History of Studies on Energy Requirements and Anthropometry in Japanese at the National Institute of Health and Nutrition

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ABSTRACT

Objective: After the National Institute of Nutrition was founded at Tokyo in 1920, one of the main research areas has been energy metabolism. This review summarizes the history of studies on energy requirements and anthropometry conducted at the National Institute of Health and Nutrition.

Methods: A literature review of the published papers from the institute, including papers published in Progress of the Science of Nutrition in Japan was conducted. Furthermore, information on the circumstances surrounding the research was obtained from the institute’s commemorative journals.

Results and Discussion: Dr. Tadasu Saiki, the first appointed director, focused on research on energy metabolism. Takahira studied the methods to measure basal metabolic rate (BMR) using a respiration chamber from Benedict in Nutrition laboratory of the Carnegie Institution in Washington. They measured basal metabolic rate to obtain the representative values in the Japanese and examined the differences in the BMR according to sex, age, body weight, and height among Japanese. Anthropometric studies were also performed to predict body surface area and percentage of body fat from skinfold thicknesses, and the predictive equations were utilized to calculate the BMR. In 2000, human calorimetry and the doubly labelled water method were introduced at the National Institute of Health and Nutrition to evaluate total energy expenditure, and determinants such as body composition and physical activity have been examined and methods for the prediction of energy expenditure have been proposed.

Conclusions: These results have contributed to the determination of energy requirements for the Dietary Reference Intakes for Japanese and provided valid methods for various types of research.

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Key words: energy requirement, basal metabolic rate, total energy expenditure, doubly labelled water method, human calorimeter

I. Introduction

The State Institute for the study of Nutrition was founded in Tokyo in December 1920, which was the first national institution for nutrition research in the world, and its first appointed director was Dr. Tadasu Saiki.

Immediately after the establishment, one of his primary works was to quantify basal metabolism, the minimal heat produced by an organism in a postabsorptive condition and muscular repose (i.e., basal metabolic rate (BMR)).

He expected that the determination of energy requirements would lead to the solution to the problem of nutrition, not only in terms of physiology but also in terms of the policies related to nutrition and food at the same time. However, it had not been solved with respect to those two aspects till that time. To understand the energy requirement for each person, Saiki stated that BMR should be measured using a respiration chamber. In 1920, he proposed the creation of a respiration chamber to measure BMR in Japan to Benedict and his collaborators in the

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nutrition laboratory of the Carnegie Institution in Washington. They were major researchers on the energy requirements of humans and had extensively studied BMR in their laboratory during the last two decades\(^2,\ 3\). In order to establish the method of quantifying energy expenditure using the chamber, Saiki asked Takahira to go to the United States and learn the method of conducting experiments related to BMR from Benedict. Later, Saiki purchased the respiration apparatus which evaluated heat production indirectly from the oxygen consumption (O\(_2\)) and the carbon dioxide production (CO\(_2\)) levels (Figure 1). After returning to Japan, Takahira and his colleagues commenced research on energy metabolism.

In the present review, the history of studies on energy requirements and anthropometry conducted at the National Institute of Health and Nutrition has been summarized.

II. Methods

Literature review of the published papers from the institute, including papers published in Progress of the Science of Nutrition in Japan and Report of the National Institute of Nutrition. Furthermore, information on the circumstances surrounding the research was obtained from the institute’s commemorative journals.

III. Results and Discussion

1. Establishment of a measurement system for energy metabolism in the Institute of Nutrition

Takahira and his colleagues measured the BMR of 120 normal healthy men (\(n = 77\)) and women (\(n = 43\)) to obtain the representative values in the Japanese population\(^3,\ 4\). They also examined the differences in BMR according to sex, age, body weight, and height among the Japanese, and BMR values was also compared between subjects of different countries. They reported that the average values of BMR were 1,373 ± 107 kcal/day (height, 158.6 cm; weight, 53.5 kg; age, 31.2 years) and 1,073 ± 110 kcal/day (height, 147.4 cm; weight, 45.6 kg; age, 30.2 years) for men and women, respectively and the BMR of the American subjects was essentially the same as that of the Japanese. Additionally, they found that BMR was related to body height, weight, and body surface area of the subjects, of which body surface area was the most important factor\(^3\). Furthermore, they found that the BMR varied considerably from individual to individual, but the BMR of men was higher than that of women, while BMR was almost constant within-person.

Takahira et al. also reported that the average BMR in the group of laborers might be higher than that in the group of merchants and teachers who were engaged in mental work\(^3,\ 5\). However, the number of physical laborers was too small to assess the differences in the BMR by occupation. In 1923, to confirm the result, they examined the BMR of 50 exclusively physical laborers (men: 30, women: 20) and found that BMR in physical laborers was about 10% higher than the normal standard value\(^3-5\).

Since then, various values of BMR have been reported in other studies. For example, Fujimoto et al. assessed the basal metabolism in pregnant women and found an increase in O\(_2\) consumption and CO\(_2\) production until
18–19 weeks of pregnancy, a decrease from then to 25–26 weeks of pregnancy, and an increase again after 27 weeks of pregnancy. Therefore, the predictive equations of BMR were created based on the following three terms: 1–18 weeks of pregnancy, 19–25 weeks of pregnancy, and 26–40 weeks of pregnancy. Furthermore, Nakagawa et al. reported about the BMR of preschoolers, elementary school students and high school students and Fujimoto et al. examined the influence of different temperature conditions on BMR. These results regarding BMR were used as evidence for the energy requirements in the First Edition of Dietary Reference Intakes (DRIs) for Japanese.

2. Studies on anthropometry

Energy requirements are strongly related to body size and/or body composition. Body weight and body composition are related to the amount of O₂ consumption, and body surface area is closely related to heat dissipation. Since the 1920s, there have been several studies on the relationship between energy expenditure and body surface area or the estimation of body surface area. Takahira measured body surface area of 10 Japanese men aged 18 to 58 years and discussed the predictive equation of body surface area for the Japanese population. In this study, he laid out fine Japanese paper made from fibers of the bark of a clove-like bush all over a body which did not have any clothing on it. He put the paper in double layers and hardened the layers using glue. Further, the surface area was measured by a planimeter. The study was thought to be troublesome but very important for the DRIs, because, in the early ages, DRIs used BMR per body surface area. From this study, he concluded that the predictive equations must be different for children and women. However, unfortunately, further research was not conducted.

Another critical study on anthropometry was the prediction of percentage of body fat mass from the skinfold measurements. The importance of the application of body composition to the evaluation of nutritional status and the effect of body composition on energy metabolism has been emphasized since early times. Nagamine and Suzuki measured 5 skinfold thicknesses with the measurement of body density using the water displacement (underwater weighing or hydrodensitometry) method in 96 men aged 18 to 27 years and 112 women aged 18 to 23 years. The highest correlations of body density were found with the abdominal skinfold in men and the subscapular skinfold in women. Additionally, they developed 5 kinds of equations using only one skinfold site and one equation using skinfolds at the triceps and subscapular. The equation using triceps and subscapular skinfolds was used for a long time. Moreover, Nagamine proposed that obesity should be determined from body fat, not from body shape evaluated from body height and body weight. Furthermore, he developed the criteria for obesity on the basis of the sum of triceps and subscapular skinfolds or estimated percent body fat from these skinfolds. Thereafter, this prediction from skinfolds was utilized by the National Nutrition Survey for a while and various investigations regarding the effect of body composition on BMR have been carried out.

3. Studies related to energy requirement for adults

Even after World War II, researchers in our institute have measured BMR consistently, and provided large quantities of data to determine energy requirements in the DRIs. Furthermore, we have conducted many basic studies related to energy requirements.

Before World War II, there were several DRIs published by different organizations. In 1941, our institute published the DRIs for energy and protein. The energy requirement for moderately active adults was calculated as follows:

\[ A = \frac{(B+B/2+B/10)}{(1-1/10)}, \]

where A is the daily energy requirement, B is the BMR.

In this calculation, the BMR was estimated using the predictive equations suggested by Takahira and Kise which used individual body surface area estimated by Takahira’s equation. Their basic equations were developed by the data measured in our institute and were first published in the institutional reports. Furthermore, discussions on nutrient requirements were held. Energy requirements proposed after 1954 have been summarized in Table 1. In 1954, diet-induced thermogenesis (DIT) was considered as A/10 based on four studies conducted in our institute, in addition to the safety factor. At that time, energy expenditure could be measured by collecting expired gas into Douglas bags. First, they measured resting metabolic rate, after which the subject consumed the experimental diet. Further, measurement was conducted every 15 minutes until 6 hours after the diet,
| Year       | Energy requirement                                                                 | Basal Metabolic Rate                                                                 | Energy requirement for different physical activity levels                                                                 |
|------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|
| 1954       | $A = B + x$ \times A/10$. Energy requirement for each sex, age group, and work intensity were shown. | Based on the data used in the DRIs of 1949.                                         | Moderate activity level was considered for estimating energy requirement according to sex and age groups. Energy expenditure was calculated from the physical activity log and metabolic rate for each activity. Dairy work coefficient was calculated by dividing TEE by BMR. Finally, activity level was divided into 5 categories depending on the intensity of main work for 8 hours. |
| 1959       | $A = B + x$ \times A/10$. A safety factor of 10% was added. Energy requirements for each sex, age group, and work intensity were shown. | Data measured between 1925 and 1956 (number of subjects was 900 each of men and women) was adjusted for outdoor temperature. Weighted means and curve fitting among the age groups were used. | Daily work coefficient was renamed to daily life coefficient to include leisure time physical activity and not only labor activity. Daily life coefficients for housewives were decreased. DIT was excluded when the energy expenditure during work was calculated. |
| 1969       | TEE = 0.3Bm + ts \times 1.2Bn + tr \times Bn/2.                                      | Data measured in the last 15 years (1950 to 1966) was used. The number of subjects was nearly 3,000. BMR was correlated to the intensity of work. For light activity levels, BMR was decreased by 2% from the people with moderate activity. The people with heavy or vigorous activity level, BMR was increased by 2% and 4%, respectively. | Subjects were divided into 4 groups based on activity level. Energy expenditure during work was recalculated according to the nearly 2,000 subjects of the Institute for Science of Labour. |
| 1975       | Energy requirement was calculated using the same equation as that of the DRIs of 1959 for energy requirement. Energy requirements for each sex, age group, and work intensity were shown. | Data of the DRIs of 1969 was recalculated from BMR per body surface area to BMR per body weight according to the recent height and body weight. In the appendix, the relation between body weight and BMR was discussed. | TEE was calculated from activity log and energy expenditure per minute and body weight (Ea) for each activity. Ea was calculated from previous data of relative metabolic rate, and was adjusted for age and sex using regression analysis. The effect on the lack of physical activity was considered along with the actual energy expenditure during work. |
| 1985       | Energy requirement was calculated using the same equation as that of the DRIs of 1959. | Data of the DRIs of 1969 was recalculated according to the recent height and body weight. The BMRs for those older than 80 years were extrapolated from the data of BMRs of those younger than 80 years. | Daily life coefficient of the DRIs of 1975 was used. The same adjustment method for body weight was described. |
| 1990       | Energy requirement was calculated using the same equation as that of the DRIs of 1959. | Data of the DRIs of 1969 was recalculated according to the recent height and body weight. | Value of activity factor was the same as the DRIs of 1985. Duration of the main physical activity for each physical activity level was modified, and muscular activity was added. |
| 1995       | Energy requirement was calculated using the same equation as that of the DRIs of 1959. | Data of the DRIs of 1969 was recalculated according to the recent height and body weight. | Activity intensity was same with the DRIs of 1990. |
| 2000       | $A = B + x$ \times A/10$. $A_d = 24T - 1,440$.                                     | Data of the DRIs of 1969 was recalculated according to the recent height and body weight. | Activity factor was defined on the basis of all physical activities including occupations and daily life. Activity factor was determined by the duration of the main physical activities including sleeping, sitting, standing and walking, along with the metabolic rate. |
| 2005       | EER = BMR x PAL.                                                                  | Data of the DRIs of 2000 was used. The values were used as there was no significant difference. | PAL was determined from the project conducted in the National Institute of Health and Nutrition using the DLW method. |
| 2010       | The same equation as that of the DRIs of 2005 was used.                           | The values were determined using the DRIs of 2000 and the published data after 1990. | Values of PAL were the same as that of the DRIs of 2005 that mainly depended on our project data. The published data using DLW method both in Japan and other countries were referred. |
| 2015       | The same equation as that of the DRIs of 2005 was used.                           | Thirteen studies comprising Japanese adults were used to determine the value. The predictive equation for BMR proposed by the National Institute of Health and Nutrition was presented. | Values of PAL were the same as that of the DRIs of 2005 that mainly depended on our project data. Duration of each intensity of physical activity was determined according to our data. For PALs among older population, 11 studies conducted both in Japan and other countries were referred. |
| 2020       | The same equation as that of the DRIs of 2005 was used.                           | The values were decided using the data measured after 1980 for the Japanese population. The predictive equation for BMR proposed by National Institute of Health and Nutrition was presented for individuals with BMI less than 30 kg/m². | PAL values for adults were determined using our project data. Type and duration of each physical activity level was set from our data. To determine PAL for the older population, 23 studies conducted both in Japan and other countries were used. |

- BMR: basal metabolic rate.
- In the DRIs of 1954, A: energy requirement, B: BMR, x: dairy work coefficient
- In the DRIs of 1959, A: energy requirement, B: BMR, x: dairy life coefficient
- In the DRIs of 1969, Bm: BMR, ts: duration of sleeping, tr: duration of waking, tw: duration of each activity
- TEE: total energy expenditure
- RMR: relative metabolic rate calculated as ([energy expenditure during activity]-[resting metabolic rate])/[basal metabolic rate]
- In the DRIs of 2000, A: activity factor (multiple of BMR), T: time of each activity
- EER: estimated energy requirement
- PAL: physical activity level, TEE divided by BMR
- DLW: doubly labelled water

The name of the recommendations changed with time. Here, we have used dietary reference intakes (DRIs) throughout the table.
then every 1 hour until the energy expenditure was back to the level of resting metabolic rate. The measurement was continued for 8 to 12 hours. The daily work coefficient was determined according to the method proposed by the Institute for Science of Labour. In the DRIs of 1959, BMR was reexamined using individual data from the same dataset as that of the DRIs of 1954. Later, the measured data was adjusted for the outdoor temperature to consider the effect of season on measurements. This adjustment was explained to have been conducted by Yukio Suzuki and Shinjirō Suzuki. However, there was no reference for these studies. Suzuki S, the chief of the Physiology division in our institute, published the article in 1960 using resting metabolic rate data measured after 1950 and discussed the seasonal differences of BMR. Additionally, the DRIs of 1959 expressed further consideration on the lack of BMR data for some populations, the need to express BMR per active tissue, and the need for further studies to determine the activity factor. Further, the noteworthy discussion in the DRIs of 1975 was the comments on the relationship between BMR and body weight that was described in the appendix. Using the BMR data measured in our institute, the relationship of the differences between predicted and measured BMR with respect to body weight was discussed. The difference was more significant with the increase in body weight. Therefore, the adjustment method was proposed for body weight.

BMR is the largest component of total energy expenditure (TEE). However, interindividual variability of physical activity is very large, which causes substantial variations in the TEE. TEE can be estimated using relative metabolic rate, which is an index of physical activity intensity developed in Japan and calculated as (EE during activity – resting metabolic rate) divided by BMR. Furthermore, there may be interactions within the EE components. Factorial methods using activity records with relative metabolic rate or metabolic equivalents cannot overcome these problems. Therefore, the establishment of objective and validated methods to capture whole EE on a daily or weekly basis (TEE) was necessary. The significant changes in the contribution to the DRIs were the introduction of the human calorimeter (Figure 2) and the doubly labelled water (DLW) method in 2000. After about one year of preparation, the accuracy of human calorimeters was confirmed and measurements for adults with both systems started in 2001. Participants ingested DLW on the first day and urine samples were collected from them for 2 weeks. On the evening 2 days before the end of the measurement period, they came to the institute again and stayed in a human calorimeter for 36 hours. Before leaving, their BMR was measured using a mask and a Douglas bag. In the human calorimeters, participants performed physical activities to simulate daily life, including cycling for one hour in total and stepping for 15 minutes. As a result, the average physical activity level (PAL), TEE divided by BMR, was over 1.5, and the PAL calculated without cycling and stepping was 1.38. These values were higher than estimated according to DRIs in 2000 for Japanese.

In the DRIs for the United States in 2001, energy requirement was set according to the data measured using the DLW method. In November 2002, we started a new project for total energy expenditure using the DLW method. At that time, two Japanese researchers (Kashiwazaki and Saitoh) and their colleagues had already published studies using the DLW method. These studies were conducted by collaborating with universities in the United Kingdom and Canada. In August 2000, our institute introduced isotope ratio mass spectrometry and was the first to analyze the samples for the DLW method in Japan. Although our data was not published by the DRIs in 2005, they were used for the DRIs in 2005. In this study, 150 healthy Japanese men and women aged 20 to 59 years were measured at four areas in Japan and based on the results, the average PAL value for Japanese adults was set at 1.75. The value is still used by the DRIs of 2020. In the DRIs of 2010, 5 of 13 studies used to determine
BMR and 2 of 24 studies using the DLW method were published from our studies. The studies used to determine BMR were conducted only for the Japanese population. However, the studies using the DLW method were mostly conducted in foreign countries. Besides, according to our study that used the DLW method and a physical activity questionnaire in 226 Japanese men and women aged 20 to 83 years\(^{28}\), the type and duration of physical activity for each PAL determined the DRIs. The procedure to determine energy requirement often followed the method conducted in the United States or the Food and Agricultural Organization. DRIs in the United States used 15% of excess post-exercise oxygen consumption (EPOC) for daily physical activity to estimate energy requirements. However, we found that EPOC for moderate or vigorous daily physical activity was 5 to 6%, using the human calorimeter\(^{29}\). Further, the DRIs of 2015 did not use the EPOC values to determine energy requirement. Moreover, internationally used predictive equations for BMR were mainly developed using the data measured in western countries. On this basis, we made the estimate equation of BMR for the Japanese population using the data of 137 Japanese men and women, using the human calorimeter\(^{15}\). In addition, we confirmed that this equation could estimate more accurately than other equations, at least for the Japanese people, with body mass indices (BMI) less than 30 kg/\(\text{m}^2\)\(^{30}\). This predictive equation was introduced in the recent DRIs (2015 and 2020) for prediction at an individual level. On the other hand, BMR was underestimated by this equation for patients with diabetes\(^{31}\).

Thus, the average values of PAL for adults with low, normal, and high activity were determined. However, the prediction methods of TEE were not developed. For adults, PAL values ranged from 1.4 to 2.2 or more, indicating a large inter-individual variability. Most of the variation was caused by variability of non-exercise activity thermogenesis (NEAT); however, the evaluation of NEAT is difficult. Therefore, we have tried to seek different types of prediction methods such as questionnaires and accelerometers.

The most convenient method for predicting PAL is the questionnaire method and, for this, the validity of various types of questionnaires have been examined\(^{27, 28}\). As a result, the prediction errors are very large, although some of them may provide comparable TEE values on an average. On the other hand, activity monitors with accelerometers have become widely available, mainly for epidemiological studies and consumers. However, the algorithm to obtain TEE varies between activity monitors, which leads to very different predicted values of TEE. Therefore, we have developed algorithms to accurately predict TEE\(^{32-34}\) and evaluated its validity for various populations\(^{35-38}\).

The TEE of obese persons was considered to be low previously; however, objective methods such as human calorimetry and the DLW method showed that the TEE in obese persons is greater than that in normal-weight persons due to a larger body size and BMR, in general. Furthermore, we showed that the PAL for Japanese obese persons is not low, except for extremely obese persons\(^{39, 40}\). Data of TEE for children/adolescents or patients are still insufficient, although we have published a few papers based on such populations\(^{41-44}\).

### IV. Conclusions

National Institute of Health and Nutrition has tried to establish energy requirements and predictive methods. Meanwhile, sophisticated technologies to evaluate total energy expenditure and determinants such as body composition and physical activity have been introduced. These results have not only contributed to the determination of energy requirements for populations, but also provided valid methods for various types of research.

\(^1\) In Japan, basal metabolic rate is usually used in the Dietary Reference Intakes. However, the measurement condition in most of the studies may be considered to be resting metabolic rate rather than basal metabolic rate (BMR).

\(^2\) The title of the recommended intakes of energy and nutrients has been changing over time (e.g. Recommended Dietary Allowances (RDA)). In this article, we use the Dietary Reference Intakes (DRIs) for all recommendations instead of the exact translation for each recommendation.

\(^3\) The term for the increase of energy expenditure after diet for digestion and absorption was called as specific dynamic action (SDA) in the report of 1954. We use diet-induced thermogenesis (DIT) throughout the article.
Conflict of Interest Statement

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国立健康・栄養研究所における日本人のエネルギー必要量と身体計測に関する研究の歴史

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【目的】1920年に栄養研究所（現・国立健康・栄養研究所）が設立されて以来，エネルギー代謝に関する研究は，本研究所の主要な研究課題の1つとして進められてきた。本総説では，これまで本研究所で実施された，ヒトにおけるエネルギー消費量とそれに関連した身体計測についての研究の歴史を概説する。

【方法】これまでの研究の歴史を概説するにあたり，主に本研究所からの論文や書籍・記念誌，およびProgress of the Science of Nutrition in Japanを参照した。

【結果・考察】本研究所のエネルギー代謝研究は，栄養研究所の初代所長である佐伯博士が注力した研究の1つであったことがきっかけであった。高比良博士は，佐伯博士の命を受け，カーネギー研究所のベネディクト博士から呼吸装置を用いた基礎代謝の測定法を学び，その後，日本人の基礎代謝基準値を作成するため，日本人の基礎代謝量を測定するとともに，性別・年齢・体重・身長といった基礎代謝量の要因について検討した。また体表面積や皮下脂肪による体脂肪率の推定など，身体計測に関する研究も並行して実施され，それらの身体計測値は基礎代謝量の推定式に用いられた。さらに2000年以降には，ヒューマンカロリメーターや二重標識水法が国立健康・栄養研究所に導入されたことにより，総エネルギー消費量や身体活動レベルに関する研究が実施され，それらを推定する方法も提案されている。

【結論】本研究所で得られた一連の結果は，日本人の食事摂取基準のエネルギー必要量の策定に活用されていると共に，多くのエネルギー代謝研究の土台となっている。

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