Nutrition（ASPEN）ガイドライン[4]においても，基礎代謝量の評価は，Harris-Benedict式による推定，または間接熱量測定が有用であるとしている．

ちなみに，やや古いデータであるが，栄養療法の実施状況に関する全国アンケートの調査

表1　TNTテキストに掲載されているエネルギー必要量の求め方

ハリス・ベネディクト式

ベースとなるエネルギーの必要量は年齢，体重，身長および性別をもとにハリス・ベネディクト式（HBE）にて，男女別に分けて求められる

男性向け＝66.47＋13.75W＋5.0H－6.76A
女性向け＝655.1＋9.56W＋1.85H－4.68A
W=体重（kg），H＝身長（cm），A＝年齢（歳）

エネルギー必要量

エネルギー必要量は，活動係数を含めて算出する必要がある．重病・重症の患者については活動係数および傷害係数も含めて算出する必要がある．

エネルギー必要量＝HBE×活動係数×傷害係数
活動係数：1.2＝寝たきり，1.3＝ベッドから出られる
傷害係数：手術＝1.1…軽度，1.2…重度，1.3…大手術
感染症＝1.2…軽度，1.5…中程度
傷＝1.35…骨格に及ぶ，1.6…ステロイド療法が必要な頭頸部への傷，1.35…鈍的外傷
火傷＝1.5…体表の40%，1.95…体表の100%

※傷害係数は代謝反応がよくなるにつれ，減少させるべきである．
Long CL, et al. JPEN 1979；3：452-6.

簡易的にエネルギー必要量を算出する方法

エネルギー必要量を簡易的に算出するには25～30kcal/体重kg/日程度のエネルギーを投与し，栄養学的な目標に一致するかモニターをする方法もある．

（井上善文．静脈経腸栄養 2010；25（2）：573-9 3)より）

報告によると，アンケートの回答をした515の医療機関のうち，60.0%が，20～35kcal/kg体重/日などの値を体重に乗じてエネルギーの設定をしているという5)．Harris-Benedict式を用いていたのは，7.2%であった．

基礎代謝量の推定式

基礎代謝量は，12時間以上の空腹状態を保ったあと，早朝に快適な室内環境（室温等）において，仰臥位安静で測定される．正確に測定することが可能であれば，個人ごとに実測するのが望ましい．しかし，対象者すべてで正確に測定するのは容易ではない．そこで，基礎代謝量はおおよそ体重などで決定されることを利用し，体重などを用いた推定式が作成されている．**表2**に，主な基礎代謝量の推定式を示した．

日本人の食事摂取基準（2010年版）1)においては，性・年齢別に体重に乗じる基礎代謝基準値（kcal/kg体重/日）が示されている．基礎代謝基準値は，日本人を対象に，主に1951～1966（昭和26～41）年に測定された基礎代謝量をもとに決められたものである6)．2010年版では，それらの妥当性を検討し，18～29歳の女性における基礎代謝基準値のみ変更された．

国立健康・栄養研究所の式は，20歳以上の健康な日本人男女を対象として考案された睡眠時代謝量と基礎代謝量の推定式の一つである7)．

Harris-Benedict式2)は，約100年前に，標準的な体格の白人の男女から作成された推定式である．Benedictは，アトウォーター係数を考案したことでも有名なAtwaterの助手として，呼気分析に基づく間接熱量測定法を発展さ

表2　主な基礎代謝量の推定式

W：体重（kg），H：身長（cm），A：年齢（歳）

推定式（kcal/日）	年代	男性	女性
基礎代謝基準値	18～29歳	24.0×W	22.1×W
	30～49歳	22.3×W	21.7×W
	50～69歳	21.5×W	20.7×W
	70歳 以上	21.5×W	20.7×W
国立健康・栄養研究所の式		(0.0481×W＋0.0234×H-0.0138×A-0.4235)×1000/4.186	(0.0481×W＋0.0234×H-0.0138×A－0.9708)×1000/4.186
Harris-Benedict式		66.4730＋13.7516×W＋5.0033×H－6.7550×A	655.0955＋9.5634×W＋1.8496×H－4.6756×A
Schofield式	18～29歳	(0.063×W＋2.896)×1000/4.186	(0.062×W＋2.036)×1000/4.186
	30～59歳	(0.048×W＋3.653)×1000/4.186	(0.034×W＋3.538)×1000/4.186
	60歳以上	(0.049×W＋2.459)×1000/4.186	(0.038×W＋2.755)×1000/4.186
FAO/WHO/UNU式	18～29歳	(64.4×W－113.0×H/100＋3000)/4.186	(55.6×W＋1397.4×H/100＋146)/4.186
	30～59歳	(47.2×W＋66.9×H/100＋3769)/4.186	(36.4×W-104.6×H/100＋3619)/4.186
	60歳以上	(36.8×W＋4719.5×H/100－4481)/4.186	(38.5×W＋2665.2×H/100－1264)/4.186

せ，得られた結果を利用して基礎代謝量推定式を作成した．これは，データおよび統計手法がしっかりしたものとしては，世界でもっとも古い基礎代謝量推定式といってよい．

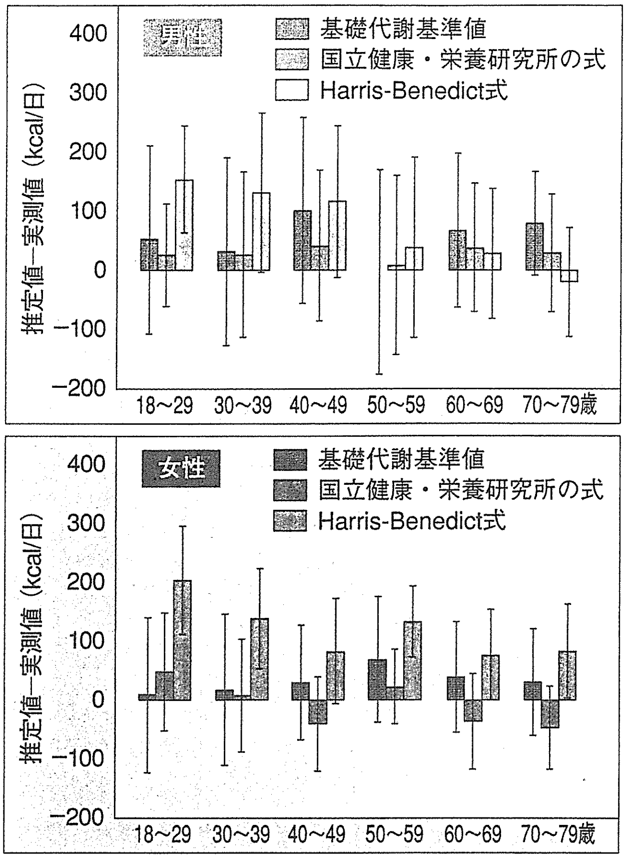
Harris-Benedict式の妥当性については多くの検討が行われており，健康な欧米人において5～15%程度過大評価する傾向がみられる．この式については，肥満者を含んでいないことや年齢が若年者と高齢者に偏っていることなどにも批判がある．なお，欧米においては，健常者に対して，FAO/WHO/UNUのエネルギー必要量（1985）算出のために作成されたSchofield式あるいはFAO/WHO/UNU式が使用されることが多い．

基礎代謝量の推定の実際

筆者らは，さまざまな対象者において，基礎代謝量の実測値と各推定式から算出された推定値の比較を行った．

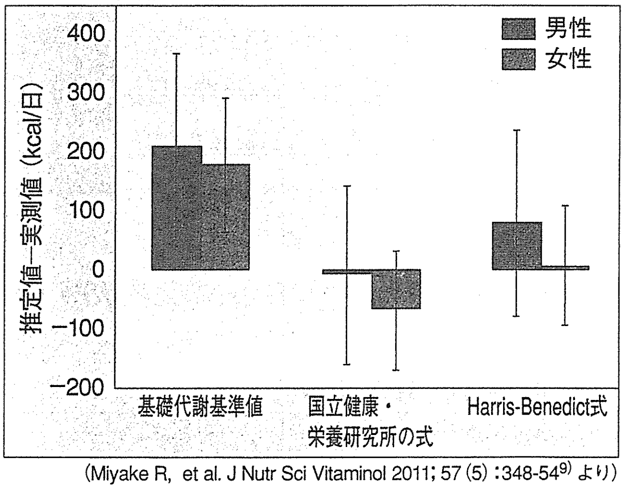
基礎代謝基準値，国立健康・栄養研究所の式およびHarris-Benedict式について，健康な成人男女を対象に，性・年齢階級別に推定誤差をまとめたのが**図1**である[8]．日本人を対象に作成された基礎代謝基準値と国立健康・栄養研究所の式は，海外の対象者を中心に作成されたHarris-Benedict式よりも，ほとんどの年代において推定誤差の平均値が小さいことがわかる．なかでも国立健康・栄養研究所の式は，いずれの性・年齢階級においても，推定誤差の平均および標準偏差ともに，相対的に良好な値が得られている．しかし，それでも，個人によっては，標準偏差相当で100kcal/日程度（±200kcal/日程度の幅）の誤差はある．基礎代謝基準値による推定値は，平均としてはそれほどずれていないものの，個人別にみると誤差が大きい．Harris-Benedict式は，高齢男性では平均値が小さいものの，18～29歳の女性をはじめとして，男女とも若いほど過大評価されている．図には示していないが，Schofield式やFAO/WHO/UNU式も，若い男女での過大評価が顕著である．

図1　基礎代謝量の各推定式による年代別の推定誤差



（Miyake R，et al. J Nutr Sci Vitaminol 2011；57 (3)：224-32[8] より）

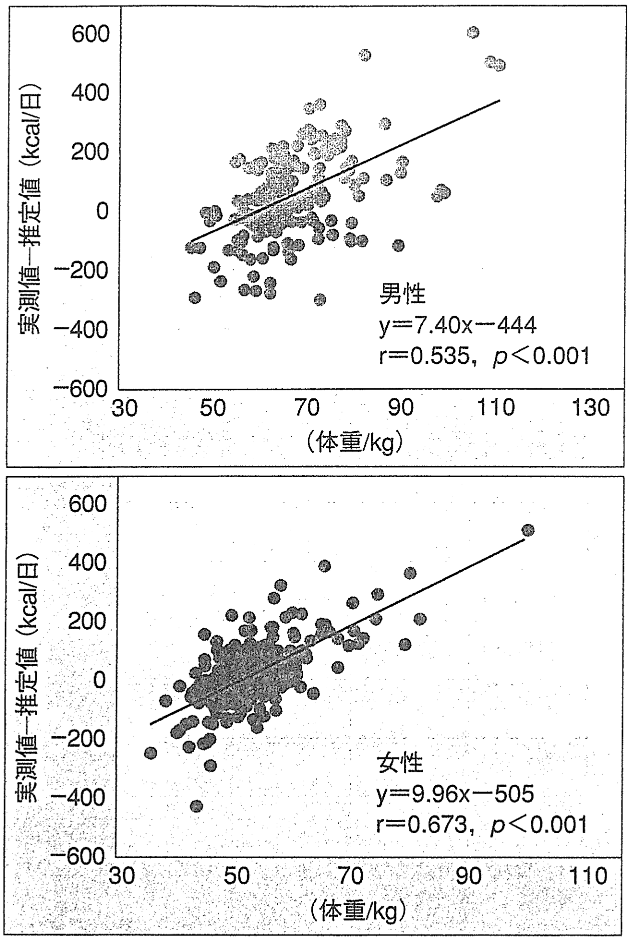
図2　基礎代謝量の各推定式による肥満者における推定誤差



（Miyake R，et al. J Nutr Sci Vitaminol 2011；57 (5)：348-54[9] より）

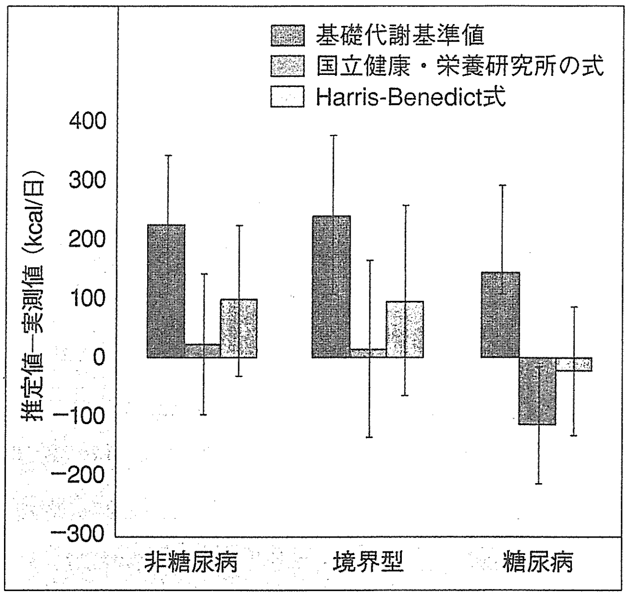
一方，BMIが30kg/m²以上の肥満者におい

図3　基礎代謝基準値による推定誤差と体重との関係



（Miyake R, et al. J Nutr Sci Vitaminol 2011；57（3）：224-32 8) より）

図4　糖尿病の有無別にみた，基礎代謝量の各推定式による推定誤差



（Miyake R, et al. J Nutr Sci Vitaminol 2011；57（5）：348-54 9) より）

ても，比較した3つの推定式のなかでは国立健康・栄養研究所の式の平均値が小さかった（**図2**）9)．一般に基礎代謝量は，a＋b×体重といった，正の切片をもつ式で推定できるが，基礎代謝基準値は基準体位にあうように決定した体重の倍数であり，切片がない．そのため，基礎代謝基準値は，基準体位から外れるほど誤差が大きくなり，過体重者ではより過大評価し，低体重者ではより過小評価される（**図3**）．したがって，過体重者や低体重者に基礎代謝基準値を使用することは控えることが望ましい．

ただし，エネルギーの設定が重要である糖尿病患者において，3つの推定式のなかではHarris-Benedict式の平均が小さかった（**図4**）9)．それに対し，国立健康・栄養研究所の式は過小評価した．これは，糖尿病患者における基礎代謝量が健常者よりも約120kcal/日程度高いため，健康な人では誤差の少なかった国立健康・栄養研究所の式で誤差が大きくなってしまったと考えられる．

なお，筆者らは，高齢者福祉施設に入居している高齢者の基礎代謝量の測定も行っている．予備的な分析によると，施設に入居している高齢女性においても，日本人を対象として得られた式よりHarris-Benedict式での推定誤差が大きく，過大評価されるようである．

以上のように，概して，日本人には日本人を対象としてえられた推定式の当てはまりがよい．欧米人とアジア人については，体格（サイズ）の違いに加え，身体組成の違いにより，欧米人での推定式がアジア人での過大評価につながるようである．ただし，同じ推定式でも年代や対象特性により推定誤差が異なるため，基礎代謝量を算出したい対象者の特性を理解したうえで推定式の選択を行うことが必要である．また，平均としては合う推定式を

用いたとしても，標準偏差相当のズレは覚悟する必要がある．

身体活動量

エネルギー必要量を算出する場合は，基礎代謝量に身体活動レベルを乗じるため，身体活動量の推定もポイントになる．身体活動によるエネルギー消費量には，歩行や運動はもちろん，家事や仕事等における動作や姿勢の保持など，さまざまな筋活動が含まれる．身体活動レベルは，スポーツ選手や重労働従事者でなくても，1.4～2.2前後の広い範囲に分布する．基礎代謝量の推定が実測値と一致したとしても，身体活動レベルの設定を誤ると，過剰もしくは過小のエネルギー必要量を設定することになってしまう．

入院患者などの対象者は，身体活動が少なく，基礎代謝量に近い値となるが，下記の点は考慮する必要がある．

- 経口摂取の場合，食事誘発性体熱産生が総エネルギー消費量の約10%を占めること（ただし，経腸栄養など人工栄養の場合はこれより少ない）．
- 仰臥位以外の時間や活動量にともなって，総エネルギー消費量は大きくなる．

このことから，ベッド上で仰臥位の時間が長い人でも，食事誘発性体熱産生を考慮して，基礎代謝の数%～10%の増加，多少の動きが加わると，合計して最大20%の増加が見込まれる．

おわりに

今回示したいずれの推定式を用いたとしてもエネルギー必要量を推定するに留まり，対象とする個人や集団に厳密に当てはまるものではない．したがって，算出されたエネルギー必要量を摂取した際の個人におけるエネルギーバランスの変化（体重，BMI）や生化学データなどを観察し，その後の調整をしていくことが重要である．

まとめ

- **国立健康・栄養研究所の式は，肥満者を含め，相対的に誤差は小さい．ただし，個人によって±200kcal程度のズレは生じてしまう．**
- **Harris-Benedict式は，健康な高齢の男性を除いて過大評価する（とくに若年者）．**
- **とくに基礎代謝基準値は，標準的な体格から外れた場合，誤差が大きい．**
- **糖尿病患者では，体重などからの推定値より基礎代謝量が高い．**
- **対象集団ごとの推定誤差を理解した上で，対象者に適した推定式を用いる．**

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Human calorimetry: Energy expenditure and substrate utilization measurements using a respiratory chamber

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Abstract Respiratory chambers are the current gold standard for assessing human energy expenditure and substrate utilization over a long period of time (several hours to several days), based on oxygen consumption, carbon dioxide production, and urinary nitrogen excretion. Analysis of human energy metabolism using a respiratory chamber provides information about the total energy expenditure (TEE), sleeping metabolic rate (SMR), resting metabolic rate, diet-induced thermogenesis (DIT), activity-induced thermogenesis (AIT), and substrate oxidation. In this review, we describe the theoretical underpinnings of the respiratory chamber, as well as the measurement reproducibility and applications as study endpoints for indirect calorimetry. In humans, the coefficients of variation in energy expenditure and substrate utilization were estimated by 24-h repeatability studies. Under the appropriate conditions, the coefficients of variation for TEE were 1% to 5%, SMR was around 1%, DIT was around 40%, AIT was around 10%, and substrate oxidation was around 5%. Factors that impact energy expenditure and substrate oxidation have been reported, and future weight changes can be predicted based on the 24-h respiratory quotient and substrate oxidation. As the 24-h energy expenditure and substrate oxidation are affected by the 24-h energy balance, it is important to consider the subject's energy balance prior to and during calorimetry. Accurate measurements of energy and substrate balance (intake minus utilization) will contribute to a better understanding of the conditions that lead to changes in body weight. Properly obtaining measurements using a respiratory chamber requires a thorough understanding of the measurement principles and calculation methods, as well as an appropriate protocol.

Keywords : indirect calorimetry, coefficient of variance, energy balance, energy expenditure components, substrate oxidation

Introduction

Interest in measuring energy metabolism has intensified worldwide in recent years due to the increase in obesity and diabetes research[1)]. Elucidation of the pathogenesis of obesity and diabetes will require a detailed understanding of the role of energy metabolism[2)]. The methods of measuring energy metabolism in humans include direct and indirect calorimetry. Indirect calorimetry has become mainstream, however, due to the relative convenience of the devices and the increase in the number of research facilities around the world. The use of Douglas bags, facemasks, ventilated hoods (canopies), and whole-body calorimeters for indirect measurements of respiratory gas exchange depends on the objective of the research. For short-term measurements of energy metabolism, Douglas bags, facemasks, and ventilated hoods are sufficient. For longer-term measurements, however, whole-body calorimetry is performed using a room-type metabolic chamber/respiratory chamber to measure energy metabolism by continuously monitoring oxygen (O_2) and carbon dioxide (CO_2) concentrations. Changes in the measured O_2 and CO_2 concentrations allow for a subject's metabolism to be calculated as O_2 consumption ($\dot{V}O_2$) and CO_2 production ($\dot{V}CO_2$). $\dot{V}O_2$, $\dot{V}CO_2$, and urinary nitrogen excretion (N) allow for the calculation of energy expenditure as well as the simultaneous calculation of substrate utilization. The ability to measure energy expenditure and substrate utilization with a high degree of accuracy and continuously over a long period (~24 h) is the unique advantage of the respiratory chamber. The advantages and disadvantages of measurements using a metabolic chamber, described previously by Murgatroyd et al.[3)], are listed in Table 1. Although it has been nearly 20 years since the report

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Table 1. Advantages and disadvantages of a respiratory chamber (modified from Murgatroyd et al.[3])

Advantages	*Disadvantages*
Accurate and precise	Expensive
Fast-responding	Artifical environment; limitation of physical activity
Provides information about substrate utilization	Requires careful design, engineering and computing
Good environment for strictly-controlled studies	Not easy to combine with invasive measurements
Much world-wide expertise	

by Murgatroyd et al.[3] was published, the basic features remain essentially the same today. The objective of the present review is to describe the theory, methodology, and measurement variation of the respiratory chamber, and to discuss the current trends and future aims of research related to measurements using a respiratory chamber and their significance.

Principles of measurements in a respiratory chamber

Pettenkofer developed the first human respiratory chamber in the 19th century. Since then, significant progress has been made in terms of implementing more advanced gas analyzers, data acquisition systems, and computing to facilitate measurement and improve response time[4,5]. The typical respiratory chamber is a small airtight room with a volume of 15,000 to 30,000 liters, and with strict control of the temperature, humidity, and air flow rate. The chamber contains facilities for living, such as a bed, desk, chair, TV, telephone, toilet, and washbasin (Fig. 1). Subjects are allowed to exercise using a treadmill, bicycle ergometer, or other equipment. Meals and beverages are passed to the subject through an air-locked pass box, and fecal and urine samples from the subject are passed out through another pass box. Subjects remain in the room from several hours to several days, and follow daily life activities similar to their free-living activities.

Respiratory chambers based on indirect calorimetry were recently developed to measure the energy expenditure and substrate oxidation in humans. Indirect calorimetry is a simple measurement method that quantitatively measures O_2 and CO_2 concentrations from a subject's gas exchanges[6]. Early respiratory chambers comprised a sealed system called a closed-circuit design, but the majority of modern devices employ an open-circuit design. The basic measurement concept of an open-circuit design respiratory chamber is the same as that of metabolic carts, such as facemask or hood systems. Outside air is continuously supplied to the respiratory chamber, mixed within the chamber so that it becomes uniform with the air breathed out by the subject, and drawn from the outlet. The flow rate, and O_2 and CO_2 concentrations at the inlet and outlet are continuously measured using a magnetic O_2 sensor, infrared CO_2 sensor, or mass spectrometer.

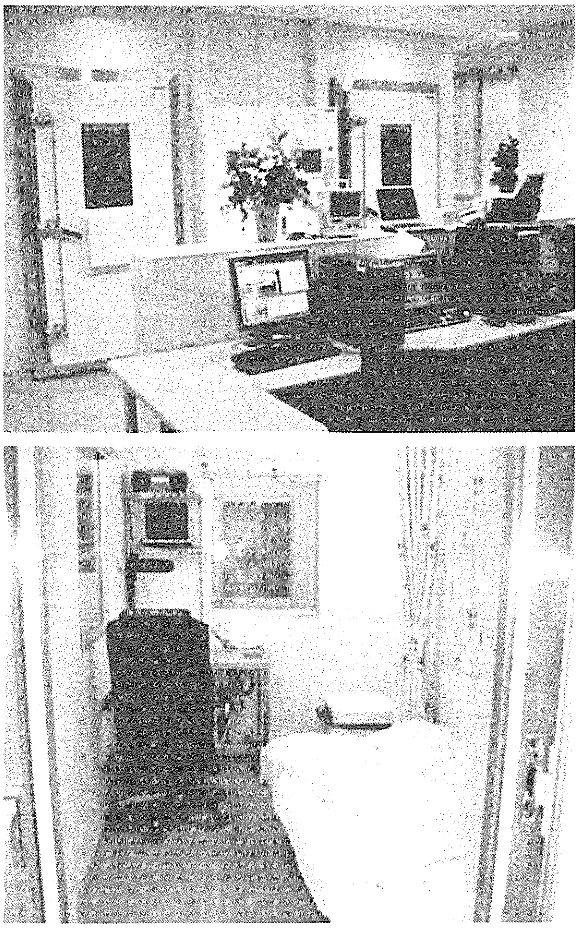

Fig. 1 The pull-type respiratory chamber based on open-circuit indirect calorimetry located at Kao Corporation. Upper photograph shows the exterior view of the respiratory chamber. Lower photograph shows the interior of the respiratory chamber, which includes a desk, chair, TV, CD player, toilet, and bed.

A detailed analysis of the gas (O_2 and CO_2) exchange in open-circuit indirect calorimetry was reported by Brown et al.[7] in which they derived equations for calculating a subject's $\dot{V}O_2$ and $\dot{V}CO_2$ in an open-circuit pull-type indirect calorimeter:

$$R_G = Fof_{N2o}(f_{Go}/f_{N2o} - f_{Gi}/f_{N2i}) + Vd/dt(f_{Go}) - f_{Gi}/f_{N2i}Vd/dt(f_{N2o})$$

where F is the flow rate in l/min, f is fractional concentration, R is rate of gas production in l/min, t is time in min, V is chamber volume in liters, i is incoming, o is outgoing, and G is any gas (volume and flow rate were assumed to be corrected to standard temperature, pressure, dry [STPD]). Several groups have developed algorithms based on fundamental equations that yield an improved transient response and suppress measurement noise in the respiratory chamber[4,5,8-10]. Various factors can introduce error into actual measurements, however, such as temperature, humidity, and air pressure. To eliminate these error factors, it is important to compare the results against standard values obtained with devices using a gas infusion test or alcohol combustion test[11].

Calculation of energy expenditure and substrate utilization

The $\dot{V}O_2$, $\dot{V}CO_2$, and protein oxidation (P) estimated from N of a subject ($P = 6.25*N$), while in the respiratory chamber, are used to calculate the subject's energy expenditure and substrate utilization. Several formulas are available for determining a subject's energy expenditure, but the most commonly used formula is that used by Weir et al.[12].

Energy expenditure (kcal) = $3.941* \dot{V}O_2$ (L) + $1.106* \dot{V}CO_2$ (L)-2.17*N (g)

Protein correction is equal to a deduction of 1% when 12.3% of the total calories come from P and, therefore, is estimated with the following formula:

Energy expenditure (kcal) = $3.9* \dot{V}O_2$ (L) + $1.1* \dot{V}CO_2$ (L)

With the exception of special cases, P is similar to protein intake, and thus this formula can be used in almost all cases. Another formula used to calculate energy expenditure is that developed by Brouwer et al.[13].

The formula used to determine fat and carbohydrate (CHO) oxidation varies depending on the researcher; however, in general, the formulas are based on the respiratory quotient (RQ: $RQ = \dot{V}CO_2 / \dot{V}O_2$). The RQ ranges from 0.7 to 1.0 in humans; CHO oxidation is greater as RQ approaches 1.0, and fat oxidation is greater as RQ approaches 0.7.

Equation from Jequier[14]:
CHO oxidation (g) = $4.113* \dot{V}CO_2$ (L) - $2.907* \dot{V}O_2$ (L) - 0.375*P (g)
Fat oxidation (g) = $1.689* \dot{V}O_2$ (L) - $1.689* \dot{V}CO_2$ (L) - 0.324*P (g)

Equation from Brouwer[15]:
CHO oxidation (g) = $4.170* \dot{V}CO_2$ (L) - $2.965* \dot{V}O_2$ (L) - 0.390*P (g)
Fat oxidation (g) = $1.718* \dot{V}O_2$ (L) - $1.718* \dot{V}CO_2$ (L) - 0.315*P (g)

Equation from Livesey & Elia[16]:
CHO oxidation (g) = $4.650* \dot{V}CO_2$ (L) - $3.311* \dot{V}O_2$ (L) - 3.518*N (g)
Fat oxidation (g) = $1.720* \dot{V}O_2$ (L) - $1.720* \dot{V}CO_2$ (L) - 1.776*N (g)

Equation from Ferrannini[17]:
CHO oxidation (g) = $4.55* \dot{V}CO_2$ (L) - $3.21* \dot{V}O_2$ (L) - 2.87*N (g)
Fat oxidation (g) = $1.67* \dot{V}O_2$ (L) - $1.67* \dot{V}CO_2$ (L) - 1.92*N (g)

The difference between each formula is the difference between the $\dot{V}O_2$ and the $\dot{V}CO_2$ used for each nutrient in the tests. For example, the RQ is the same for glucose and starch, but the $\dot{V}O_2$ and $\dot{V}CO_2$ differ. Samples containing fats and proteins also have different $\dot{V}O_2$ and $\dot{V}CO_2$ values. The equation for measuring substrate oxidation should be selected based on consideration of the dietary constituents. In addition, indirect calorimetry can be combined with other research methods. For example, tracer techniques can be used with a respiratory chamber to measure the oxidation turnover rate of various substrates[18,19].

Assessment of physical activity in the respiratory chamber

Spontaneous physical activity of subjects in the respiratory chamber can be measured with a radar system based on the Doppler effect (Doppler radar[20]) or microwave[21]. The radar system records the amount of activity as the ratio of activity per unit time over a certain interval rather than as a continuous record of activity intensity. Records of the amount of activity in the respiratory chamber are important for identifying abnormal activity in the chamber and for calculating the constituents of energy expenditure outlined below. In a number of recent cases, this radar system was replaced with, or run simultaneously with, an advanced accelerometer to measure the subject's activity[22, 23].

Applications

Total energy expenditure. Total energy expenditure (TEE), also referred to as daily energy expenditure, is the simplest measurement value commonly applied in research using the respiratory chamber, and is considered one of the most appropriate endpoints for this measurement method. The reproducibility of TEE has been validated by repeated studies[21,24-28]. The coefficient of variation (CV) obtained with repeated measurements from an individual subject using a respiratory chamber over a 24-h period ranges from 1% to 5%. Spontaneous physical activity is limited in the respiratory chamber, which may explain the low CV of 24-h TEE[29]. Although, the CV for spontaneous physical activity in the respiratory chamber is around 8% to 10%[21,27,30], the CV for 24-h TEE is essentially the same after adjusting for day-to-day differences in spontaneous physical activity[28].

TEE measurement using a respiratory chamber is the most accurate method of measuring energy balance (energy intake minus energy expenditure) and is used to describe changes in body weight[31,32]. The features of the respiratory chamber are used to study the effects of controlling food quantity and quality, exercise, drugs or food ingredients, and environmental factors (temperature and humidity)[3]. In addition to subjects suffering from obesity, identified by clear increases in body weight, TEE can also be measured to estimate changes in body weight in subjects with Alzheimer's Disease[33], Huntington's Disease[34], hyperthyroidism[35], diabetes[36], and a range of other diseases.

Components of total energy expenditure (resting metabolic rate, diet-induced thermogenesis, and activity-induced thermogenesis). Energy expenditure can be categorized into three main constituents based on information regarding the amount of activity simultaneously measured in the respiratory chamber: basal metabolic rate (BMR), diet-induced thermogenesis (DIT), and activity-induced thermogenesis (AIT)[37]. A linear graph of energy expenditure, calculated over a 15- to 30-min time period, is plotted against the amount of activity measured using the radar system within the same time period, and the resting metabolic rate (RMR) is then obtained by extrapolating the interception point when the amount of activity is zero. AIT is calculated by subtracting the RMR from the TEE, while DIT is calculated by subtracting the BMR from the RMR (Fig. 2). BMR, the largest component of TEE comprising 60% to 70%, is the energy expenditure of an individual after a 12- to 14-h overnight fast during a period of physical rest in a thermoneutral environment, and reflects energy use for such basic functions as maintenance of the human body. Frequently, "resting energy expenditure" is measured in preference to BMR. Resting energy expenditure is quantitatively similar to the BMR, but is not subject to all the exacting requirements of BMR[38]. BMR is usually measured using metabolic carts with hoods or masks, but there are reports that similar CV has been identified during BMR measurements using a respiratory chamber (CV = 5.0%)[24]. Compared to TEE, however, BMR is less reproducible and has a significantly larger CV[29]. The lower degree of reliability for BMR is thought be related to the short time period of measurement[24].

DIT, a term commonly used to describe the thermic effect of food, is defined as the increase in energy expenditure after food ingestion, and is calculated using the measurement for resting energy expenditure after eating[39]. DIT is measured using a respiratory chamber according to the method of Schutz et al.[37], as described above; the reproducibility of this method within individuals is 43% to 48%[21,40]. The reproducibility is low compared to that of measurements obtained using a metabolic cart (6% to 30%)[41,42], possibly related to methodologic issues. Measurements made using a respiratory chamber can be obtained over a long period of time and are based on a continuous stream of data. Therefore, this method is extremely valuable for obtaining DIT information, and improved DIT measurement methods were recently reported[22,43].

AIT is the index of energy expenditure resulting from activity in a respiratory chamber. As the respiratory chamber has limited space, the AIT is lower compared to that during a normal non-restricted lifestyle; however, it is reported to correspond to activities conducted without any restrictions in day-to-day life[44]. AIT can be categorized as exercise energy expenditure and non-exercise activity thermogenesis, which is derived from activities based on day-to-day life[29]. Exercise energy expenditure involves measurements with many changes over a short period of time, so using a mask or Douglas bag is considered ideal; however, respiratory chambers are used to observe subsequent changes over a long period of time. Non-exercise activity thermogenesis is one of the constituents of energy expenditure that varies most between individual subjects and is considered a major factor for determining energy balance.

Sleeping Metabolic Rate. Measuring sleeping energy expenditure is one of the major features of a respiratory chamber. The sleeping energy expenditure of subjects can only be measured with a respiratory chamber under conditions that are similar to daily life without affect-

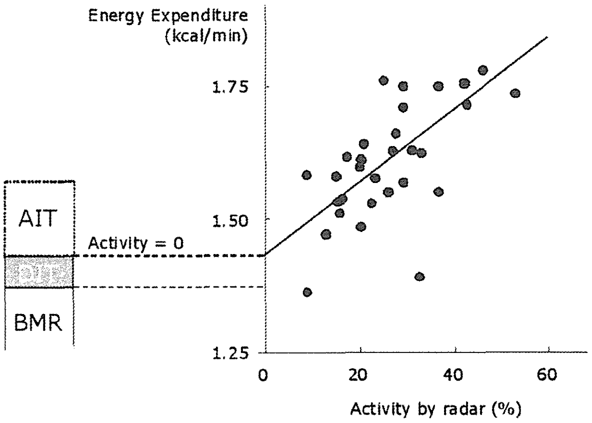

Fig. 2 Evaluation of diet-induced thermogenesis (DIT) and activity-induced thermogenesis (AIT) from total feeding over the day in a respiratory chamber (modified from Schutz et al.[37]). DIT was estimated as the difference between energy expenditure without physical activity and basal metabolic rate (BMR).

ing sleep[45-47]. Sleeping energy expenditure decreases by around 10% compared to resting[48], likely due to the decrease in energy cost of arousal. Sleep among humans is generally categorized into rapid-eye-movement (REM) or non-rapid-eye-movement (NREM); and NREM sleep is categorized into stages 1 to 4[49]. A constant relationship is observed between the categorized stages of sleep and energy expenditure. Studies using a facemask, ventilation hood, or small sleep-calorimeter have demonstrated lower energy expenditure during deep NREM sleep (stages 3 and 4) compared to that during REM or stages 1 and 2 NREM sleep[50-54]. In studies using a facemask, ventilation hood, or small sleep-calorimeter[55], the measurements are conducted under extremely restrictive conditions. Katayose et al.[56] reported higher energy expenditure for REM sleep than deep sleep using a respiratory chamber, even with sleep under conditions similar to a natural environment.

There are numerous methods available for calculating the sleeping metabolic rate (SMR). SMR can be calculated as the lowest energy expenditure value over a period of 3 hours of continuous sleep[30], as the energy expenditure during the time period when the amount of activity is the lowest[57], or as the morning energy expenditure when waking consciousness is at its lowest[58].

As SMR is not affected by activity within the body, it has a high degree of reproducibility depending on the calculation method, and is a vital measurement in long-term intervention trials. Long-term calorie intake restriction can reduce energy expenditure and lead to longer life in rodents[59,60]. Calorie intake restriction in humans also leads to a reduction in both 24-h TEE and SMR, after adjusting for fat-free mass, and improvement of some biomarkers has been demonstrated[61]. Timmers et al.[62] reported that a 30-day continuous administration trial of resveratrol decreases SMR, having an effect similar to calorie restriction. In those trials, they used a respiratory chamber to measure both TEE and SMR, and changes in these values were considered to be important endpoints.

Substrate oxidation. Long-term continuous quantitative measurements of substrate utilization are characteristic of measurements using a respiratory chamber. Protein oxidation calculated from a subject's urinary nitrogen excretion and the subject's $\dot{V}O_2$ and $\dot{V}CO_2$ measured in a metabolic chamber can be used to calculate the RQ, fat oxidation, and CHO oxidation. Toubro et al.[28] reported the reproducibility of 24-h substrate oxidation in repeated measurements of an individual subject. CV is 0.8% for RQ, 6.7% for fat oxidation, and 5.6% for CHO oxidation, if dietary conditions are completely controlled before measurements are conducted. The 24-h substrate oxidation is mainly affected by the food quotient for the period before the measurements are obtained in a respiratory chamber[63]. Accordingly, the reproducibility of 24-h substrate oxidation, in repeated measurements of an individual subject when dietary conditions are not controlled prior to measurements, is worse with a CV of 2.6% for RQ, 24.9% for fat oxidation, and 15.3% for CHO oxidation.[64] It is important that subjects maintain their achieved energy balance when estimating substrate oxidation while in the respiratory chamber[30,65,66].

The most important information related to substrate oxidation in humans was reported by Zurlo et al.[67], who stated that the 24-h RQ can be used to predict weight change. A 24-h RQ measurement, using a respiratory chamber in Pima Indians without diabetes, was positively correlated with body weight after 25 months; and subjects with low daily fat availability were predicted to have increased body weight in the future. Pannacciulli et al.[68] also observed a correlation between 24-h RQ and CHO oxidation and subsequent amount of ingestion, and postulated this as the mechanism for increases in body weight.

A small positive energy balance (50 ~ 100 kcal) in free-living life can increase body weight over the long-term[69]. The use of respiratory chambers to accurately measure energy balance can contribute to elucidating the conditions that lead to changes in body weight, including obesity. Measurements obtained using a respiratory chamber, however, are plagued by methodologic problems, excessive errors, and incorrect measurement results related to measurement protocols[6]. To properly obtain measurements using a respiratory chamber, measurement principles and calculation methods must be thoroughly understood, and an appropriate protocol used. For over a century, energy expenditure measurements have been made using respiratory chambers, and the methods used continue to evolve. Proper utilization of these measurement devices and a better understanding of their disadvantages will facilitate new findings.

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Dietary Reference Intakes for Japanese 2010: Energy

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Summary For energy of Dietary Reference Intakes for Japanese (DRIs-J), the concept of Estimated Energy Requirement (EER) is applied. The EER has been established as an index for individuals and groups. The definition of EER for individuals is "habitual energy intake in a day which is predicted to have the highest probability that energy balance (energy intake−energy expenditure, in adults) becomes zero in an individual of a given age, gender, height, body weight, and level of physical activity in good health." In contrast, the definition of EER for a group is "habitual energy intake in a day which is predicted to have the highest probability that energy balance (energy intake−energy expenditure, in adults) becomes zero in a group." The EER is calculated as follows: EER (kcal/d)=basal metabolic rate (BMR) (kcal/d)×physical activity level (PAL). Representative values for BMR per kg body weight are determined based on a number of reports for Japanese. This is called the reference value of BMR (reference BMR). Total energy expenditure measured by the doubly labeled water (DLW) method is utilized to determine PAL for each sex and age group. For adults, physical activity levels are determined based on data for Japanese adults. For children, energy deposition is added to the total energy expenditure. For pregnant and lactating women, additional values compared to EER before pregnancy for each stage of pregnancy and during lactation are calculated. Excess post-exercise oxygen consumption is not added to calculate EER in addition to energy expenditure during physical activity.

Key Words estimated energy expenditure (EER), total energy expenditure, basal metabolic rate (BMR), physical activity level (PAL), doubly labeled water method

Background Information

Daily energy expenditure (total energy expenditure) consists of basal metabolic rate (BMR), physical activity energy expenditure, and thermic effect of food (diet-induced thermogenesis). In children and infants, the need for additional energy for growth also requires determination of not only the energy necessary for meeting daily needs but also the energy necessary for increased tissue for growth (energy deposition) and the energy necessary for tissue formation. Of the two forms of energy required for growth, only energy for tissue formation is currently included in determination of total energy expenditure for children and infants. Therefore, to determine energy requirement, energy deposition needs to be added to total energy expenditure. Determining the energy requirement for pregnant women requires determination of the energy expenditure of the fetus and the energy necessary for the growth of fetal tissues. Determining the energy requirement for lactating women requires determination of the energy required to produce breast milk and consideration of weight loss corresponding to breast milk production. Therefore, increased or decreased energy requirements corresponding to an increase or decrease in tissue growth must be considered in addition to total energy expenditure, as reflected in the formula used to calculate energy requirements:

Energy requirement
=total energy expenditure+energy for the increased or decreased tissue.

For adults undergoing no body weight change, no

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Table 1. Basal metabolic rate of the Japanese population.

Sex	Males			Females		
Age	Reference BMR (kcal/kg weight/d)	Reference weight (kg)	BMR (kcal/d)	Reference BMR (kcal/kg weight/d)	Reference weight (kg)	BMR (kcal/d)
1–2 y	61.0	11.7	710	59.7	11.0	660
3–5 y	54.8	16.2	890	52.2	16.2	850
6–7 y	44.3	22.0	980	41.9	22.0	920
8–9 y	40.8	27.5	1,120	38.3	27.2	1,040
10–11 y	37.4	35.5	1,330	34.8	34.5	1,200
12–14 y	31.0	48.0	1,490	29.6	46.0	1,360
15–17 y	27.0	58.4	1,580	25.3	50.6	1,280
18–29 y	24.0	63.0	1,510	22.1	50.6	1,120
30–49 y	22.3	68.5	1,530	21.7	53.0	1,150
50–69 y	21.5	65.0	1,400	20.7	53.6	1,110
≥70 y	21.5	59.7	1,280	20.7	49.0	1,010

BMR, basal metabolic rate.

additional energy is required above that for meeting daily needs. Therefore, when energy intake exceeds energy requirements, the unutilized energy substrate is accumulated mainly in adipose tissue as triglycerides. An increase in adipose tissue may increase body weight and body fat in the short term and lead to obesity, a risk factor for many lifestyle-related diseases and increased total mortality, in the long term. In contrast, an energy intake less than that of energy expenditure may cause a decrease in the amount of accumulated fat in adipose tissues and in the amount of body protein, such as that contained in muscle tissue; a decrease in bodily functioning and quality of life; and an increase in morbidity due to infectious disease and certain cancers as well as in total mortality. Therefore, the optimal energy intake of adults—their true energy requirement—is that equal to the amount of energy expended when they are at an appropriate body weight.

Determining DRI

Estimated energy requirement

1. Definition of estimated energy requirement

In the determination of the Dietary Reference Intakes for Japanese (DRIs-J) for energy, the concept of estimated energy requirement (EER) was applied in the same way as it had been in determining the DRIs for the United States and Canada (*1*, *2*). The EER is established for individuals and groups; the EER for individuals is defined as "habitual energy intake in a day which is predicted to have the highest probability that energy balance (energy intake−energy expenditure, in adults) becomes zero in an individual of a given age, sex, height, body weight, and level of physical activity in good health."

When the energy intake of an individual is the same as the EER, the probability of inadequate intake—that the individual's energy intake is below his/her true energy requirement—is 50% and the probability of excessive intake is 50%. For many nutrients, the probability of adequate energy intake decreases as energy intake decreases, and the probability of adequate energy intake increases as intake increases while remaining sufficiently below the UL. However, the probability of inadequate energy balance increases equally whether intake is below or above the EER. That is, the probability of weight gain increases when an individual's energy intake is above the EER and the probability of weight loss increases when the individual's energy intake is below the EER. For this reason, the DRI concepts used for determination of other nutrients cannot be applied to determination of energy requirements.

In contrast to that for individuals, the EER for a group is defined as "habitual energy intake in a day which is predicted to have the highest probability that energy balance (energy intake−energy expenditure, in adults) becomes zero in a group." When the energy intake of a defined group is the same as the EER, the probability that the energy intake is below a group member's true energy requirement is 50% and probability that the energy intake is above the requirement is 50%. The components with great impact on total energy expenditure are BMR and energy expenditure for physical activities. Therefore, determination of an accurate EER requires determination of the defined individuals' or groups' BMR and the amount of physical activity.

2. Basal metabolic rate

As shown in Table 1, BMR in kcal/d is calculated as follows:

BMR (kcal/d)
=Reference BMR (kcal/kg body weight/d)×reference body weight (kg).

BMR is measured early in the morning while resting in the supine position in a comfortable indoor environment at a comfortable room temperature. The reference BMR is based on the reference BMR reported in the 2005 DRIs-J as well as the BMR values that have been reported by several studies conducted since 1980 (*3–15*).

3. Physical activity level

Physical activity level (PAL) is an index of level of physical activity that considers diet-induced thermogenesis, also. PAL is calculated as total energy expenditure divided by BMR (*16–18*), as shown in the following

Table 2. BMI and PAL at each physical activity level (mean±SD).

PAL (range)	n	Sex ratio (% male)	Age (y)	BMI (kg/m^2)	PAL
Level I (<1.6)	38	55	40±11	23.9±2.5	1.50±0.08
Level II (≥1.6, ≤1.9)	65	52	39±11	22.8±3.1	1.74±0.08
Level III (>1.9)	36	39	40±9	21.3±2.6	2.03±0.13
Total	139	50	39±10	22.7±2.9	1.75±0.22

n, number of subjects; BMI, body mass index; PAL, physical activity level.

formula:

PAL=total energy expenditure (kcal/d)/BMR(kcal/d).

The doubly labeled water (DLW) method, the most accurate method for measuring total energy expenditure that was employed in determining the DRIs of the United States and Canada, was utilized to determine the PAL for each sex and age group. Considering the range of inter-individual variability in energy expenditure based on individual characteristics and evidence, a number of PALs were established to calculate a more accurate EER.

4. Calculation of EER

Using PALs obtained from daily total energy expenditure of Japanese measured using the DLW method (*19*), the EER is calculated as follows:

EER (kcal/d)=BMR (kcal/d)×PAL.

For children, pregnant women, and lactating women, energy deposition is added to the EER to account for increased tissue due to growth, the products of conception and accretion of maternal tissues, and the energy costs corresponding to postpartum lactation and weight change, respectively.

5. Adults

In a study aimed at determining the PAL of Japanese adults (n=139, aged 20 to 59 y) (*19*), the subjects were divided into 3 groups using the 25th and 75th percentile values (1.60 and 1.90, respectively; Table 2). Based on the results of the stratification, the groups were labeled according to activity level as Level I (low activity level, representative value=1.50), Level II (moderate activity level, representative value=1.75), and Level III (high activity level, representative value=2.00). According to this classification, the ratio of individuals allocated to each level could be roughly expressed as 1 : 2 : 1. As shown in Table 2, the mean±standard deviation (SD) for the PAL of all subjects was 1.75±0.22. The representative value (or mean) for Level I generally corresponds to the value (mean−1×SD) for the entire group and the representative value (or mean) for Level III to the value of (mean+1×SD).

According to the results of studies of total energy expenditure and PAL of the Japanese using the DLW method (*19–33*), the use of these 3 levels appears appropriate.

6. The elderly

Among the many studies that have attempted to determine the PAL of healthy, independently living elderly subjects (*33–42*), the mean value was 1.69, leading the reference PAL for elderly subjects to be set as 1.70. However, the subjects' mean age in most of these reports (11 out of 13) ranged from 70 to 75 y, and many examined only relatively healthy independently living elderly subjects. These facts, as well as the fact that few studies have examined the average PAL of subjects in their 90 s, makes it difficult to identify reference PALs for the elderly over 70 y. One report (*43*) found that the PAL of subjects in their 90 s tends to be low.

7. Children

Children in the growth stage require energy not only for physical activity but also for tissue formation and increased tissue (energy deposition). As the energy used for tissue formation is included in the calculation of total energy expenditure, the EER (kcal/d) was calculated as follows:

EER (kcal/d)=BMR (kcal/d)×PAL+energy deposition (kcal/d).

As PALs differ by age group, a systematic review was conducted of reports of children's PALs using the DLW method. Values of PAL were determined based on reports with measured BMR data (*44–66*). For children younger than 5 for whom such data were unavailable, PAL values were also based on estimated BMR (*31, 67–74*). The mean PAL was found to be 1.36, 1.47, 1.57, 1.59, 1.63, 1.66, and 1.76 for ages 1 to 2 y, 3 to 5 y, 6 to 7 y, 8 to 9 y, 10 to 11 y, 12 to 14 y, and 15 to 17 y, respectively, showing a tendency to increase with age (Fig. 1). The Grouping of PALs at each age group is shown in Table 3. The similar tendency was observed in a systematic review (*75*).

Although individual variability was observed for ages 1 to 2 y and ages 3 to 5 y, the PALs for these groups were not categorized into levels due to the lack of data for categorizing PAL for individuals or groups. In contrast, the PALs for those aged 6 and over were categorized into 3 levels to consider individual variability. The means of the standard deviation of selected references weighted by the number of subjects based on age group differed in the range 0.17 to 0.25, with a mean value of 0.21. Therefore, the PAL in each age group of children was increased or decreased by 0.20 from the corresponding group's "moderate" value. As there were no data regarding PAL for these age groups in Japan, Level I (low) was established for school-age children for the first time, with consideration of the wide variations in PAL reported in previous studies conducted in foreign countries. In the future, the status and determinants of the PALs of Japanese school-age children need to be studied.

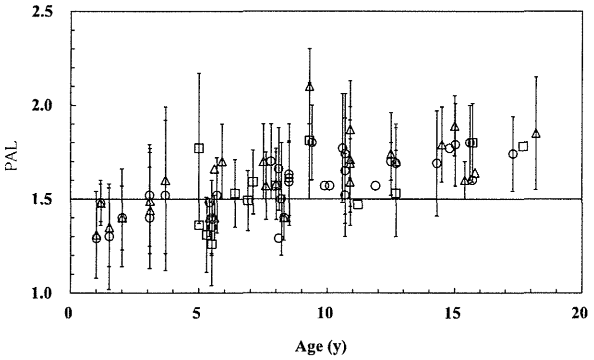

Fig. 1. PAL of children. The data presented for all age groups were taken only from studies that measured basal metabolic rate except for those for children aged 3 to 5 y, for whom data were also taken from studies that estimated basal metabolic rate, and children aged 1 to 2 y, for whom data were also taken from studies that measured sleeping metabolic rate and estimated basal metabolic rate, due to the lack of studies for these age groups. △, boys; ○, girls; □, boys and girls; mean±SD. PAL: physical activity level.

Table 3. PAL by physical activity level of each age group of both males and females.

PAL	Level I (low)	Level II (moderate)	Level III (high)
1–2 y	—	1.35	—
3–5 y	—	1.45	—
6–7 y	1.35	1.55	1.75
8–9 y	1.40	1.60	1.80
10–11 y	1.45	1.65	1.85
12–14 y	1.45	1.65	1.85
15–17 y	1.55	1.75	1.95
18–29 y	1.50	1.75	2.00
30–49 y	1.50	1.75	2.00
50–69 y	1.50	1.75	2.00
≥70 y	1.45	1.70	1.95

PAL: physical activity level.

Energy for increased tissue was determined as the product of increased weight per day calculated from the reference weight and the energy density of increased tissue (*1*) (refer to Table 4 for details).

8. Infants

For infants, as for older children, energy is required for not only physical activity but also tissue formation and energy deposition. As the energy required for tissue formation is included in total energy expenditure, the EER was calculated as follows:

EER (kcal/d)

=total energy expenditure (kcal/d)+energy deposition (kcal/d).

For determining the total energy expenditure of infants, the Food and Agricultural Organization (FAO), World Health Organization (WHO), and United Nations University (UNU) have reported that total energy expenditure of breast-fed infants can be modeled by the following regression equation, which uses body weight as an independent variable and considering the relationships among sex, age (months), body weight, body height, and total energy that were identified in previous studies (*76, 77*):

Total energy expenditure (kcal/d)

=92.8×reference weight (kg)−152.0.

As no study has determined Japanese infants' total energy expenditure using the DLW method, total energy expenditure was determined by substituting the reference weights of the Japanese into the regression equation. As with children, energy deposition is calculated as the product of increased weight per day as calculated using the reference weight and energy density of increased tissue for infants (*67*) (Table 4).

The EER is determined for infants at 3 different ages: 0 to 5 mo, 6 to 8 mo, and 9 to 11 mo. For infants aged 0 to 5 mo who undergo large weight changes, attention must be placed on the large difference in the EER between the first and second half of this period. As formula-fed infants typically have greater total energy expenditure than breast-fed infants (*76*), the FAO, WHO, and UNU have reported that the EER of formula-fed infants should be determined using the following regression equation (*76, 77*).

Total energy expenditure (kcal/d)

=82.6×body weight (kg)−29.0.

9. Additional values for pregnant women

The EER of pregnant women is calculated as follows:

EER (kcal/d)

=EER before pregnancy (kcal/d)+additional energy required by pregnant women (kcal/d).

Considering that the female reproductive period encompasses several age groups, it is necessary to determine the additional amounts of energy needed to maintain good health during pregnancy and for normal delivery for each stage of pregnancy. Longitudinal studies using the DLW method found that although PAL decreases during the early and late stage of pregnancy, increased rates of total energy expenditure during the early, mid, and late stage of pregnancy correspond to increased rates of weight gain, as does an increase in BMR during the late stage of pregnancy (*76–82*). Therefore, differences between pre-pregnancy EER and total energy expenditure during each stage (*76, 77*) adjusted by an average total weight gain of 11 kg during pregnancy (*83*) are as follows: +19 kcal/d during the early stage, +77 kcal/d during the mid-stage, and +285 kcal/d during the late stage. Total energy deposition is calculated as the sum of energy deposition of protein and fat that yields a final weight gain of 11 kg, based on protein deposition and body fat deposition on a per-stage basis (*76, 77*). Thus, energy deposition is 44 kcal/d during the early stage, 167 kcal/d during the mid-stage, and 170 kcal/d during the late stage.

As a result, total additional energy for each stage is calculated as follows:

Additional energy for pregnant women (kcal/d)

Table 4. Energy for tissue increase associated with growth (energy deposition).

Sex	Males				Females			
			Tissue increase				Tissue increase	
Age	A. Reference body weight (kg)	B. Body weight increase (kg/y)	C. Energy density (kcal/g)	D. Energy deposition (kcal/d)	A. Reference body weight (kg)	B. Body weight increase (kg/y)	C. Energy density (kcal/g)	D. Energy deposition (kcal/d)
0–5 mo	6.4	9.5	4.4	120	5.9	8.7	5.0	120
6–8 mo	8.5	3.4	1.5	15	7.8	3.4	1.8	15
9–11 mo	9.1	2.4	2.7	15	8.5	2.5	2.3	15
1–2 y	11.7	2.1	3.5	20	11.0	2.1	2.4	15
3–5 y	16.2	2.1	1.5	10	16.2	2.2	2.0	10
6–7 y	22.0	2.5	2.1	15	22.0	2.5	2.8	20
8–9 y	27.5	3.4	2.5	25	27.2	3.1	3.2	25
10–11 y	35.5	4.5	3.0	35	34.5	4.1	2.6	30
12–14 y	48.0	4.2	1.5	20	46.0	3.1	3.0	25
15–17 y	58.4	2.0	1.9	10	50.6	0.8	4.7	10

Body weight increase (B) was calculated using the reference body weight (A) and the proportional distribution method, as shown in the following example:

Weight increase (kg/y) in females from 9 to 11 mo (*X*)
=[(reference weight between 9 and 11 mo (=reference weight at 10.5 mo)
−(reference weight between 6 and 8 mo (=reference weight of 7.5 mo))]/[0.875 (y)−0.625 (y)]+[(reference weight between 1 and 2 y)−(reference weight between 9 and 11 mo)]/[2 (y)−0.875 (y)].

Body weight increase=*X*/2
=[(8.5−7.8)/0.25+(11.0−8.5)/1.125]/2
≒2.5.

The energy density for tissue increase (C) was computed based on the DRIs for the United States and Canada (*1*).

The energy deposition for tissue increase (D) was calculated by multiplying weight increase (B) and by the energy density of tissue increase (C), as in the following example:

Energy (kcal/d) for tissue increase for females aged 9 and 11 mo
=[(2.5 kg/y)×1,000/365)]×2.3 (kcal/g)
=16
≒15.

=difference between pre-pregnancy total energy expenditure and pregnancy total energy expenditure (kcal/d)+energy deposition (kcal/d).

When the final values are rounded into 50-kcal units, an additional 50 kcal/d is required during the early stage, 250 kcal/d during the mid-stage and 450 kcal/d during the late stage.

10. *Additional values for lactating women*

The EER of lactating women is calculated as follows:

EER (kcal/d)
=EER before pregnancy (kcal/d)+additional energy required by lactating women (kcal/d).

Although BMR is considered to be elevated immediately after delivery, primarily due to the 2 processes of maintenance of increased body weight compared to pre-pregnancy weight and breast milk production, an obvious increase in BMR is not observed. Of 4 longitudinal studies using the DLW method, 1 reported that energy expenditure by physical activity decreased significantly (*78*) whereas the other 3 reported a 10% decrease in absolute quantity but no significant difference was observed (*79, 81, 84*). These findings indicate that total energy expenditure during lactation is the same as that during pregnancy (*77, 79, 81, 84*). Regarding change in total energy expenditure, there is no need to calculate an additional value for lactating women. Meanwhile, lactating women must intake additional energy for breast milk production since it is not included in total energy expenditure.

Assuming that the amount of breast milk secreted is equal to the amount suckled by the infant (0.78 L/d) (*85, 86*) and that breast milk provides 663 kcal/L (*87*), the following equation can be used to determine the total energy provided by breast milk:

Total energy provided by breast milk (kcal/d)
=0.78 L/d×663 kcal/L
≒517 kcal/d.

Recognizing that the energy requirement decreases due to energy obtained from weight loss (decomposition of tissue) and assuming that the energy corresponding to the body weight reduction is 6,500 kcal/kg and the amount of body weight loss is 0.8 kg/mo (*76–80*), the energy to be subtracted in the equation shown above can be calculated as follows:

Table 5. PAL of adults aged 15 to 69 y during daily activities for typical durations.[1]

PAL[2]	Low level (I)	Moderate level (II)	High level (III)
	1.50 (1.40–1.60)	1.75 (1.60–1.90)	2.00 (1.90–2.20)
Description of activity[3]	Subjects largely remain sedentary and perform activities that require low expenditure.	Subjects largely remain sedentary but perform any of the following: moving within the workplace, working while standing, serving customers, commuting, shopping, housekeeping, and participating in light sport activities.	Subjects engage in work that requires moving or standing or habitually engage in active athletic activities.
Types of each activity (h/d)			
Sleeping (0.9)[4]	7–8	7–8	7
Remaining sedentary or remaining still while standing (1.5: 1.0–1.9)[4]	12–13	11–12	10
Engaging in slow walking or light intensity activities, such as housekeeping (2.5: 2.0–2.9)[4]	3–4	4	4–5
Performing moderate-intensity activities that can be sustained for an extended period, including normal walking (4.5: 3.0–5.9)[4]	0–1	1	1–2
Performing vigorous activities that require frequent rest (7.0: ≥6.0)[4]	0	0	0–1

PAL, physical activity level.

[1] The values presented are the standard values for each activity based on the PALs obtained using the DLW method and BMR, and the hours from 3 d of activity records for adult subjects living in Tokyo and its suburbs.

[2] Representative values. The range is shown in parentheses.

[3] Prepared using Black et al. (*17*) as a reference and giving due consideration to the significant effects of occupation on PAL.

[4] Data in parentheses are MET values (representative value: lower threshold–upper threshold).

6,500 kcal/kg body weight
×0.8 kg/mo÷30 d
≒173 kcal/d.

Therefore, the additional energy required by lactating women who have experienced a normal pregnancy and delivery is calculated as follows:

Additional energy required by lactating women (kcal/d)
=breast milk energy (kcal/d)−energy of weight loss (kcal/d).

Thus, the additional energy required for breast-feeding is 517–173=344 kcal/d, which, when rounded by 50-kcal units, is 350 kcal/d.

Application

Concept of reference basal metabolic rate

Reference basal metabolic rate (reference BMR) is designed such that the estimated value corresponds to a measured value for a reference physique. Therefore, for individuals with a body physique largely different from the reference physique, the prediction error tends to be large. Among the Japanese, for example, the BMR tends to be overestimated when the reference BMR is applied to obese individuals (*88*) and underestimated when applied to lean individuals. An EER obtained by multiplying an overestimated or underestimated BMR and PAL would have a high possibility of being above the

Table 6. Dietary Reference Intakes for energy: estimated energy requirement (kcal/d).[1]

Sex	Males			Females		
PAL	I	II	III	I	II	III
0–5 mo	—	550	—	—	500	—
6–8 mo	—	650	—	—	600	—
9–11 mo	—	700	—	—	650	—
1–2 y	—	1,000	—	—	900	—
3–5 y	—	1,300	—	—	1,250	—
6–7 y	1,350	1,550	1,700	1,250	1,450	1,650
8–9 y	1,600	1,800	2,050	1,500	1,700	1,900
10–11 y	1,950	2,250	2,500	1,750	2,000	2,250
12–14 y	2,200	2,500	2,750	2,000	2,250	2,550
15–17 y	2,450	2,750	3,100	2,000	2,250	2,500
18–29 y	2,250	2,650	3,000	1,700	1,950	2,250
30–49 y	2,300	2,650	3,050	1,750	2,000	2,300
50–69 y	2,100	2,450	2,800	1,650	1,950	2,200
≥70 y[2]	1,850	2,200	2,500	1,450	1,700	2,000
Pregnant women (amount to be added)						
Early stage				+50	+50	+50
Mid-stage				+250	+250	+250
Late stage				+450	+450	+450
Lactating women (amount to be added)				+350	+350	+350

[1] The estimated energy requirement (EER) for adults is calculated as follows:
$\text{EER (kcal/d)} = \text{BMR (kcal/d)} \times \text{PAL}$.
The PALs were 1.50 (Level I), 1.75 (Level II), and 2.00 (Level III) for adults aged 18 to 69 y and 1.45 (Level I), 1.70 (Level II), and 1.95 (Level III) for adults aged over 70 y, respectively.

[2] Calculation of PAL was largely based on research findings regarding relatively healthy, independently living elderly subjects aged 70 to 75 y.

true requirement for an obese individual and below that for a lean individual. Thus, designing an energy intake plan based on such an EER would increase the probability of further obesity or leanness in such individuals.

Relationship between reference BMR and fat-free mass

BMR has been found to be more strongly associated with fat-free mass (FFM) than body weight (*5*, *8*, *11*, *89*). In the future, the combined use of adequate body composition assessment and corresponding predictive equations will likely yield more accurate estimation of BMR.

Measurement errors in the EER

In the DRIs for the United States and Canada (*1*, *2*), the standard error of estimate of total energy expenditure is approximately 300 kcal/d for males. Assuming this variability is divided into biological and experimental variances, such as measurement error in using the DLW method, and that both variances are equal, biological variability can be estimated at approximately±200 kcal/d as a standard deviation. Thus, when EER is calculated as 2,500 kcal/d, the probability of the true energy requirement being between 2,300 and 2,700 kcal/d is approximately 68% and of being between 2,100 and 2,900 kcal/d approximately 95%. In other words, if the EER were 2,500 kcal/d, 1 out of 3 individuals' true energy requirement would be below 2,300 kcal/d or above 2,700 kcal/d.

Physical activity level

Metabolic equivalent (MET), a multiple of the resting metabolic rate in the sitting position, was used as physical activity intensity to estimate PAL rather than activity factor (Af), a multiple of BMR (*90*). This was done to avoid confusion in using MET and Af representing physical activity intensity. As fasting BMR in the sitting position is approximately 10% higher than the resting metabolic rate in the supine position (*1*, *90*), MET is calculated as follows:

$\text{MET value} \times 1.1 \fallingdotseq \text{Af}$.

The PAL of adults aged 15 to 69 y during the performance of daily activities for typical durations is shown in Table 5.

Effect of excessive post-exercise oxygen consumption on total energy expenditure

In the DRIs for the United States and Canada, excessive post-exercise oxygen consumption (EPOC), which is assumed to be 15% of certain activities, was added to calculate the EER in addition to energy expenditure during physical activity. However, EPOC was not added to the DRIs-J because it is considered to be very small in daily life (*91*). Therefore, only energy expenditure during certain activity was considered energy expended during physical activity in the DRI-Js. The EER values for