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Sustained Hypertensive-Range Blood Pressure and Its Association with Adiposity Indicators in Children Aged 5–6 Years in Poland: A Cross-Sectional Study

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Abstract

Background/Objectives: Excess adiposity is associated with elevated blood pressure (BP) in childhood, but evidence for children aged 5–6 years is limited. We estimated the proportion of children with sustained hypertensive-range BP across three study visits and examined associations of adiposity indicators with systolic (SBP) and diastolic BP (DBP). **Methods:** This cross-sectional study included 133 children aged 5–6 years. BMI, WHtR, BFP, and FMI were assessed by anthropometry and bioelectrical impedance. BP was measured twice at each of three visits and interpreted using sex-, age-, and height-specific Polish percentiles. Sustained hypertensive-range BP was defined as SBP and/or DBP at or above the 95th percentile at all three visits. **Results:** Sustained hypertensive-range BP was observed in 24.8% of participants; however, elevated readings were not confirmed by auscultation or ambulatory BP monitoring. Per one-SD increment, BMI, BFP, and FMI were associated with 3.02 mmHg (95% CI: 1.55–4.48), 2.65 mmHg (1.06–4.24), and 2.74 mmHg (1.12–4.36) higher SBP, respectively; all remained significant after FDR correction. No adjusted associations were found for DBP. BFP was nominally associated with sustained hypertensive-range BP (OR = 1.55, 95% CI: 1.04–2.31; $p = 0.032$), but no adiposity marker remained significant after FDR correction. Optimism-corrected AUCs ranged from 0.502 to 0.595. **Conclusions:** Greater adiposity was associated with higher SBP, but not DBP. BMI, BFP, and FMI showed comparable associations with SBP, whereas the examined adiposity indicators had limited discriminatory ability for sustained hypertensive-range BP. These findings support concurrent assessment of adiposity and BP in early childhood rather than adiposity-based screening alone.

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1. Introduction

Childhood overweight and obesity represent a major and increasingly early public health challenge. Recent global evidence indicates that approximately one in five children and adolescents has excess weight, with obesity affecting about 8.5% of this population [1]. Excess adiposity is associated with an unfavorable cardiovascular profile, including

an increased prevalence of elevated blood pressure (BP) and hypertension already during childhood [1,2]. This is clinically important because BP shows significant tracking from childhood into adulthood, with childhood BP levels contributing to later cardiovascular risk [3]. Early identification of factors associated with elevated BP may therefore provide an important opportunity for cardiovascular prevention beginning in the first years of life.

The age of 5–6 years represents a clinically relevant period for investigating early cardiovascular risk, as children are still prepubertal and routine BP monitoring is already recommended at this age [4]. Importantly, subclinical vascular alterations may already be detectable in early childhood. In a study involving 306 healthy 5-year-old children, greater body mass and abdominal adiposity were associated with increased carotid intima–media thickness and less favorable arterial mechanical properties [5].

Although pediatric hypertension has been extensively investigated in school-aged children and adolescents, evidence in younger children remains comparatively limited. Recent meta-analyses indicate that the prevalence of pediatric hypertension varies substantially according to age, weight status, diagnostic criteria, BP measurement technique, and, importantly, the number of assessment visits [2,6,7]. In a large global meta-analysis, the pooled prevalence of sustained hypertension confirmed on at least three separate occasions was 3.89%, compared with 11.85% when hypertension was identified during a single screening visit. Importantly, the burden of pediatric hypertension appears to be increasing over time. Evidence indicated a marked temporal rise in sustained hypertension, with an average annual increase of approximately 7% between 2006 and 2021 [6]. Excess body weight further increases this burden, with sustained hypertension reported considerably more often in children with overweight or obesity than in those with normal weight [6]. Previous studies, including the Polish OLA study [8], the European IDEFICS study [9], and Chinese preschool cohorts [10], have provided important BP data in young children. However, evidence specifically addressing sustained hypertensive-range BP across three separate visits and its associations with multiple adiposity indicators in children aged 5–6 years remains limited. In the present study, hypertension classification was based on measurements obtained during three separate visits, providing a more stringent assessment of sustained hypertension in this age group. Importantly, BP reference values and measurement techniques may influence reported hypertension prevalence, as Polish preschool oscillometric percentiles are generally lower than several international references, while current AAP [11] and ESH [12] guidelines recommend auscultatory confirmation of elevated oscillometric BP readings.

Excess adiposity is consistently associated with higher BP in children, although the strength of this relationship may differ depending on the adiposity marker used [13–15]. Body mass index (BMI) remains the most widely used indicator because of its simplicity and clinical accessibility; however, it does not distinguish fat mass from lean mass and provides limited information on fat distribution [13,16]. Alternative measures, including waist-to-height ratio (WHtR), body fat percentage (BFP), and fat mass index (FMI), may better reflect central or total adiposity, but evidence that these markers are superior to BMI in identifying elevated BP is inconsistent [14,16]. Meta-analytic data from 21 cross-sectional studies involving nearly 178,000 children and adolescents aged 3–19 years have shown that BMI, waist circumference, and WHtR display broadly comparable discriminatory performance for elevated BP and hypertension, with no index emerging as consistently superior; notably, all indices performed better at identifying hypertension than milder elevations in BP, particularly BMI among girls [15]. Whether more direct measures of adiposity, such as BFP and FMI, provide additional information beyond BMI specifically in very young children remains uncertain.

Therefore, the aim of this study was to estimate the proportion of children with sustained hypertensive-range BP based on repeated BP measurements and to examine the

associations of different adiposity indicators with SBP and DBP in children aged 5–6 years. We additionally compared conventional anthropometric indices with body-composition-derived measures to assess whether the strength of these associations differed across markers of adiposity.

2. Materials and Methods

2.1. Study Participants

This cross-sectional study was conducted among children aged 5–6 years attending four preschools randomly selected from eligible preschools located in a suburban municipality in southeastern Poland. Following selection of the preschools, parents or legal guardians of all eligible children aged 5–6 years attending these institutions were invited to participate. A total of 17 preschools were eligible for selection, of which four were randomly selected. Across these preschools, 328 children met the age eligibility criteria and were invited to participate. Of these, 150 children were enrolled (response rate: 45.73%). The final analytical sample comprised 133 children, distributed across the four preschools as follows: [n = 24], [n = 46], [n = 21], and [n = 42].

The inclusion criteria were: (1) age 5–6 years; (2) attendance at one of the selected preschools; (3) written informed consent provided by a parent or legal guardian; (4) ability to participate in the anthropometric, body-composition, and BP assessment procedures and to follow instructions required for standardized measurements; (5) absence of contraindications to BIA, including implanted electronic medical devices; and (6) no use of medications known to affect BP. Age groups were defined according to completed years of age: 5-year-olds (5.00–5.99 years) and 6-year-olds (6.00–6.99 years). The exact age ranged from 5.21 to 6.98 years.

The sample-size calculation was based on the prevalence objective and the expected prevalence of hypertension in young children. Assuming an anticipated prevalence of approximately 6%, a 95% confidence level, and an absolute margin of error of 5 percentage points, the minimum required analytical sample was estimated at 87 participants. Although this represented the minimum required sample, a substantially larger recruitment target of approximately 150 children was adopted to improve the precision of the estimates and to account for potential absences, incomplete assessments, and failure to complete the repeated BP measurement protocol.

A total of 150 children were enrolled in the study. For inclusion in the final analytical sample, participants were required to have complete anthropometric and body-composition assessments and valid BP measurements obtained during all three study visits. Seventeen children were excluded because of absence during scheduled assessments or incomplete BP data across the three visits, resulting in a final analytical sample of 133 children (Figure 1). The recruitment process, inclusion flow, and reasons for exclusion are detailed in Figure 1.

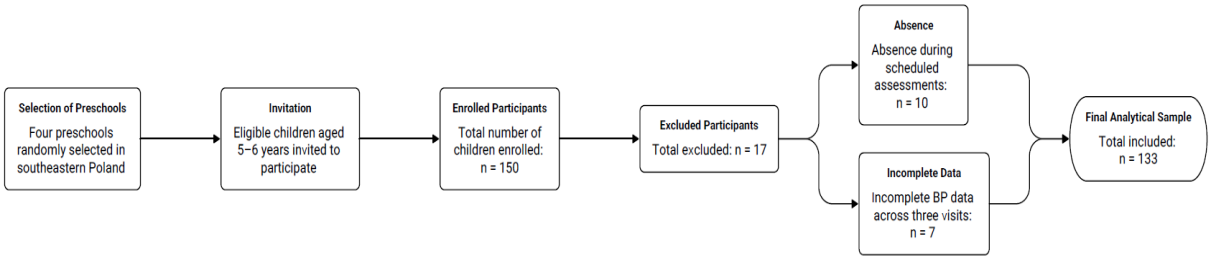


Figure 1. Flow diagram of participant screening, inclusion, and completion of the examinations.

Written informed consent was obtained from the parents or legal guardians of all participating children prior to study participation. The study protocol received approval from the Bioethics Committee of the Scientific Board of Physiotherapists at the Polish Physiotherapy Association (Resolution No. 2/01/2024, dated 17 January 2024). All procedures were carried out in accordance with the ethical standards of the Declaration of Helsinki.

2.2. Anthropometric Measurements

Anthropometric measurements were performed according to standardized procedures of the International Society for the Advancement of Kinanthropometry (ISAK). Body height was measured without shoes using a portable stadiometer (Tanita HR-001, Tokyo, Japan), with participants standing upright in the standardized anatomical position. Body mass was measured to the nearest 0.1 kg using a segmental body composition analyzer (Tanita MC-780 P MA; Tanita Corporation, Tokyo, Japan); the device provides bodyweight measurements in 0.1 kg increments.

Waist circumference and hip circumference were measured using a flexible, non-stretchable anthropometric tape in accordance with ISAK procedures. All circumference measurements were recorded to the nearest 0.1 cm. Measurements were obtained with the child standing in a relaxed upright position and were performed by trained researchers using the same standardized protocol for all participants. BMI was calculated as body mass in kilograms divided by height in meters squared (kg/m^2).

2.3. Body Composition Assessment

Body composition was assessed using multi-frequency segmental bioelectrical impedance analysis (BIA) with a Tanita MC-780 P MA analyzer (Tanita Corporation, Tokyo, Japan). The device uses eight electrodes and three measurement frequencies (5, 50, and 250 kHz) to estimate whole-body and segmental body-composition parameters. Measurements were performed in the morning, between 7:00 and 10:00 a.m., under standardized conditions. Children were assessed barefoot and wearing light indoor clothing. Parents were instructed to ensure that the children attended the assessment in a fasted state. During measurement, participants stood upright on the analyzer platform while maintaining contact with the foot and hand electrodes, according to the manufacturer's instructions. The parameters used in the present study included BFP, fat mass, muscle mass, fat-free mass (FFM), and total body water (TBW), expressed in kilograms and/or as percentages where applicable.

2.4. Adiposity Indices and Classification

BMI values were interpreted using sex- and age-specific Polish reference charts from the OLA study, developed for children aged 3–6 years [17]. Children were classified as having normal weight, overweight, or obesity; overweight was defined as BMI >85th percentile and obesity as BMI >97th percentile for age and sex [18]

WHR was calculated as waist circumference divided by hip circumference, whereas WHtR was calculated as waist circumference divided by height. In accordance with current recommendations for children aged ≥5 years, WHtR was dichotomized using a cutoff of 0.50, with values <0.50 classified as below the central-adiposity risk threshold and values ≥0.50 as increased central adiposity [19].

For exploratory categorical analyses, BFP was classified using the sex- and age-specific reference curves proposed by McCarthy et al. Children were categorized as below normal (<2nd percentile), normal (≥2nd to <85th percentile), excess adiposity (≥85th to <95th percentile), or obese (≥95th percentile) [20].

FMI was calculated as fat mass in kilograms divided by height in meters squared (kg/m^2). Because no categorical FMI thresholds were applied in the present study, FMI was analyzed as a continuous measure of adiposity.

2.5. Blood Pressure

BP was assessed using a validated automated oscillometric monitor (Welch Allyn, model 4200B-E2, Skaneateles Falls, NY, USA). Measurements were performed under standardized conditions in a quiet room. Before each assessment, children remained seated and rested for at least 5 min. BP was measured on the right arm, supported at heart level, using an appropriately sized cuff selected according to the child's arm circumference. BP assessment was performed during three separate study visits. At each visit, two consecutive BP measurements were obtained under the same standardized conditions. The same measurement protocol was applied at all three visits. The mean of the two readings was used as the BP value for each visit. BP values were interpreted using sex-, age-, and height-specific Polish reference percentiles developed for preschool children within the OLA study. The completed-year age classification was applied when assigning BP reference percentiles. These reference values were derived from oscillometric BP measurements obtained in a nationally representative sample of Polish children aged 3–6 years [8].

BP categories were based on the percentile-based classification of the 2016 ESH guidelines for children younger than 16 years [4], with the ≥95th-percentile threshold for hypertension also retained in the 2023 ESH guidelines [12]. The numerical percentile thresholds were derived from the Polish OLA oscillometric reference charts for children aged 3–6 years [8], rather than from the auscultatory reference tables used in ESH or AAP guidelines. Normal BP was defined as both SBP and DBP below the 90th percentile, whereas high-normal BP was defined as SBP and/or DBP from the 90th to below the 95th percentile, provided that neither value reached the hypertensive range. Hypertension was defined as SBP and/or DBP at or above the 95th percentile for sex, age, and height. For the purposes of this epidemiological analysis, hypertension was classified as sustained only when the hypertensive BP range was confirmed across all three separate study visits. Thus, classification was not based on a single screening assessment. Because BP was measured oscillometrically and ambulatory BP monitoring was not performed, this repeated-visit classification reflects study-visit BP status rather than a definitive clinical diagnosis of hypertension. For statistical analyses, all hypertension phenotypes and severity categories were pooled into a single hypertension group because of the small number of children within individual categories. None of the participating children had previously been diagnosed or treated for hypertension, and none were taking antihypertensive medication.

2.6. Statistical Analysis

Continuous variables were assessed for distributional characteristics using the Shapiro–Wilk test, skewness, and visual inspection of their distribution. Data are presented as mean ± standard deviation (SD) or median with interquartile range (IQR), as appropriate, whereas categorical variables are reported as n (%). Between-sex comparisons were performed using Welch's independent-samples *t*-test or the Mann–Whitney U test, with Hedges' g and rank-biserial correlation reported as effect sizes. Categorical variables were compared using Pearson's chi-square test or the Fisher–Freeman–Halton exact test when expected cell counts were small, with Cramer's V as the corresponding effect size. For binary BP analyses, children with normal and high-normal BP were combined into a single non-hypertension reference group. Crude odds ratios (ORs) with 95% confidence intervals (CIs) were estimated for hypertension across adiposity categories using two-sided Fisher's exact tests. Differences in SBP and DBP across adiposity categories were assessed using the Kruskal–Wallis test or Mann–Whitney U test, as appropriate;

significant Kruskal–Wallis tests were followed by Dunn's post hoc comparisons with Holm adjustment. Associations between continuous adiposity indicators and SBP or DBP were examined using Spearman's rank correlation coefficients. The prevalence of sustained hypertensive-range BP was calculated as the unweighted proportion of affected children in the analytical sample, without adjustment for preschool-level clustering.

Separate multivariable linear regression models were fitted for SBP and DBP, with BMI, WHtR, BFP, and FMI analyzed individually after standardization to one sample SD. This scaling allowed associations to be expressed per sample SD but did not represent age- or sex-specific z-scores. Models were adjusted for exact age, sex, and height, and HC3 heteroscedasticity-consistent standard errors were used. Separate logistic regression models evaluated associations of each standardized adiposity marker with hypertension and were adjusted for exact age and sex; results are presented as adjusted ORs with 95% CIs. Unlike the linear models, which used absolute SBP and DBP values as outcomes, the logistic models used a binary outcome defined according to age-, sex-, and height-specific BP percentiles. Height was therefore not included as an additional covariate in the logistic models. Model discrimination was assessed using the area under the receiver operating characteristic curve (AUC). Statistical significance was set at $p < 0.05$. Multiplicity was examined in sensitivity analyses by applying the Benjamini–Hochberg false discovery rate procedure to the main statistical comparisons summarized in Table S1. Additional sensitivity analyses included modified Poisson regression for prevalence ratios, bootstrap internal validation of logistic models using 2000 resamples, and linear models additionally adjusted for preschool as a fixed effect. Analyses were performed in Python 3.12 using SciPy 1.17.0 and scikit-learn 1.8.0.

3. Results

Table 1 summarizes the characteristics of the study population overall and by sex. Girls had significantly higher BFP than boys ($p = 0.012$), whereas boys were significantly taller and had higher muscle mass, FFM (both absolute and percentage values), and TBW (both absolute and percentage values) (all $p < 0.01$). No significant between-sex differences were observed for the remaining anthropometric and adiposity indicators, including BMI, waist circumference, hip circumference, WHR, WHtR, fat mass, and FMI. SBP and DBP were also comparable between girls and boys.

Table 1. Characteristics of the study population overall and by sex.

Variable	Overall	Girls	Boys	*p* Value	Effect Size
Age (years)	6.39 ± 0.59	6.36 ± 0.60	6.43 ± 0.58	0.489	g = −0.120
Height (cm)	119.8 ± 6.5	117.7 ± 6.0	121.6 ± 6.4	**<0.001**	**g = −0.625**
Body mass (kg)	22.1 (4.8)	21.6 (4.6)	22.6 (5.0)	0.074	r = −0.180
BMI (kg/m²)	15.51 (2.04)	15.58 (2.44)	15.39 (1.49)	0.697	r = 0.039
Waist circumference (cm)	54.1 ± 4.3	53.4 ± 4.1	54.7 ± 4.3	0.069	g = −0.316
Hip circumference (cm)	63.4 ± 4.7	62.8 ± 4.8	64.0 ± 4.7	0.135	g = −0.260
WHR	0.854 ± 0.039	0.852 ± 0.039	0.856 ± 0.040	0.533	g = −0.108
WHtR	0.451 (0.045)	0.454 (0.048)	0.448 (0.043)	0.403	r = 0.084
BFP (%)	18.0 (4.9)	18.8 (6.6)	17.5 (3.7)	**0.012**	**r = 0.254**
Fat mass (kg)	3.9 (1.7)	4.1 (2.0)	3.8 (1.2)	0.601	r = 0.053

Muscle mass (kg)	17.5 ± 2.7	16.8 ± 2.3	18.1 ± 2.8	**0.005**	**g = −0.494**
Muscle (%)	76.6 ± 3.8	75.9 ± 4.2	77.2 ± 3.2	0.053	g = −0.343
FFM (kg)	18.5 ± 2.8	17.7 ± 2.5	19.2 ± 3.0	**0.002**	**g = −0.546**
FFM (%)	81.1 ± 4.0	80.1 ± 4.3	82.0 ± 3.5	**0.004**	**g = −0.506**
TBW (kg)	13.6 ± 2.1	13.0 ± 1.8	14.1 ± 2.2	**0.002**	**g = −0.538**
TBW (%)	59.4 ± 2.9	58.7 ± 3.2	60.1 ± 2.5	**0.007**	**g = −0.476**
SBP (mmHg)	106.8 ± 8.6	106.5 ± 8.8	107.2 ± 8.4	0.652	g = −0.078
DBP (mmHg)	65.1 ± 7.8	65.6 ± 8.6	64.6 ± 7.1	0.473	g = 0.126
Pulse (beats/min)	88.3 ± 8.7	88.5 ± 9.3	88.2 ± 8.3	0.833	g = 0.037
FMI (kg/m²)	2.76 (0.92)	2.89 (1.51)	2.66 (0.72)	0.061	r = 0.188

Data are presented as mean ± SD or median (IQR), as appropriate. For variables presented as medians, values in parentheses represent the IQR, calculated as the difference between the third and first quartiles. Between-sex comparisons were performed using Welch's *t*-test for variables presented as mean ± SD and the Mann–Whitney U test for variables presented as median (IQR). Effect sizes are reported as Hedges' g and rank-biserial correlation (r), respectively; positive effect-size values indicate higher values in girls. BFP, body fat percentage; BMI, body mass index; BP, blood pressure; DBP, diastolic BP; FFM, fat-free mass; FMI, fat mass index; SBP, systolic BP; TBW, total body water; WHR, waist-to-hip ratio; WHtR, waist-to-height ratio. Significant *p* values are shown in bold.

As shown in Table 2, overweight and obesity according to BMI were identified in 16.5% and 8.3% of participants, respectively. An above-reference WHtR was observed in 6.0% of the sample. Based on BFP, excess adiposity and obesity were identified in 15.8% and 15.0% of participants, respectively. Normal BP, high-normal BP, and sustained hypertension according to the repeated-visit definition were identified in 63.9%, 11.3%, and 24.8% of participants, respectively. No significant sex differences were observed in BMI, WHtR, BFP, or BP categories.

Table 2. Distribution of adiposity categories and blood pressure status overall and by sex.

Domain	Category	Overall n (%)	Girls n (%)	Boys n (%)	*p* Value	Effect Size
BMI category	Normal	100 (75.2)	45 (71.4)	55 (78.6)	0.483	V = 0.105
	Overweight	22 (16.5)	13 (20.6)	9 (12.9)		
	Obesity	11 (8.3)	5 (7.9)	6 (8.6)		
WHtR category	Within reference range	125 (94.0)	60 (95.2)	65 (92.9)	0.721	V = 0.050
	Above reference threshold	8 (6.0)	3 (4.8)	5 (7.1)		
BFP category	Below normal	2 (1.5)	2 (3.2)	0 (0.0)	0.237	V = 0.181
	Normal	90 (67.7)	43 (68.3)	47 (67.1)		
	Excess adiposity	21 (15.8)	7 (11.1)	14 (20.0)		
	Obesity	20 (15.0)	11 (17.5)	9 (12.9)		
BP category	Normal	85 (63.9)	36 (57.1)	49 (70.0)	0.287	V = 0.137

High-normal	15 (11.3)	9 (14.3)	6 (8.6)
Hypertension	33 (24.8)	18 (28.6)	15 (21.4)

Data are presented as n (%); percentages are calculated within the overall sample or the respective sex group. Hypertension required SBP and/or DBP at or above the 95th percentile at all three study visits and includes all hypertension phenotypes and severity categories pooled into a single group. *p* values and Cramer's V are reported for the overall comparison within each domain. Pearson's chi-square test was used when expected cell counts were adequate; Fisher's exact test or the Fisher–Freeman–Halton exact test was used otherwise. BP, blood pressure; BFP, body fat percentage; BMI, body mass index; WHtR, waist-to-height ratio.

The distribution of adiposity categories according to BP status is presented in Table 3. In crude analyses, children with obesity had higher odds of hypertension than those with normal weight (OR = 4.80, 95% CI: 1.08–21.70; $p = 0.019$). The combined overweight/obesity category was also associated with higher odds of hypertension (OR = 2.60, 95% CI: 1.00–6.58; $p = 0.036$). Similarly, children with WHtR above the reference threshold had higher odds of hypertension than those within the reference range (OR = 5.77, 95% CI: 1.03–38.82; $p = 0.023$). However, none of these associations remained statistically significant after FDR correction (Table S1).

Table 3. Distribution of adiposity categories according to blood pressure status and crude associations with hypertension.

Adiposity Classification	Category	Normal/High-Normal BP n (%)	Hypertension n (%)	Crude OR (95% CI)	*p* Value
BMI category	Normal weight	80 (80.0)	20 (60.6)	Reference	-
	Overweight	15 (15.0)	7 (21.2)	1.87 (0.56–5.67)	0.259
	Obesity	5 (5.0)	6 (18.2)	**4.80 (1.08–21.70)**	**0.019**
	Overweight + obesity	20 (20.0)	13 (39.4)	**2.60 (1.00–6.58)**	**0.036**
BFP category	Below/normal fat	72 (72.0)	20 (60.6)	Reference	-
	Excess adiposity	16 (16.0)	5 (15.2)	1.12 (0.29–3.75)	0.779
	Obesity	12 (12.0)	8 (24.2)	2.40 (0.74–7.40)	0.096
	Excess adiposity + obesity	28 (28.0)	13 (39.4)	1.67 (0.67–4.08)	0.277
WHtR category	Within reference range	97 (97.0)	28 (84.8)	Reference	-
	Above reference threshold	3 (3.0)	5 (15.2)	**5.77 (1.03–38.82)**	**0.023**

Data are presented as n (%); percentages were calculated within BP-status groups. Crude ORs compare each category with the stated reference category; 95% CIs are conditional exact intervals, and *p* values are from two-sided Fisher's exact tests. Hypertension required SBP and/or DBP at or above the 95th percentile at all three study visits and includes all hypertension phenotypes pooled into a single group. BFP, body fat percentage; BMI, body mass index; BP, blood pressure; CI, confidence interval; OR, odds ratio; WHtR, waist-to-height ratio. Significant estimates and *p* values are shown in bold.

SBP differed significantly across both BMI and BFP categories (Table 4; both global $p < 0.001$). Dunn–Holm post hoc comparisons showed significantly higher SBP in children with overweight and obesity than in those with normal weight (adjusted $p = 0.029$ and $p =$

0.001, respectively), whereas SBP did not differ significantly between the overweight and obesity groups (adjusted $p = 0.144$). For BFP categories, only the comparison between the below/normal-fat and obesity groups remained significant after Holm adjustment (adjusted $p = 0.001$). Children with WHtR above the reference threshold had higher SBP and DBP than those within the reference range ($p = 0.007$ and $p = 0.043$, respectively); however, only the SBP comparison remained statistically significant after FDR correction (Table S1). In Table 5, nominal differences in WHR and BFP between children with and without hypertension did not remain statistically significant after FDR correction (Table S1).

Table 4. Systolic and diastolic blood pressure according to adiposity category.

Adiposity Classification	Category	SBP (mmHg)	DBP (mmHg)	Global/ Contrast *p* Value	Post Hoc Comparisons, Holm-Adjusted *p*
BMI category	Normal weight	105.2 (10.1)	63.6 (10.1)	**SBP: <0.001;** DBP: 0.181	Normal weight vs Overweight: **0.029**
	Overweight	110.1 (7.5)	64.6 (8.0)		Normal weight vs Obesity: **0.001**
	Obesity	116.8 (12.8)	67.0 (8.3)		Overweight vs Obesity: 0.144
	Overweight + obesity	111.7 (10.0)	65.8 (7.7)	**SBP: <0.001;** DBP: 0.149	
BFP category	Below/normal fat	105.2 (10.1)	63.8 (9.5)	**SBP: <0.001;** DBP: 0.201	Below/normal fat vs Excess adiposity: 0.071
	Excess adiposity	110.4 (11.0)	63.5 (10.2)		Below/normal fat vs Obesity: **0.001**
	Obesity	112.0 (8.8)	67.0 (5.7)		Excess adiposity vs Obesity: 0.235
	Excess adiposity + obesity	110.7 (11.7)	65.2 (8.8)	**SBP: <0.001;** DBP: 0.293	
WHtR category	Within reference range	106.3 (10.9)	63.8 (8.8)	**SBP: 0.007; DBP: 0.043**	Not applicable (two categories)
	Above reference threshold	116.7 (8.3)	69.2 (6.0)		

SBP and DBP are presented as median (IQR), with IQR calculated as the difference between the third and first quartiles. For BMI and BFP classifications, *p* values reported for the three mutually exclusive categories are from the Kruskal–Wallis test. Statistically significant SBP omnibus tests were followed by Dunn's pairwise post hoc tests with Holm adjustment. No DBP post hoc comparisons were performed because the corresponding omnibus tests were not statistically significant. *p* values for the combined categories are from the Mann–Whitney U test comparing each combined group with its reference group. For WHtR, *p* values are from the Mann–Whitney U test comparing the two categories; post hoc testing was therefore not applicable. BFP, body fat percentage; BMI, body mass index; DBP, diastolic BP; IQR, interquartile range; SBP, systolic BP; WHtR, waist-to-height ratio. Significant *p* values are shown in bold.

Table 5. Anthropometric and body-composition indicators according to blood pressure status.

Variable	Normal/High-Normal BP	Hypertension	*p* Value
WHR	0.858 ± 0.039	0.842 ± 0.038	**0.045**
WHtR	0.451 (0.039)	0.449 (0.064)	0.710
BFP (%)	18.0 (4.7)	18.4 (6.8)	**0.046**
Muscle (%)	77.3 (4.5)	77.1 (5.6)	0.084
FFM (%)	81.8 (4.7)	81.6 (6.3)	0.107
BMI (kg/m^2)	15.55 (1.61)	15.41 (2.97)	0.403
FMI (kg/m^2)	2.72 (0.87)	2.81 (1.59)	0.133

The normal/high-normal BP group combines children with normal and high-normal BP. Data are presented as mean ± SD for WHR and median (IQR) for all other variables; for variables presented as medians, values in parentheses represent the IQR, calculated as the difference between the third and first quartiles. *p* values are from Welch's *t*-test for WHR and the Mann–Whitney U test for all other variables. Hypertension includes all hypertension phenotypes pooled into a single group. BFP, body fat percentage; BMI, body mass index; BP, blood pressure; FFM, fat-free mass; FMI, fat mass index; IQR, interquartile range; SD, standard deviation; WHR, waist-to-hip ratio; WHtR, waist-to-height ratio. Significant *p* values are shown in bold.

Positive correlations with SBP were observed for BMI, waist circumference, hip circumference, BFP, and FMI (Table 6), and all five associations remained statistically significant after FDR correction (Table S1). None of the examined adiposity indicators were significantly correlated with DBP. In the multivariable linear regression models adjusted for exact age, sex, and height, each one-SD higher BMI, BFP, and FMI was associated with 3.02 mmHg (95% CI: 1.55–4.48), 2.65 mmHg (95% CI: 1.06–4.24), and 2.74 mmHg (95% CI: 1.12–4.36) higher SBP, respectively (Table 7). These associations remained statistically significant after FDR correction (Table S1). WHtR was nominally associated with higher SBP (1.46 mmHg per one-SD increment, 95% CI: 0.10–2.82; $p = 0.036$), but this association did not remain significant after FDR correction (q = 0.071). No adjusted associations between the examined adiposity indicators and DBP were observed.

Table 6. Spearman correlations of adiposity indicators with systolic and diastolic blood pressure.

Indicator	SBP, ϱ	*p* Value	DBP, ϱ	*p* Value
BMI (kg/m^2)	**0.357**	**<0.001**	0.038	0.665
Waist circumference (cm)	**0.244**	**0.005**	0.096	0.271
Hip circumference (cm)	**0.349**	**<0.001**	0.128	0.143
WHR	−0.091	0.300	−0.004	0.965
WHtR	0.090	0.304	−0.002	0.978
BFP (%)	**0.310**	**<0.001**	0.027	0.754
FMI (kg/m^2)	**0.316**	**<0.001**	0.015	0.862

Values are Spearman's rank correlation coefficients (ϱ). BFP, body fat percentage; BMI, body mass index; DBP, diastolic BP; FMI, fat mass index; SBP, systolic BP; WHR, waist-to-hip ratio; WHtR, waist-to-height ratio. Significant coefficients and *p* values are shown in bold.

Table 7. Adjusted associations of adiposity indicators with systolic and diastolic blood pressure.

Adiposity Marker	SBP: Adjusted Coefficient (95% CI), mmHg per 1 SD	*p* Value	DBP: Adjusted Coefficient (95% CI), mmHg per 1 SD	*p* Value
BMI	**3.02 (1.55–4.48)**	**<0.001**	0.23 (−1.29–1.75)	0.766
WHtR	**1.46 (0.10–2.82)**	**0.036**	0.01 (−1.38–1.40)	0.986
BFP (%)	**2.65 (1.06–4.24)**	**0.001**	0.10 (−1.62–1.82)	0.908
FMI (kg/m²)	**2.74 (1.12–4.36)**	**0.001**	0.27 (−1.33–1.86)	0.742

Each adiposity marker was analyzed in a separate model and standardized to one sample SD. The corresponding SDs were 1.73 kg/m² for BMI, 0.029 for WHtR, 4.09 percentage points for BFP, and 1.01 kg/m² for FMI. Coefficients represent the adjusted difference in BP (mmHg) per one-SD increase in the adiposity marker. All models were adjusted for exact age, sex, and height and used HC3 heteroscedasticity-consistent standard errors. BFP, body fat percentage; BMI, body mass index; BP, blood pressure; CI, confidence interval; DBP, diastolic BP; FMI, fat mass index; SBP, systolic BP; SD, standard deviation; WHtR, waist-to-height ratio. Significant estimates and *p* values are shown in bold.

In the multivariable logistic regression models adjusted for exact age and sex, BFP was nominally associated with hypertension (adjusted OR = 1.55 per one-SD increment, 95% CI: 1.04–2.31; $p = 0.032$) (Table 8). However, this association did not remain statistically significant after FDR correction (q = 0.101), and none of the other adiposity indicators were significantly associated with hypertension in the adjusted logistic models (Table S1). Apparent model discrimination was modest, with AUC values ranging from 0.576 for WHtR to 0.642 for BFP (Table 8).

Table 8. Adjusted associations of adiposity indicators with hypertension and apparent model discrimination.

Adiposity Marker	Adjusted OR per 1 SD (95% CI)	*p* Value	AUC (95% CI)
BMI	1.41 (0.96–2.08)	0.079	0.629 (0.523–0.734)
WHtR	1.00 (0.67–1.49)	0.983	0.576 (0.466–0.687)
BFP (%)	**1.55 (1.04–2.31)**	**0.032**	0.642 (0.534–0.749)
FMI (kg/m²)	1.47 (1.00–2.15)	0.051	0.632 (0.526–0.739)

Each adiposity marker was analyzed in a separate model and standardized to one sample SD. The corresponding SDs were 1.73 kg/m² for BMI, 0.029 for WHtR, 4.09 percentage points for BFP, and 1.01 kg/m² for FMI. All models were adjusted for exact age and sex; 33 hypertension events were observed. The outcome was coded as 0 for normal or high-normal BP and 1 for sustained hypertension, defined as SBP and/or DBP at or above the 95th percentile at all three study visits; all hypertension phenotypes and severity categories were pooled into a single group. AUC values refer to the complete model and represent apparent (in-sample) discrimination; 95% CIs were calculated using DeLong's method. AUC, area under the receiver operating characteristic curve; BFP, body fat percentage; BMI, body mass index; BP, blood pressure; CI, confidence interval; FMI, fat mass index; OR, odds ratio; SD, standard deviation; WHtR, waist-to-height ratio. Significant estimates and *p* values are shown in bold.

In the prevalence-ratio sensitivity analysis, BMI-defined obesity was associated with a higher prevalence of hypertension after adjustment for exact age and sex (adjusted PR = 3.70, 95% CI: 1.71–8.04; $p < 0.001$). Significant associations were also observed for the combined overweight/obesity category (adjusted PR = 1.97, 95% CI: 1.08–3.57; $p = 0.027$) and WHtR above the reference threshold (adjusted PR = 2.96, 95% CI: 1.53–5.71; $p = 0.001$) (Table S2).

Bootstrap internal validation showed attenuation of model discrimination, with optimism-corrected AUC values ranging from 0.502 for WHtR to 0.595 for BFP, indicating weak discrimination for hypertension (Table S3). Finally, additional adjustment for preschool as a fixed effect did not materially alter the pattern of the linear regression results: BMI, WHtR, BFP, and FMI remained positively associated with SBP, whereas none of the adiposity indicators were associated with DBP (Table S4).

4. Discussion

The principal finding of this study is that greater adiposity in children aged 5–6 years was associated predominantly with higher SBP rather than DBP. Among the examined adiposity indicators, BMI, BFP, and FMI showed consistent independent associations with SBP after adjustment for age, sex, and height, and these associations remained significant after FDR correction, whereas no corresponding associations were observed for DBP. Sustained hypertension according to the study's repeated-visit definition was identified in 24.8% of the study population; however, associations between adiposity and categorical hypertension were less consistent, with only nominal significance in the adjusted logistic models and no association remaining significant after FDR correction. Moreover, the modest apparent and optimism-corrected AUC values indicated limited discriminatory ability of the adiposity markers for identifying hypertension.

The most consistent finding of the present study was the association between greater adiposity and higher SBP, whereas no corresponding relationship was observed for DBP. Each one-SD increase in BMI, BFP, and FMI was associated with approximately 3.02, 2.65, and 2.74 mmHg higher SBP, respectively, after adjustment for age, sex, and height. This pattern is consistent with previous pediatric studies suggesting that adiposity is more strongly related to the systolic than the diastolic component of BP, although the dissociation was more complete in the present study: in a cohort of 6863 nine-year-old children, both BMI and total fat mass were positively associated with SBP and, to a lesser extent, DBP, whereas in the present sample of younger children (5–6 years) no adjusted association with DBP was detected at all [13]. Similarly, in a study of Chinese children and adolescents aged 6–18 years, adiposity measures were more strongly associated with SBP than DBP, with DBP reaching significance only in the youngest stratum (6–11 years) and not in adolescents, and BMI showing the strongest overall association with BP [21]. A study using both office and home BP measurements likewise found that obesity exerted a more pronounced effect on SBP than on DBP, regardless of measurement setting [22]. Importantly, associations between adiposity and BP have also been demonstrated in children as young as 4–7 years, indicating that adverse BP–adiposity relationships may already be detectable in early childhood, although that study observed associations with both SBP and DBP [23]. Potential mechanisms include obesity-related sympathetic nervous system activation, altered sodium homeostasis, activation of the renin–angiotensin–aldosterone system, inflammation, and endothelial dysfunction [24]. These mechanisms may increase cardiac output and peripheral vascular load and could contribute to the early elevation of SBP observed in children with greater adiposity. The absence of corresponding associations with DBP may indicate that, at this early age, adiposity-related BP differences are expressed predominantly through the systolic component. This interpretation is biologically plausible given the influence of excess adiposity on cardiac output, sympathetic

activity, vascular function, and volume regulation; however, the cross-sectional design of the present study does not allow the underlying mechanisms to be determined.

An important finding of the present study is that more direct measures of adiposity did not demonstrate a clear advantage over BMI in relation to SBP. BMI, BFP, and FMI showed comparable adjusted associations with SBP, whereas the association for WHtR was weaker and did not remain significant after FDR correction. This is broadly consistent with previous pediatric evidence showing that more sophisticated or centrally focused adiposity measures do not necessarily outperform BMI for identifying BP abnormalities. In the QUALITY Study, which compared BMI, waist circumference, WHtR, skinfold-derived body fat, and DXA-derived total and central fat, neither WHtR nor DXA measures showed superior ability to identify children with elevated SBP compared with BMI [25]. Similarly, a systematic review and meta-analysis including 21 studies and 177,943 children and adolescents found no statistically significant superiority of BMI, waist circumference, or WHtR for discriminating elevated BP or hypertension [15]. Evidence specifically from young children also supports this interpretation: in a general-population sample of children aged 3–7 years, WHtR was not superior to BMI or waist circumference in relation to body fatness, and in a separate sample of overweight/obese children aged 3–5 years, WHtR also showed the weakest correlation with cardiometabolic risk factors, including SBP, compared with BMI and WC [26]. Taken together, these findings suggest that the additional complexity of body-composition assessment may not translate into a substantially stronger association with BP in young children. Accordingly, our findings do not indicate a clear advantage of body-composition-derived adiposity measures over BMI in identifying children with higher SBP.

The prevalence of sustained hypertension according to the study definition was 24.8%, which is considerably higher than estimates reported for general pediatric populations. A recent global meta-analysis including more than 3.6 million children and adolescents estimated the prevalence of sustained hypertension, confirmed on at least three separate occasions, at 3.89%, compared with 11.85% when classification was based on a single screening visit [6]. An earlier meta-analysis using repeated BP assessments similarly reported a pooled prevalence of 4.0%, with an estimated prevalence of 4.32% among 6-year-old children—one of the lowest values across the age range studied, well below the pubertal peak of 7.89% at age 14 [2]. Although BP classification in our study was based on measurements obtained during three separate visits, several methodological factors may have contributed to the higher estimate. In particular, we applied age-, sex-, and height-specific Polish BP reference values derived from the OLA study using oscillometric measurements in preschool children [8]. Importantly, the 90th and 95th percentiles in these Polish reference charts are generally lower than corresponding US, German, and other European reference values [8]. In the comparisons reported by Grajda et al. [8], differences in the 95th-percentile thresholds reached 5 mmHg for SBP and 7 mmHg for DBP in boys, with smaller differences observed in girls. Such differences in reference thresholds may influence the proportion of children classified as having hypertensive-range BP, even when measurements are repeated across separate visits. However, because the participants were not reclassified using alternative reference systems, the extent to which the choice of reference values contributed to the observed proportion of 24.8% cannot be quantified. Other potential contributing factors include population characteristics, adiposity distribution, situational stress, and measurement-related factors, including limitations of oscillometric assessment and possible cuff-related error. Recruitment from only four preschools and the absence of cluster-adjusted prevalence estimates further limit the precision and generalizability of the findings. Accordingly, the 24.8% figure should be interpreted as the proportion of children meeting the study's repeated-visit hypertensive-range BP definition under the applied Polish oscillometric reference system, rather than

as an estimate of clinically confirmed hypertension in the general population of Polish children aged 5–6 years.

From a clinical perspective, these findings support attention to BP already in early childhood. Current European recommendations advise BP screening from 3 years of age, with more frequent assessment in children with risk factors for hypertension [4]; our findings support continued attention to BP within this existing framework, particularly in children with excess adiposity. However, the weak discriminatory performance of all examined adiposity indicators—BMI, BFP, FMI, and WHtR alike—indicates that none of these measures can substitute for direct BP measurement or serve as a stand-alone screening tool for hypertension. Rather, because BMI performed comparably to the more complex body-composition measures, routinely available anthropometric data may help identify children in whom careful BP assessment is particularly relevant. Our findings therefore support integrating assessment of adiposity and BP within routine pediatric preventive care, but do not by themselves justify population-based hypertension screening in preschool settings beyond current recommendations.

The stronger and more consistent associations observed for continuous SBP than for categorical hypertension should not be regarded as contradictory. Indeed, children with hypertensive-range BP did not have higher median BMI or WHtR, while differences in FMI were small (Table 5). Moreover, 20 of 33 children (60.6%) with hypertensive-range BP had normal BMI, reflecting the predominance of normal-weight children in the study sample. Nevertheless, hypertensive-range BP was observed in 20.0% of normal-weight children compared with 54.5% of children with BMI-defined obesity (Table 3). Categorization of BP reduces information and statistical power, which is particularly relevant given the 33 hypertension events in the present sample. Although the nominal association between BFP and hypertension did not survive FDR correction, modified Poisson models suggested higher hypertension prevalence for BMI-defined obesity and combined overweight/obesity. An association was also observed for WHtR ≥ 0.50, but this finding was based on only eight children and was not consistently supported by analyses using continuous WHtR. Nevertheless, optimism-corrected AUC values of only 0.502–0.595 indicated weak discrimination. Thus, adiposity indicators appear to capture variation in SBP more consistently than they identify children crossing a categorical hypertension threshold and should not be considered stand-alone screening tools for hypertension.

Strengths and Limitations

The main strengths of this study include the focus on a very young and relatively understudied age group, classification of BP based on measurements obtained during three separate visits, and the simultaneous assessment of several anthropometric and body-composition indicators. SBP and DBP were analyzed separately, and the robustness of the findings was further examined using FDR correction, modified Poisson regression, bootstrap internal validation, and models additionally adjusted for preschool. Several limitations should also be acknowledged. The cross-sectional design precludes causal inference. The sample-size calculation was based on prevalence estimation, and the modest sample size (n = 133), including only 33 children with hypertension, limited the precision of categorical and multivariable analyses. Although height was incorporated into the percentile-based BP classification, residual height-related confounding in the logistic models cannot be excluded. Furthermore, continuous age-, sex-, and height-standardized BP z-scores were not analyzed, limiting direct comparisons between modeling approaches. BP was measured oscillometrically, and neither auscultatory confirmation nor ambulatory BP monitoring was performed; therefore, white-coat effects and some classification uncertainty cannot be excluded. Participants were recruited from four preschools in a single suburban municipality, limiting geographic generalizability. Furthermore, the prevalence

estimate was not adjusted for within-preschool clustering, which may have affected its precision. Body composition was assessed using BIA rather than DXA. Previous research in children aged 3–8 years demonstrated discrepancies between BIA- and DXA-derived estimates [27]. Although the MC-780 uses multiple measurement frequencies (5, 50, and 250 kHz), body-composition estimates remain dependent on device-specific prediction algorithms and assumptions regarding tissue hydration. In young children, age-related differences in body proportions and fat-free mass hydration, as well as variations in hydration status and electrode contact, may affect measurement accuracy despite the use of multiple frequencies [28]. Furthermore, McCarthy's BFP reference curves were developed using a different BIA device (Tanita BC-418MA), potentially leading to misclassification when applied to the MC-780. Finally, sample-based standardization did not account for age- and sex-specific adiposity distributions, although age and sex were included in the regression models. Agreement between BMI-, BFP-, and WHtR-based classifications was not formally assessed; therefore, differences in the proportions of children assigned to adiposity categories should not be interpreted as measures of concordance. Similarly, applying the 6-year reference values to children aged 6.00–6.99 years may have introduced some classification uncertainty, particularly among those exceeding the original OLA preschool reference sample's age range. Finally, only eight children had WHtR ≥ 0.50, resulting in imprecise categorical estimates with wide confidence intervals. The lack of consistent associations in continuous WHtR analyses further limits the robustness of these findings, which should therefore be interpreted as exploratory.

5. Conclusions

In children aged 5–6 years, greater adiposity was consistently associated with higher SBP, whereas no corresponding associations were observed for DBP. BMI, BFP, and FMI remained independently associated with SBP after adjustment for age, sex, and height and after FDR correction, with no clear evidence that body-composition-derived measures provided an advantage over conventional BMI. Hypertensive-range BP sustained across all three study visits was observed in 24.8% of participants under the study definition; however, associations between adiposity and categorical hypertension were less robust, and the examined adiposity indicators showed limited discriminatory ability for identifying hypertension. These findings suggest that the relationship between excess adiposity and BP may already be evident in early childhood, predominantly through the systolic component. Although concurrent assessment of adiposity and BP may be useful in routine pediatric care, the limited discriminatory performance of adiposity indicators does not support their use as stand-alone screening tools for hypertensive-range BP. Larger prospective studies are needed to confirm these findings and determine their long-term cardiovascular significance.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/jcm15239303/s1, Table S1: False discovery rate sensitivity analysis for the main statistical comparisons; Table S2: Crude and adjusted prevalence ratios for hypertension across adiposity categories; Table S3: Bootstrap internal validation of the multivariable logistic models for hypertension; Table S4: Preschool-adjusted associations of adiposity indicators with systolic and diastolic blood pressure.

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Abbreviations

AUC	area under the receiver operating characteristic curve
BFP	body fat percentage
BIA	bioelectrical impedance analysis
BMI	body mass index
BP	blood pressure
CI	confidence interval
DBP	diastolic blood pressure
DXA	dual-energy X-ray absorptiometry
FDR	false discovery rate
FFM	fat-free mass
FMI	fat mass index
IQR	interquartile range
ISAK	International Society for the Advancement of Kinanthropometry
OR	odds ratio
PR	prevalence ratio
SBP	systolic blood pressure
SD	standard deviation
TBW	total body water
WHR	waist-to-hip ratio
WHtR	waist-to-height ratio

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