Table 1 Characteristics of selected studies in this paper

Reference	*RCT or nonRCT*	*Intervention*		*Subject*			
		Duration	*Type of group*	*Gender*	n	*Age (year)*	*Specific characteristics*
Despres *et al.*[34]	NonRCT	6 months	A	F	13	38.8±5.3	
Donnelly *et al.*[15]	RCT	16 months	A	F	25	24±5	
			C	F	18	21±4	
			A	M	16	22±4	
			C	M	15	24±4	
Green *et al.*[17]	nonRCT	20 weeks	Dr+A	F	30	56.4±5.4	Estrogen replacement therapy (ERP), postmenopausal
			A	F	18	52.3±6.3	Non ERP, postmenopausal
Halverstadt *et al.*[18]	nonRCT	24 weeks	A	M+F	83 (34+49)	57.9±0.6	Combined LIPG (endothelial lipase gene) genotype CC and CT/TT
Irwin *et al.*[19]	RCT	12 months	A	F	87	61.0 (59.6–62.5)	Menopausal
			C	F	86	60.6 (59.1–62.1)	Menopausal
Miyatake *et al.*[20]	nonRCT	1 year	A	M	31	(32–59)	
Park *et al.*[21]	nonRCT	24 weeks	C	F	10	43.1±1.67	
			A	F	10	42.2±1.91	
			A+R	F	10	43.4±1.04	
Ross *et al.*[22]	RCT	14 weeks	Di	F	15	43.9±4.9	
			A	F	17	43.2±5.1	
			A^a	F	12	41.3±7.2	
			C	F	10	43.7±6.4	
Ross *et al.*[29]	RCT	12 weeks	Di	M	14	42.6±9.7	
			A	M	16	45.0±7.5	
			A^a	M	14	44.7±7.6	
			C	M	8	46.0±10.9	
Schwartz *et al.*[27]	nonRCT	27 weeks	A	M	13	28.2±2.4	
			A	M	15	67.5±5.8	
Short *et al.*[23]	RCT	16 weeks	A	M+F	65	40.5±1.1	
			C	M+F	37	40.7±1.4	
Wilund *et al.*[25]	nonRCT	12 weeks	A	M+F	16 (6+10)	56±1	CETP (cholesteryl ester transfer protein) genotype (B1B1)
			A	M+F	14 (8+6)	56±1	CETP (cholesteryl ester transfer protein) genotype (B1B2)
Boudou *et al.*[33]	RCT	8 weeks	A	M	8	42.90±5.20	Type 2 diabetics
Giannopoulou *et al.*[16]	RCT	14 weeks	Di+A	F	11	57.4±1.7	Diabetics, menopausal
			Di	F	11	58.5±1.7	Diabetics, menopausal
			A	F	11	55.5±1.7	Diabetics, menopausal
Mourier *et al.*[9]	RCT	8 weeks	A	M+F	10	45±2	Diabetics
			C	M+F	11	46±3	Diabetics
Slentz *et al.*[24]	RCT	32 weeks	A^b	M+F	40	54.0±5.5	Dyslipidemia, postmenopausal
			A^b	M+F	46	53.0±7.0	Dyslipidemia, postmenopausal
			A^b	M+F	42	51.5±5.3	Dyslipidemia, postmenopausal
			C	M+F	47	52.3±7.65	Dyslipidemia, postmenopausal

Abbreviations: A, aerobic exercise therapy; A^a, aerobic exercise therapy without a weight loss; A^b, three different types of aerobic exercise therapy in the study; C, control; Di, diet therapy; Dr, drug therapy; F, female subjects; M, male subjects; *n*, number of subjects (number of males+number of females); R, resistance training therapy; RCT, randomized control trials. Age expressed by mean±s.d. (range).

Table 2 Summary of aerobic exercise groups in this paper

Reference	*Subjects*				*Aerobic exercise*	
	Gender	*Age (yr)*	*BMI (kg/m²)*	*% fat (%)*	*Session time and intensity*	*Mode or used exercise instrument*
Despres *et al.*[34]	F	38.8	34.5	47.0	90 min, 55%HRmax	Walking
Donnelly *et al.*[15]	M	22	29.7	28.3	45 min, 70%VO2max	Treadmill
Green *et al.*[17]	F	56.4	29.3	40.8	75%VO2max	Ergometer
Halverstadt *et al.*[18]	M+F	57.9		36.0	70%VO2max	
Irwin *et al.*[19]	F	61	30.5	47.6	Mean 81%HRmax	Treadmill walking and stationary bicycling in Lab, and aerobic exercise (e.g. walking, aerobics, bicycling) at home
Miyatake *et al.*[20]	M	32–59	28.6	29.3	7012→8839 steps/day (plus 1827 steps/days)	Normal walking
Park *et al.*[21]	F	42.2	25.3	42.2	60–70%HRmax	Fast walking
Ross *et al.*[22]	F	43.2	32.8		Mean 80%HRmax	Brisk walking or light jogging on treadmill
	F	41.3	32.9		Mean 82%HRmax	Brisk walking or light jogging on treadmill
Ross *et al.*[29]	M	45	32.3		Mean 77%HRmax	Brisk walking or light jogging on treadmill
	M	44.7	31.3		Mean 77%HRmax	Brisk walking or light jogging on treadmill
Schwartz *et al.*[27]	M	67.5	26.2	24.7	45 min, 85%HRreserve	Walking/jogging
Short *et al.*[23]	M+F	40.5	26.6	31.4	80%HRmax	Stationary bicycling
Wilund *et al.*[25]	M+F	56		38.0	40 min, 70%VO2max	
	M+F	56		34.0	40 min, 70%VO2max	
Boudou *et al.*[33]	M	42.9	28.3		1) 2 times/week, 45 mi n, 75%VO2peak, 2) 1 time/week, 10 min, 85%VO2peak, and 12 min, 50%VO2peak	Ergometer
Giannopoulou *et al.*[16]	F	55.5	35.9		60 min, 65–70%VO2max, energy expenditure: 250.95–298.75 kcal/session	Walking
Mourier *et al.*[9]	M+F	45	30.4	24.4	1) 2 times/week, 45 min, 75%Vo2peak, 2) 1 time/week, 10 min, 75%VO2peak, and 12 min, 50%VO2peak	Ergometer
Slentz *et al.*[24]	M+F	54	29.8		40–55%VO2max, 14 kcal/kg/wk (12 miles/week)	Treadmill walking
	M+F	53	29.7		65–80%VO2max, 14 kcal/kg/wk (12 miles/week)	Treadmill jogging
	M+F	51.5	29.1		65–80%VO2max, 23 kcal/kg/wk (20 miles/week)	Treadmill jogging

Table 2 (Continued)

Aerobic exercise					Weight						Visceral fat								
VO2max (baseline)	*Frequency (times/ week)*	*Time (min/ session)*	*Energy expenditure (kcal/week)*	*METs·h/w*	*Before (kg)*	*After (kg)*	*Δ (kg)*	*%Δ (%)*	*%Δ (%/ week)*	*Sig^1*	*Before*	*After*	*Δ*	*Unit*	*%Δ (%)*	*%Δ (%/ week)*	*Sig^2*	*Method*
	4–5	90	1913	20.2	90.0	86.3	−3.7	−4.11	−0.069	*	124.7	121.3	−3.4	cm^2	−2.73	−0.045	NS	CT
	5	45	3300	33.4	94.0	85.2	−8.8	−9.36	−0.136	*	97.9	75.5	−22.4	cm^2	−22.88	−0.334	*	
21.3±4.0	3	50	920	11.4	76.8	76.9	0.1	0.13	0.007	NS	121.6	117.8	−3.8	cm^2	−3.13	−0.156	NS	CT
25.2±0.5	3	40	853	10.1	80.6	79.5	−1.1	−1.36	−0.057	*	127.8	113.4	−14.4	cm^2	−11.27	−0.469	*	CT
20.1 (19.3–20.9)	3.5	176/week	1051	12.3	81.6		−1.3	−1.59	−0.031	*	147.6		−8.5	cm^2	−5.76	−0.113	*	CT
	7	18.27	507	5.9	82.0	79.0	−3.0	−3.66	−0.091	*	108.7	87.0	−21.7	cm^2	−19.96	−0.499	*	CT
34.2±3.2	6	60	1908	28.5	63.7	59.0	−4.7	−7.38	−0.307	*	195.0	112.4	−82.6	cm^2	−42.36	−1.765	*	CT
	7	64	3668 (524±52/session)	40.2	86.9	80.9	−6.0	−6.90	−0.493	*	2.3	1.6	−0.7	kg	−30.43	−2.174	*	MRI
	7	63	3619 (517±58/session)	39.1	88.1	87.6	−0.5	−0.57	−0.041	NS	2.2	1.8	−0.4	kg	−18.18	−1.299	*	
	7	60.4	4886 (698/session)	45.8	101.5	94.0	−7.5	−7.39	−0.616	*	186.0	134.0	−52.0	cm^2	−27.96	−2.330	*	MRI
	7	63.3	4844 (692/session)	47.1	97.9	97.4	−0.5	−0.51	−0.043	NS	191.0	159.0	−32.0	cm^2	−16.75	−1.396	*	
29.1±4.4	4.44±0.43	45	2009	24.0	79.6	77.1	−2.5	−3.14	−0.131	*	144.5	109.0	−35.5	cm^2	−24.57	−1.024	*	
25.6 (40.5±1.1/ FFM)	4	40	1166	14.0	79.2	78.7	−0.5	−0.63	−0.039	*	133.0	124.0	−9.0	cm^2	−6.77	−0.423	*	CT
25±1	3	40	882	10.0	84.0	83.2	−0.8	−0.95	−0.079	NS	146.0	130.0	−16.0	cm^2	−10.96	−0.913	*	CT
26±1	3	40	863	10.4	79.0	77.8	−1.2	−1.52	−0.127	*	128.0	109.0	−19.0	cm^2	−14.84	−1.237	*	
23.45±3.60	3	1) 45, 2) 22	836	9.2	86.9	85.0	−1.9	−2.19	−0.273	NS	153.3	84.2	−69.1	cm^2	−45.06	−5.632	*	MRI
	3–4	60	962	9.9	92.9	91.2	−1.7	−1.83	−0.131	NS	5204.0	4675.0	−529.0	cm^3	−10.17	−0.726	*	MRI
23.0±1.2	3	1) 45, 2) 22	795	8.9	85.3	83.8	−1.5	−1.76	−0.220	NS	156.1	80.4	−75.7	cm^2	−48.49	−6.062	*	MRI
	3.5	178	1232	6.9	88.0			−0.70	−0.022	*	173				1.70	0.053	NS	CT
	3.1	120	1190	13.3	85.0			−0.80	−0.025	*	154				2.50	0.078	NS	
	3.6	173	1971	21.9	85.7			− 2.60	−0.081	*	168				−6.90	−0.216	*	

Abbreviations: CT; computed tomography; F, female subjects; M, male subjects; METs·h/w, ∑(metabolic equivalents × hour) per week; MRI, magnetic resonance imaging; Sig^1, a significant weight change was observed during the intervention ($P<0.05$); Sig^2, a significant visceral fat change was observed during the intervention ($P<0.05$); Δ, change. Results expressed by mean (range) or mean ± s.d.

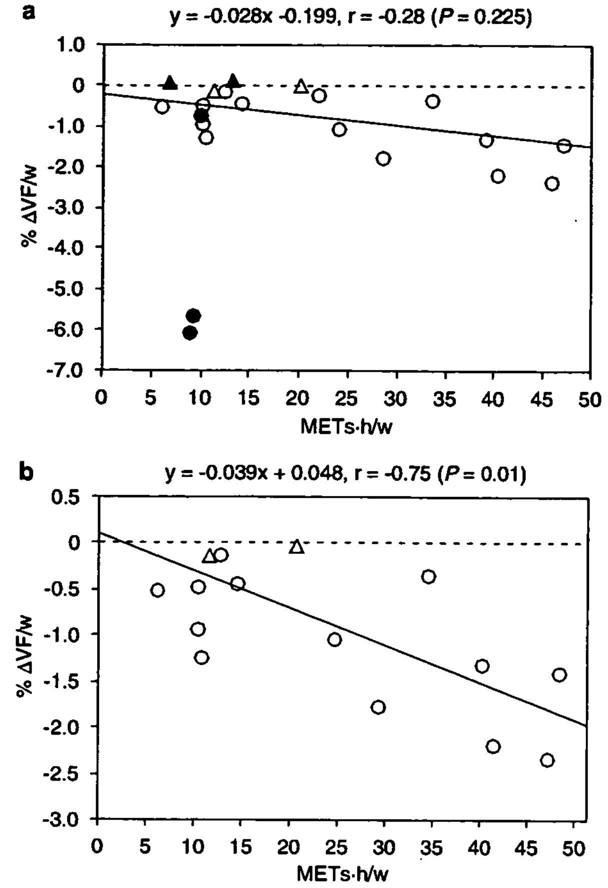

Figure 1 Relations between METs · h/w and %ΔVF/w during interventions in the all selected groups (a) and the groups without metabolic-related disorder subjects (b). Abbreviations: METs · h/w, $\sum$(metabolic equivalents × hour) per week; %ΔVF/w, percentage of visceral fat change per week; *r*, Pearson's correlation coefficient weighted for the number of subjects in each group; ○, the no metabolic-related disorder group with a significant visceral fat reduction ($P<0.05$); △, the no metabolic-related disorder group without a significant visceral fat reduction ($P<0.05$); ●, the metabolic-related disorder group with a significant visceral fat reduction ($P<0.05$); ▲, the metabolic-related disorder group without a significant visceral fat reduction ($P<0.05$).

physical activity and total or regional fat reduction. As a result, even though some literatures were added for the analysis, whether physical activity was associated with reductions in abdominal fat in a dose–response manner was still unclear. Kay and Fiatarone Singh[10] also reviewed the beneficial influence of physical activity on visceral fat reduction, but dose–response data were not examined. These previous reviews did not include studies involving large amounts of exercise. In our analysis, some additional studies, especially three studies with values of 35 METs · h/w or more,[21,22,29] were included in addition to papers used by previously published reviews. Furthermore, the amount of aerobic exercise undertaken during the intervention was expressed as METs · h/w, because METs · h could adjust the EE for each subject's weight. As a result, there was no relationship between METs · h/w and %ΔVF in the 21 groups from 16 studies including the metabolic-related disorder subjects. However, in subjects without metabolic-related disorders, we found a dose–response relationship between aerobic exercise and visceral fat reduction. Indeed, if obese subjects without metabolic-related disorders practiced aerobic exercise, the degree of visceral fat reduction could be directly attributed to the aerobic exercise amount. For example, if an obese person without metabolic-related disorders tries to reduce 10% of his VF amount in 10 weeks, instructors should prescribe about 27 METs · h/w, because 27 METs · h/w corresponds to 1% of ΔVF/w. Thus, our findings could be used to affect decisions on the amount of aerobic exercise recommended for visceral fat reduction in obese people.

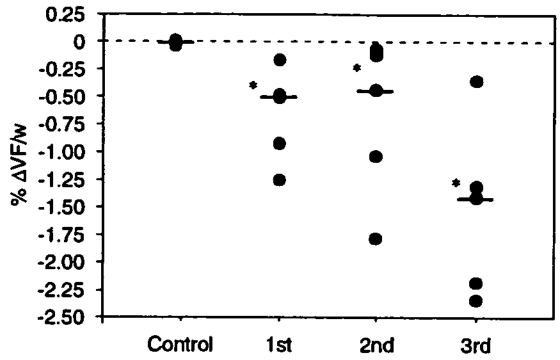

Figure 2 Comparison of mean %ΔVF/w between a control group and exercise groups divided into tertiles by METs · h/w amount in the groups without metabolic-related disorder groups. Ranges of METs · h/w in each categorized group were 5.9–11.4 (1st), 12.3–28.5 (2nd), 33.4–47.1 (3rd). Side bar means median in each group. Statistically significant difference between the groups were observed ($P=0.003$). * A significant difference was found in comparison with the control group using the *post hoc* test ($P<0.05$). Abbreviations: %ΔVF/w, percentage of visceral fat change per week; METs · h/w, $\sum$(metabolic equivalents × hour) per week.

In the selected studies, six groups from four studies consisted of metabolic-related disorder subjects. Results from the metabolic-related disorder subjects were contradictory. Two groups with type 2 diabetes[9,38] clearly exhibited a significant visceral fat reduction, although these results may have been exaggerated by the shortest-term intervention (8 weeks) in the selected studies. Two groups with dyslipidemia[24] did not significantly reduce visceral fat, while the group with type 2 diabetes reported by Giannopoulou *et al.*[16] was close to the regression line for identifying a dose–response relationship. Kelly and Simoneau[39] showed that the capacity of fat oxidation during aerobic exercise in individuals with type 2 diabetes was lower than that for healthy individuals. However, several other investigators did not find any significant difference in fat oxidation capacity between subjects with or without type 2 diabetes.[40,41] Furthermore, Raguso *et al.*[42] observed that fat oxidation during aerobic exercise in the group with type 1 diabetes was higher than that of the control group. These studies were conducted

Table 3 Mean METs · h/w and %ΔVF/w, and correlate coefficients between METs · h/w and %ΔVF/w during interventions in the groups categorized by intervention duration or gender

Groups	*Intervention duration*		*Gender*	
	≤16 week	*>16 week*	*Women only*	*Men only*
From all the selected groups				
Number of groups	10	11	7	6
Number of subjects	183	399	168	98
METs · h/w	23.5±17.1	17.1±9.1	23.1±13.0	27.6±17.7
%ΔVF/week	−2.22±2.00	−0.41±0.55	−0.90±0.86	−1.83±1.98
r (*P* value)	−0.06 (0.877)	−0.34 (0.302)	−0.89 (0.007)	−0.05 (0.931)
From the groups without metabolic-related disordered subjects				
Number of groups	7	8	6	5
Number of subjects	154	271	157	90
METs · h/w	29.5±17.2	18.2±9.8	25.3±12.7	31.3±17.1
%ΔVF/w	−1.40±0.67	−0.55±0.58	−0.93±0.94	−1.07±0.73
r (*P* value)	−0.81 (0.027)	−0.36 (0.378)	−0.93 (0.008)	−0.71 (0.184)

Abbreviations: METs · h/w, ∑(metabolic equivalents × hour) per week; *r*, Pearson's correlate coefficient; %ΔVF/w, percentage of visceral fat change per week. *r* values were weighted for the number of subjects in each group.

under conditions where the subjects with or without diabetes had fasted.[39–42] Thus, visceral fat reduction in the metabolic-related disorder subjects could be due to more complex mechanisms. Therefore, formulation of a dose–response relationship between aerobic exercise and visceral fat reduction has to take into account the separation of subjects with and without metabolic-related disorders.

How much exercise is needed for significant visceral fat reduction?

It is important to suggest a lower limit for the quantity of aerobic exercise required for significant visceral fat reduction. In our selected groups, METs · h/w values ranged from 5.9 to 47.1. Except for the lowest METs · h/w obtained from Miyatake *et al.*[20] in which the subjects were instructed to increase the number of steps walked every day for 1 year, significant visceral fat reduction was observed from about 10 METs · h/w.[16,18,25] Thus, at least 10 METs · h/w is required for significant visceral fat reduction by aerobic exercise, such as brisk walking, light jogging or stationary ergometer usage. For the purpose of weight or body fat loss, the American College of Sports Medicine (ACSM) recommends obese individuals to engage in moderately intense physical activity for minimum 150 min/w, and preferably more than 200–300 min/w.[43] The minimum value in this recommendation nearly equals to 10 METs · h/w when performing moderate physical activities such as brisk walking. In the present study, we divided the aerobic exercise groups into tertiles by their METs · h/w amount to determine the boundary of obvious visceral fat reduction. As a result, each exercise group category had a higher visceral fat reduction than the control group. However, there was no significant difference between %ΔVF/w values in the three exercise categories. This result may be due to an insufficient number of groups. The median of %ΔVF/w in the 3rd tertile exercise group was 40.2, which was much higher than that of the 1st and 2nd tertile exercise groups. That is to say, approximately 40 METs · h/w or more may be required to reduce visceral fat solely by aerobic exercise, such as brisk walking, light jogging or stationary ergometer usage. Forty METs · h/w equates to approximately 3780 kcal/w for a person with 90 kg body weight. Although this value is slightly lower than the ACSM's recommendation corresponding to a minimum 4500 kcal/w for combined exercise and diet with intakes of not lower than 1200 kcal/d, this results in an energy deficiency of approximately 500–1000 kcal/d, which could be hard for obese people with low physical fitness to practice continuously. Therefore, for an individual's prescription for visceral fat reduction, recommendations that balance diet and exercise should be examined in another research.

Influences of intervention duration or gender on the dose–response relationship

Ross and Janssen[13] revealed that an increase in physical activity is positively associated with a reduction in total fat in a dose–response manner in short-term interventions (≤16 week), but not in long-term interventions (≤26 week). In the review by Kay and Fiatarone Singh,[10] there was no relation between change in abdominal fat and intervention duration. In the present study, EE by aerobic exercise was positively correlated with visceral fat reduction in the short-term (≤16 wk) studies when the metabolic-related disorder groups were discounted. Ross and Janssen[13] suggested that in long-term exercise studies, it is difficult to complete a weight loss of an expected volume from expended energy consumption, although it is not clear which factors, such as the adherence to interventions, or over-reporting of exercise amount, influenced the results. Our results support this trend with

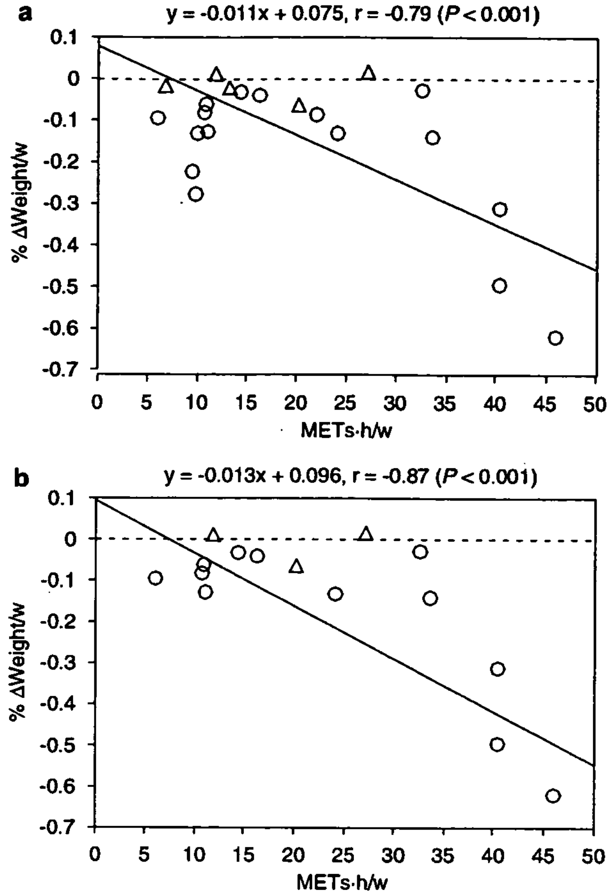

Figure 3 Relations between METs · h/w and %ΔWeight/w during interventions in the all selected groups (a) and after excluding the groups with metabolic-related disorder subjects (b). Abbreviations: METs · h/w, ∑(metabolic equivalents × hour) per week; %ΔWeight/w, percentage of weight change per week; *r*, Pearson's correlate coefficient; ○, the group with a significant visceral fat reduction ($P < 0.05$); △, the group without a significant visceral fat reduction ($P < 0.05$). The groups without a weight loss intentionally were excluded for these analysis.

respect to visceral fat reduction. That is, if subjects can complete the instructed exercise volume, short-term interventions could be more efficient than long-term interventions for weekly visceral fat reduction. Generally, if participants do not quickly observe the benefits of a weight-loss program, their motivation for continuing the regimen is reduced.[44,45] Accordingly, for significant visceral fat reduction, obese people should initially practice a relatively high volume of aerobic exercise, which can then be reduced to a manageable amount that they can practice for the long term.

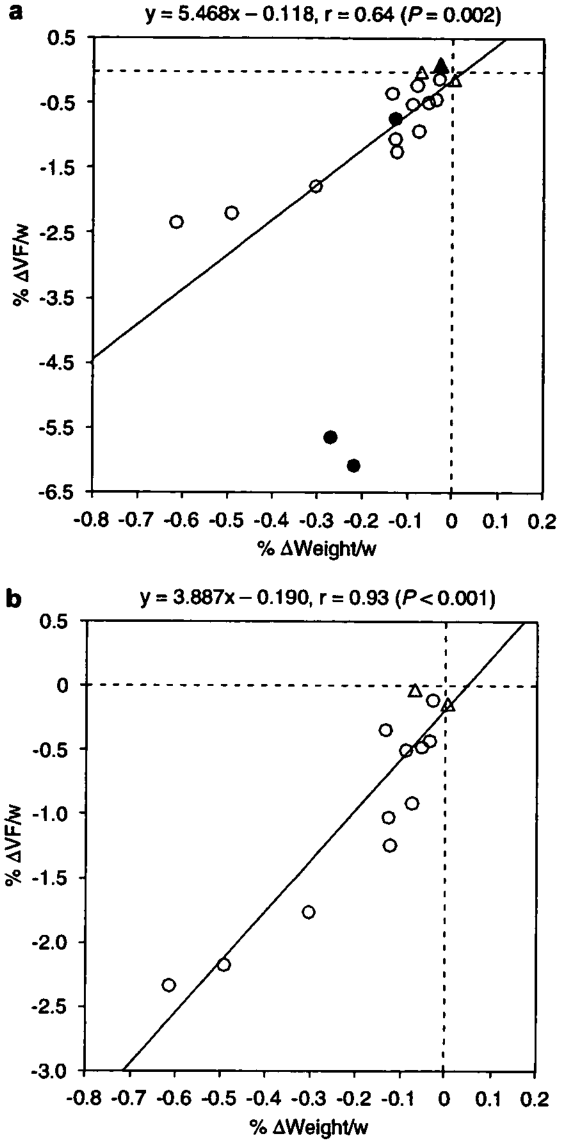

Figure 4 Relations between %ΔVF/w and %ΔWeight/w during interventions in the all selected groups (a) and after excluding the groups with metabolic-related disorder subjects (b). Abbreviations: %ΔVF/w, percentage of visceral fat change per week; %ΔWeight/w, percentage of weight change per week; *r*, Pearson's correlation coefficient weighted for the number of subjects in each group; ○, the no metabolic-related disorder group with a significant visceral fat reduction ($P < 0.05$); △, the no metabolic-related disorder group without a significant visceral fat reduction ($P < 0.05$); ●, the metabolic-related disorder group with a significant visceral fat reduction ($P < 0.05$); ▲, the metabolic-related disorder group without a significant visceral fat reduction ($P < 0.05$).

In the present study, a significant relationship between METs · h/w and %ΔVF was observed in women-only groups, with and without the metabolic-related disorder subjects, while there was no significant relationship in the men-only groups. The limited number of studies was insufficient to determine the influence of gender on the dose–response relationship. However, it is difficult to compare differences of the amount of visceral fat reduction by aerobic exercise between men and women, as women generally store a greater total fat mass relative to body weight than men.[46] Also, body fat distribution is different between men and women as men tend to have more central obesity than women.[47] Initial values of visceral fat could contribute to the amount of visceral fat lost during intervention. If these biases between men and women were excluded, that is, if the absolute amount of total and visceral fat were matched between men and women, then the relative obesity levels for each gender would be much different. It is likely that gender, as well as intervention duration, could be factors in the differences in rate of visceral fat reduction per week.

Relationship between visceral fat reduction and weight reduction

Weight reduction during interventions could be seen solely as the result of fat mass reduction, because fat-free mass reduction accounts for only a small part of weight reduction.[38] Visceral fat volume is about 10–20% of total fat volume[48,49] and reduction of the subcutaneous fat volume largely reflects weight reduction. In a limited number of selected studies, METs·h/w and %ΔWeight/w had a significant correlation in both the groups with and without metabolic-related disorders. Therefore, metabolic-related disorders, especially type 2 diabetes, may have a small impact on a dose-relation between weight loss and aerobic exercise during intervention compared to the amount of visceral fat reduction.

On the other hand, our results indicate a significant relationship between %ΔWeight/w and %ΔVF/w, especially in the subjects without metabolic-related disorders. We can say that %ΔVF/w corresponds to four to five times %ΔWeight/w when obese people practice aerobic exercise. However, previous studies suggest that visceral fat is used more quickly as an energy resource than subcutaneous fat during aerobic exercise-induced weight loss.[50] In our analysis, the intercept of the regression line between %ΔWeight/w and %ΔVF/w in the subjects without metabolic-related disorders was significantly different from zero. Although the trend showed that the more weight was lost, the more visceral fat was reduced, a significant reduction of visceral fat, which occupies less than 5% of body weight,[48,49] may also occur without a significant weight reduction with aerobic exercise. In fact, this phenomenon was reported by studies that examined whether or not visceral fat was reduced by aerobic exercise, if energy intake corresponding to the EE value by prescribed aerobic exercise was added to the baseline. Such an adjustment in the calculation did not lead to a significant weight reduction.[22,29] Generally, it is difficult for obese people to reduce weight largely by practicing exercise alone, compared to diet.[8] Therefore, exercise is inclined to be optional with a diet therapy for weight loss. However, even if insufficient weight loss does occurs, visceral fat could be reduced by doing aerobic exercise, a prescription supported by recent studies.[16,22] These results provide evidence of the usefulness of aerobic exercise for visceral fat reduction.

There are a number of limitations in the present study. The number of selected studies, especially those which measured EE for the prescribed exercises, were still insufficient for defining a clear aerobic exercise amount that resulted in significant visceral fat reduction. Additionally, the influence of several factors, such as metabolic-related disorders, gender and intervention duration, on visceral fat reduction remains unclear. Most of trials in the selected studies had applied brisk walking, light jogging and stationary ergometer, so whether or not other types of activities could lead to a similar result cannot be clarified from this study. Furthermore, while the present study investigated visceral fat reduction, studies with visceral fat gain should also be included in the analyses.

In conclusion, data collected from selected studies suggested that aerobic exercise as a weight loss intervention has a dose–response relationship with visceral fat reduction in obese subjects, excluding groups with metabolic-related disorders. Additionally, visceral fat reduction is significantly related to weight reduction during aerobic exercise intervention, although a significant visceral fat reduction may also occur without significant weight loss. Furthermore, for significant visceral fat reduction, at least 10 METs·h/w of aerobic exercise is required. However, since the number of selected studies was still insufficient, further studies are required.

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ORIGINAL ARTICLE

Interindividual variability in sleeping metabolic rate in Japanese subjects

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Introduction: Basal metabolic rate (BMR) or sleeping metabolic rate (SMR) is the largest component of total energy expenditure (EE). An accurate prediction of BMR or SMR is needed to accurately predict total EE or physical activity EE for each individual. However, large variability in BMR and SMR has been reported.
Objectives: This study was designed to develop prediction equations using body size measurements for the estimation of both SMR and BMR and to compare the prediction errors with those in previous reports.
Methods: We measured body size, height, weight and body composition (fat mass and fat-free mass) from skinfold thickness in adult Japanese men ($n=71$) and women ($n=66$). SMR was determined as the sum of EE during 8 h of sleep (SMR-8h) and minimum EE during 3 consecutive hours of sleep (SMR-3h) measured using two open-circuit indirect human calorimeters. BMR was determined using a human calorimeter or a mask and Douglas bag.
Results: The study population ranged widely in age. The SMR/BMR ratio was 1.01 ± 0.09 (range 0.82–1.42) for SMR-8h and 0.94 ± 0.07 (range 0.77–1.23) for SMR-3h. The prediction equations for SMR accounted for a 3–5% larger variance with 2–3% smaller standard error of estimate (SEE) than the prediction equations for BMR.
Discussion: SMR can be predicted more accurately than previously reported, which indicates that SMR interindividual variability is smaller than expected, at least for Japanese subjects. The prediction equations for SMR are preferable to those for BMR because the former exhibits a smaller prediction error than the latter.
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Keywords: sleeping metabolic rate; basal metabolic rate; prediction; variability; body size; Japanese

Introduction

There are three principal components of energy expenditure (EE) in humans: basal metabolic rate (BMR), thermic effect of food and EE of physical activity. The FAO/WHO/UNU expert panel (1985) adopted the principle of expressing the energy requirements of adults in terms of multiples of BMR. Thus, BMR is used to estimate 24-h EE and physical activity level (24-h EE divided by BMR).

Sleeping metabolic rate (SMR), similar to BMR, is approximately 60% of the total EE. Although both are measured in the supine position, SMR is measured during sleep whereas BMR is measured in the postabsorptive state when the subject is awake. They thus involve slightly different thermogenic processes. EE is lower during sleep than under BMR conditions (Garby *et al*., 1987; Goldberg *et al*., 1988; Seale and Conway, 1999; Zhang *et al*., 2002), probably due to the absence of arousal and maybe to less body movement. Moreover, EE gradually increases after awakening (Kashiwazaki, 1990). Therefore, SMR, not BMR, should be the minimum EE for humans. SMR may be measured more accurately than BMR as it is measured during sleep when there is no arousal. Also, SMR can be measured using equipment (e.g., a human calorimeter) that gives highly reproducible and accurate results (Murgatroyd *et al*., 1993).

Many equations have been developed to estimate BMR or SMR from body size measurements (Cunningham, 1991; Frankenfield *et al*., 2005), which can be helpful when actual metabolic measurements are not available. Their accuracy and applicability to specific ethnic groups must be considered. The body size of Japanese differs from that of other ethnicities (Popkin and Doak, 1998; WHO, 1998). Most

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equations currently available apply to Caucasians (Frankenfield *et al.*, 2005). Studies have found that they are not applicable to nonwhite groups (Liu *et al.*, 1995; Case *et al.*, 1997; Yamamura and Kashiwazaki, 2002).

We studied the association of SMR and BMR with body size and composition (anthropometry) in adult Japanese men and women who ranged widely in age. The purpose of this study was to develop simple-to-use prediction equations for both SMR and BMR and to compare the variability in prediction errors after adjustment for body size and composition with those found in previous studies.

Methods

Subjects

The data used for the current analysis were collected from different experimental studies that followed a similar methodology. All 137 apparently healthy Japanese subjects (71 male and 66 female subjects; $\geqslant 20$ years) residing in the Tokyo metropolitan area were volunteers approached through personal contact, internet communication or poster advertisement. None had diseases that might affect metabolic rates. The study protocol was explained in advance to the subjects, who were instructed to eat a normal diet and do normal, but not vigorous, physical activity beginning 1 day before monitoring.

All studies were carried out in the National Institute of Health and Nutrition (Tokyo). The study protocol was approved by the Ethics Committee of the National Institute of Health and Nutrition. All of the subjects signed an informed consent form.

Study protocol

The indirect human calorimeter (IHC) data for SMR and BMR were obtained from several studies conducted at the National Institute of Health and Nutrition in Japan. Subjects entered the IHC at 1800–1900 on the study day, had dinner at 1830 or 1900, went to bed at 2300 after sedentary activities and slept until 0700 the following morning. Each subject was provided a standardized dinner to meet EE during the chamber stay using predicted BMR and an assumed physical activity level of 1.5. Energy intake at dinner was set as a third of the total energy. BMR was measured in the supine position and in the postabsorptive state (about 12 h after the last meal).

Measurements

SMR was defined as the average EE of all EEs at 15-min intervals between 2300 and 0700 over an 8 h of sleep (SMR-8h) and the minimum EE during 3 consecutive hours of sleep (SMR-3h) (Schrauwen *et al.*, 1997; Westerterp-Plantenga *et al.*, 2002). Two open-circuit IHCs were used to evaluate SMR. Details of the IHC are shown elsewhere (Futami *et al.*, 2003). In brief, the two respiratory chambers were airtight rooms (20 000 and 15 000 l, respectively) containing a bed, desk, chair, TV, etc. The temperature and relative humidity in the room were controlled at 25°C and 55%, respectively. The O_2 and CO_2 concentrations of the air supply and exhaust were measured by mass spectrometry. For each experiment, a gas analyser (ARCO SYSTEM Inc., ARCO-1000A-CH, Kashiwa, Japan) was initially calibrated using a certified gas mixture and atmospheric air. The flow rate exhausted from the chamber was measured by a pneumotachograph (ARCO SYSTEM Inc., FLB1, Kashiwa, Japan). The flow meter was calibrated before each measurement, and the flow rate was fixed in both chambers. VO_2 and VCO_2 were determined from the flow rate exhausted from the chamber and the concentrations of the inlet and outlet air of the chamber, respectively (Futami *et al.*, 2003). The values of VO_2 and VCO_2 were expressed under standard temperature, pressure and dry air conditions. EE was estimated from VO_2 and VCO_2 using Weir's equation (Weir, 1949). The accuracy and precision of the IHC for measuring EE, as evaluated by the alcohol combustion test, were $99.2 \pm 0.7\%$ in 6 h and $99.2 \pm 3.0\%$ in 30 min, respectively.

BMR was determined in the postabsorptive state (12 h or more after the last meal) and in a supine position. The measurement was performed using a human calorimeter from 0715 to 0800, or using a mask and Douglas bag for 20 min with a minute of intermission. The detailed protocol is described in Yamamura *et al.* (2003). To examine whether slightly different conditions caused a significant difference in the observed BMR, analysis of covariance with BMR as the dependent variable and gender, age, stature and body weight as covariates was employed. No significant effect of the measurement conditions was observed.

Anthropometric measurements. Body weight was measured to the nearest 0.1 kg and height to the nearest 0.1 cm using a stadiometer. Measurements were performed in light clothing and underwear. The light clothing was weighed and subtracted from the total to obtain body weight with minimal clothing (underwear). Triceps, subscapular and umbilicus skinfold thicknesses were measured by two trained observers using a standardized protocol and a Holtain caliper (Holtain Ltd, Crosswell, Crymych, Dyfed, UK). There were no significant inter-observer differences in any of the measurements. BMI was calculated as weight (kg)/height (m^2).

Tahara's equations (2002) for Japanese adults were used to predict body density from the sum of skinfold thickness measurements, and the Brozek equation (1963) was used to estimate body fat percentage (% FAT) from the predicted body density.

Statistics. Results are presented as the mean ± standard deviation (s.d.). The relationship between SMR, BMR and body size and composition measurements was examined using Pearson's correlation. Age and sex were adjusted for in partial correlation analysis. Stepwise multiple regression analysis was done to examine the predictors of metabolic rate. Statistical significance was set at $P<0.05$ for all predictors. Gender was treated as a binomial variable (0 for male subjects, 1 for female subjects). The % difference in prediction error was calculated as the residual divided by the measured value for each subject. Statistical analyses were performed using SPSS for Windows (version 11.0; SPSS Inc., Chicago, IL, USA). Statistical significance was set at $P< 0.05$.

Results

The study population consisted of adult Japanese men ($n=71$) and women ($n=66$) of a wide range of ages (Table 1). The average height and weight of subjects in each age and gender group were similar to national standard heights and weights (The National Nutrition Survey in Japan, 2002). Although the age range was wide, variability in body size and composition was small.

BMR and SMR were highly correlated (Figure 1). The SMR/BMR ratio was 1.01±0.09 (range 0.82–1.42) for SMR-8h and 0.94±0.07 (range 0.77–1.23) for SMR-3h, which was not gender sensitive. On the other hand, the ratios (SMR-8h/BMR and SMR-3h/BMR) were weakly correlated with age ($r=0.38$ and 0.36, respectively). SMR-3h was significantly lower than SMR-8h and BMR, whereas SMR-8h was not significantly different from BMR. In most cases, SMR-3h was observed during the latter part of the sleep cycle (2300–0700), around 0300–0600. The phase of the menstrual cycle did not affect BMR and SMR in women (data not shown).

Metabolic rate was strongly correlated with body size and body composition irrespective of age and gender. Metabolic rate was positively correlated with body weight ($r=0.83$, 0.85 and 0.79 for SMR-8h, SMR-3h and BMR, respectively). The strongest correlation of metabolic rate was with fat-free mass ($r=0.85$, 0.87 and 0.79, for SMR-8h, SMR-3h and BMR, respectively) after adjustment for age and gender.

Table 1 Basic characteristics, body size, composition and metabolic rates

	Males (71) *Mean±s.d.*	*Females (66)* *Mean±s.d.*
Age (years)	36±16	37±16
Stature (cm)	170.5±7.1	159.1±5.6
Weight (kg)	68.3±11.5	54.0±9.2
BMI (kg/m^2)	23.4±3.1	21.4±3.3
Fat mass (kg)	12.9±6.4	14.2±5.2
Fat-free mass (kg)	55.3±7.4	39.8±5.1
SMR-8h (MJ/day)	6.376±0.749	4.929±0.607
SMR-3h (MJ/day)	5.954±0.736	4.552±0.548
BMR (MJ/day)	6.368±0.916	4.837±0.569

Abbreviations: BMI, body mass index; BMR, basal metabolic rate; s.d., standard deviation; SMR, sleeping metabolic rate.

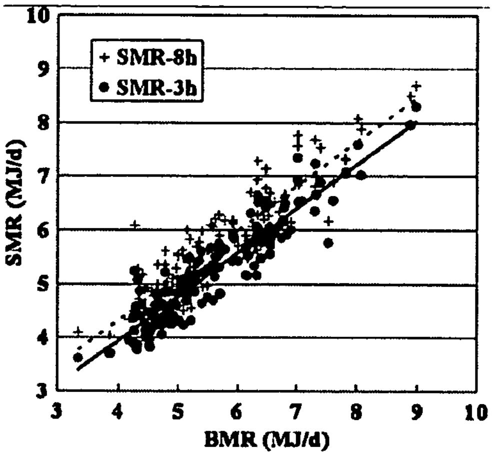

Figure 1 Relationship between SMR and BMR. Regression lines between SMR-8h (dashed line) or SMR-3h (straight line) and BMR.

Table 2 Stepwise regression of BMR, SMR-8h and SMR-3h with body size measurements

Outcome	*Predictors*	*Un std coefficients*		*Change in % R^2*	*SEE (MJ/day)*
		B	*Standard error*		
SMR-8h	Constant	1.2142	1.1912		
	Weight	0.0498***	0.0038	75.9	0.494
	Gender	−0.5590***	0.0967	8.2	0.402
	Stature	0.0146*	0.0071	1.1	0.389
	Age	−0.0046*	0.0021	0.4	0.385
	Total			85.6	
SMR-3h	Constant	0.1004	1.0439		0.000
	Weight	0.0469***	0.0033	74.9	0.456
	Gender	−0.4925***	0.0845	9.6	0.368
	Stature	0.0197**	0.0063	2.5	0.343
	Age	−0.0050**	0.0021	0.8	0.339
	Total			87.8	
BMR	(Constant)	0.1238	1.4054		0.000
	Weight	0.0481***	0.0046	65.4	0.619
	Stature	0.0234**	0.0084	11.8	0.510
	Age	−0.0138***	0.0025	2.9	0.485
	Gender	−0.5473***	0.1138	3.3	0.448
	Total			83.4	

Abbreviations: BMR, basal metabolic rate; SMR, sleeping metabolic rate; SEE, standard error of estimate; Un std coefficients, unstandardized coefficients. *$P<0.05$; **$P<0.01$; ***$P<0.001$.

A stepwise multiple regression analysis of predictors of metabolic rate (including height, weight, age and gender) revealed that weight was the strongest predictor of metabolic rate (Table 2). Age, gender and height were additional predictors. These models accounted for 85.6% of the variance in SMR-8h (prediction error 6.7%) and 87.8% of the variance in SMR-3h (prediction error 6.2%). Adjustment for the predictors reduced the variance from 0.996 MJ/day to 0.385 MJ/day (238–92 kcal/day) in SMR-8h and 0.958–0.339 MJ/day (229–81 kcal/day) in SMR-3h. Adjustment for all predictors accounted for 83.4% of the variance in BMR

Table 3 Stepwise regression of BMR, SMR-8h and SMR-3h with body composition measurements

Outcome	*Predictors*	*Un std coefficients*		*Change in % R^2*	*SEE (MJ/day)*
		B	*Standard error*		
SMR-8h	Constant	1.8175	0.3678		
	Fat-free mass	0.0812***	0.0054	86.3	0.368
	Fat mass	0.0213***	0.0067	0.9	0.360
	Gender	−0.2125*	0.1063	0.4	0.356
				87.6	
SMR-3h	Constant	0.8878	0.1372		
	Fat-free mass	0.0874***	0.0029	88.3	0.331
	Fat mass	0.0151**	0.0046	0.8	0.318
				89.1	
BMR	Constant	2.3958	0.5602		
	Fat-free mass	0.0787***	0.0079	82.2	0.460
	Age	−0.0109***	0.0029	0.6	0.452
	Fat mass	0.0268**	0.0088	0.5	0.448
	Gender	−0.3314*	0.1477	0.6	0.439
				84.0	

Abbreviations: BMR, basal metabolic rate; SMR, sleeping metabolic rate; SEE, standard error of estimate; Un std coefficients, unstandardized coefficients. *$P<0.05$; **$P<0.01$; ***$P<0.001$.

(prediction error 7.3%) and reduced the variance from 1.084 MJ/day to 0.448 MJ/day (259–107 kcal/day).

Fat-free mass was the strongest predictor of metabolic rate in stepwise multiple regression analysis using metabolic rate as the independent variable and fat mass, fat-free mass, age and gender as the dependent variables (Table 3). Fat-free mass, fat mass and gender accounted for 86.7% of the total variation in SMR-8h (difference for prediction error 6.2%). Adjustment for the predictors reduced variance in SMR-8h from 0.996 MJ/day to 0.356 MJ/day (238–85 kcal/day). For SMR-3h, fat-free mass and fat mass accounted for 89.1% of the variation (difference in prediction error 5.9%) and adjustment for the predictors reduced variance in SMR-3h from 0.958 to 0.318 MJ/day (229–76 kcal/day). Adjustment for fat-free mass, fat mass, age and gender predicted 84.0% of the variance in BMR (difference in prediction error 7.6%) and reduced the variance from 1.084 MJ/day to 0.439 MJ/day (259–105 kcal/day).

The mean difference between predicted BMR using FAO/WHO/UNU equations and observed BMR was +0.519±0.494 MJ/day (+0.565±0.556 MJ/day for male subjects and +0.469±0.414 MJ/day for female subjects).

Discussion

This study was performed to develop predictive equations for SMR-3h and SMR-8h that predict SMR with much lower prediction errors than previously reported (Tataranni and Ravussin, 1995; Weyer *et al.*, 1999; Nielsen *et al.*, 2000; Henry, 2005). The findings indicate that interindividual variability in SMR after adjustment for body size or body composition is much smaller than expected, at least in healthy Japanese adults.

BMR and SMR are measured in a similar manner, but BMR is slightly larger as SMR is measured only in part during sleep (SMR/BMR, 0.88–0.95) (Garby *et al.*, 1987; Goldberg *et al.*, 1988; Seale and Conway, 1999; Zhang *et al.*, 2002; Kumahara *et al.*, 2004). The SMR-3h/BMR ratio in this study was in good agreement with those previous values, whereas SMR-8h was found to be slightly higher than the BMR. In the first hour of sleep, the metabolic rate was higher than BMR by an average of 20%, probably due to sleeping status and diet-induced thermogenesis. In addition, the metabolic rate during periods when body movements were observed using a radar system was excluded from the SMR calculation in some of the previous studies. Thus, evaluation methods appear to affect the slight discrepancy of the ratio between studies. BMR is measured in the morning hours when heat production increases after awakening (Garby *et al.*, 1987) and causes gradual increases in resting EE (Kashiwazaki, 1990). BMR and SMR (although measured in a similar manner) thus might represent different thermogenic processes.

Metabolic rates can be predicted using equations that involve body size and composition measurements. Many prediction equations are available for estimating metabolic rates, but their applicability to other ethnic groups is uncertain (Hayter and Henry 1993; Frankenfield *et al.*, 2005). In the present study, FAO/WHO/UNU equations overestimated BMR by more than 0.45 MJ/day on average, with a prediction error comparable to previously published reports.

We developed two types of equations using stepwise regression to predict metabolic rates in adult Japanese subjects ranging widely in age. The first equation uses weight and height, which are simple body size measurements that can be easily obtained in clinical as well as epidemiological settings. In this equation, body weight accounted for 65–75% of the variation in metabolic rates. Age, gender and height were additional predictors. The second equation uses fat-free mass, which is a more valid predictor than body mass of resting metabolic rate (RMR) because it is associated with a much higher rate of resting EE (Elia, 1992). Sophisticated methods can be used to provide more insight into the metabolically active components of fat-free mass, such as the liver, heart and kidney, in relation to energy metabolism (Muller *et al.*, 2002), but their applicability to epidemiological studies is restricted. Anthropometry, a relatively simpler technique used to predict RMR, has an accuracy rate similar to that of more complicated techniques (Van der Ploeg *et al.*, 2001). In our equations, fat-free mass (measured using skinfold thickness) accounted for 84–89% of the variation in SMR, which is better than previously reported (Ravussin *et al.*, 1990; Toubro *et al.*, 1996; Weyer *et al.*, 1999). In addition, results for the BMR equations are in good agreement with those of others (Cunningham, 1991; Ravussin and Bogardus, 1989; Tataranni and Ravussin, 1995). After fat-free mass, fat mass predicted metabolic rate, but accounted for less than 1% of variation in SMR. The relationship of age and gender with metabolic rates disappeared after adjustment for fat mass and fat-free mass, except for SMR-8h. Similar results have been reported showing that the effect of age and gender on metabolic rates is mainly due to fat-free mass (Ravussin *et al.*, 1986; Astrup *et al.*, 1990; Cunningham, 1991; Nelson *et al.*, 1992) and fat mass (Dionne *et al.*, 1999).

Relatively smaller variations in body size and composition are observed in Japanese than in Caucasians or African Americans. Although the subjects varied widely in age (20–50 years), the variance (s.d.) in their weights were 11.5 kg (male subjects) and 9.2 kg (female subjects). These variations were much lower than reported in other studies. For example, although Weyer *et al.* (1999) worked with subjects with a smaller age range than in this study, the s.d. values of their weights were 25.9 kg (male subjects) and 26.3 kg (female subjects). A larger percentage of explained variance in metabolic rate calculated from an equation can be due to large variance in the body size of the study subjects. The percentage of explained variance thus does not necessarily indicate better prediction. Therefore, the two measures used to compare prediction errors were standard error of estimate (SEE) and percentage difference in the residuals. The SEE of both equations was lower than that reported by other studies, even those using sophisticated techniques.

The smaller prediction error indicates that variation in minimum metabolic rate (measured as SMR or BMR after adjusting for body size or composition) may be smaller than previously indicated. In general, the reported interindividual CV is about 8–13% (Shetty *et al.*, 1996, Muller *et al.*, 2004). For our SMR equations, the SEE was much lower than the SEE reported by Weyer *et al.* (1999), which was based on fat-free mass measured using sophisticated methods. In Weyer's equation, age, impaired glucose tolerance and waist-to-thigh ratio were additional predictors. In the equation, the SEE was 0.611 MJ/day (146 kcal/day) and fat-free mass accounted for 0.808 MJ/day (193 kcal/day) of the total 1.347 MJ/day (322 kcal/day) variance. Similarly, the new Oxford equations (Henry, 2005) for prediction of BMR in tropical regions have reported an SEE of 0.5–0.7 MJ/day in age group and gender-specific equations, which is higher than our SMR equations. Tataranni and Ravussin (1995) also reported a higher SEE (0.703 MJ/day (168 kcal/day)) in BMR prediction equations, with fat-free mass accounting for 0.268 MJ/day (64 kcal/day) of the total 1.318 MJ/day (315 kcal/day) variance. A similarly high SEE of 0.753 MJ/day (180 kcal/day) in men and 0.628 MJ/day (150 kcal/day) in women was reported by Nielsen *et al.* (2000), who developed equations that used dual-energy X-ray absorptiometry (DXA) measurements of fat-free mass. Bader *et al.* (2005) reported that s.d. of BMR adjusted for fat-free mass was from 0.81 to 0.92 MJ/day. Thus, most researchers have indicated larger interindividual variability in SMR or BMR compared to the SEE in the present study, particularly for SMR. Although the reasons are unclear, ethnicity may be an explanation. In addition, measurement of SMR using a human calorimeter is very accurate, particularly prolonged measurements (99.2±0.7% in 6 h), and may have contributed to the lower prediction error in our study.

One of the limitations of the present study was that a different method was used for measurement of BMR. This might partially explain why the SEE was greater for the BMR equation than the SMR equation. However, the study by Soares *et al.* (1989) showed that the energy outputs were comparable using different methods (e.g., whole-body indirect calorimetry) to measure metabolic rates. In the present study, the method used for measurement of BMR was also found to have no statistically significant effect on the metabolic rates and s.d. values for the difference between different BMR measurement groups were within 1%. Another limitation was the method of determining body composition using skinfold thicknesses. More sophisticated measures of body composition would have produced better results.

In conclusion, our equations, which use body size and body composition, are useful for estimating metabolic rates in the Japanese population. The prediction error of SMR was smaller than reported for BMR or SMR, which indicates small interindividual variability in SMR after adjustment for body size or body composition. When metabolic rates are needed to estimate 24 h EE or physical activity level, prediction equations of SMR (or, if necessary, the SMR/BMR ratio) should be used rather than BMR because SMR correlates very well with BMR and the SMR/BMR ratio is fairly constant.

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Evaluation of Low-Intensity Physical Activity by Triaxial Accelerometry

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Abstract

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Objective: To develop regression-based equations that estimate physical activity ratios [energy expenditure (EE) per minute/sleeping metabolic rate] for low-to-moderate intensity activities using total acceleration obtained by triaxial accelerometry.

Research Methods and Procedures: Twenty-one Japanese adults were fitted with a triaxial accelerometer while also in a whole-body human calorimeter for 22.5 hours. The protocol time was composed of sleep (8 hours), four structured activity periods totaling 4 hours (sitting, standing, housework, and walking on a treadmill at speeds of 71 and 95 m/min, 2 × 30 minutes for each activity), and residual time (10.5 hours). Acceleration data (milligausse) from the different periods and their relationship to physical activity ratio obtained from the human calorimeter allowed for the development of EE equations for each activity. The EE equations were validated on the residual times, and the percentage difference for the prediction errors was calculated as (predicted value − measured value)/measured value × 100.

Results: Using data from triaxial accelerations and the ratio of horizontal to vertical accelerations, there was relatively high accuracy in identifying the four different periods of activity. The predicted EE (882 ± 150 kcal/10.5 hours) was strongly correlated with the actual EE measured by human calorimetry (846 ± 146 kcal/10.5 hours, $r = 0.94$ $p < 0.01$), although the predicted EE was slightly higher than the measured EE.

Discussion: Triaxial accelerometry, when total, vertical, and horizontal accelerations are utilized, can effectively evaluate different types of activities and estimate EE for low-intensity physical activities associated with modern lifestyles.

Key words: accelerometry, energy expenditure, indirect calorimetry, physical activity

Introduction

Activity thermogenesis can be separated into two components: exercise-related activity thermogenesis and non-exercise activity thermogenesis (NEAT)[1] (1). NEAT, composed mainly of the energy expenditure (EE) related to low-to-moderate intensity daily physical activity (PA), is likely to have greater individual variation than exercise-related activity thermogenesis and body size-dependent basal metabolic rate. Levine et al. (2) used inclinometers and triaxial accelerometers to reveal that obese participants were seated for 164 min/d more than and were upright for 152 min/d less than lean participants. Moreover, if the obese subjects had the same posture allocation as the lean subjects, they would have expended an additional 352 kcal/d. Therefore, NEAT has been highlighted recently for helping to prevent weight gain. However, there are currently few effective methods to objectively and noninvasively evaluate the type or quantity of low-intensity PA in free-living conditions.

Triaxial accelerometers that are small in size and minimally intrusive to normal subject movement can be useful

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[1] Nonstandard abbreviations: NEAT, non-exercise activity thermogenesis; EE, energy expenditure; PA, physical activity; IHC, indirect human calorimeter; mG, milligausse; $\dot{V}O_2$, oxygen uptake; $\dot{V}CO_2$, carbon dioxide production; SD, standard deviation; PAR, PA ratio; SEE, standard error of estimation.

devices for predicting PA EE (3). Previous studies demonstrated higher correlation coefficients between counts obtained with triaxial accelerometry and the EE measured by chamber in comparison with counts from uniaxial accelerometry (4–6). However, these previous studies researched moderate-intensity PA such as slow and brisk walking and jogging, not low-intensity lifestyle activities. Moreover, Bassett et al. (7) found that uniaxial waist-mounted accelerometers overestimated the EE of walking and underestimated the EE of all other activities. Thus, we hypothesized that methods for estimating EE would be improved by the development of equations for each daily lifestyle PA.

To accurately predict EE using equations for each activity, it is necessary to classify each daily lifestyle PA using triaxial accelerometry. There are currently no published data concerning the identification of body posture in free-living conditions using triaxial accelerometry, especially light-to-moderate intensity PA with upper body movement such as sweeping, mopping, and window washing, which is a relatively high-energy cost during daily living (4,7). However, a previous study that evaluated standing balance using a triaxial accelerometer found that the accelerometer measurements, especially horizontal acceleration, were able to distinguish between the different test conditions and simultaneous force platform measurements (8). Concomitantly, it is speculated that household activities with upper body movement (e.g., cleaning and sweeping) may have larger horizontal acceleration than sitting and standing. We hypothesized that low-intensity PA in free-living conditions can be identified by using horizontal acceleration obtained from triaxial accelerometry.

Thus, the purpose of the present study was to develop regression-based equations that estimate EE from total acceleration, which was based on the defined thresholds of accelerations that can be used to delineate low-to-moderate intensity PA. Furthermore, we compared the ability to identify the type and quantity of the low-intensity PA and predicted EE using either triaxial acceleration or only vertical acceleration from a triaxial accelerometer.

Research Methods and Procedures

Subjects

Twenty-one Japanese adults (8 men and 13 women) living in the Tokyo metropolitan area were recruited for the study (Table 1). All subjects were adults (≥20 years) and were without any chronic diseases that could affect EE or daily PA. All subjects received a verbal and written description of the study and gave their informed consent to participate before testing. The study protocol was approved by the Ethical Committee of the National Institute of Health and Nutrition.

Table 1. Subject characteristics

	Men ($n = 8$)	**Women** ($n = 13$)
Age (yrs)	33 ± 15	31 ± 10
Standing height (cm)	171.2 ± 4.7	161.0 ± 5.3
Body weight (kg)	65.3 ± 4.1	55.8 ± 9.8
BMI (kg/m^2)	22.3 ± 2.0	21.5 ± 3.5
Fat (%)	13.2 ± 3.7	23.3 ± 8.4
Fat-free mass (kg)	52.0 ± 5.8	32.6 ± 5.4

Anthropometry

Body weight was measured on a digital balance to the nearest 0.1 kg, and height was measured on a stadiometer to the nearest 0.1 cm. BMI was calculated as the body weight in kilograms divided by the height in meters squared. Body composition was evaluated by the skinfold method at two skinfolds (triceps and subscapular) to the nearest 0.1 mm. The measurements were repeated until the difference between the two readings reached within 1 mm, and the mean value was used. Body density was assessed using the equations for Japanese (9), and the percentage of body fat was estimated using the equation of Brozek et al. (10). Body fat mass and the fat-free mass were calculated from body weight and percent of body fat.

Study Protocol

Subjects were fitted at the left hip with a triaxial accelerometer (AC-301, 51 × 77 × 15 mm, 87 grams; or AC-210, 48 × 67 × 16 mm, 57 grams; GMS, Tokyo, Japan) while also in the indirect human calorimeter (IHC) for 22.5 hours (from 6 PM to 4:30 PM the next day). The triaxial accelerometer obtained three-dimensional accelerations every 40 ms with a sensitivity of 2 milligausse (mG) and a band-pass filter of 0.3 to 100 Hz. The acceleration count was calculated as the average of the absolute values for acceleration in each direction for a given interval (1 minute). The subjects ate breakfast, lunch, and dinner at 8:15 AM, 12:30 PM, and 6:30 PM, respectively. They went to bed at 11 PM and were gently awakened at 7 AM. They were permitted to go to the toilet and were asked to return to bed immediately. The schedule included 8 sessions of standardized activities: 2 × 30 minutes sessions each of walking on a treadmill (95 m/min in the morning and 71 m/min in the afternoon), sitting, standing, and housework representative of typical activities in free-living conditions. Subjects were permitted to spend time freely in a sitting or standing position as long as posture was maintained and to rest periodically during the housework period. During the remaining time periods, subjects were only permitted to do light activities such as reading, writing, viewing television, dressing, and undressing. They were asked to refrain from sleeping and planned strenuous exercise except during the walking periods. Meals were given three times a day to provide the predicted basal metabolic rate (11) multiplied by the estimated PA level (1.5).

IHC

An open-circuit IHC was used to evaluate the EE of the four standardized activities totaling 4 hours, the sleeping time for 8 hours, and the residual time for 10.5 hours. Details of IHC have been reported previously (12,13). Briefly, the respiratory chamber was an air-tight room (20,000 liters), equipped with a bed, desk, chair, television with video deck, compact disc player, telephone, toilet, sink, and treadmill. The temperature and relative humidity in the room were controlled at 25 °C and 55%, respectively. The O_2 and CO_2 concentrations of the air supply and exhaust were measured by mass spectrometry. For each experiment, the gas analyzer (ARCO-1000A-CH; Arco System, Inc., Kashiwa, Japan) was initially calibrated using a certified gas mixture and atmospheric air. The flow rate exhausted from the chamber was measured by pneumotachograph (FLB1; Arco System, Inc.). The flow meter was calibrated before each measurement, and the flow rate was maintained at ~60 L/min. Oxygen uptake ($V\text{O}_2$) and carbon dioxide production ($V\text{CO}_2$) were determined by the flow rate of exhaust from the chamber and the concentrations of the inlet and outlet air of the chamber, respectively (12). Values of $V\text{O}_2$ and $V\text{CO}_2$ were expressed under the conditions of standard temperature and pressure and under dry conditions. EE was estimated from $V\text{O}_2$ and $V\text{CO}_2$ using Weir's equation (14). The accuracy and precision of our IHC for measuring EE as determined by the alcohol combustion test was 99.8 ± 0.5% [mean ± standard deviation (SD)] in 6 hours and 99.4 ± 3.1% in 30 minutes. Sleeping metabolic rate was defined as the average EE over 8 hours of sleep. The PA ratio (PAR) was calculated as the EE during sitting, standing, housework, or walking periods divided by the sleeping metabolic rate.

Identification of the Types for PA

Minute-to-minute anterior-posterior (x-axis), mediolateral (y-axis), vertical (z-axis), and total (synthesized triaxes) accelerations were obtained from a triaxial accelerometer during four standardized periods (sitting, standing, housework, and walking on a treadmill, 2 × 30 minutes each activity). Twenty-eight of the 30 minutes of each structured period, which excluded the first and last minute of each session, were used for the analysis (i.e., 28 data points × two replicate sessions × 21 subjects = 1176 data points for four types of activity). One of the acceleration data for walking on a treadmill at 71 m/min was excluded for the analysis because the subject walked at a different speed. In addition, because the hip-fitted triaxial accelerometer could shift horizontally while the subject was in the IHC, anterior-posterior (x-axis) and mediolateral (y-axis) were synthesized as horizontal acceleration for the analysis. Optimal thresholds for classifying total acceleration and the ratio of vertical to horizontal acceleration into sitting, standing, housework, and walking were determined by receiver operating characteristic analysis, which is the standard approach to evaluate the sensitivity and specificity of test results. We adopted the acceleration for the highest product of sensitivity and specificity as optimal thresholds for each binary classification. Furthermore, the threshold of each activity was defined using only vertical acceleration.

Prediction and Validation of EE

The total accelerations from the different periods and the data's relationship to PAR obtained from the IHC allowed for the development of EE equations for four types of activity (sitting, standing, housework, and walking). The averaged value of minute-to-minute total acceleration for each activity was used for the analysis (i.e., one data point × 21 subjects = 21 data points for four types of activity), which corresponded to the 30-minute averaged PAR data obtained by IHC. The validation of the EE equations was tested on the residual time (10.5 hours). Initially, the minute-to-minute total acceleration for the residual time was classified into four types of activity using thresholds we developed. Subsequently, the PAR for each minute was predicted using a selected equation among four types of regression-based equations and/or constant value. The estimated EE for 1 minute was calculated as follows: the predicted PAR × the measured sleeping metabolic rate, which is a highly stable value in IHC. The estimated EE per 1 minute for the residual time (i.e., 630 minutes = 10.5 hours) was totaled. We investigated the validity of the equations by comparing the EE measured by IHC with the EE estimated using the developed equations. Similarly, in cases that only utilized vertical acceleration, the development and validation of equations were conducted.

Supplementary Experiment

To supplement the data of housework and walking, additional protocols that tested these activities were conducted using the same triaxial accelerometer and a portable gas analyzer (Metamax3B; CORTEX, Leipzig, Germany). Japanese adults (5 men and 7 women) 21 to 38 years old were recruited for the study. The measurement time was 4 minutes for housework (pull up weeds and sweep up) and 5 minutes for walking (walk in place and walk slowly). The relationship between the acceleration data (mG) from the different periods and PAR was tested.

Statistics

Statistical analyses were performed using SPSS for Windows (version 10.0; SPSS, Inc., Chicago, IL). All results are

Table 2. Minute-to-minute acceleration data for each activity

Activity	Acceleration (mG)			Vertical/ Horizontal
	Total	Horizontal	Vertical	
Sit	6.1 ± 8.5	3.5 ± 6.7	0.7 ± 2.3	0.05 ± 0.17
Stand	19.0 ± 20.8	13.0 ± 16.2	4.4 ± 7.3	0.18 ± 0.21
Housework	52.8 ± 31.6	37.5 ± 23.6	18.7 ± 14.0	0.44 ± 0.22
Walk	436.3 ± 107.7	261.2 ± 62.7	281.1 ± 87.3	1.08 ± 0.27

mG, milligausse.

presented as the mean ± SD. The relationship between two variables was evaluated by Pearson's and Spearman's correlation. The percentage difference was calculated as follows: [(predicted value − measured value)/measured value] × 100. Agreement of EE between the predicted and measured values was further examined by plotting the difference in predicted values against the mean with limits of agreement (mean difference ± 2 SD of the differences, which gives an indication of the precision of the method), as suggested by Bland and Altman (15). Differences were regarded as significant when the probabilities were <0.05.

Results

The physical characteristics of the subjects are shown in Table 1. In general, the mean values were comparable with those obtained in the National Nutrition Survey, although a slightly larger variation was observed for body weight among women. Means and SD of total, horizontal, and vertical acceleration and the ratio of vertical-to-horizontal acceleration for structured activities are listed in Table 2. Only the vertical-to-horizontal acceleration ratio for walking exceeded 1.00. The resulting receiver operating characteristic curve characterized the performance of a binary classification by describing the trade-off between sensitivity and specificity over an entire range of possible thresholds (Table 3). The thresholds for sitting vs. standing and standing vs. housework were classified by total acceleration. Because it is possible to combine the total acceleration between housework and walking activities, the threshold for housework vs. walking was determined by the vertical-to-horizontal acceleration ratio and 30 mG or more of total acceleration. Sensitivities and specificities were >75% for each combination of two activities, except for specificity of sitting vs. standing. Moreover, when classifying PA by the

Table 3. Threshold, sensitivity, and specificity (%) for each activity

Activity	Acceleration (mG)		Sensitivity (%)	Specificity (%)	
	Total	Vertical/ horizontal			
When using tri-axes acceleration:					
Sit	<7	<0.750	75.3	64.6	Sit vs. stand
Stand	8 to 29	<0.750	78.9	76.3	Stand vs. housework
Housework	>30	<0.750	95.9	94.5	Housework vs. walk
Walk	>30	>0.751			
When using vertical acceleration:					
Sit	<7				Sit vs. stand
Stand	<7		82.4	73.5	Stand vs. housework
Housework	8 to 99		99.8	99.5	Housework vs. walk
Walk	>100				

mG, milligausse.

Table 4. Prediction equation for each activity

Activity	PAR		
	Model	R^2	SEE
When using tri-axes acceleration:			
Sit	1.3786		
Stand	0.0093AC (mG) + 1.3566	0.66	0.05
Housework	0.0123AC (mG) + 1.7208	0.45	0.18
Walk	0.0081AC (mG) + 0.9234	0.72	0.32
When using vertical acceleration			
Sit	0.0329AC (mG) + 1.3846	0.51	0.02
Stand			
Housework	0.0333AC (mG) + 1.7316	0.60	0.13
Walk	0.0092AC (mG) + 1.8443	0.64	0.29

PAR, physical activity ratio; SEE, standard error of the estimate; AC, acceleration count; mG, milligausse.

threshold in the present study, the percentage of each classified PA was calculated during standardized periods of sitting (sitting, 75.3%; standing, 22.2%; housework, 2.5%; and walking, 0%), standing (sitting, 35.4%; standing, 43.5%; housework, 20.6%; and walking, 0.5%), housework (sitting, 8.2%; standing, 15.5%; housework, 72.4%; and walking, 3.8%), and walking (sitting, 0%; standing, 0.4%; housework, 5.1%; and walking, 94.4%). The same thresholds were also obtained by discriminant analysis. In contrast, when using vertical acceleration only, standing, housework, and walking activities were identified as accurately as total acceleration (sensitivity and specificity: standing vs. housework, 82% and 74%; housework vs. walking, 99% and 99%); however, it was not possible to distinguish between sitting and standing positions.

The averaged values of PAR were 1.38 ± 0.07 for sitting, 1.54 ± 0.18 for standing, 2.39 ± 0.27 for housework, and 4.34 ± 0.84 for walking, which corresponded to total acceleration values of 7.0 ± 2.9, 19.5 ± 14.7, 54.2 ± 14.6, and 426.0 ± 95.3 mG, respectively. Significant simple correlations were observed between PAR obtained by IHC and total acceleration obtained by triaxial accelerometry for standing, housework, and walking [$R^2 = 0.45$ to 0.72, $p < 0.01$, standard error of estimation (SEE) = 0.05 to 0.32] (Table 4, Figure 1A). Because PAR for sitting was not associated with total acceleration, the averaged value of PAR (i.e., 1.3786) was used for predicting EE. Thresholds between the activities and three equations, or a constant value, for each kind of activity to predict EE were applied to the residual time for validation. There was a strong correlation between the measured and predicted EE ($r = 0.94$, $p < 0.01$) (Figure 2), although the predicted EE (882 ± 150 kcal/10.5 hours) was slightly higher than the EE measured by IHC (846 ± 146 kcal/10.5 hours; 4.4 ± 6.2% difference) (Figure 3). The same analyses were also performed using only vertical acceleration. Three EE equations (1, sitting and standing; 2, housework; 3, walking) were developed using only vertical acceleration ($R^2 = 0.51$ to 0.64, $p < 0.01$, SEE = 0.02 to 0.29) (Table 4) but overestimated EE ($p < 0.01$) (981 ± 181 kcal/10.5 hours, 16.0 ± 10.0% difference).

In the supplemental experiment, the average values of PAR and total acceleration were, respectively, 3.22 and 91.8 mG in men ($n = 5$), and 3.12 and 85.3 mG in women ($n = 7$) for pulling up weeds and 3.12 and 106.4 mG in men and 3.16 and 117.6 mG in women for sweeping up, which were categorized as housework in our study (Figure 1B, open triangle). Similarly, the PAR and total acceleration were, respectively, 2.90 and 170.2 mG in men, and 2.84 and 188.2 mG in women for walking in place and 3.21 and 202.1 mG in men and 2.84 and 218.1 mG in women for walking slowly, which were categorized as walking (Figure 1B, closed rhombus).

Discussion

The major finding of this study is that we can accurately identify four different periods of activity (i.e., sitting, standing, housework, and walking) using total acceleration and the vertical-to-horizontal acceleration ratio obtained from a triaxial accelerometer under close-to-normal living conditions. When we used vertical accelerations only, it was not possible to distinguish between sitting and standing positions. In addition, the sensitivity and specificity between housework and walking using the vertical-to-horizontal acceleration ratio, which was our original method, was over 90%. A recent study found that the time allocated to sitting and standing was closely related to weight gain (2). Moreover, PA with upper body movement such as housework has a relatively high energy cost during daily living (4,7).