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Association of different obesity indices with blood pressure and blood lipids in children and adolescents

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The aim of the present study was to compare individual associations of BMI, triceps skinfold (TSF), waist circumference (WC) and percentage fat mass (%FM) with blood pressure (BP) and blood lipids in children and adolescents. Cross-sectional data on BMI, TSF, WC, %FM as well as on BP, TAG and HDL were analysed in 4220 (BP) and 729 (lipids) 9–11-year-old children and 3174 (BP) and 536 (lipids) 13–16-year-old adolescents as part of the Kiel Obesity Prevention Study. All obesity indices were similarly associated with BP and blood lipids. In girls, WC had closer correlations to BP than BMI (systolic BP: 0·27 and 0·24 for BMI, 0·34 and 0·28 for WC in 9–11- and 13–16-year-olds). Subjects with an obesity index ≥ 90th percentile had higher prevalences of elevated BP and blood lipids than subjects with a normal index. In children with normal BMI or WC, an additionally elevated second obesity index was associated with a 2·5–7·4-fold higher prevalence of high BP when compared with children with normal indices. In adolescents, an elevated WC plus an elevated second obesity index was associated with a 2·6–8·2-fold higher prevalence of high BP when compared with adolescents with an elevated WC plus a normal second index. We conclude that (i) both BMI and WC are appropriate to estimate CVD risk, (ii) the use of a second obesity index is recommended in children with normal BMI or normal WC as well as in adolescents with elevated WC and (iii) all obesity indices seemed to be appropriate for risk assessment.

Overweight: Children: Blood lipids: Cardiovascular disease risk factors

Childhood overweight is a public health problem. Defining overweight in children and adolescents is not uniform with respect to obesity indices and cut-offs used. BMI is widely used as a measure of fat mass (FM) and international BMI reference values for children and adolescents have been published[1]. However, BMI is only an indirect parameter of total body fat and does not reflect body fat distribution[2,3]. In addition, the association between BMI and disease risk is unproven in children and adolescents. In adults, BMI cut-offs for overweight and obesity were defined according to overweight- and obesity-associated co-morbidity[4]. However, in children prospective data on the association between obesity indices and disease risk are rare; for example, longitudinal data of the Bogalusa Heart Study showed a relationship between childhood obesity and incidence of metabolic disorders in young adulthood[5]. The International Obesity Taskforce Working Group recommended that BMI cut-offs for defining overweight and obesity in children should be linked to the adult disease-related cut-off points of 25 and 30 kg/m^2[1].

In addition to BMI, triceps skinfold thickness (TSF), waist circumference (WC) and percentage FM (%FM) as derived from bioelectrical impedance analysis have been recommended to identify individuals with increased overweight-associated disease risks[3]. However, the use of these obesity indices is limited because of methodological aspects as well as of the absence of adequate reference databases. Recently, reference databases have been published for WC and %FM in children[6,7]. However, since these reference databases differ with respect to populations, data on prevalence, based on either direct or indirect measures of FM, are not comparable. In addition, comparing different indices of FM, WC showed the strongest association to CVD risks. WC correlates with visceral FM (in adults[8] as well as in children[9]) and visceral adipose tissue is associated with metabolic disorders and CVD risk factors[10].

At present, only a few studies have investigated the value of the combined use and the possible additive value of using different obesity indices in children and adolescents. This is of particular interest, since in adults two independent studies indicated that combining BMI and WC is a better predictor of metabolic risk than either measure alone[11,12]. In fact, in the Bogalusa Heart Study[13], the presence of elevated health risk among children and adolescents could also be better identified by a combination of BMI and WC. Following this idea, we compared BMI, TSF, WC and %FM with respect to their association with blood pressure (BP) and blood lipids

Abbreviations: BP, blood pressure; FM, fat mass; %FM, percentage fat mass; IQR, interquartile range; KOPS, Kiel Obesity Prevention Study; 90 P, 90th BMI percentile; TSF, triceps skinfold; WC, waist circumference.

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in a greater group of children and adolescents using cross-sectional data of the Kiel Obesity Prevention Study (KOPS). We hypothesised that (i) a direct measure of FM or WC exceeds the value of BMI and (ii) combining BMI or WC with a second obesity index further improves the identification of children and adolescents with CVD risk.

Methods

Study populations

KOPS is an ongoing study which started in 1996 and will run up to 2009. The design of KOPS has been described previously[14–16]. Up to now three samples of 4997 first graders (5–7 years old), 4487 fourth graders (9–11 years old) and 3196 eighth graders (13–16 years old) have been recruited. These samples have been shown to be representative for all children of the respective age groups in Kiel[16]. In the present paper two samples of 9–11-year-old children and 13–16-year-old adolescents were analysed in which BP and blood lipid measurements have been performed. BP was measured in 4220 children and 3174 adolescents. Blood lipids were screened in a randomly selected subgroup of 15–20 % of subjects only (due to high costs, i.e. in 729 children and 536 adolescents). These samples are characterised and compared with the complete KOPS samples (Fig. 1) and overweight children (≥90th BMI percentile (90 P)) were under-represented. Regarding blood lipid screening, overfat children (≥90 P of %FM) were over-represented. At age 13–16 years, there was an over-representation of 'overwaist' adolescents (≥90 P of WC). All parents gave their informed written consent. The study protocol was approved by the local ethical committee.

Measurement of obesity indices

Obesity indices were measured anthropometrically and by bioelectrical impedance analysis as described previously[14,16]. Briefly, WC was measured midway between the lowest rib and the top of the iliac crest at the end of gentle expiration. FM was calculated from bioelectrical impedance analysis measurements using a population-specific algorithm derived and cross-validated in a randomly selected sample of 158 5–18-year-old children and adolescents (56 % girls) using air-displacement plethysmography as the reference method[17]. The bioelectrical impedance analysis algorithm was:

$$\text{Fat-free mass (kg)} = 0{\cdot}66 \times (\text{height}^2\ (\text{cm}^2)/\text{resistance}\ (\Omega)) + 0{\cdot}196 \times \text{weight (kg)} + 0{\cdot}157 \times \text{reactance}\ (\Omega) + 0{\cdot}348 \times \text{age (years)} - 12{\cdot}083.$$

FM was then calculated from the difference between body weight and fat-free mass.

The intra-observer CV were 0·5, 4·2, 0·4 and 1·5 % for BMI, TSF, WC and %FM, respectively (for three repeated measurements in forty-two (BMI, WC), 150 (TSF) and ten (%FM) children). The corresponding inter-observer CV were 0·5, 5·7, <1 and 0·7 %, respectively (for three different observers in forty-two (BMI, WC), fifteen (TSF) and ten (%FM) children). To compare different obesity indices the population-, age- and sex-specific 90 P were used (Table 1). Subjects above the 90 P of BMI were defined as overweight; children exceeding the 90 P of TSF, WC or FM were described as overfat.

Tanner stage (pubic hair stages for sexes, breast stage for girls, and genitalia stages for boys) was self-estimated by the adolescents using standard pictures[18] on scales from 2 to 5. This procedure has been validated by Duke *et al.* [19].

Measurement of cardiovascular disease risk factors

BP was measured using a sphygmomanometer on the right arm after a 5 min rest. Hypertension was defined by the age-specific 95 P for systolic and diastolic BP as recommended by the Second Task Force on Blood Pressure Control in Children[20]. Measurements of blood lipids were performed

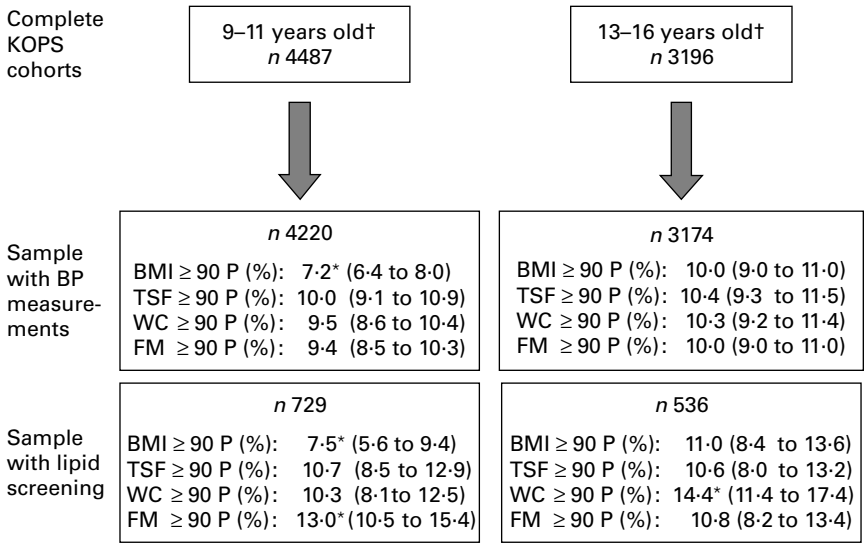

Fig. 1. Numbers and bias of the samples with blood pressure (BP) measurements and lipid screening in comparison with the complete Kiel Obesity Prevention Study (KOPS) samples of 9–11-year-old children and 13–16-year-old adolescents. 90 P, 90th percentile; TSF, triceps skinfold; WC, waist circumference; FM, fat mass. * Significantly different from the complete KOPS samples. † Samples of which 90 P of BMI, TSF, WC and FM were calculated.

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Table 1. Population-, age- and sex-specific 90th percentiles (10th percentile for high-density lipoprotein) as derived from the complete cohorts of Kiel Obesity Prevention Study

Age groups (years)	Sex	No. of subjects for obesity indices	No. of subjects for blood lipids	BMI (kg/m^2)	TSF (mm)	WC (cm)	FM (%)	TAG (mg/l)	HDL (mg/l)	LDL (mg/l)	Total cholesterol (mg/l)
≥ 9 to < 10	Boys	959	189	21·62	22·0	75·0	31·28	1720	399	1410	2190
	Girls	1120	151	21·97	24·0	76·0	33·26	1648	400	1448	2225
≥ 10 to < 12	Boys	1250	229	22·32	24·0	77·4	32·00	1680	410	1310	2080
	Girls	1128	197	22·42	24·7	77·5	33·62	1772	386	1371	2200
≥ 13 to < 15	Boys	1076	209	24·44	25·0	82·7	28·25	1610	260	1150	1787
	Girls	1243	254	24·97	29·0	80·0	33·74	1565	320	1160	1880
≥ 15 to < 17	Boys	470	99	26·06	25·7	86·9	29·08	1550	210	1198	1730
	Girls	407	96	26·50	30·0	82·0	35·26	1600	314	1190	1853

TSF, triceps skinfold; WC, waist circumference; FM, fat mass derived from bioelectrical impedance analysis.

before noon in school. Blood lipids were analysed with the Cholestech L-D-X® (Cholestech, Hayward, CA, USA) from capillary blood. Since there are neither German reference data for blood lipids nor international reference data based on analyses with the Cholestech L-D-X®, our own age- and sex-specific 10 P of HDL-cholesterol and 90 P of TAG, LDL-cholesterol and total cholesterol were used to define low and high levels (Table 1). Measurements were done under fasting conditions in 18 and 12 % of the children and adolescents. A total of 82 and 88 % of the children and adolescents had breakfast at about 1·45 (range 1·00–2·25) h and 1·20 (range 0·34–2·10) h before measurement, respectively. Comparing fasting with non-fasting values, TAG levels in fasting children were only marginally lower (median and interquartile range (IQR) of fasting/non-fasting TAG (mg/l): 820 (IQR 560–1240)/880 (IQR 580–1240)). The prevalence of elevated TAG was 28 and 30 % in fasting and non-fasting children. At age 13–16 years, non-fasting adolescents had slightly higher values when compared with fasting adolescents (770 (IQR 600–1030)/850 (IQR 600–1240)). Of fasting and non-fasting adolescents, 10 and 23 % had elevated levels. Because of the small differences, fasting and non-fasting values were analysed together.

Statistical analysis

All analyses were performed with SPSS (version 13.0; SPSS Inc., Chicago, IL, USA) for windows. Data are presented as medians and IQR. The Mann–Whitney *U* test was used to evaluate sex differences in subject characteristics. Levels of blood lipids were log-transformed to normalise the distribution. Pearson and partial correlation coefficients were used to determine the associations among the obesity indices and CVD risk factors. To compare the (correlated) correlation coefficients between different obesity indices, the test of significance according to Meng *et al.* [21] was performed. Stepwise linear regression analyses were done to estimate the explained variance of CVD risk factors by BMI and WC. Initially, the R^2 was determined for a base model based on age and pubertal development. Then, BMI and/or WC were added to the base model, to determine the additional variance above the base model that was explained by BMI and/or WC.

Logistic regression analyses were performed to estimate OR for elevations in BP and blood lipids from TSF, WC and %FM within children and adolescents having normal (<90 P) and elevated (≥90 P) BMI and WC values, respectively. Level of significance was set at $P<0·05$ (two-sided).

Results

Subject characteristics

The main characteristics of the samples are shown in Table 2. All obesity indices increased with age with the exception of %FM in boys. Sex differences in obesity indices were seen in both samples: when compared with boys, BMI, %FM and TSF were higher in girls, whereas WC was greater in boys. At age 9–11 years, girls had higher total-cholesterol and LDL levels than boys. At age 13–16 years, boys had lower TAG, HDL and total-cholesterol levels but higher BP than girls.

Table 2. Main characteristics of the study samples of 9–11- and 13–16-year-old children and adolescents (Medians and interquartile ranges (IQR))

Age range (years)...	9–11				13–16			
Sex...	Boys (*n* 2228)		Girls (*n* 2259)		Boys (*n* 1546)		Girls (*n* 1650)	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
Age (years)	10·1*	10·1–10·2	10·1	10·0–10·1	14·7*	14·3–15·1	14·6	14·2–15·0
Tanner stage (%)		–		–				
II						2·6*		2·1
III						29·2*		20·0
IV						59·3*		62·9
V						8·8*		14·8
Weight (kg)	37·0	36·6–37·3	36·9	36·6–37·3	60·5*	53·5–68·4	55·9	51·0–62·3
Height (m)	1·43*	1·43–1·43	1·42	1·42–1·43	1·72*	1·67–1·78	1·65	1·61–1·69
BMI (kg/m^2)	17·9*	17·8–18·0	18·1	17·9–18·2	20·2*	18·5–22·3	20·4	18·9–22·5
TSF (mm)	12·7*	9·7–18·0	15·0	11·7–20·0	13·7*	10·0–18·8	20·3	16·0–24·7
WC (cm)	63·0*	59·5–69·0	63·0	58·0–69·0	72·0*	67·7–77·0	68·5	65·0–74·0
FM (%)	19·7*	15·1–22·0	22·3	17·1–28·4	17·1*	13·6–22·5	25·6	21·9–29·7
BP_{sys} (mmHg)	108	100–112	106	100–113	120*	115–130	118	110–124
BP_{dias} (mmHg)	60	50–70	60	50–70	74*	68–80	70	68–80
TAG (mg/l)	900	630–1240	910	660–1330	710*	450–1020	770	510–1130
HDL (mg/l)	560	490–640	550	470–640	420*	330–500	470	400–560
LDL (mg/l)	910*	720–1140	1000	800–1230	810	710–970	850	660–1000
Total cholesterol (mg/l)	1640*	1470–1920	1730	1550–1970	1430*	1280–1590	1490	1340–1700

TSF, triceps skinfold; WC, waist circumference; FM, fat mass derived from bioelectrical impedance analysis; BP_{sys}, systolic blood pressure; BP_{dias}, diastolic blood pressure.
* Significantly different from girls ($P<0·05$; Mann–Whitney *U* test).

Correlation of obesity indices with cardiovascular disease risk factors

The correlation coefficients between individual obesity indices and either BP or blood lipids are shown in Table 3. In children, BMI and WC had higher correlation coefficients than %FM. When compared with BMI, WC had a closer correlation with BP in girls only. In adolescents, BMI showed higher correlation coefficients to BP than %FM and TSF; in boys this was also true for log HDL. Because individual

Table 3. Correlation coefficients, adjusted for pubertal development, between obesity indices and blood pressure and blood lipids in 9–11- and 13–16-year-old children and adolescents†

	Correlation coefficients							
					BMI adjusted for			
	BMI	TSF	WC	%FM	TSF	WC	%FM	WC adjusted for BMI
9–11-year-old boys								
BP_{sys}	0·33**‡	0·32**	0·33**	0·25**‡	0·12**	0·08**	0·22**	0·11**
BP_{dias}	0·12**‡	0·14**	0·11**	0·07**‡	−0·00	0·05*	0·12**	0·01
Log TAG	0·09	0·09	0·11*	0·06	0·03	−0·01	0·07	0·07
Log HDL	−0·15**	−0·17**	−0·17**	−0·11*	−0·02	−0·02	−0·09	−0·07
9–11-year-old girls								
BP_{sys}	0·27**‡	0·27**	0·34**‡	0·22**‡	0·11**	0·01	0·17**	0·21**
BP_{dias}	0·13**‡	0·15**	0·18**‡	0·09**‡	0·03	−0·03	0·10**	0·14**
Log TAG	0·30**‡	0·27**	0·31**	0·24**‡	0·17**	0·08	0·22**	0·11
Log HDL	−0·23**	−0·18**	−0·28**	−0·20**	0·16**	−0·04	−0·12*	−0·13*
13–16-year-old boys								
BP_{sys}	0·35**‡	0·16**‡	0·35**	0·20**‡	0·32**	0·10*	0·29**	0·10**
BP_{dias}	0·26**‡	0·12**‡	0·27**	0·18**‡	0·24**	0·06*	0·17**	0·09**
Log TAG	0·25**	0·19**	0·25**	0·21**	0·18**	0·07	0·16**	0·07
Log HDL	−0·24**‡	−0·10*‡	−0·24**	−0·14**‡	−0·21**	−0·07	−0·18**	−0·05
13–16-year-old girls								
BP_{sys}	0·24**‡	0·13**‡	0·28**‡	0·20**‡	0·21**	0·05	0·14**	0·15**
BP_{dias}	0·21**‡	0·14**‡	0·19**	0·21**	0·14**	0·10**	0·07**	0·05*
Log TAG	0·14**	0·03	0·18**	0·10*	0·17**	0·03	0·10	0·11*
Log HDL	−0·18**	−0·19**	−0·12*	−0·17**	−0·06	−0·11*	−0·05	0·00

TSF, triceps skinfold; WC, waist circumference; FM, fat mass derived from bioelectrical impedance analysis; BP_{sys}, systolic blood pressure; BP_{dias}, diastolic blood pressure.
Significant correlation coefficients: *$P<0·05$, **$P<0·01$.
† For 9–11- and 13–16-year-old boys, *n* 2112 and *n* 2108 for blood pressure and *n* 419 and *n* 348 for blood lipids; for 9–11- and 13–16-year-old girls, *n* 1534 and *n* 1640 for blood pressure and *n* 307 and *n* 350 for blood lipids.
‡ Significantly different to the correlation coefficient of BMI (Meng *et al.*[21]).

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Table 4. Prevalence of elevations in systolic and diastolic blood pressure (BP_{sys} and BP_{dias}) and blood lipids in 9–11- and 13–16-year-old children and adolescents stratified by sex and different obesity indices being normal (<90th percentile; 90 P) and elevated (≥90 P)

(Percentages and 95 % confidence intervals)

	High BP_{sys}				High BP_{dias}				High TAG				Low HDL			
	Boys		Girls		Boys		Girls		Boys		Girls		Boys		Girls	
	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI
9–11-year-olds																
Normal																
n (Boys)																
BMI				2002								403				
TSF				1895								373				
WC				1908								381				
FM				1912								369				
n (Girls)																
BMI				1914								225				
TSF				1379								232				
WC				1911								228				
FM				1910								215				
BMI < 90 P	4·4*	3·5, 5·3	4·1*	3·2, 5·0	7·1	6·0, 8·2	7·4*	6·2, 8·6	9·9	7·0, 12·8	11·1*	7·0, 15·2	9·5	6·6, 12·4	8·9*	5·2, 12·6
TSF < 90 P	3·4*	2·6, 4·2	4·4*	3·5, 5·3	6·0*	4·9, 7·1	7·4*	6·2, 8·6	8·8*	5·9, 11·7	12·5	8·2, 16·8	8·1*	5·3, 10·9	9·3	5·6, 13·0
WC < 90 P	3·5*	2·7, 4·3	4·1*	3·2, 5·0	6·3*	5·2, 7·4	7·5*	6·3, 8·7	9·2*	6·3, 12·1	11·8*	7·6, 16·0	8·4*	5·6, 11·2	8·4*	4·8, 12·0
%FM < 90 P	3·8*	2·9, 4·7	4·6*	3·7, 5·5	6·2*	5·1, 7·3	7·7*	6·5, 8·9	9·2	6·3, 12·1	10·7*	6·6, 14·8	9·0	6·1, 11·9	8·4*	4·7, 12·1
Elevated																
n (Boys)																
BMI				110								16				
TSF				217								46				
WC				204								38				
FM				200								50				
n (Girls)																
BMI				194								27				
TSF				207								20				
WC				197								24				
FM				198								37				
BMI ≥90 P	15·5	8·7, 22·3	17·5	12·2, 22·8	11·8	5·8, 17·8	21·6	15·8, 27·4	18·8	0·0, 37·9	33·3	15·5, 51·1	18·8	0·0, 37·9	20·0	4·9, 35·1
TSF ≥90 P	18·9	13·7, 24·1	13·5	8·8, 18·2	18·9	13·7, 24·1	20·3	14·8, 25·8	21·7	9·8, 33·6	25·0	6·0, 44·0	23·9	11·6, 36·2	17·6	0·9, 34·3
WC ≥90 P	19·1	13·7, 24·5	16·8	11·6, 22·0	16·7	11·6, 21·8	20·3	14·7, 25·9	21·1	8·1, 34·1	29·2	11·0, 47·4	23·7	10·2, 37·2	24·3	7·1, 41·5
%FM ≥90 P	16·5	11·4, 21·6	12·6	8·0, 17·2	18·0	12·7, 23·3	18·2	12·8, 23·6	18·0	7·4, 28·6	29·7	15·0, 44·4	16·0	5·8, 26·2	20·8	7·7, 33·9
13–16-year-olds																
Normal																
n (Boys)																
BMI				1380								278				
TSF				1379								276				
WC				1381								276				
FM				1381								278				
n (Girls)																
BMI				1476								311				
TSF				1466								310				
WC				1466								298				
FM				1476								313				
BMI < 90 P	12·6*	10·8, 14·4	3·9*	2·9, 4·9	5·7*	4·5, 6·9	4·5*	3·4, 5·6	9·0*	5·6, 12·4	8·4*	5·3, 11·5	8·6*	5·3, 11·9	9·6*	6·3, 12·9
TSF < 90 P	12·8*	11·0, 14·6	4·4*	3·4, 5·4	6·4*	5·1, 7·7	5·0*	3·9, 6·1	8·6*	5·3, 11·9	9·7	6·4, 13·0	9·3	5·9, 12·7	9·7	6·4, 13·0
WC < 90 P	12·6*	10·8, 14·4	4·0*	3·0, 5·0	6·1*	4·8, 7·4	4·9*	3·8, 6·0	8·3*	5·0, 11·6	8·1*	5·0, 11·2	9·4	6·0, 12·8	10·4	6·9, 13·9
%FM < 90 P	13·2*	11·4, 15·0	4·2*	3·2, 5·2	6·0*	4·7, 7·3	4·7*	3·6, 5·8	8·6*	5·3, 11·9	9·3	6·1, 12·5	8·6*	5·3, 11·9	9·6*	6·3, 12·9

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Table 4. *Continued*

	High BP_{sys}				High BP_{dias}				High TAG				Low HDL			
	Boys		Girls		Boys		Girls		Boys		Girls		Boys		Girls	
	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI	%	95 % CI
Elevated																
n (Boys)																
BMI					154						29					
TSF					155						28					
WC					153						31					
FM					153						29					
n (Girls)																
BMI					164						39					
TSF					174						40					
WC					174						52					
FM					164						37					
BMI ≥ 90 P	35·7	28·1, 43·3	14·0	8·7, 19·3	24·7	17·9, 31·5	15·9	10·3, 21·5	20·7	6·0, 35·4	23·1	9·9, 36·3	27·6	11·3, 43·9	20·5	7·8, 33·2
TSF ≥ 90 P	33·5	26·1, 40·9	9·2	4·9, 13·5	18·7	12·6, 24·8	11·5	6·8, 16·2	25·0	9·0, 41·0	12·5	2·3, 22·7	21·4	6·2, 36·6	20·0	7·6, 32·4
WC ≥ 90 P	35·9	28·3, 43·5	12·6	7·7, 17·5	21·6	15·1, 28·1	12·1	7·3, 16·9	25·8	10·4, 41·2	21·2	10·1, 32·3	19·4	5·5, 33·3	13·5	4·2, 22·8
%FM ≥ 90 P	30·7	23·4, 38·0	11·6	6·7, 16·5	22·2	15·6, 28·8	14·6	9·2, 20·0	24·1	8·5, 39·7	16·2	4·3, 28·1	27·6	11·3, 43·9	21·6	8·3, 34·9

TSF, triceps skinfold; WC, waist circumference; FM, fat mass derived from bioelectrical impedance analysis.
*Significantly different from subjects with elevated (≥ 90 P) levels in obesity indices ($P < 0{\cdot}05$; Fisher's exact test).

obesity indices were highly inter-correlated (9–11/13–16-year-old boys: BMI-TSF, r 0·81/0·67; BMI-WC, r 0·86/0·87; BMI-%FM, r 0·86/0·75; girls: BMI-TSF, r 0·71/0·71; BMI-WC, r 0·80/0·75; BMI-%FM, r 0·85/0·82; for all: $P < 0{\cdot}001$) BMI was further adjusted for TSF, WC or %FM. After adjustment for either TSF or %FM, BMI still had significant associations with BP, log TAG and log HDL. By contrast, adjustment of BMI for WC reduced the correlation coefficients, although correlation coefficients with BP remained significant in boys. Vice versa, WC adjusted for BMI still had significant associations with BP and blood lipids (in girls only). There were no associations between the obesity indices and either total cholesterol or LDL levels. These two variables were therefore excluded from further analyses.

Prevalence of cardiovascular disease risk factors at normal or elevated obesity indices

The prevalences of elevated BP and blood lipids at normal (< 90 P) and elevated (≥ 90 P) obesity indices are shown in Table 4. When compared with normal-weight or normal-fat subjects, overweight and overfat subjects had higher BP. The prevalence of elevated blood levels was not significantly different for all obesity indices between subjects with normal and high indices.

Explained variance of cardiovascular disease risks by body mass index and waist circumference

Using stepwise regression analyses, a considerable variance in BP and blood lipids could be explained by BMI and WC (Table 5). The base model included age and pubertal development. The R^2 value for BMI and WC represented the additional variance (above the base model) explained by the obesity indices. BMI explained up to 10·9 % of the variance in CVD risk factors and WC explained up to 11·6 %. Combining BMI and WC explained up to 12·2 % of the CVD risks. Although the added variance above that predicted by BMI alone or WC alone was minimal, the combination of BMI and WC provided the best prediction.

Odds ratios of cardiovascular disease risks according to obesity indices

The results of the logistic regression models conducted within groups with normal (< 90 P) and elevated (≥ 90 P) BMI are presented in Table 6. Prevalence of hypertension, high TAG and low HDL was higher in 9–11-year-old boys with normal BMI but elevated either TSF or WC or %FM when compared with those having normal values in all obesity indices. In 9–11-year-old girls this was also seen for BP in girls with elevated TSF and for low HDL in girls with elevated WC. In adolescents, the prevalence of elevated systolic BP was increased in boys with an elevated TSF but normal BMI. In addition, the prevalence of high TAG was higher in adolescent boys with elevated WC but normal BMI when compared with normal BMI and normal WC. At increased BMI, the additional use of TSF or %FM did not increase the estimation of CVD risk factors (except estimation for high diastolic BP in 13–16-year-old boys which improved by adding a high FM). By contrast, using

Table 5. Explained variance (R^2) in systolic and diastolic blood pressure (BP_{sys} and BP_{dias}) and blood lipids by age, pubertal development, body mass index and waist circumference (linear regression analysis)

	Variation (R^2) explained by base model* (%)	Additional variation (R^2) explained by (%)		
		BMI	WC	BMI + WC
9–11-year-olds				
Boys				
BP_{sys}	0·4	10·9	11·6	12·2
BP_{dias}	3·3	1·7	1·6	1·8
Log TAG	0·0	0·8	0·7	0·4
Log HDL	0·2	1·7	2·5	2·3
Girls				
BP_{sys}	0·8	7·8	12·3	12·3
BP_{dias}	5·8	2·3	4·7	4·9
Log TAG	0·8	7·8	8·4	8·6
Log HDL	0·1	5·1	7·7	7·5
13–16-year-olds				
Boys				
BP_{sys}	2·1	10·7	10·6	11·4
BP_{dias}	1·3	5·7	5·1	5·3
Log TAG	1·2	6·4	6·5	6·7
Log HDL	3·4	4·0	3·7	3·8
Girls				
BP_{sys}	0·6	5·4	7·3	7·4
BP_{dias}	1·0	6·6	2·9	3·6
Log TAG	0·0	1·4	2·4	2·3
Log HDL	0·7	2·0	0·9	1·7

* The base model was a function of age and pubertal development.

increased WC as an additional obesity index further improved the estimation of elevated systolic BP in 9–11-year-old girls and adolescents.

OR of increases in BP and blood lipids for individual obesity indices stratified according to normal and elevated WC are shown in Table 7. Boys, aged 9–11 years, with normal WC had an increased prevalence of high BP when either TSF or %FM was elevated. This was contrary in girls of the same age, where the prevalence of hypertension was elevated when TSF or BMI was elevated. In addition, the prevalence of high TAG was elevated in children with normal WC but elevated BMI. Adolescents with normal WC but increased BMI had a higher diastolic BP. Systolic BP was increased in adolescent boys with elevated TSF but normal WC. In males of both age groups, increased TSF plus increased WC was associated with an increased prevalence of elevated systolic BP. In 9–11-year-old girls and adolescents, prevalence of high BP was elevated when BMI was elevated in addition to WC.

Discussion

In this cross-sectional study, we compared four obesity indices with respect to their association with CVD risk factors in children and adolescents. The main results of the present paper were that (i) all four obesity indices showed significant associations with CVD risk factors, (ii) correlation coefficients were similar for BMI and WC which both exceeded those of %FM and TSF and (iii) in children with normal BMI (especially in boys) or normal WC as well as in adolescents with elevated WC the additional use of a second obesity index further improved identification of CVD risk factors.

Body mass index v. *other obesity indices*

Although several anthropometric parameters have been shown to be associated with CVD risk factors, controversy still exists regarding the best anthropometric marker assessing the relationship between body fat (including fat distribution) and CVD risk factors. BMI is a well-established measure of relative FM in children and adolescents. However, BMI has some limitations: the relationship between BMI and fat and fat-free mass varies at different ages. Maynard *et al.* [22] could show that up to late adolescence, annual increases in BMI were driven primarily by increases in fat-free mass. Moreover, the sensitivity of BMI (in relation to %FM) is low[23]. Therefore, BMI is recommended for screening of overweight in population studies. By contrast, in the clinical setting, a more accurate measure of body fat is needed. Nevertheless, in children, overweight defined by BMI was shown to be a strong predictor of obesity and risk of CHD in young adulthood[5,24]. In addition, there was a close relationship between increased body weight and elevated BP[25]. In contrast, in another study in children WC rather than BMI was the best predictor of the metabolic syndrome[26]. Several studies have also shown that body size accounts for a greater proportion of variance in systolic BP than %FM[27–29]. In adults, Shen *et al.* [30] as well as Bosy-Westphal *et al.* [31] have recently shown that %FM had no advantage over BMI and WC in predicting obesity-related metabolic risk factors. In adolescents, Steinberger *et al.* [32] showed that when compared with %FM, BMI had a closer correlation with CVD risk factors. Our data support this idea for children.

In contrast, our data did not support our hypothesis that direct measures of FM or WC exceed the value of BMI. WC and BMI were similarly correlated to CVD risk factors. In addition, the association of either WC or BMI with CVD

Table 6. Prediction of elevated systolic and diastolic blood pressure (BP_{sys} and BP_{dias}) and blood lipids (BL) from elevations in obesity indices in children and adolescents with normal (<90th percentile; 90 P) and elevated (≥90 P) body mass index (logistic regression analyses)*

(Odds ratios and 95 % confidence intervals)

	BMI < 90 P						BMI ≥90 P					
	+TSF ≥90 P		+WC ≥90 P		+FM ≥90 P		+TSF ≥90 P		+WC ≥90 P		+FM ≥90 P	
	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI
9–11-year-old boys												
n†												
BP												
< 90 P	1860		1880		1886		35		28		26	
≥ 90 P	142		122		116		75		82		84	
BL												
< 90 P	370		377		366		3		4		3	
≥ 90 P	33		26		37		13		12		13	
High BP_{sys}	7·4‡	4·5, 12·0	6·9‡	4·2, 11·6	4·8‡	2·7, 8·3	1·6	0·5, 5·4	2·9	0·6, 13·6	2·6	0·6, 12·3
High BP_{dias}	4·2‡	2·7, 6·5	3·9‡	2·4, 6·3	4·2‡	2·6, 6·7	2·8	0·6, 13·6	0·7	0·2, 2·6	1·8	0·4, 8·7
High TAG	2·7‡	1·1, 6·8	3·8‡	1·5, 9·8	2·9‡	1·2, 6·8		–	0·1	0·0, 1·5	0·1	0·0, 1·0
Low HDL	3·6‡	1·5, 8·7	4·1‡	1·6, 10·5	2·0	0·8, 5·2		–	0·6	0·0, 9·2	0·4	0·0, 6·2
9–11-year-old girls												
n†												
BP												
< 90 P	1815		1846		1855		86		65		55	
≥ 90 P	99		68		59		108		129		139	
BL												
< 90 P	217		218		214		15		10		1	
≥ 90 P	8		7		11		12		17		26	
High BP_{sys}	2·5‡	1·2, 5·2	1·9	0·8, 4·9	1·3	0·4, 4·2	1·0	0·5, 2·1	2·7‡	1·1, 7·0	0·7	0·3, 1·5
High BP_{dias}	3·1‡	1·8, 5·3	1·7	0·8, 3·7	1·4	0·6, 3·4	1·1	0·5, 2·2	1·8	0·8, 4·0	1·0	0·5, 2·1
High TAG	1·1	0·1, 9·7	3·4	0·6, 18·5	1·8	0·4, 9·1	1·0	0·2, 5·0	0·6	0·1, 3·2		–
Low HDL	3·4	0·6, 18·2	8·3‡	1·7, 39·8	2·3	0·5, 11·2	0·4	0·0, 4·5	2·1	0·2, 23·3		–
13–16-year-old boys												
n†												
BP												
< 90 P	1309		1339		1330		70		42		51	
≥ 90 P	71		41		50		84		112		103	
BL												
< 90 P	269		169		269		10		7		9	
≥ 90 P	9		9		9		19		22		20	
High BP_{sys}	2·6‡	1·4, 4·6	1·6	0·7, 3·5	0·8	0·1, 1·8	1·5	0·7, 1·9	3·0‡	1·2, 7·1	1·9	0·9, 4·2
High BP_{dias}	1·1	0·4, 3·1	0·8	0·2, 3·5	1·2	0·4, 3·8	1·5	0·7, 3·3	1·9	0·8, 4·8	2·8‡	1·1, 7·1
High TAG	3·1	0·6, 15·6	5·6‡	1·3, 24·0	3·1	0·6, 16·4	2·8	0·3, 29·0	1·0	0·1, 13·5	2·3	0·2, 24·9
Low HDL	3·4	0·7, 17·6		–	4·2	0·8, 22·8	0·4	0·1, 2·2	1·1	0·1, 8·2	1·5	0·2, 9·8
13–16-year-old girls												
n†												
BP												
< 90 P	1396		1402		1433		70		64		43	
≥ 90 P	80		74		43		94		100		121	
BL												
< 90 P	292		285		302		18		13		11	
≥ 90 P	19		26		9		21		26		28	
High BP_{sys}	1·7	0·6, 4·3	1·0	0·3, 3·3	0·6	0·1, 4·2	0·6	0·3, 1·5	3·8‡	1·2, 11·9	1·4	0·5, 3·9
High BP_{dias}	1·4	0·6, 3·7	0·9	0·3, 2·9	1·0	0·2, 4·4	1·0	0·4, 2·3	1·6	0·7, 4·1	2·2	0·7, 6·9
High TAG	1·4	0·3, 6·6	1·6	0·4, 5·9		–	0·3	0·1, 1·5	7·1	0·7, 70·5	0·7	0·1, 3·8
Low HDL	1·8	0·5, 6·8	0·4	0·1, 2·7	2·8	0·6, 14·2	1·5	0·3, 7·7	1·7	0·3, 10·1	1·2	0·2, 7·4

TSF, triceps skinfold; WC, waist circumference; FM, fat mass derived from bioelectrical impedance analysis.
* OR indicate TSF, WC or %FM ≥90 P relative to TSF, WC or %FM < 90 P (OR = 1) within subjects with BMI < 90 P and BMI ≥90 P.
† Numbers of subjects for BP and BL measurements with obesity indices < 90 P and ≥90 P.
‡ Significant OR (P<0·05); models are adjusted for age and pubertal development.

risk factors remained even after controlling for each other (Table 3). The latter finding is in line with data of Lee *et al.* [33].

Identification of a risk group with cardiovascular disease risk factors

The present data argue in favour of the idea that (i) WC as well as BMI are appropriate to estimate CVD risk factors but (ii) more detailed information may result from their combined use. Of children and adolescents with an elevated obesity index, 20–30 % also had elevated levels in BP and blood lipids (Table 4). The characterisation of a risk group with elevated BP, high TAG or low HDL levels was improved by using an additional obesity index (Tables 6 and 7). However, in adolescents with normal BMI or normal WC the additional use of a second obesity index did not exceed the

Table 7. Prediction of elevated systolic and diastolic blood pressure (BP_{sys} and BP_{dias}) and blood lipids (BL) from elevations in obesity indices in children and adolescents with normal (<90th percentile; 90 P) and elevated (≥90 P) waist circumference (WC) (logistic regression analyses)*

(Odds ratios and 95 % confidence intervals)

	WC < 90 P						WC ≥90 P					
	+TSF ≥90 P		+BMI ≥90 P		+FM ≥90 P		+TSF ≥90 P		+BMI ≥90 P		+FM ≥90 P	
	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI
9–11-year-old boys												
n†												
BP												
< 90 P	1857		1929		1886		96		131		80	
≥ 90 P	103		31		74		128		93		144	
BL												
< 90 P	310		322		605		11		25		10	
≥ 90 P	16		4		21		25		11		26	
High BP_{sys}	4·4‡	2·3, 8·5	2·1	0·5, 9·4	2·7‡	1·1, 6·5	2·6‡	1·2, 5·7	0·9	0·4, 1·9	1·4	0·7, 3·0
High BP_{dias}	3·6‡	2·1, 6·2	2·5	0·9, 7·4	2·8‡	1·4, 5·5	1·7	0·8, 3·8	0·5	0·2, 1·1	1·8	0·8, 4·1
High TAG	2·8	0·9, 9·1	10·4‡	1·4, 76·4	2·2	0·7, 6·9	1·3	0·2, 7·6	0·2	0·0, 2·3	0·6	0·1 to 3·1
Low HDL	1·3	0·3, 5·9	3·7	0·4, 36·7	–		–		0·5	0·1, 3·1	4·2	0·5, 38·6
9–11-year-old girls												
n†												
BP												
< 90 P	1855		1911		1890		122		72		93	
≥ 90 P	124		68		89		102		152		131	
BL												
< 90 P	254		254		246		16		10		10	
≥ 90 P	11		11		19		21		27		27	
High BP_{sys}	2·5‡	1·3, 4·9	2·5‡	1·0, 5·9	1·2	0·4, 3·2	1·5	0·7, 3·1	3·5‡	1·3, 9·5	1·4	0·6, 3·0
High BP_{dias}	2·9‡	1·7, 4·8	2·3‡	1·2, 4·7	1·7	0·9, 3·4	1·6	0·8, 3·1	2·5‡	1·1, 5·7	1·5	0·7, 3·1
High TAG	2·6	0·5, 13·6	5·6‡	1·5, 21·5	4·1‡	1·4, 12·0	0·7	0·1, 3·9	1·0	0·1, 7·3	0·7	0·1, 5·6
Low HDL	0·9	0·1, 7·2	2·1	6·4, 9·8	1·9	0·5, 7·0	0·9	0·2, 4·3	0·7	0·1, 3·4	1·4	0·2, 8·2
13–16-year-old boys												
n†												
BP												
< 90 P	1315		1350		1335		76		41		57	
≥ 90 P	78		42		57		78		113		97	
BL												
< 90 P	264		269		266		15		9		12	
≥ 90 P	12		7		10		16		22		19	
High BP_{sys}	1·9‡	1·0, 3·4	1·6	0·7, 3·6	0·5	0·2, 1·5	2·6‡	1·3, 5·3	3·2‡	1·3, 7·8	3·3‡	1·5, 7·2
High BP_{dias}	1·5	0·6, 3·6	3·3‡	1·4, 7·7	1·3	0·5, 3·7	2·2	1·0, 5·0	7·3‡	1·6, 32·5	8·2‡	2·3, 28·7
High TAG	1·0	0·1, 8·0	1·8	0·2, 15·6	1·3	0·2, 10·4	3·2	0·5, 20·4	0·4	0·1, 2·4	1·9	0·3, 12·1
Low HDL	3·4	0·8, 13·6	3·3	0·6, 18·4	5·1‡	1·2, 22·1	0·8	0·1, 5·2	–		3·7	0·4, 37·8
13–16-year-old girls												
n†												
BP												
< 90 P	1364		1411		1397		112		75		89	
≥ 90 P	111		64		78		63		100		86	
BL												
< 90 P	273		285		283		37		26		30	
≥ 90 P	25		13		15		15		26		22	
High BP_{sys}	2·0	0·9, 4·3	1·6	0·6, 4·7	1·7	0·6, 4·4	0·9	0·4, 2·4	5·4‡	1·5, 19·1	1·9	0·7, 4·7
High BP_{dias}	1·8	0·9, 3·7	3·0‡	1·3, 6·6	2·7‡	1·3, 5·8	2·0	0·8, 5·1	5·1‡	1·4, 18·0	2·8‡	1·0, 7·6
High TAG	1·1	0·2, 4·8	1·2	0·1, 9·5	0·9	0·1, 7·1	0·8	0·2, 3·7	3·3	0·8, 14·4	1·1	0·3, 4·4
Low HDL	1·7	0·6, 5·4	1·6	0·3, 7·8	2·3	0·6, 8·6	4·3	0·8, 23·9	7·5	0·8, 67·7	4·1	0·7, 23·5

TSF, triceps skinfold; FM, fat mass derived from bioelectrical impedance analysis.

* OR indicate TSF, BMI or %FM ≥90 P relative to TSF, WC or %FM < 90 P (OR = 1) within subjects with WC < 90 P and WC ≥90 P.

† Numbers of subjects for BP and BL measurements with obesity indices < 90 P and ≥90 P.

‡ Significant OR ($P<0·05$); models are adjusted for age and pubertal development.

value of an individual BMI only. In contrast, in adolescents with elevated WC, the identification of high BP was improved by the use of a second obesity index (Table 7). This is in line with other cross-sectional data of 5–18-year-old children where TAG levels as well as BP values were highest when both BMI and WC were elevated[13]. However, using elevated BMI only, the additional use of a second obesity index did not improve risk estimation beyond that provided by BMI alone (Table 6). Regarding our second hypothesis the combined use of obesity indices can be recommended in subgroups only.

Faced with four different obesity indices we could not definitively say which index should be used. This is because similar risk estimations were observed for different indices. BMI and WC had the highest correlation to CVD risk factors;

thus the combination of these two parameters can be recommended. In addition, they are easy to measure.

Study limitations and methodological considerations

It should be mentioned that we have used our own population-specific 90 P of individual obesity indices to define overweight and overfat. Using different reference databases and cut-offs would lead to different prevalences of elevated parameters and therefore to differences in the association with CVD risk factors. For example, in our 9–11-year-old children the use of American[34], German[35] and worldwide[1] reference databases for BMI led to prevalences of overweight and obesity of 7·5, 17·6 and 23·3 %, respectively. However, focusing on the 10 % highest values of each obesity index allows a direct comparison of data.

Regarding measurements of blood lipids the use of fasting levels is preferable. However, in population studies blood sampling cannot always be performed under perfectly standardised conditions. Thus, we could not investigate all children and adolescents under fasting conditions. This obviously affects plasma TAG levels. However, reanalysis of TAG levels in our children showed only minor differences between fasting and non-fasting levels (see Methods). In contrast, larger differences were seen in adolescents, which may slightly bias the results.

We have used our own percentiles to define elevated or decreased levels in blood lipids. This was due to the lack of German reference data. Nevertheless, recalculating all analyses using American reference values[36] led to nearly the same significances.

In a linear regression analysis, we could only explain about 12 % of the variance in systolic BP and 2–9 % of the variance in blood lipids by BMI plus WC. These low numbers are comparable with data obtained in other cross-sectional studies; for example, explained variance of a lipid-related metabolic risk score was 8·5 and 6 % in 15-year-old boys and girls for BMI and 7·3 and 6 % for WC[37]. The association between obesity indices and CVD risk factors should become more obvious using longitudinal data. In addition, genetic factors add to the manifestation of CVD risk factors, for example, in a group of KOPS families we have recently analysed heritabilities of single traits of the metabolic syndrome which varied between 18 % (systolic BP) and 39 % (HDL)[38].

Conclusion

BMI and WC had similar associations with CVD risk factors. These associations exceeded those of other obesity indices. Risk estimations were improved by using a second obesity index in children with normal BMI (especially in boys) or normal WC and in adolescents with elevated WC.

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S. P.-D. had the original idea, did the statistical analyses and interpretation of the data, and wrote the manuscript. B. L., M. J. and D. L. acquired data. M. J. M. supervised the study, did the interpretation of the data and wrote the paper. All authors discussed the data and approved the final version of the paper.

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