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ORIGINAL ARTICLE

Adiposity rebound is misclassified by BMI rebound

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BACKGROUND/OBJECTIVES: Adiposity rebound (AR) is defined as the nadir or the inflexion point of body mass index (BMI) percentiles between the age of 3 and 7 years. An early rebound is seen as a risk of obesity and, thus, AR is considered as a suitable time period for prevention. As BMI does not reflect body composition, we aimed to examine the rebounds of fat mass index (FMI) and fat-free mass index (FFMI) together with BMI.
SUBJECTS/METHODS: Cross-sectional data of 19 264 children aged 3–11 years were pooled from three German studies (Kiel Obesity Prevention Study, the project 'Better diet. More exercise. KINDERLEICHT-REGIONS' and regular examinations of Jena children). Height and weight were measured. Fat mass (FM) and fat-free mass (FFM) were obtained from bioelectrical impedance analysis and analysed using a population-specific algorithm. Percentiles of BMI, FMI and FFMI were constructed by the LMS method.
RESULTS: Both BMI and FMI percentiles showed a rebound, whereas FFMI percentiles steadily increased with age. On P90, FMI rebound was about 1.6–1.8 years later compared with that of BMI, that is, at ages 4.2 years (BMI) and 5.8 years (FMI) in boys and at 4.2 years (BMI) and 6.0 years (FMI) in girls. At AR, the slope of the BMI-P90 was explained by increases in FFMI rather than FMI. By contrast, at FMI rebound, the slope of BMI was strongly related to FMI.
CONCLUSIONS: BMI rebound does not equal the rebound of FM. At AR, the slope in BMI is determined by the increase in FFMI. AR should be defined as FMI rebound rather than BMI rebound.

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INTRODUCTION

Following body mass index (BMI) percentiles, BMI declines after infancy and then there is a second rise in BMI between the age of 3 and 7 years until adulthood.[1] Adiposity rebound (AR) is defined as the nadir or the inflexion point of BMI percentiles with age. AR was first described in the 1980s by Rolland-Cachera *et al.*,[2] who found a relationship between the age at AR and later manifestation of adiposity. Children with an early AR had a higher risk to become obese adolescents[2] and/or adults.[3,4] Inter-individual differences in BMI during AR were due to weight gain rather than height velocity.[5] Thus, time at AR is seen as a critical period for higher than average weight gain and the development of obesity.

It is assumed that both the size and the number of adipocytes increase and, thus, FM begins to accumulate at age of AR.[2,3] However, there are only a few detailed studies on changes in body composition at AR that investigated this idea,[5,6] and no unequivocal results were found. Contrary to the original assumption, AR was characterized by an increase in fat-free mass (FFM) rather than fat mass (FM).[6] By contrast, other studies indicated that differences in FM acquisition determine changes in BMI during the time of AR.[7,8] In addition, sex differences in AR-related changes in body composition have been proposed: BMI differentials between early and late AR were found to be due to increased deposition of FM in girls but of FFM in boys.[5] Thus, it is still unclear whether an early AR reflects an increased fat or lean mass.[4] These studies had a longitudinal design with regular assessments of body composition but were based on limited data sets of 40–458 children.

In this study, we aimed to assess body composition in a large database to characterize BMI, fat mass index (FMI) and fat-free mass index (FFMI) during the time when AR occurs.

SUBJECTS AND METHODS

Study population

A representative group of 19 264 (9777 boys and 9487 girls) children aged 3–11 years was analysed, and data were pooled from three German studies (Kiel Obesity Prevention Study,[9,10] the German-wide project 'Better diet. More exercise. KINDERLEICHT-REGIONS' and regular examinations of Jena children[11]). Details of the study design and recruitment procedure have been described recently.[12]

Anthropometry

Anthropometric measurements were performed by trained staff following standard procedures. Body weight was measured to the nearest 0.1 kg

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using a calibrated electronic scale, with subjects wearing minimal clothing. Body height was sized to the nearest 0.5 cm (Kiel) or 0.1 cm (Jena and KINDERLEICHT regions). BMI was calculated from weight and height as kg/m^2. Prevalence of overweight was defined according to the worldwide standard BMI-for-age growth charts.[13] In all studies, bioelectrical impedance analysis (BIA) was conducted with tetrapolar body impedance analyser BIA 2000-C (Data Input, Frankfurt, Germany). Subjects were measured in the morning and for ethical reasons without fasting. Percentage body FM was calculated from BIA data using a Kiel Obesity Prevention Study population-based algorithm:[12]

FFM (kg) $= 0.66$ (height^2 (cm^2)/resistance (Ω)) $+ 0.196 \times$ weight (kg) $+ 0.157 \times$ reactance (Ω) $+ 0.348 \times$ age (years) $- 12.083$

FM was then calculated from the difference between body weight and FFM. According to BMI, FM and FFM were adjusted for height and, thus, FMI (in kg/m^2) and FFMI (in kg/m^2) were obtained.

For BIA measurement, inclusion criteria were BIA resistance values between >400 and $<1000\,\Omega$, phase angle between $>2°$ and $<9°$, (reactance/resistance) $\times 100 = <15\%$, appropriate hand and foot resistance during BIA measurement and FM $\geqslant 5\%$.

Statistics

Statistical analyses were performed with IBM SPSS Statistics 20 for Windows. The LMS models were fitted by the R Project for Statistical Computing version 2.11.0 (http://www.r-project.org) using the gamlss package.[14] Results were presented as median and interquartile range. Spearman correlation coefficients were used to determine the associations between BMI and FMI.

Modelling of percentiles

The age-specific percentile curves of BMI, FMI and FFMI were modelled by the LMS method.[15] The goodness of fit was examined by the visual inspection of the percentiles, a graphical comparison of the empirical and the fitted centiles, the analysis of the percentage of data outside the smoothed percentiles, *Q*-tests[16] and worm plots.[17] Age at rebound on different percentiles was defined at the minimum value of the curve.

Slopes of BMI, FMI and FFMI were calculated from changes in parameters per year as derived from percentiles.

To analyse body composition at the time of BMI and FMI rebound, we divided our population into percentile groups (P3, P10, P25, P50, P75 and P90). To achieve more children in each group, children were included if their individual BMI values were in $\pm$ half percentile channel. In the second step, in each weight group medians of percentage FM and the ratio of FM/FFM were calculated only for children who were at the age of BMI rebound (± 0.25 years). Same procedure was performed for FMI groups. As there were too few children around P97, this group was not considered. Level of significance was set at $P<0.05$ (two sided).

RESULTS

The study population is characterized in Table 1. Prevalence of overweight was 15.9% and 18.3% in boys and girls, respectively. Additionally, medians of BMI, FMI and FFMI are given in Table 2 for each 1-year age group. Within the age range investigated, both BMI and FMI showed rebounds, whereas FFMI percentiles increased steadily with age (Figure 1). There were differentials in rebounds of BMI and FMI: FMI rebound followed BMI rebound, with a time lag of 2–3 years (Table 3 and Figure 2).

The more obese the children were, the earlier was the rebound (Table 3). This was seen for BMI as well as FMI. For each percentile, BMI rebound preceded FMI rebound.

Sex differences

At BMI rebound as well as at FMI rebound, girls were slightly younger than boys until P75. Thereafter, boys and girls were about the same age during rebound (Table 3).

Comparing individual percentiles, up to P50, the time lag between FMI and BMI rebound was shorter in girls compared with boys; thereafter, there were no differences in the time lag between boys and girls (Table 3).

Table 1. Characterization of the study population

Median (interquartile range)	*Boys* (n = 9777)	*Girls* (n = 9487)
Age (years)	7.0 (6.0–8.6)	6.9 (6.0–8.6)
Weight (kg)	25.0 (21.0–31.0)	24.7 (20.6–30.6)
Height (m)	1.25 (1.17–1.35)	1.24 (1.16–1.34)
BMI (kg/m^2)	16.0 (15.0–17.4)	16.0 (15.0–17.6)
FMI (kg/m^2)	3.3 (2.5–4.5)	3.5 (2.5–4.8)
FFMI (kg/m^2)	12.9 (12.0–13.8)	12.8 (12.0–13.6)
Overweight[a] (% (95% CI))	15.9 (15.2–16.6)	18.3 (17.5–19.1)

Abbreviations: BMI, body mass index; CI, confidence interval; FFMI, fat-free mass index; FMI, fat mass index. [a]According to Cole *et al.*[13]

Table 2. Descriptive statistics[a] of BMI, FMI and FFMI in 1-year age groups of the study population by sex

Age (years)	*Sample size* (n)	*BMI (kg/m^2)*	*FMI (kg/m^2)*	*FFMI (kg/m^2)*
Boys				
3.0–3.99	558	15.7 (15.1–16.6)	4.9 (4.1–5.9)	10.8 (10.1–11.6)
4.0–4.99	821	15.5 (14.7–16.4)	4.1 (3.2–4.9)	11.5 (10.9–12.3)
5.0–5.99	1006	15.4 (14.7–16.4)	3.3 (2.7–4.1)	12.2 (11.6–12.9)
6.0–6.99	2458	15.6 (14.7–16.4)	3.2 (2.4–4.0)	12.5 (11.9–13.2)
7.0–7.99	1721	16.1 (15.1–17.5)	3.0 (2.2–4.0)	13.2 (12.6–13.9)
8.0–8.99	1090	16.5 (15.3–18.5)	3.0 (2.1–4.6)	13.6 (12.9–14.3)
9.0–9.99	1144	16.9 (15.7–18.9)	3.1 (2.2–4.6)	13.8 (13.1–14.6)
10.0–10.99	979	17.3 (15.9–19.5)	3.4 (2.4–5.2)	14.0 (13.3–14.7)
Girls				
3.0–3.99	546	15.7 (14.9–16.7)	4.9 (3.8–5.8)	11.0 (10.2–11.7)
4.0–4.99	742	15.5 (14.6–16.4)	4.1 (3.2–4.9)	11.5 (10.9–12.1)
5.0–5.99	1023	15.5 (14.6–16.5)	3.4 (2.5–4.3)	12.2 (11.6–12.9)
6.0–6.99	2446	15.7 (14.7–16.9)	3.3 (2.4–4.3)	12.5 (11.9–13.1)
7.0–7.99	1602	16.0 (15.0–17.5)	3.2 (2.3–4.3)	13.0 (12.4–13.6)
8.0–8.99	997	16.3 (15.1–18.2)	3.2 (2.2–4.6)	13.3 (12.6–13.9)
9.0–9.99	1228	17.1 (15.7–19.1)	3.6 (2.5–5.2)	13.5 (12.9–14.3)
10.0–10.99	903	17.7 (16.2–20.0)	4.0 (2.9–5.8)	13.8 (13.1–14.5)

Abbreviations: BMI, body mass index; FFMI, fat-free mass index; FMI, fat mass index. [a]Median (interquartile range).

Slopes of percentiles

The slope of BMI is the sum of the slopes of FMI and FFMI. As the FMI still declined during the BMI rebound, the increase of BMI was due to the increase of FFMI (Table 4). Thus, we conclude that BMI rebound was determined by FFMI rather than FMI.

Compared with P50, the slope of FMI was much steeper at P90, whereas the slopes of FFMI were nearly similar at both percentiles (Table 4). Thus, after FMI rebound, the slope of BMI was mainly determined by FMI rather than FFMI (especially in higher percentiles).

Body composition at the time of AR

Body composition of the children at the time of BMI and FMI rebound is shown in Table 5. Compared with FMI rebound, percentage FM as well as the ratio of FM/FFM was higher at BMI rebound at all percentiles, which was explained by the fact that FMI is still decreasing up to the time of FMI rebound. Percentage FM as well as the ratio of FM/FFM was similar between boys and girls. The FM/FFM ratio showed high variance across all percentiles at FMI rebound compared with BMI rebound.

At BMI rebound, the correlation between BMI and FMI was 0.604 and 0.674 for boys and girls, respectively. Slightly higher correlation coefficients were observed at FMI rebound (boys: $r = 0.785$; girls: $r = 0.845$).

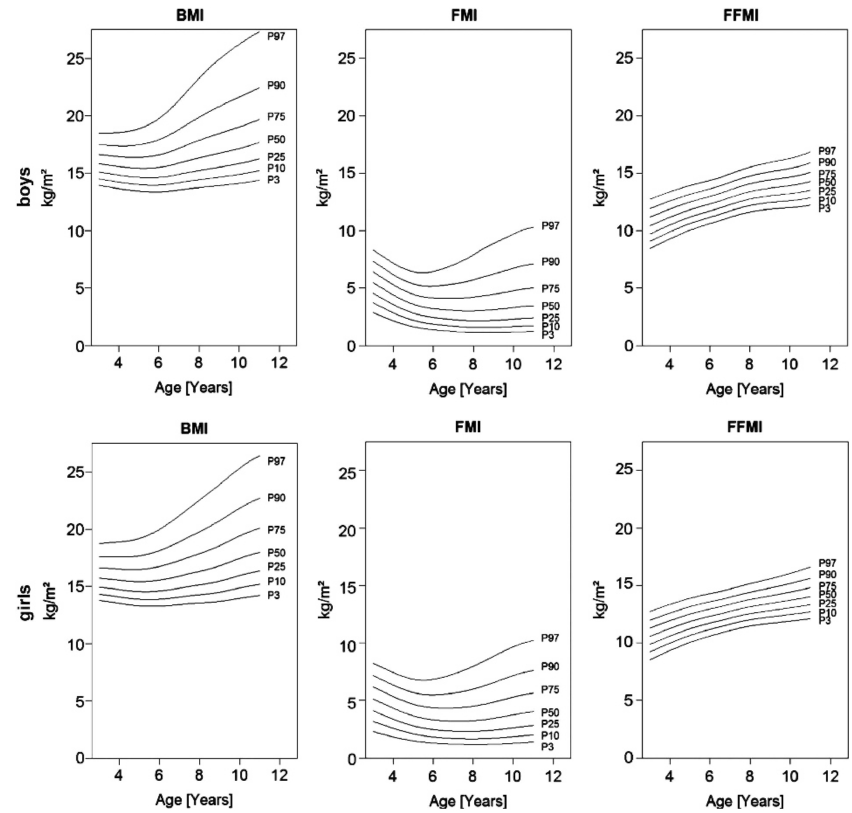

Figure 1. Percentiles of BMI, FMI and FFMI as derived from our study population.

Table 3. Age[a] at BMI and FMI rebound on different percentiles by sex

	Boys			*Girls*		
	BMI	*FMI*	*ΔFMI − BMI*	*BMI*	*FMI*	*ΔFMI − BMI*
P3	5.8	8.7	2.9	5.6	8.1	2.5
P10	5.7	8.5	2.8	5.5	7.9	2.4
P25	5.5	8.1	2.6	5.3	7.7	2.4
P50	5.2	7.8	2.6	5.0	7.3	2.3
P75	4.8	6.8	2.0	4.7	6.6	1.9
P90	4.2	5.8	1.6	4.2	6.0	1.8
P97	3.0	5.5	2.5	3.0	5.5	2.5

Abbreviations: BMI, body mass index; FMI, fat mass index. [a]In years.

DISCUSSION

This study shows that rebound of BMI does not equal the rebound of FMI. Compared with BMI, the increase in FMI is about 2 years later. Thus, with regard to the FMI percentiles, the present definition of AR based on BMI percentiles cannot be considered as the true obesity rebound. By contrast, AR defined by BMI is mostly explained by age-related and linear increases in FFMI rather than FMI. This is in line with the longitudinal data of Campbell *et al.*.[6] The similarity of the slopes of BMI and FFMI during BMI rebound suggests that the BMI rebound describes growth rather than increases in body fatness in this age group.

Although an early AR is seen as a risk of later obesity and obesity-related complications, for example, impaired glucose tolerance and diabetes mellitus,[18–20] our data question the idea that BMI-defined AR is an optimal period for prevention. Defining AR according to the age-dependent course of BMI P90, prevention of overweight may start at the age of 3–5 years. However, this strategy may interfere with the steady increase in FFMI (and thus growth) with age and may, thus, affect normal development of children. However, a measure to promote physical activity can increase FFM and bone mass independent of changes in FM. Using the period of FMI rebound, prevention may start at the age of 5–7 years. The latter recommendation is in line with recent studies showing that, up to 6 years of age, there was a very high remission rate of overweight, but at school entry the incidence and persistence of overweight sharply increased.[21,22] Our present data argue in favour of the idea that BMI rebound is misleading with respect to characteristics of obesity (i.e., increased FM) as well as possible consequences in terms of prevention.

Compared with the original data of Rolland-Cachera *et al.*,[2] AR occurs earlier today.[23] The time of AR depends on the extent of overweight, and a higher prevalence of overweight is observed in more recent studies (e.g., Stolzenberg *et al.*[24]). By contrast, a recent longitudinal study showed that children born after 1970 did not have higher BMI values at AR compared with children born between 1929 and 1953.[25] As children born in the seventieth years were not struck by the obesity epidemic as 5- to 7-year olds, it has to be proven in a more recent longitudinal study whether the AR occurs earlier today due to a higher extent of overweight.

The time of AR is used as a risk marker of obesity in adolescence and adulthood: the earlier the AR, the more obese the subjects might be in later life. Overweight children have an earlier AR than normal-weight children (Table 3). However, there are also normal-weight children who have an early AR.[4] These children are also considered to be at risk for later obesity. It can be hypothesized that these children are still normal weight but already have

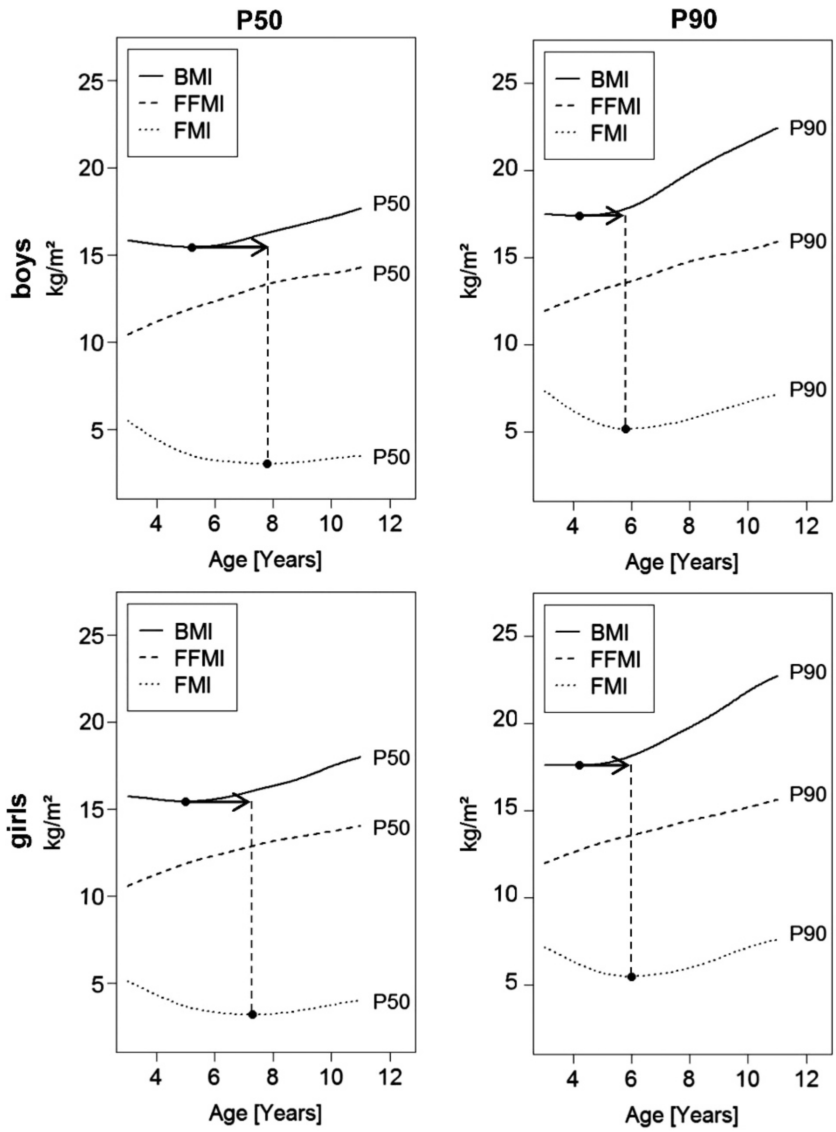

Figure 2. Comparison of rebounds of BMI and FMI at P50 and P90 for boys and girls.

an increased FM or are crossing FM percentiles upwards. This hypothesis can be analysed only in longitudinal studies. In fact, Cole[1] showed that an early AR was associated with a high BMI percentile or upwards crossing of percentiles; thus, AR had been considered as a statistical rather than a physiological phenomenon that may apply at different ages.[1] With respect to body composition, Taylor *et al.*[5,7] found that the annual velocity of FM was twofold higher in so-called 'early rebounders' compared with 'late rebounders', whereas there were no between-group differences in FFM velocity. Thus, these longitudinal data also argue in favour of the idea that timing of AR is determined by FM and not by FFM. This finding is contrary to our cross-sectional results; however, due to study design, we could not compare 'early' and 'late' rebounders.

Strengths and limitations

- We have used a large and representative German database taking into account a considerable age range to classify the rebounds of BMI and FMI. However, our analyses were based only on cross-sectional data; we could not analyse

Table 4. Slopes[a] of BMI, FMI and FFMI at P50 and P90 by age and sex

Age (years)	*P50*			*P90*		
	BMI	*FMI*	*FFMI*	*BMI*	*FMI*	*FFMI*
Boys						
3.0–4.0	−0.24	−1.08	0.74	−0.09	−1.15	0.67
4.0–5.0	−0.15	−0.81	0.65	0.08	−0.82	0.58
5.0–6.0	0.07	−0.38	0.52	0.44	−0.20	0.47
6.0–7.0	0.38	−0.15	0.55	0.9	0.19	0.56
7.0–8.0	0.45	−0.05	0.51	1.05	0.36	0.56
8.0–9.0	0.41	0.10	0.31	0.94	0.50	0.37
9.0–10.0	0.42	0.19	0.22	0.82	0.50	0.30
10.0–11.0	0.51	0.15	0.34	0.81	0.37	0.48
Girls						
3.0–4.0	−0.18	−0.8	0.68	−0.01	−0.83	0.63
4.0–5.0	−0.12	−0.66	0.60	0.10	−0.65	0.56
5.0–6.0	0.13	−0.35	0.46	0.45	−0.21	0.42
6.0–7.0	0.36	−0.12	0.42	0.77	0.15	0.41
7.0–8.0	0.41	0.04	0.40	0.88	0.35	0.43
8.0–9.0	0.48	0.21	0.29	0.96	0.56	0.37
9.0–10.0	0.65	0.31	0.28	1.11	0.62	0.39
10.0–11.0	0.53	0.27	0.32	0.85	0.44	0.45

Abbreviations: BMI, body mass index; FFMI, fat-free mass index; FMI, fat mass index. [a]ΔParameter/year.

Table 5. Body composition at the time of BMI and FMI rebound by percentile and sex

	BMI rebound				FMI rebound			
	Age (years)	n	*FM (%)*[a]	*FM/FFM*[a]	*Age (years)*	n	*FM (%)*[a]	*FM/FFM*[a]
Boys								
P3 (P1–P6)	5.8 ± 0.25	47	16.6 (11.0–20.1)	0.20 (0.12–0.25)	8.7 ± 0.25	22	8.1 (7.5–8.8)	0.09 (0.08–0.10)
P10 (P7–P17)	5.7 ± 0.25	60	19.3 (16.2–21.2)	0.24 (0.19–0.27)	8.5 ± 0.25	45	11.5 (10.5–12.3)	0.13 (0.12–0.14)
P25 (P18–P37)	5.5 ± 0.25	75	19.7 (16.0–22.9)	0.24 (0.19–0.30)	8.1 ± 0.25	132	14.5 (13.7–15.5)	0.17 (0.16–0.18)
P50 (P38–P62)	5.2 ± 0.25	58	22.8 (17.1–25.8)	0.30 (0.21–0.35)	7.8 ± 0.25	191	18.8 (17.8–19.8)	0.23 (0.22–0.25)
P75 (P63–P82)	4.8 ± 0.25	67	25.4 (22.2–30.2)	0.34 (0.29–0.43)	6.8 ± 0.25	212	24.1 (23.0–25.4)	0.32 (0.30–0.34)
P90 (P83–P93)	4.2 ± 0.25	48	29.6 (25.9–32.4)	0.42 (0.35–0.48)	5.8 ± 0.25	78	29.1 (28.2–30.8)	0.41 (0.39–0.45)
Girls								
P3 (P1–P6)	5.6 ± 0.25	26	15.0 (12.2–18.6)	0.18 (0.14–0.23)	8.1 ± 0.25	39	8.6 (8.3–9.2)	0.09 (0.09–0.10)
P10 (P7–P17)	5.5 ± 0.25	47	16.1 (12.0–18.8)	0.19 (0.14–0.23)	7.9 ± 0.25	81	12.0 (11.3–12.6)	0.14 (0.13–0.14)
P25 (P18–P37)	5.3 ± 0.25	54	19.1 (15.1–22.1)	0.24 (0.18–0.28)	7.7 ± 0.25	159	15.7 (14.9–16.9)	0.19 (0.17–0.20)
P50 (P38–P62)	5.0 ± 0.25	68	23.4 (18.1–26.1)	0.31 (0.22–0.35)	7.3 ± 0.25	220	20.3 (19.1–21.4)	0.25 (0.24–0.27)
P75 (P63–P82)	4.7 ± 0.25	80	27.2 (24.0–30.3)	0.37 (0.32–0.43)	6.6 ± 0.25	256	25.2 (24.0–26.5)	0.34 (0.32–0.36)
P90 (P83–P93)	4.2 ± 0.25	36	31.5 (29.5–36.9)	0.46 (0.42–0.59)	6.0 ± 0.25	124	30.4 (29.0–32.2)	0.44 (0.41–0.48)

Abbreviations: BMI, body mass index; FFM, fat-free mass; FM, fat mass; FMI, fat mass index. [a]Median (interquartile range).

intra-individual and age-related changes in body composition during AR and assess the individual percentile tracking.

- Further limitations may relate to body composition analysis by BIA in children. In children, BIA has been validated against dual-energy X-ray absorptiometry, air displacement plethysmography and also the gold standard used in body composition analysis, the so-called 4-compartment or 4C method, as described previously.[26,27] In these studies, BIA was found to be precise and accurate; 95% of the variance in lean mass could be explained by the impedance index.[27] However, there was an age-related inconsistency in the prediction equation, which may relate to age-related differences in body shape and/or tissue hydration. BIA measures total body water, and FFM and FM are estimated indirectly using certain assumptions on tissue hydration. In children, FFM hydration is not constant but changes with age (i.e., between 77.4 and 76.5% in 3- and 10-year-old children[28,29]). Using a constant hydration may underestimate FM in younger children. However, we have addressed this issue and our algorithm to calculate FFM took into account Lohman's age-specific constants for tissue hydration in each age group. In addition, standardization of BIA measurements was optimized in our multicentre study population.
- For ethical reasons, a fasting condition was not a prerequisite for measurement. However, some authors including ourselves found no significant differences in BIA estimates of body FM in fasting versus postprandial conditions.[30,31] In a previous study, we had also compared the influence of meals on BIA measurements. We found that, compared with fasting, meals slightly lowered resistance, but this did not result in a significant lower FM (Sawinski *et al.*, 2002, unpublished data). It should be mentioned that whole-body resistance is markedly influenced by arms and legs rather than trunk, with contribution to approximately 10–15%.
- We adjusted weight as well as FM and FFM for height by using the squared term from ages 3 to 11 years. This may be incorrect as at younger ages the ponderal index (weight/height^3) might be a better index of weight adjusted for height.[32] In addition, to reach a height-independent measure in young children, FM was adjusted for height by FM/height[6,33] We thus feel that it remains to be proven (i) which is the best normalization of BMI, FM and FFM for height in several age groups and (ii) whether normalization of height influences timing of AR.

CONCLUSIONS

FMI rebound follows BMI rebound, with a time lag of 2–3 years. At AR, the course of BMI percentile is determined by the linear increase in FFMI with age, whereas the increase in BMI resembles FMI after FMI rebound. As interfering with the steady increase in FFM is detrimental, FMI rebound is considered as a considerable time period to prevent childhood obesity. This has to be proven in a longitudinal study. Our data suggest that for future risk assessment of obesity, BMI rebound should be replaced by FMI rebound.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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DISCLAIMER

The sponsors of the study had no role in study design, data collection, data analysis, data interpretation or writing of the paper. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit the paper for publication..

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