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ORIGINAL COMMUNICATION

Lower resting metabolic rate in the elderly may not be entirely due to changes in body composition

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Objective: To investigate whether or not the lower resting metabolic rate (RMR) in the elderly is entirely due to changes in body composition.
Design: Cross-sectional data of 132 female (age 69.9 ± 5.5 y, body mass index (BMI) 26.5 ± 4.0 kg/m^2) and 84 male (age 68.9 ± 5.1 y, BMI 26.1 ± 2.8 kg/m^2) participants of the longitudinal study on nutrition and health status in an aging population of Giessen, Germany, as well as that of 159 young women (age 24.8 ± 3.0 y, BMI 21.1 ± 2.5 kg/m^2) and 67 young men (age 26.8 ± 3.4 y, BMI 23.3 ± 2.4 kg/m^2) were analysed. RMR was measured by indirect calorimetry after an overnight fast and body composition was estimated by bioelectrical impedance analysis and predictive equations from the literature. Analysis of covariance was used to adjust RMR for body composition, body fat distribution and smoking habits. Additionally, RMR that is to be expected theoretically, was calculated on the basis of the subjects' body composition and the specific metabolic rate of the different organs and was compared to measured RMR.
Results: Compared to young subjects adjusted RMR was significantly lower in elderly women (5432 ± 82 *vs* 5809 ± 70 kJ/day, $P<0.01$) and men (6971 ± 99 *vs* 7558 ± 121 kJ/day, $P<0.001$). In both elderly women and men, measured RMR was markedly lower than calculated RMR (−625 ± 404, −515 ± 570 kJ/day). By contrast, measured and calculated RMR were nearly the same in young men (159 ± 612 kJ/day); in young women the difference between measured and calculated RMR was only −300 ± 457 kJ/day. In both sexes, these differences are significantly larger in the elderly when compared to young adults.
Conclusion: These results support the point of view that the decline in RMR with advancing age cannot be totally due to changes in body composition.
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Introduction

From several studies it is well known that resting metabolic rate (RMR) declines with advancing age (Keys *et al*, 1973; Robinson *et al*, 1975; Tzankoff & Norris, 1978). Aging is also associated with a decrease in fat-free mass (FFM), which is the main determinant of RMR (Steen *et al*, 1979; Reed *et al*, 1991; Baumgartner *et al*, 1995; Suominen, 1997). At present, it is unclear whether the decrease in RMR is entirely a consequence of this age-dependent decrease in FFM or whether it is additionally due to a decline in metabolic rate per unit of tissue mass. This question was addressed already in several studies; however, the results are still inconsistent. While some authors could not find significant differences between RMR of young and elderly subjects after adjustment for FFM (Shock *et al*, 1963; Keys *et al*, 1973; Tzankoff & Norris, 1977; Poehlman *et al*, 1993a), other studies showed that RMR in elderly subjects was significantly lower in comparison to young adults even after correcting for body composition (Fukagawa *et al*, 1990; Vaughan *et al*, 1991; Visser *et al*, 1995; Klausen *et al*, 1997; Piers *et al*, 1998). The latter results indicate that besides changes in body composition increasing age might also be associated with a decrease in metabolic rate per unit of tissue mass.

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As FFM consists of numerous tissues and organs, each with a specific rate of metabolic activity, changes in the proportion of these tissues on FFM with age might explain the lower RMR in elderly subjects (Elia, 1992; Gallagher *et al*, 2000). One approach to investigate this question is to calculate RMR on the basis of individual tissue masses and their specific metabolic rates and to compare calculated RMR to RMR assessed by indirect calorimetry (Gallagher *et al*, 1998). Gallagher *et al* (2000) employed this approach of calculated and measured RMR in a small sample of seven elderly women and six elderly men. Calculated RMR was determined from measured tissue and organ masses and their specific metabolic rate using the data of Elia (1992). In both elderly women and men, measured RMR was significantly lower than calculated RMR. These data from Gallagher *et al* (2000) suggest that the decline of RMR with advancing age cannot be explained totally by changes in body composition. Bosy-Westphal *et al* (2003) measured RMR in 26 young and 26 elderly subjects and also obtained detailed body composition analysis. In contrast to the results from Gallagher *et al* (2000), in this study no differences between measured and calculated RMR were reported in young and elderly subjects, respectively.

In summary, the studies so far indicate that any contribution to the decrease in RMR with age not related to changes in body mass probably is rather small. We hypothesize therefore that the conflicting results could be due to the relatively small numbers of subjects in some of the studies and partly also due to different methodological procedures employed. Possibly confounding factors not considered in former studies such as smoking habits, fat distribution or physical activity could have also masked age-dependent effects on RMR not related to changes in body composition. The purpose of this study therefore was to compare RMR in elderly subjects with RMR in young adults with special consideration of body composition by using two different statistical approaches in a relatively large group of subjects.

Subjects and methods

Subjects

Subjects were participants of the longitudinal study on an aging population of Giessen, Germany (GISELA) and of the Giessen study on health and nutrition of young adults (GEJE), respectively. The GISELA study is a prospective cohort study, in which the nutrition and health status of elderly citizens in Giessen have been observed at annual and biannual intervals since 1994. For enrolment study participants had to be at least 60 y of age, physically mobile and available around Giessen on a long-term basis. Subjects were recruited by physicians, notices, senior citizens' meetings, advertisements in local newspapers and by recruitment through subjects who had already been participants. The GEJE study was designed as a control study to the GISELA study, and included subjects between 20 and 35 y of age. The young adults were recruited by notices, at seminars and lectures at the Justus-Liebig-University, Giessen, and by recruitment through study participants.

All investigations took place in the Institute of Nutritional Science in Giessen, Germany, from June to November between 0600 and 1100 after an overnight fast. After subjects were familiarized with the experimental procedure, a written informed consent was obtained from each study participant. The study protocol was approved by the Ethical Committee of the faculty of medicine at the Justus-Liebig- University, Giessen, Germany.

The present report includes cross-sectional data from the GISELA study obtained in 1998 and data from the GEJE study obtained in 1997 and 1999. A total of 43 subjects with incomplete data on RMR and body composition as well as 143 subjects who suffered from hypothyroidism, hyperthyroidism, edema, or took thyroid hormones or diuretics were excluded. Data of 159 young and 132 elderly women as well as 67 young and 84 elderly men remained for further analysis.

Resting metabolic rate

RMR was measured by indirect calorimetry using a Deltatrac metabolic monitor (Hoyer, Bremen, Germany). Oxygen consumption and carbon dioxide production were measured every minute for 25 to 35 min by respiratory gas analysis using an open-circuit ventilated-canopy measurement system. The subjects were in a supine position and in a thermoneutral environment. Furthermore, they were instructed to relax and avoid sleeping during measurements. The Deltatrac was calibrated before each measurement using standard oxygen and carbon dioxide gases. Before measurements were started, subjects were allowed to acclimatize appropriately. Data collected during the initial 10 min of the measurements were discarded. RMR was calculated using Weir's (1949) equation. Repeatability of RMR measurements was determined by five measurements on five consecutive days. In our laboratory, the mean coefficient of variation for measured RMR was 1.05%.

In addition, RMR that is to be expected theoretically ($RMR_{calculated}$) was calculated on the basis of six organ masses (brain, heart, liver, kidneys, skeletal muscle, fat mass) and residual FFM and the specific metabolic rate of the respective tissues using the data of Elia (1992) ($RMR_{calculated}$ (kJ/day) $= 1004 \times$ brain mass (kg) $+ 1841 \times$ heart mass (kg) $+ 837 \times$ liver mass (kg) $+ 1841 \times$ kidney mass (kg) $+ 54 \times$ skeletal muscle mass (kg) $+ 50 \times$ residual mass (kg) $+ 19 \times$ fat mass (kg)).

Anthropometric data and body composition

Standing height was determined by a height measurement device integrated in a calibrated digital scale (SECA, Vogel & Halke, Frankfurt, Germany) to the nearest 0.5 cm with subjects in standing position without shoes. Body weight was measured with the same scale to the nearest 0.1 kg after

shoes, coats and sweaters had been removed. From the measured weight, 0.5 to 1.0 kg was subtracted depending on the estimated weight of the remaining clothes immediately after each measurement. Body mass index (BMI) was calculated from body weight and height (kg/m^2). Waist-to-hip-ratio (WHR) was used as a marker for body fat distribution. Waist and hip circumferences were measured with a tape to the nearest 1.0 cm in upright position. Waist circumference was assessed at the smallest circumference between the lower rib and the iliac crest. Hip circumference was measured at the widest circumference over the greater trochanter. FFM and fat mass (FM) were assessed by use of bioelectrical impedance analysis (BIA). We used a body impedance analyser at a frequency of 50 kHz (Akern-RJL BIA 101/S, Data Input, Frankfurt, Germany) with the subjects in a supine position according to the manufacturer's instruction. Coefficient of variation for measured body impedance in our laboratory was 1.15 %. FFM and FM were calculated by applying the equation from Deurenberg *et al* (1991) derived from a cross-validation study (Akern-RJL BIA 101 *vs* underwater weighing). The equation was developed from data of 661 subjects between 16 and 83 years of age and considers height, weight, age and sex. Weights of brain, heart, liver and kidneys were calculated by the sex-specific regression equations according to Garby *et al* (1993) including body weight, body height and age. These equations are based upon 1598 autopsied Danish adults ($\geq$16 years of age), who prior to death were healthy or apparently healthy. Skeletal muscle mass was calculated from the data of FFM according to Forbes (1987) (skeletal muscle mass (kg) = 0.49 × FFM (kg)). Residual FFM was defined as the difference between FFM and the sum of the brain, heart, liver, kidney and skeletal muscle mass.

Subjects' characteristics

Subjects were asked if they were current smokers and were requested to refrain from smoking on the day of the investigation. Further information on age, diseases and medication of the study participants was obtained by a questionnaire. Physical activity level (PAL) was derived from RMR measurements and physical activity records as described in detail elsewhere (Krems *et al*, 2004). Energy expenditure of the different activities was calculated using multipliers for RMR according to the WHO (1985).

Statistical methods

Statistical analyses were carried out with the SPSS/PC Statistical Package version 9.0 (SPSS Inc, Chicago, USA). Data were checked concerning normal distribution by Kolmogorow–Smirnow test. Values are given as mean and standard deviation (s.d.). Differences in anthropometric data, body composition, physical activity and energy expenditure between the two age groups were examined by using Student's unpaired *t*-test. Comparison of smoking status between age groups was performed by using χ^2 test. Stepwise multiple linear regression analyses with RMR as the dependent variable and FFM, FM, WHR, PAL and smoking status as independent variables were used to examine potential predictors of RMR. Regression equations are presented together with probability (*P*), coefficient of multiple correlation (*R*), R^2, and standard error of the estimate (s.e.e.). Analysis of covariance was used to adjust RMR for body composition, body fat distribution and smoking habits. Results were considered statistically significant if *P*-values were less than 0.05.

Results

Subjects' characteristics are presented in Table 1. Elderly women had a significantly higher body weight than young women, whereas body weight of young and elderly men was not different. Body height was significantly lower and BMI and WHR were significantly higher in elderly relative to young subjects. Elderly women had a significantly higher PAL than young women, whereas elderly men had a significantly lower PAL than young men. More young women and men reported being current smokers than elderly women and men. Elderly subjects had significantly lower FFM and significantly higher FM than young subjects. The calculated sum of the brain, heart, liver and kidney masses as well as skeletal muscle mass were significantly lower in the elderly compared to young subjects (Table 2). Measured RMR was also significantly lower in both elderly women and men when compared to respective young subjects (Table 4).

Individual RMR *vs* FFM in young and elderly women and men are presented in Figure 1. Results of multiple linear regression analysis of RMR for each age and gender group are

Table 1 Characteristics of the subjects (mean ± s.d.)

	Women		*Men*	
	Young (n = *159*)	*Elderly* (n = *132*)	*Young* (n = *67*)	*Elderly* (n = *84*)
Age (y)	24.8 ± 3.0	69.9 ± 5.5*	26.8 ± 3.4	68.9 ± 5.1*
Body weight (kg)	59.9 ± 8.8	68.1 ± 11.7*	77.0 ± 9.6	77.7 ± 9.7
Body height (cm)	168.4 ± 6.0	160.2 ± 5.5*	181.8 ± 7.5	172.6 ± 6.6*
BMI (kg/m^2)	21.1 ± 2.5	26.5 ± 4.0*	23.3 ± 2.4	26.1 ± 2.8*
Fat-free mass (kg)	42.9 ± 4.7	37.5 ± 5.5*	61.4 ± 6.2	52.6 ± 5.2*
Fat mass (kg)	17.0 ± 4.8	30.6 ± 6.9*	15.6 ± 5.1	25.2 ± 5.4*
Fat mass (%)	28.0 ± 4.1	44.7 ± 3.4*	19.9 ± 4.6	32.1 ± 3.7*
WHR	0.70 ± 0.04	0.84 ± 0.07*	0.82 ± 0.05	0.93 ± 0.05*
PAL	1.64 ± 0.13	1.69 ± 0.14*	1.70 ± 0.15	1.66 ± 0.15**
Current smokers (%)	27.0	6.1*	43.3	11.9*

Significant difference between young and elderly subjects: *$P<0.001$; **$P<0.05$.
WHR = waist-to-hip ratio, PAL = physical activity level.

Table 2 Calculated organ masses of the subjects (mean ± s.d.)

	Women		*Men*	
	Young (n = *159*)	*Elderly* (n = *132*)	*Young* (n = *67*)	*Elderly* (n = *84*)
Brain mass (kg)	1.36 ± 0.02	1.28 ± 0.03*	1.55 ± 0.03	1.44 ± 0.03*
Heart mass (kg)	0.28 ± 0.02	0.36 ± 0.03*	0.40 ± 0.04	0.46 ± 0.04*
Liver mass (kg)	1.60 ± 0.15	1.57 ± 0.18	1.93 ± 0.17	1.74 ± 0.17*
Kidney masses (kg)	0.27 ± 0.02	0.25 ± 0.02*	0.28 ± 0.02	0.25 ± 0.02*
Sum of the brain, heart, liver and kidney mass (kg)	3.51 ± 0.21	3.46 ± 0.25**	4.15 ± 0.25	3.89 ± 0.25*
Skeletal muscle mass (kg)	21.0 ± 2.3	18.4 ± 2.7*	30.1 ± 3.0	25.8 ± 2.6*
Residual FFM (kg)	18.4 ± 2.2	15.6 ± 2.6*	27.1 ± 2.9	22.9 ± 2.4*

Significant difference between young and elderly subjects: *$P<0.001$; **$P<0.05$.

shown in Table 3. In all four subject groups FFM proved to be the main factor and explained between 33 and 64% of the variance in RMR. In young women, 3% of the variance in RMR could be additionally explained by WHR. In elderly women, WHR and FM accounted for 3 and 2%, respectively, of the variance in RMR. In young men, other factors apart from the influence of FFM did not show any significant effects on RMR. In elderly men, in addition to FFM, 5 and 8% of the variability in RMR were explained by FM and smoking status. In none of the study groups, was PAL an additional significant predictor of RMR.

Based on these results, RMR was adjusted for FFM, FM, WHR and smoking status by analysis of covariance. Mean adjusted RMR was significantly lower by 377 kJ/day in the elderly women and by 587 kJ/day in the elderly men when compared to respective young subjects (5432 ± 82 *vs* 5809 ± 70, $P<0.01$ and 6971 ± 99 *vs* 7558 ± 122, $P<0.01$).

In Table 4, mean values for calculated RMR and the differences between measured and calculated RMR for all study groups are presented. Measured and calculated RMR are nearly the same in the young men. In all other groups measured RMR is lower than the calculated one. In both sexes, these differences are significantly larger in the elderly when compared to young adults.

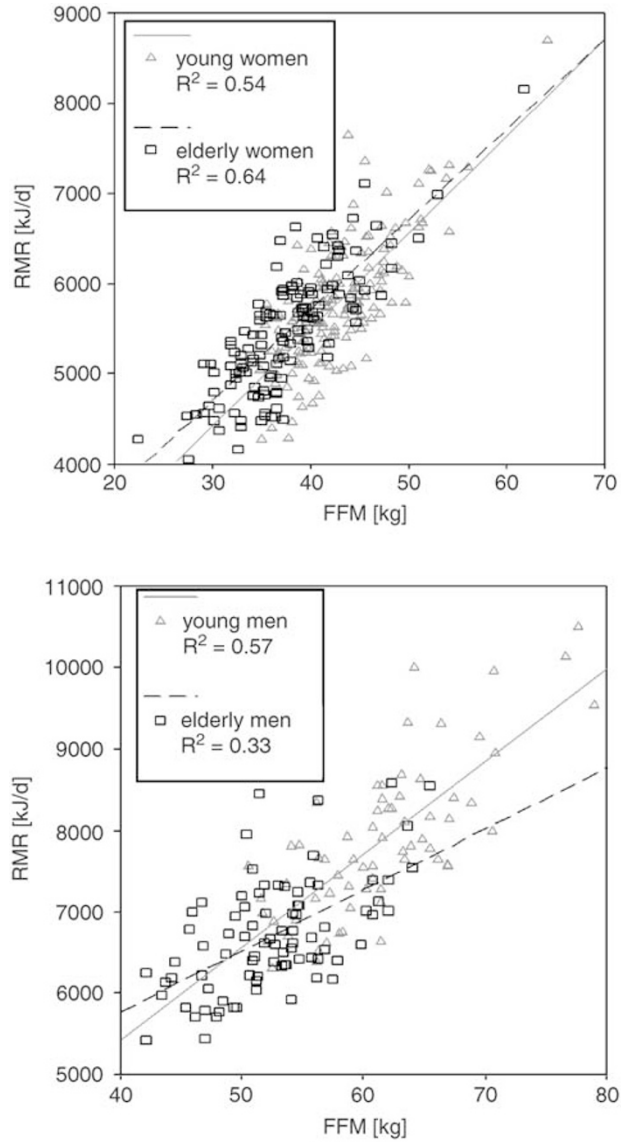

Figure 1 Correlation between RMR and FFM in young and elderly women and men.

Discussion

The goal of this study was to contribute to the question of whether or not the difference in RMR between young and elderly subjects is entirely due to differences in body composition. As can be concluded from several studies available so far, other age-related changes may contribute to the lower RMR in the elderly (Fukagawa *et al*, 1990; Vaughan *et al*, 1991; Visser *et al*, 1995; Klausen *et al*, 1997; Piers *et al*, 1998). However, the influence of these factors is rather small and a sufficient large number of subjects is required to detect these effects. Thus, the main advantage of this investigation is the relative large number of subjects included. Furthermore, we used two different statistical procedures for appropriate consideration of body composition and in order to test whether our results are robust.

First of all, we examined the potential determinants of RMR. As expected, in all study groups, most of the variance

Table 3 Results of stepwise multiple linear regression analysis of RMR considering FFM, FM, WHR, physical activity level and smoking status in women and men

		P	R	R^2	*s.e.e.*
Young women ($n=155$)	RMR = 1221 + 106.9 FFM	0.000	0.74	0.54	462
	RMR = −462 + 103.3 FFM + 2615 WHR	0.000	0.75	0.57	450
Elderly women ($n=129$)	RMR = 1700 + 100.3 FFM	0.000	0.8	0.64	411
	RMR = 356 + 95.0 FFM + 2615 WHR	0.000	0.82	0.67	369
	RMR = 731 + 76.3 FFM + 1491 WHR + 19.8 FM	0.000	0.83	0.69	389
Young men ($n=66$)	RMR = 873 + 114.0 FFM	0.000	0.75	0.57	620
Elderly men ($n=84$)	RMR = 2786 + 74.8 FFM	0.000	0.57	0.33	566
	RMR = 3182 + 48.9 FFM + 38.5 FM	0.000	0.62	0.38	547
	RMR = 2785 + 53.2 FFM + 42.3 FM + 614 SS	0.000	0.68	0.46	512

RMR = resting metabolic rate (kJ/day), FFM = fat-free mass (kg), WHR = waist-to-hip ratio, FM = fat mass (kg), SS = smoking status (nonsmokers = 0, smokers = 1).

Table 4 Measured and calculated RMR (kJ/day) in young and elderly subjects (mean ± s.d.)

	Women		*Men*	
	Young (n = *159*)	*Elderly* (n = *132*)	*Young* (n = *67*)	*Elderly* (n = *84*)
$RMR_{measured}$	5809 ± 680	5455 ± 685*	7867 ± 936	6720 ± 686*
$RMR_{calculated}$	6109 ± 519	6081 ± 639	7708 ± 630	7235 ± 602*
Difference ($RMR_{measured} - RMR_{calculated}$)	−300 ± 457	−625 ± 404*	159 ± 612	−515 ± 570*

Significant difference between young and elderly subjects: *$P<0.001$; $RMR_{measured}$ = measured resting metabolic rate (kJ/day), $RMR_{calculated}$ = calculated resting metabolic rate (kJ/day).

in RMR could be attributed to FFM. The other factors like FM, WHR and smoking habits partly also explained a small fraction of the variability of RMR (2 to 8%) in the various groups. The influence of FM on RMR usually is rather small and therefore not always detected or considered. It can be of significance, however, with an increasing FM of subjects under investigation like in our elderly subjects. The same applies for WHR, which in addition to FM is an independent predictor of RMR due to a higher metabolic activity of visceral adipose tissue compared to FM located in the gluteal-femoral region (Arner, 1995; Jones *et al*, 1996; Hoffstedt *et al*, 1997). As elderly subjects usually have more FM and a higher WHR than young adults, it is of importance to consider both FM and WHR when studying age effects on RMR. With regard to smoking, it is well known that smoking directly leads to an increase in RMR. Results for chronic influences of smoking on RMR, however, are contradictory. Hofstetter *et al* (1986) and Warwick and Busby (1993) showed that smoking of many cigarettes spread over the whole day increases energy expenditure for several hours because of an additive effect. This could be the reason that in our study, in addition to body composition smoking status was a significant predictor of RMR only in the elderly men as they were smoking more cigarettes per day than subjects of the other study groups (data not shown). However, since biochemical measurements of smoking status were not used in this study, it is nevertheless possible that some of our study participants smoked before RMR measurements. Physical activity was shown to influence changes in RMR associated with aging. Van Pelt *et al* (1997) could not observe an age-related decline in RMR in women who regularly perform endurance exercise. This was supported by the fact that elderly women who perform endurance exercise on a regular basis demonstrated levels of RMR adjusted for FFM and FM by analysis of covariance not different from young adult endurance athletes, whereas a significantly lower adjusted RMR was observed in elderly compared to young sedentary women. These results are consistent with a previous investigation by Poehlman *et al* (1991) in men. We therefore considered physical activity in our study. In comparison to the subjects investigated by Van Pelt *et al* (1997), subjects in our study on average were neither sedentary nor especially active but showed moderate PALs. Despite the significant differences we observed in PAL between young and elderly subjects, these were very small (elderly *vs* younger women: 1.69 *vs* 1.64; elderly *vs* younger men: 1.66 *vs* 1.70) and PAL was not a significant predictor of RMR in our subjects.

The influence of FM, body fat distribution, PAL and smoking on RMR has been discussed in detail elsewhere (Hofstetter *et al*, 1986; Weststrate *et al*, 1990; Moffat & Owens, 1991; Leenen *et al*, 1992; Nelson *et al*, 1992; Svendsen *et al*, 1993; Pannemans & Westerterp, 1995; Ryan *et al*, 1996; Withers *et al*, 1998; Nielsen *et al*, 2000; Kimm *et al*, 2001; Lührmann *et al*, 2001).

Next, we examined by two different statistical procedures whether the lower RMR of the elderly subjects is

independent of changes in body composition when compared to RMR of the young adults. In our first approach, we used analysis of covariance including FFM, FM, WHR and smoking habits as covariates. This analysis revealed that in the elderly women and men, RMR was significantly lower by an average of 377 kJ/day and by 587 kJ/day when compared to respective young subjects, irrespective of differences in body composition based on the traditional two-compartment model approach (FFM and FM) and smoking habits. Our findings are in accordance with those of several other studies using analysis of covariance (Fukagawa *et al*, 1990; Vaughan *et al*, 1991; Pannemans & Westerterp, 1995; Poehlman & Toth, 1995; Visser *et al*, 1995). Piers *et al* (1998) determined body composition with dual energy X-ray absorptiometry in 38 young and 24 elderly subjects and used a model incorporating four tissue compartments: fat, bone mineral, appendicular lean tissue mass and nonappendicular lean tissue mass. In the elderly, RMR adjusted for body composition was significantly lower by 644 kJ/day compared to young subjects. This difference is remarkably similar to our results. The authors concluded that the age-related decline in RMR is partly explained by a reduction in the quantity as well as the metabolic activity of lean tissue components.

Besides the decline in FFM, age-related changes in its composition, especially in relative masses of metabolically active organs like the heart, liver, kidneys or brain and of metabolically less active tissues like muscle, bone or skin could also be responsible for the decline in RMR during aging. This was discussed in some recent studies (Gallagher *et al*, 2000; Bosy-Westphal *et al*, 2003). In our second approach, we therefore considered the detailed composition of the FFM and investigated whether age-related differences in the proportions of the miscellaneous organ masses on FFM could account for the lower RMR in elderly subjects. Both in women and men, differences between measured RMR and RMR calculated on the basis of the detailed body composition were significantly larger in the elderly compared to young subjects. This indicates that the lower RMR in elderly subjects cannot be entirely due to age-related differences in the organ masses or different proportions of the miscellaneous organ masses on FFM. These results support the hypothesis that the specific organs estimated in this study do not account for the lower RMR in the elderly. The reason for the greater sex difference of the differences between measured and calculated RMR in the young subjects is unclear. There is not much evidence in the literature for sex-specific factors influencing RMR independently from differences in body composition. However, as our data were analysed separately for the two sexes, potential sex-specific causes cannot have an impact on our results.

Our results regarding RMR that is to be expected theoretically confirm those of Gallagher *et al* (2000), who used the same approach in only seven elderly women and six elderly men. Calculated RMR was developed from measured tissues and organs and energy expenditure was assigned for each of the seven tissue/organ components as reported by Elia (1992). Elderly women and men had significantly lower measured RMRs compared to calculated RMR. The magnitudes of the differences were 612 and 601 kJ/day, respectively, for women and men and are very similar to those observed in our study (625 and 515 kJ/day). This correspondence of the results is even more remarkable in that by contrast to the study of Gallagher *et al* (2000) organ masses were not measured in our study but derived from the regression equations developed by Garby *et al* (1993).

Bosy-Westphal *et al* (2003) also measured RMR and body composition including several organ masses in 26 young (13 females, 13 males) and 26 elderly subjects (15 females, 11 males) and specific organ metabolic rates were taken from the literature. RMR adjusted for differences in FFM according to Ravussin and Bogardus (1989) was significantly lower in elderly relative to young subjects and differences between measured and calculated RMR were 30 and −360 kJ/day in young and elderly subjects, respectively. However, the exclusion of five elderly subjects with cardiac hypertrophy resulted in agreement between measured and calculated RMR in the elderly. The authors therefore argued that the age-related decline in RMR is not caused by a decreasing organ metabolic rate, but is attributed to a reduction in FFM as well as in proportional changes in its metabolically active components. The reason for this disagreement to the results of Gallagher *et al* (2000) and our study is not clear. Bosy-Westphal *et al* (2003) discuss that subject bias might have posed limitations on their study as in female subjects there was no decrease in FFM with age. Thus, the relatively small number of subjects investigated could have biased the results in this study. However, there might also be a possibility that we overestimated calculated RMR of the elderly. Although the sum of organ masses as calculated with the equations from Garby *et al* (1993) in our study was significantly lower in the elderly when compared to young subjects, heart mass was nevertheless significantly higher in the elderly. As discussed by Bosy-Westphal *et al* (2003), an increased heart mass could also add to the observed age-group differences between measured and calculated RMR in case the heart metabolic rate decreased with an increasing heart mass in the elderly. If an increased heart mass was more frequently present in Garby's autopsy population than in the GISELA subjects, the algorithm derived from Garby *et al* (1993) could have resulted in an overestimation of the calculated RMR of the subjects in our study.

Several findings support the observation that aging is associated with a decline in metabolic rate per unit of tissue mass. Poehlman *et al* (1993b) examined the hypothesis that a decline in Na–K pump activity contributes to the lower RMR in older males, independent of the loss of FFM. They found that the age-related reduction in Na–K pump activity is a partial contributor to the decline in RMR in older men. Conley *et al* (2000) determined the decline in oxidative capacity per volume of human vastus lateralis muscle between younger and elderly human subjects. They reported

mitochondrial volume density and oxidative capacity per mitochondrial volume to be significantly lower in muscles of the elderly compared to younger subjects. Furthermore, sympathetic nervous system (SNS) activity may also account for a lower RMR adjusted for body composition in elderly subjects. Despite the higher level of SNS activity, aging is also marked by a blunted response to sympathetic activation, which may explain the decreased RMR in elderly subjects (Heinsimer & Lefkowitz, 1986; Vaughan *et al*, 1991).

There are some limitations in the assessment of body composition in our study. Results for FFM and FM obtained by bioelectrical impedance analysis can vary substantially depending on the respective algorithms used to estimate these compartments. In order to select the most appropriate equation, experimental conditions under which the various equations were derived were evaluated with regard to comparability of the study population, experimental protocol, impedance equipment and electrode placement. On the basis of these criteria, and also as it has been validated by densitometry we found the equation of Deurenberg *et al* (1991) to be most appropriate for use in our study. A further limitation of our study is that weights of the brain, heart, liver and kidneys were not measured but calculated by using the regression equations from Garby *et al* (1993). This approach was used, because within the scope of our study, including a rather large number of subjects, it was not possible to assess the weights of the different organs by extensive methods like computer tomography or magnetic resonance imaging. The literature on equations for calculating weights of these organs is scarce; thus, we used the regression equations from Garby *et al* (1993), which, however, were derived from a large number of subjects from a country bordering the one of our subjects. Furthermore, in our study, skeletal muscle mass was calculated from the data of FFM according to Forbes (1987) and therefore can be considered only as an estimate. However, as the metabolic rate of skeletal muscle and the residual FFM are nearly the same (54 *vs* 50 kJ/kg/day), this imprecise assessment of skeletal muscle mass may be negligible.

In summary, our results obtained in a relatively large sample support these findings indicating a decline in RMR with advancing age, which cannot be totally explained by changes in body composition. Irrespective of the approach employed, there is a striking correspondence in the magnitude of differences between adjusted RMR of elderly and younger subjects and of differences between measured and calculated RMR of elderly subjects detected in our study and those reported by Piers *et al* (1998) and by Gallagher *et al* (2000). This is even more remarkable when considering that in these latter studies, results were derived from much smaller samples and by using different methodological procedures.

However, neither with the results of our investigation in which weights of the brain, heart, liver and kidneys were calculated by regression equations according to Garby *et al* (1993) nor with the results of Gallagher *et al* (2000), who measured the volumes of the organs and tissues by magnetic resonance imaging, can it be explained whether the decline in RMR independently of changes in body composition relates to a reduction in the organs' metabolic rate or whether this is due, for example, to morphological changes like infiltration of the organs with fat, oedema or cystic structures (Gallagher *et al*, 1998). Future studies should focus therefore on oxygen consumption of specific organs and its relation to respective anatomical, physiological or biochemical changes in these tissues associated with age.

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