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Original Article

Blood pressure values in healthy normal weight children and adolescents in eight European countries: auscultatory and oscillometric measurements

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ABSTRACT

Aim: The aim of the study is to provide BP values adjusted for sex, age and height in a large sample of healthy and normal weight children and adolescents 3–17 years in eight European countries, using standardized BP measurement by oscillometric and auscultatory methods.

Subjects and Methods: In 38.374 children (20.189 girls) BP values were measured following the European Society of Hypertension guidelines. To derive BP percentiles the estimated influences of age and height simultaneously on BP levels were estimated.

Results: The estimated BP values corresponding to 90th, 95th, and 99th systolic and diastolic percentiles according to height percentiles, age and sex were calculated. In both methods, the 90th and 95th percentiles of systolic blood pressure, tended to increase with both age and height, higher in boys than in girls without differences in diastolic blood pressure. The study illustrates the differences in 95th Blood Pressure percentile obtained by oscillometric and auscultatory methods in both sexes at the 50th height percentile. The threshold corresponding to 95th percentile at age 13 is close to 130/80 mmHg in both sexes and measurement methods at median height and at age 17 it is around 140/90 mmHg for boys.

Conclusions: The progressive increment of blood pressure in children across age is largely influenced by height. In boys blood pressure values still increase after 13 years old, while in girls the BP increment after this age was lower. Differences in systolic blood pressure and diastolic blood pressure among the two used methods are minimal except in the oldest age group.

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1. Introduction

The importance of high blood pressure (BP) as a modifiable risk factor for early disability and death is well established [1]. Although the majority of adverse outcomes occur in adulthood, high BP is a lifelong problem that can become apparent early in life, its importance in the young being recognized by the recommendation of guidelines [2–7] to start measuring BP at the age of three years and at any available occasion thereafter. Childhood hypertension (HTN) is not uncommon, 2–4 % and increasing over decades [8], but its actual prevalence varies in different studies due to normative data used and demographic changes over time. Other problems of paramount importance are the lack of data on future adverse outcomes (heart failure, stroke, chronic kidney disease, effect on neurocognitive function) associated with BP values and the progressive BP increase with age and body size. This means that it is difficult to establish a fixed cut-off for systolic and diastolic BP elevations, leading to the use of percentiles values based on age, sex and height and the definition of the hypertensive BP level at the 95th or higher percentile of the normal BP distribution.

From the very beginning, the auscultatory method has been used as a reference for the assessment of BP in the upper arm, with a methodology adapted to each child [2,9]. Oscillometric devices have replaced the mercury sphygmomanometer in a large number of medical centres, especially in European countries, due to the ban of mercury [10,11]. The development of oscillometric methods provides easy-to-use devices and facilitates BP measurements. However, the use of this method requires a robust validation process in children. In addition, although in children both auscultatory and oscillometric methods are now largely used no large-scale head-to-head comparisons has ever been done [4]. Previous European paediatric recommendations [3,4] used named American data to establish the BP percentiles (Fourth Report) and the diagnosis of hypertension [2]. Former studies on the distribution of BP values in Europe have been performed with heterogeneous methodologies [12–16].

In 2020, the European Commission approved and funded a network of excellence, the COST (CO-operation in Science and Technology) Action HyperChildNET, in which 26 countries were included. Considering that current reference values are built upon 40 years old American data, members of HyperChildNET recognized the opportunity to establish a collaborative analysis with available cohorts in some of the participating countries.

The aim of the present study is to provide BP values adjusted for sex, age and height in a large sample of healthy and normal weight children and adolescents aged 3–17 years in eight European countries participating in the COST HyperChildNET Action, using standardised BP measurement by oscillometric and auscultatory methods.

2. Subjects and methods

2.1. Study population

The HyperChildNET Database contains data from eight European country cohorts, whose data have in part been published [17–23]. The study includes healthy and normal weight children and adolescents of both sexes aged 3 to 17 from Croatia, Czech Republic, Greece, Hungary, Poland, Portugal, Spain and Turkey. In all cohorts BP values have been obtained cross-sectionally. The Spanish cohort includes 4.14 % children with more than one observation. Overall, the study included 39.711 evaluations from 38.374 children.

Information about the origin of the data is shown in Supplementary Table 1, including the year of collection, the number of subjects, age range, sex, devices used, measurement protocol, and number of measurements. Height and weight were collected in all children at the time of examination and their weight status was categorized, according to the World health Organisation (WHO), by the definition of normal weight as a body mass index lower than the 85th percentile specifically for age and sex [24].

In children younger and older than 12 years, parents and participants, respectively, gave informed written consent to participation of the children in the study. The data were initially stored in Institutions or Universities of the participating centres and transfer to a central database was supervised and approved by the corresponding Data Protection Officer (DPO). The database was hosted by a Spanish internet service provider, with its storage systems within Spain, with backups from data processing centre in Madrid. The database meets all privacy and security criteria as well as the norms of the European Union. The DPO of the General Hospital of Valencia and the DPO of the University of las Palmas de Gran Canaria (Spain) signed an agreement to perform the statistical analyses by two of the authors who both signed an agreement of confidentiality. The Institutional Committee for the Protection of Human Subjects of each Institution gave its approval of the study and the DPOs of the participating institutions approved the way the data storage and the transfer to the central data file was done.

2.2. BP and weight measurement procedures

Blood pressure values were obtained by trained examiners in accordance with the ESH Guidelines [3,4] on the use of a sphygmomanometer of mercury or oscillometric devices. After 5 min of rest and with no eating or exercise in the 30 min before the measurement, BP and heart rate were obtained on the right arm of the seated children with back supported by the chair, legs uncrossed, and feet flat on the floor. Subjects should rest their bare arm with the mid-arm at heart level on table and should not talk during or between measurements using an appropriately sized cuff according to arm width (40 % of the arm circumference) and length (4×8 cm, 6×12 cm, 9×18 cm, 10×24 cm, to cover 80–100 % of the individual's arm circumference). Blood pressure was measured three times with an interval of 3 min between measurements and the average of the last two or alternatively the two available measurements were used. With the auscultatory method, Korotkoff sounds were used to assess systolic blood pressure (SBP) (K1) and diastolic blood pressure (DBP) (K5) while deflating the cuff. Validated automatic oscillometric BP devices were used according to the criteria for use in children and adolescents (OMRON M4 [25,26], Omron 705 IT [27], OMRON M3500 [28], Riester Ri-Champion N [29], Datascope Accutor Plus [30]). The monitors were validated by ISO [25–28], or alternatively by the ESH International protocol [30] and one device was considered equivalent to an ISO validated device [29]. Almost all subjects in the oscillometric and auscultatory sample (99.93 % and 56.56 % respectively) had three BP readings. The mean BP was calculated using the second and third measurements [4], or alternatively the two available measurements.

Body weight was recorded to the nearest 0.1 kg with the subjects wearing light indoor clothing and no shoes. Height was recorded to the nearest 0.5 cm using a standardized wall-mounted height board. To assess the weight status, WHO reference values were used. These reference values, widely accepted and disseminated, are based on data collected from a "healthy" population during the late 70 s, a period before the development of the childhood obesity epidemic [24].

The WHO standards use a consistent methodology and cut-offs, facilitating comparisons across different settings. The WHO growth charts are widely available online and in print, making them easily accessible to healthcare professionals and parents [24].

2.3. Sample of analysis

We applied three key inclusion criteria to select the sample of analysis to compute BP percentiles by age and height for each sex. First, participants were required to have no missing information on relevant variables, including BP readings, age, weight, and height (around 98 % of the original sample). Second, only children and adolescents aged between 3 and 17 years (inclusive) at the time of the reading were considered. The analysis included only normal weight children and adolescents, defined according to the WHO growth charts [24]. Two samples were selected according to the measurement methodology, i.e. auscultatory or oscillometric.

Blood pressure percentiles were calculated and reported for both methodologies. After applying the inclusion criteria, the oscillometric sample consisted of 25,048 evaluations, while the auscultatory sample consisted of 14,663 evaluations (Table 1).

2.4. Statistical analysis

We computed two alternative sets of height percentiles; one based on the WHO growth charts [24] and the other on the height distribution of our sample. We used height percentiles derived from our sample, as this provides the best fit for the height distribution.

To compute BP values, we related BP to sex, age and height using a polynomial regression methodology according to previous studies [31]. This approach enabled us to identify the simultaneous influence of age and height on BP levels for each sex. The model accommodates nonlinear relationships by including power terms for height and age up to the fourth degree. The contribution of height and age to SBP and DBP for child “i” is estimated as follows:

$$BP_i = \alpha + \sum_{j=1}^{4} \beta_j {}^* \left(\ddot{age}_i \right)^j + \sum_{k=1}^{4} \gamma_k {}^* (Zh_i)^k + \varepsilon_i \quad (1)$$

where $\varepsilon_i \sim N(0, \sigma^2)$. BP_i refers to the mean systolic or diastolic BP for child “i”, while $\ddot{age}_i = age_i - \overline{age}$ represents the age of individual “i” centred at the average age in the sample. Additionally, Zh_i identifies the Z-score of the individual “i” height. Robust standard errors were used to account for heteroscedasticity, correcting the computation of residuals for potential non-constant variance across different age or height groups. Eq. (1) was estimated separately for each sex. Residual diagnoses were performed to assess model specification.

Next, to derive BP percentiles by height, age, and sex, we used the estimated influences of these factors on BP levels, as captured by the coefficients from Eq. (1). The *pth* percentile of BP for a child of a given age x_i and height Z-score Zh_t is then estimated by Rosner et al. [31]:

$$\theta_p = \hat{\alpha} + \sum_{j=1}^{4} \hat{\beta}_j {}^* \left(\ddot{age}_i \right)^j + \sum_{k=1}^{4} \hat{\gamma}_k {}^* (Zh_i)^k + Z_p \hat{\sigma} \quad (2)$$

where Z_p refers to the *pth* percentile of a standard normal distribution and $\hat{\sigma}$ is the standard deviation of the residuals from Eq. (1).

The goodness of fit for the selected model was evaluated by comparing the predicted mean BP values with the observed values.

2.5. Robustness analysis

As mentioned before, the Spanish cohort included 4.14 % of subjects with more than one set of BP readings. The potential bias that could arise from repeated observations was addressed by a weighted regression analysis which mitigated the overrepresentation of these individuals by treating all the observations from the same child as a single observation. Repeated measurements were weighted using the inverse of the number of observations for child "i". This approach ensures that children with multiple records do not disproportionately influence the results, allowing for a more balanced analysis of BP levels across the sample. No significant differences are reported in BP percentiles with respect to the unweighted approach.

3. Results

3.1. General characteristics of the study population

The characteristics of the study population aged 3 to 17-years, and grouped by sex, are shown in Table 1. All included children and adolescents were healthy and with a normal weight for both sexes. The vast majority of the recruited individuals was white Caucasians. Concerning oscillometric measurements, the study included 25.048 clinical evaluations in 24.390 children and adolescents (12.936 females) while the auscultatory method included 14.663 clinical evaluations in children and adolescents (7.253 females) (Table 1). The number of evaluations grouped by age and sex according to the BP measurement method is shown in Supplementary Fig. 1A and 1B.

3.2. BP percentiles

For both BP measurement methodologies height and age were significant predictors of SBP and DBP in both sexes ($p < 0.001$). Height seemed to affect BP nonlinearly in boys, but linearly in girls. The effects of age on SBP and DBP were nonlinear for both sexes. The models were able to explain from 21.8 % to 42.56 % of the variation of SBP and from 12.8 % to 18.6 % of the DBP variation, performing better with SBP and boys in both the auscultatory and oscillometric BP measuring samples (Supplementary Table 2A and 2B).

3.3. Oscillometric and auscultatory BP values

Fig. 1 (Panel A, B, C and D) shows the predicted 95th percentiles for systolic BP by sex, across age and height percentiles (5th, 50th' and 95th) for the oscillometric and auscultatory BP measurement sample. The corresponding data for DBP are shown in Fig. 2. Overall, in both methods SBP was higher in boys than in girls without differences in DBP. In contrast with the BP data, heart rate was significantly higher in girls than in boys (Table 1).

The SBP and DBP 95th percentile (the value commonly used to define HTN in children and adolescents) across age in subjects in the 50th height percentile is shown in Fig. 3 (Panel A, B, C, D). SBP and DBP gradually increased with age, with a more noticeable rise between age 9–11 years, particularly for SBP, whose slope was steeper than that of DBP. SBP and DBP were similar in boys and girls until 13 years after which the increment was more pronounced in boys. As a result, at 17 years of age SBP was 4 and 11 mmHg higher in boys than in girls with

Table 1
General characteristics of the study population measured BP with oscillometric and auscultatory method: BP values grouped by sex.

Variable	Boys	Girls	Total
OSCILLOMETRIC			
Number of subjects	11,454	12,936	24,390
Number of evaluations	11,782	13,266	25,048
Age (years)	12.36 (4.33)	12.46 (4.30)***	12.36 (4.33)
Weight (kg)	44.48 (17.36)	42.96 (15.42)***	44.48 (17.36)
Height (cm)	151.67 (24.46)	149.53 (22.19)***	151.67 (24.46)
BMI (kg/m^2)	18.27 (2.57)	18.29 (2.56)	18.27 (2.57)
BP values			
Systolic (mmHg)	108.94 (13–62)	107.28 (12.31)***	108.94 (13.62)
Diastolic (mmHg)	63.55 (9.84)	63.58 (9.13)	63.57 (9.47)
Heart rate	80.81 (13.15)	83.38 (13.16)***	82.16 (13.21)
AUSCULTATORY			
Number of subjects	6731	7253	13,984
Number of evaluations	7136	7627	14,663
Age (years)	14.49 (4.29)	11.67 (4.25)*	11.58 (4.27)
Weight (kg)	43.13 (18.93)	41.18 (15.77)***	42.12 (17.40)
Height (cm)	149.89 (26.00)	146.70 (22.07)***	148.24 (24.10)
BMI (kg/m^2)	17.95 (2.56)	18.15 (2.64)***	18.05 (2.60)
BP values			
Systolic (mmHg)	107.53 (16.03)	106.36 (15.20)***	106.92 (15.61)
Diastolic (mmHg)	64.30 (10.76)	62.24 (19.22)	64.27 (10.48)
Heart rate (beats/min)	80.61 (13.14)	84.73 (12.56)***	82.61 (13.02)

Values are average and (standard deviation); * Denotes significant differences between boys and girls $p < 0{,}01$; *** Denotes significant differences between boys and girls $p < 0.001$;.
SBP Systolic Blood Pressure; DBP Diastolic Blood Pressure; HR Heart Rate.

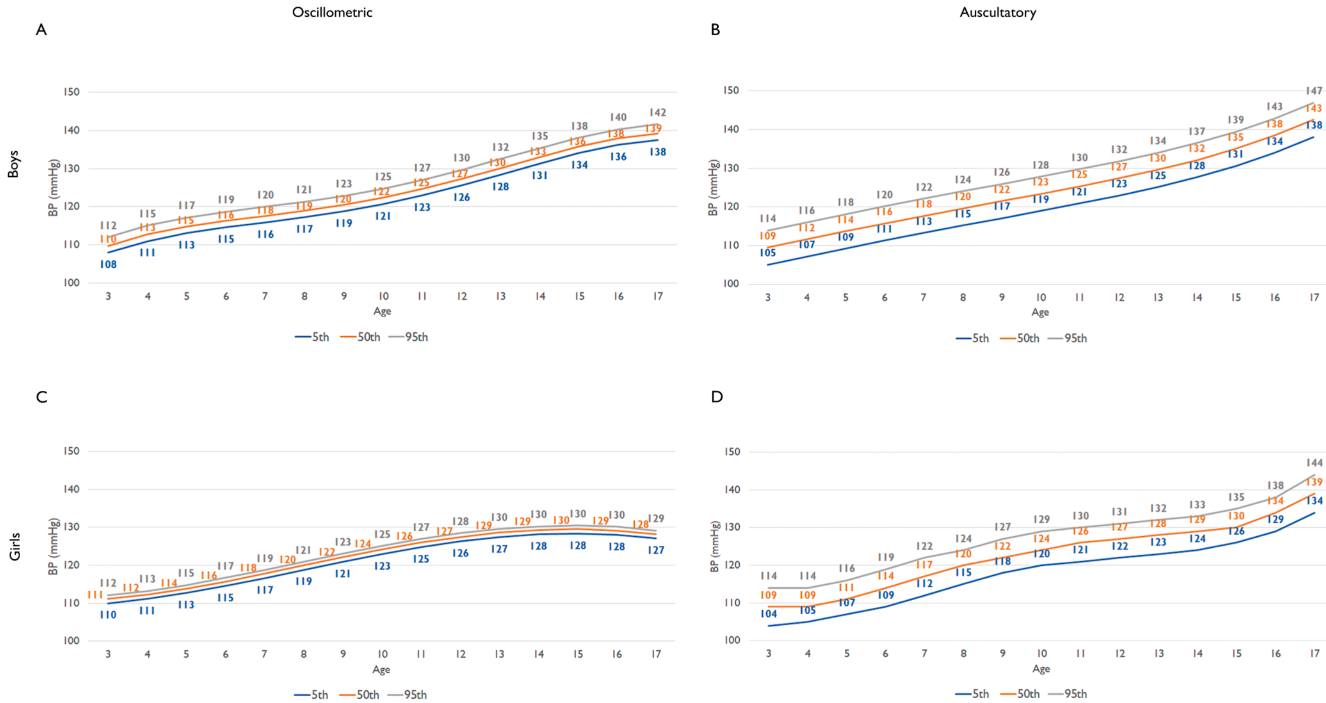

Fig. 1. Tracking of SBP 95th percentile in boys and girls across the age at different height percentiles (5th, 50th and 95th). *Panel A: Tracking of Oscillometric SBP 95th percentile in boys across the age at different height* percentiles. *Panel B: Tracking of Auscultatory SBP 95th percentile in boys across the age at different height percentiles. Panel C: Tracking of Oscillometric SBP 95th percentile in girls across the age at different height percentiles. Panel D: Tracking of Auscultatory SBP 95th percentile in girls across the age at different height percentiles.*

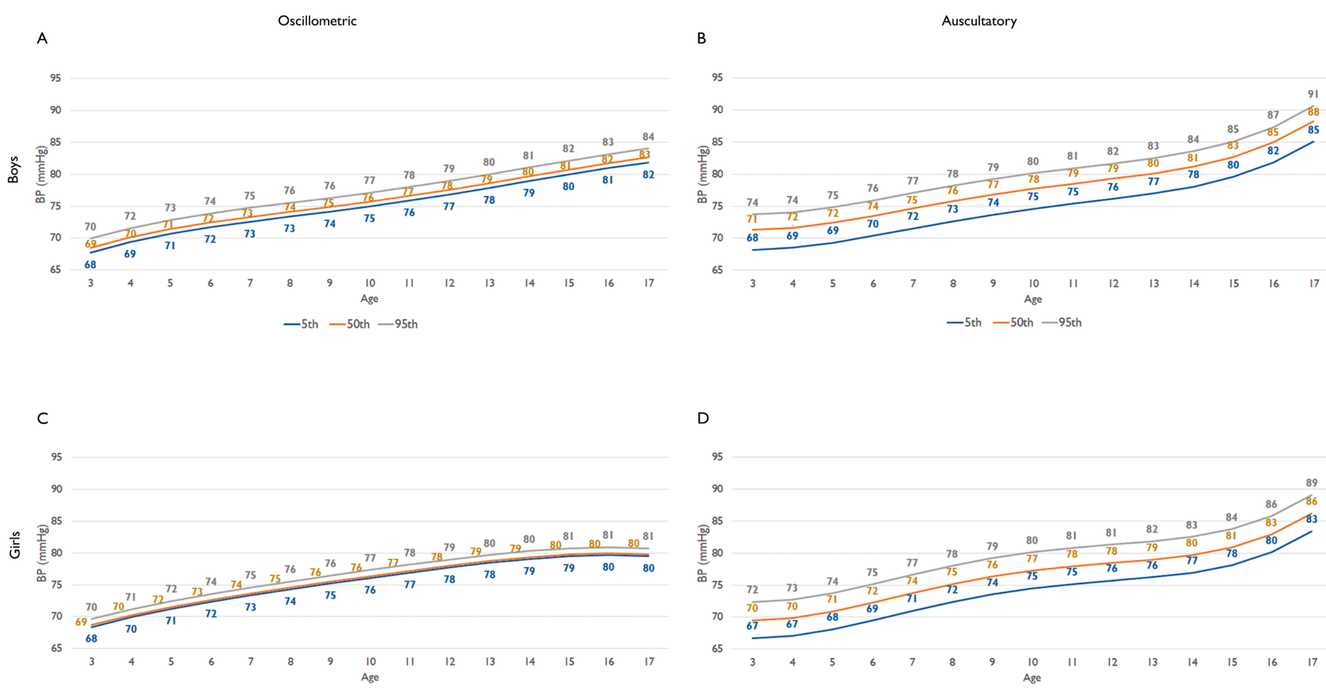

Fig. 2. Tracking of DBP 95th percentile in boys and girls across the age at different height percentiles (5th, 50th and 95th). *Panel A: Tracking of Oscillometric DBP 95th percentile in boys across the age at different height percentiles. Panel B: Tracking of Auscultatory DBP 95th percentile in boys across the age at different height percentiles. Panel C: Tracking of Oscillometric DBP 95th percentile in girls across the age at different height percentiles. Panel D: Tracking of Auscultatory DBP 95th percentile in girls across the age at different height percentiles.*

the auscultatory and the oscillometric method, respectively. The corresponding differences for DBP were 2 and 3 mmHg with both methods, respectively.

With both methods, the 90th percentile of SBP, tended to increase with both age and height, although the relationship was non-linear, particularly with age. Among children of the same age, taller individuals exhibited a higher BP in the context of a linear trend, while the age effect remained nonlinear. SBP was consistently higher in boys than

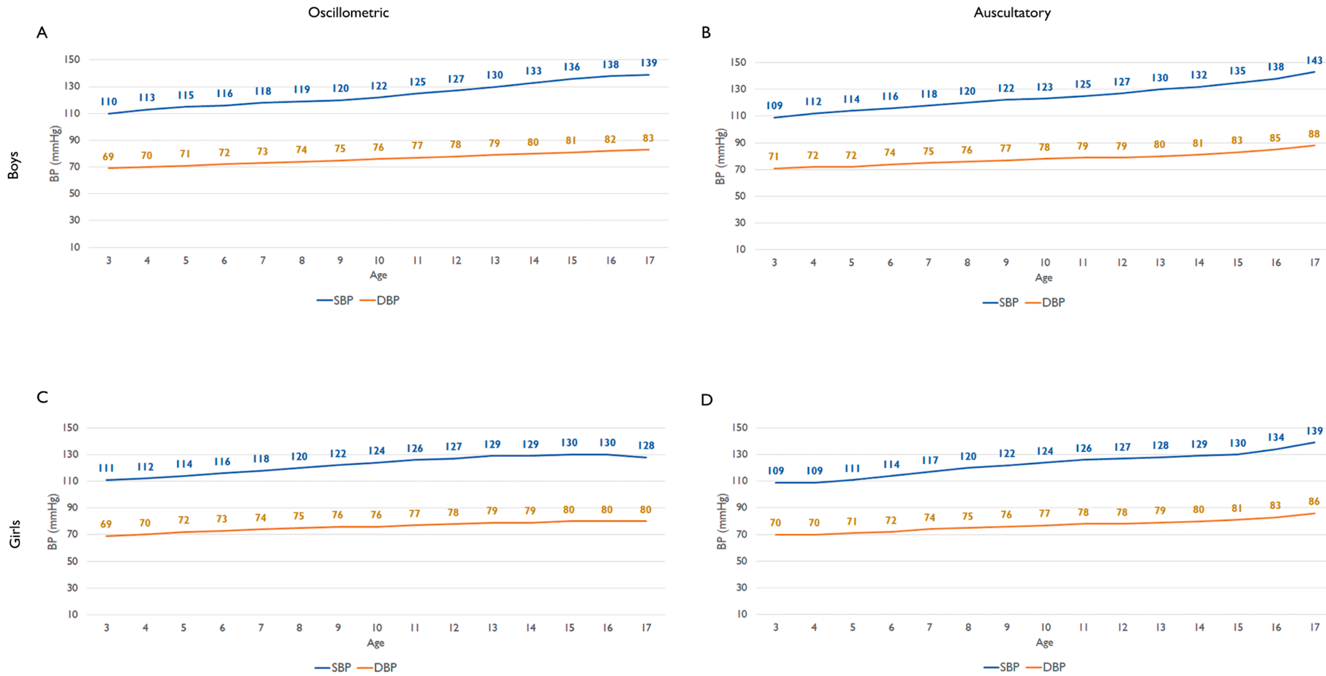

Fig. 3. SBP and DBP 95th percentile in boys and girls across the age in the 50th height percentile. *Panel A. Oscillometric SBP and DBP 95th percentile in boys across the age in the 50th height percentile. Panel B. Auscultatory SBP and DBP 95th percentile in boys across the age in the 50th height percentile. Panel C. Oscillometric SBP and DBP 95th percentile in girls across the age in the 50th height percentile. Panel D. Auscultatory SBP and DBP 95th percentile in girls across the age in the 50th height percentile.*

in girls, while sex-related differences in DBP were smaller (See Supplementary Figs 2 and 3). The 95th percentile of SBP and DBP increased with age for a given height percentile and rose with height at a specific age (Supplementary Figs 4 and 5). Among children of the same age, taller individuals exhibited a higher BP over a linear trend, while the age effect remained nonlinear. SBP was consistently higher in boys than in girls, with less DBP differences between sexes.

The estimated oscillometric and auscultatory SBP and DBP values corresponding to percentiles 90th, 95th, and 99th percentiles according to height percentiles 5th, 10th, 25th, 50th, 75th, 90th, 95th are shown in Tables 2, 3, 4 and 5 for girls and boys, respectively. Height percentiles are also provided in centimeters. In general, BP exhibited the same pattern across age and height percentiles with both methods, increasing with age at a given height percentile and with height at a given age. BP percentiles for boys were equal to or higher than those for girls within the same height and age groups, with average differences of about 1 mmHg per year.

In boys the 95th auscultatory SBP percentile ranged from 105 mmHg at 3 years of age- and the shortest height to 147 mmHg at 17-years of age and the tallest height. The corresponding values for the oscillometric SBP were 108 mmHg and 142 mmHg while in girls they were 104 mmHg and 144 mmHg (auscultatory method) and 110 mmHg and 129 mmHg (oscillometric method). In boys the 95th DBP percentile ranged from 68 mmHg and 68 mmHg (auscultatory and oscillometric method) at 3 years of age and the shortest height to 91 mmHg and 84 mmHg respectively for 17-years of age and the tallest height, while in girls the corresponding values ranged from 67 mmHg and 68 mmHg to 89 mmHg and 81 mmHg (Tables 2, 3, 4 and 5).

3.4. Percentile distribution

Based on the BP percentiles reported in Tables 2, 3, 4 and 5, in the oscillometric sample 6.15 % children had high normal BP, with SBP and/or DBP levels above the 90th but below the 95th percentile. SBP and/ or DBP levels higher or equal to the 95th percentile was observed in 9.27 % of children in the first and only visit (Supplementary Table 3). This reflects the percentage of readings higher or equal to the 95th percentile in the first examination. For comparison in a metanalysis performed by Sun et al. [32], the prevalence of BP readings equal to or higher than the 95th percentile was 12.1 % (10.1–14.0 %) at the 1st visit, 5.6 % (4.3–7.0 %) at the second visit and 2.7 % (2.1–3.3 %) at the third visit. It is important to highlight that in children and adolescents the definition of HTN requires a persistent BP elevation on at least three separate occasions [3–7].

3.5. Differences between oscillometric and auscultatory BP values

Supplementary Figure 6 shows the differences in the 95th percentile of SBP and DBP obtained by oscillometric and auscultatory methods in boys and girls at the 50th height percentile.

In boys, the SBP differences at the median height ranged from –1 to 1 mmHg, with oscillometric values generally being higher than the auscultatory ones and a peak difference of −3 mmHg at age 17. In girls, the differences ranged from –4 to 3 mmHg, with oscillometric values also higher than auscultatory values, and a peak difference at age 17 of –11 mmHg. The corresponding DBP differences were smaller, ranging from –2 to −1 mmHg in boys and from −1 to 0 mmHg in girls, with values peaking at age 17 and auscultatory values generally higher.

The threshold corresponding to 95th percentile at the age of 13 at a median height was close to 130/80 mmHg in both sexes and measurement methods. At age 16 at median height SBP was around 140 and DPB ranged from 82 to 88 mmHg in both methods.

4. Discussion

The present study provides information on the distribution of BP percentiles in healthy normal weight children and adolescents according to age, sex and height percentiles. Data were collected in eight cohorts across Europe, ranging from South to Central and Eastern countries, obtained with a standardized auscultatory or oscillometric methodology. The subjects included were distributed over an age range of 3 to 17 years. The inclusion of healthy and normal weight children and

Table 2
Oscillometric systolic and diastolic blood pressure values for girls by age and height percentiles.

		SBP (mmHg)							DBP (mmHg)						
		Height percentile							Height percentile						
Age		5th	10th	25th	50th	75th	90th	95th	5th	10th	25th	50th	75th	90th	95th
3	Height (cm)	90	91	94	97	99,5	102	104	90	91	94	97	99,5	102	104
	BP 90th	106	106	107	107	108	108	108	65	65	65	66	66	66	67
	BP 95th	110	110	111	111	112	112	112	68	68	69	69	69	69	70
	BP 99th	117	118	118	119	119	119	120	74	74	74	75	75	75	75
4	Height (cm)	96	97	100	103	106	109	110	96	97	100	103	106	109	110
	BP 90th	107	108	108	108	109	109	109	67	67	67	67	67	68	68
	BP 95th	111	111	112	112	113	113	113	70	70	70	70	71	71	71
	BP 99th	119	119	119	120	120	120	121	76	76	76	76	76	77	77
5	Height (cm)	103	104	107	111	113	116	118	103	104	107	111	113	116	118
	BP 90th	109	109	110	110	110	111	111	68	68	68	68	69	69	69
	BP 95th	113	113	113	114	114	115	115	71	71	71	72	72	72	72
	BP 99th	120	120	121	121	122	122	122	77	77	77	77	78	78	78
6	Height (cm)	108	110	113	117	120	124	125	108	110	113	117	120	124	125
	BP 90th	111	111	111	112	112	113	113	69	69	69	70	70	70	71
	BP 95th	115	115	115	116	116	116	117	72	72	73	73	73	73	74
	BP 99th	122	122	123	123	124	124	124	78	78	78	78	79	79	79
7	Height (cm)	114	116	119	123	127	130	132	114	116	119	123	127	130	132
	BP 90th	113	113	113	114	114	115	115	70	70	70	71	71	71	72
	BP 95th	117	117	117	118	118	119	119	73	73	74	74	74	74	75
	BP 99th	124	124	125	125	126	126	126	79	79	79	80	80	80	80
8	Height (cm)	120	121	125	129	133	136	138	120	121	125	129	133	136	138
	BP 90th	115	115	116	116	116	117	117	71	71	71	72	72	72	72
	BP 95th	119	119	120	120	120	121	121	74	74	74	75	75	75	76
	BP 99th	126	127	127	127	128	128	128	80	80	80	80	81	81	81
9	Height (cm)	125	127	131	135	138	142	145	125	127	131	135	138	142	145
	BP 90th	117	117	118	118	119	119	119	72	72	72	72	73	73	73
	BP 95th	121	121	122	122	123	123	123	75	75	75	76	76	76	76
	BP 99th	128	129	129	130	130	130	131	81	81	81	81	82	82	82
10	Height (cm)	130	132	136	140	144	149	152	130	132	136	140	144	149	152
	BP 90th	119	119	120	120	121	121	121	73	73	73	73	74	74	74
	BP 95th	123	123	124	124	125	125	125	76	76	76	76	77	77	77
	BP 99th	130	131	131	132	132	132	133	82	82	82	82	82	83	83
11	Height (cm)	133	136	141	146	152	158	160	133	136	141	146	152	158	160
	BP 90th	121	121	122	122	122	123	123	74	74	74	74	74	75	75
	BP 95th	125	125	126	126	126	127	127	77	77	77	77	78	78	78
	BP 99th	132	133	133	133	134	134	134	83	83	83	83	83	84	84
12	Height (cm)	142	145	149	153	159	163	165	142	145	149	153	159	163	165
	BP 90th	122	123	123	124	124	124	124	75	75	75	75	75	76	76
	BP 95th	126	127	127	127	128	128	128	78	78	78	78	78	79	79
	BP 99th	134	134	135	135	135	136	136	84	84	84	84	84	85	85
13	Height (cm)	148	150	154	159	162	166	168	148	150	154	159	162	166	168
	BP 90th	124	124	124	125	125	125	126	75	75	76	76	76	76	77
	BP 95th	127	128	128	129	129	129	130	78	79	79	79	79	79	80
	BP 99th	135	135	136	136	136	137	137	84	84	84	85	85	85	86
14	Height (cm)	152	154	158	162	166	170	172	152	154	158	162	166	170	172
	BP 90th	124	125	125	125	126	126	126	76	76	76	76	77	77	77
	BP 95th	128	129	129	129	130	130	130	79	79	79	79	80	80	80
	BP 99th	136	136	136	137	137	137	138	85	85	85	85	85	86	86
15	Height (cm)	155	157	161	165	169	173	175	155	157	161	165	169	173	175
	BP 90th	124	125	125	126	126	126	127	76	76	77	77	77	77	78
	BP 95th	128	129	129	130	130	130	130	79	80	80	80	80	80	81
	BP 99th	136	136	137	137	137	138	138	85	85	85	86	86	86	87
16	Height (cm)	155	158	161	165	170	173	175	155	158	161	165	170	173	175
	BP 90th	124	124	125	125	126	126	126	77	77	77	77	77	78	78
	BP 95th	128	128	129	129	130	130	130	80	80	80	80	80	81	81
	BP 99th	135	136	136	137	137	137	138	85	86	86	86	86	86	87
17	Height (cm)	156	158	162	166	170	174	176	156	158	162	166	170	174	176
	BP 90th	123	123	124	124	125	125	125	76	76	77	77	77	77	78
	BP 95th	127	127	128	128	129	129	129	80	80	80	80	80	80	81
	BP 99th	135	135	135	136	136	136	137	85	85	85	86	86	86	87

adolescents allowed us to obtain information on normal BP levels across this young age range avoiding the impact of excess body weight on BP values.

The study provides the following new findings. First, our data reinforce the importance of height for the BP values in children and adolescents, because the progressive increment of BP with height was observed across the entire age range explored in both sexes and with both methods, as documented with the statistical approach shown in Supplementary Fig.s 2 and 3.

Second, the BP increase that was seen in children and adolescents across height percentiles and age was similar in both sexes until 13 years (Figs. 1 and 2). However, after this age our observations revealed a dissimilarity insofar a further increase of BP values was seen in boys who were still growing, while in girls the BP increment as shown in previous studies after 13 years was lower [33].

Third, while previous studies on normal BP values in children and adolescents have mainly or exclusively made use of the auscultatory BP measurement method, our study is the first to collect data and set a first

Table 3
Oscillometric systolic and diastolic blood pressure values for boys by age and height percentiles.

		SBP (mmHg)							DBP (mmHg)						
		Height percentile							Height percentile						
Age		5th	10th	25th	50th	75th	90th	95th	5th	10th	25th	50th	75th	90th	95th
3	Height (cm)	91	93	95	98	101	103	104	91	93	95	98	101	103	104
	BP 90th	104	104	105	106	106	107	108	65	65	65	65	66	66	67
	BP 95th	108	108	109	110	111	111	112	68	68	68	69	69	70	70
	BP 99th	116	116	117	117	118	119	120	74	74	74	75	75	76	76
4	Height (cm)	97	99	102	105	108	111	113	97	99	102	105	108	111	113
	BP 90th	107	107	108	109	110	110	111	66	66	67	67	67	68	68
	BP 95th	111	111	112	113	114	114	115	69	70	70	70	71	71	72
	BP 99th	119	119	120	120	121	122	123	75	76	76	76	77	77	78
5	Height (cm)	104	105	108	111	114	118	120	104	105	108	111	114	118	120
	BP 90th	109	109	110	111	112	113	113	67	68	68	68	69	69	70
	BP 95th	113	113	114	115	116	117	117	71	71	71	71	72	73	73
	BP 99th	121	121	122	122	123	124	125	77	77	77	78	78	79	79
6	Height (cm)	109	111	114	117	121	125	127	109	111	114	117	121	125	127
	BP 90th	111	111	112	112	113	114	115	68	69	69	69	70	70	71
	BP 95th	115	115	116	116	117	118	119	72	72	72	72	73	74	74
	BP 99th	122	123	123	124	125	126	126	78	78	78	79	79	80	80
7	Height (cm)	115	117	121	124	128	130	133	115	117	121	124	128	130	133
	BP 90th	112	112	113	114	114	115	116	69	69	70	70	71	71	72
	BP 95th	116	116	117	118	118	119	120	73	73	73	73	74	74	75
	BP 99th	124	124	124	125	126	127	128	79	79	79	79	80	80	81
8	Height (cm)	121	123	126	130	133	137	140	121	123	126	130	133	137	140
	BP 90th	113	114	114	115	116	117	117	70	70	71	71	71	72	72
	BP 95th	117	118	118	119	120	121	121	73	73	74	74	75	75	76
	BP 99th	125	125	126	127	127	128	129	79	80	80	80	81	81	82
9	Height (cm)	126	128	131	135	139	143	146	126	128	131	135	139	143	146
	BP 90th	115	115	116	116	117	118	119	71	71	71	72	72	73	73
	BP 95th	119	119	120	120	121	122	123	74	74	75	75	75	76	76
	BP 99th	126	127	127	128	129	130	130	80	80	81	81	81	82	82
10	Height (cm)	128	131	136	140	145	149	152	128	131	136	140	145	149	152
	BP 90th	117	117	118	118	119	120	121	72	72	72	72	73	74	74
	BP 95th	121	121	122	122	123	124	125	75	75	75	76	76	77	77
	BP 99th	128	129	129	130	131	132	132	81	81	81	82	82	83	83
11	Height (cm)	133	136	141	145	150	154	157	133	136	141	145	150	154	157
	BP 90th	119	119	120	121	121	122	123	73	73	73	73	74	74	75
	BP 95th	123	123	124	125	126	126	127	76	76	76	77	77	78	78
	BP 99th	131	131	132	132	133	134	135	82	82	82	83	83	84	84
12	Height (cm)	140	142	146	152	157	162	165	140	142	146	152	157	162	165
	BP 90th	122	122	122	123	124	125	126	74	74	74	74	75	75	76
	BP 95th	126	126	127	127	128	129	130	77	77	77	78	78	79	79
	BP 99th	133	134	134	135	136	137	137	83	83	83	84	84	85	85
13	Height (cm)	145	148	153	159	165	171	175	145	148	153	159	165	171	175
	BP 90th	124	125	125	126	127	128	128	75	75	75	75	76	76	77
	BP 95th	128	129	129	130	131	132	132	78	78	78	79	79	80	80
	BP 99th	136	136	137	138	139	140	140	84	84	84	85	85	86	86
14	Height (cm)	150	155	161	167	173	177	180	150	155	161	167	173	177	180
	BP 90th	127	128	128	129	130	131	131	76	76	76	76	77	78	78
	BP 95th	131	132	132	133	134	135	135	79	79	79	80	80	81	81
	BP 99th	139	139	140	141	142	142	143	85	85	85	86	86	87	87
15	Height (cm)	160	164	169	174	179	184	186	160	164	169	174	179	184	186
	BP 90th	130	130	131	132	133	134	134	77	77	77	78	78	79	79
	BP 95th	134	134	135	136	137	138	138	80	80	80	81	81	82	82
	BP 99th	142	142	143	143	144	145	146	86	86	86	87	87	88	88
16	Height (cm)	165	167	172	176	181	185	188	165	167	172	176	181	185	188
	BP 90th	132	133	133	134	135	136	136	78	78	78	79	79	80	80
	BP 95th	136	137	137	138	139	140	140	81	81	81	82	82	83	83
	BP 99th	144	144	145	146	146	147	148	87	87	87	88	88	89	89
17	Height (cm)	168	170	174	178	183	187	190	168	170	174	178	183	187	190
	BP 90th	133	134	134	135	136	137	138	79	79	79	79	80	80	81
	BP 95th	138	138	139	139	140	141	142	82	82	82	83	83	84	84
	BP 99th	145	146	146	147	148	149	149	88	88	88	89	89	90	90

attempt to explore the differences in the results obtained by the auscultatory and oscillometric methods. Both methods fulfilled the quality standards for its use in children. The auscultatory sphygmomanometer of mercury-based method, the classical procedure used and recommended for decades, has been banned in European countries due to restrictions in the use of mercury. Concomitantly the measurement with oscillometric methods has gained ground based on its easier use, avoidance of the interobserver's variability, and expansion of its application out of the medical environment. The oscillometric devices used in the present study were validated in children and adolescents [25–30]. All the data were collected and analysed in the setting of the European COST Action HyperChildNET (https://hyperchildnet.eu/), a European sustainable and multidisciplinary network. The study shows that the differences in SBP and DBP among the two methods are minimal with the exception of the oldest age groups. Age-specific differences in the 95th percentile of SBP at the 50th height percentile ranged from 0 to 1 mmHg higher in the oscillometric sample for boys. In girls, values ranged from –1 to 3 mmHg, generally higher in the oscillometric sample;

Table 4
Auscultatory systolic and diastolic blood pressure values for girls by age and height percentiles.

Age		SBP							DBP						
		Height percentile							Height percentile						
		5th	10th	25th	50th	75th	90th	95th	5th	10th	25th	50th	75th	90th	95th
3	Height (cm)	90	92	94	97	99	102	103	90	92	94	97	99	102	103
	BP 90th	100	101	102	104	106	108	109	64	64	65	66	68	69	69
	BP 95th	104	105	107	109	111	113	114	67	67	68	70	71	72	72
	BP 99th	112	113	115	117	119	121	122	73	73	74	76	77	78	78
4	Height (cm)	99	101	104	106	108	113	116	99	101	104	106	108	113	116
	BP 90th	100	101	103	105	107	109	110	64	64	65	67	68	69	70
	BP 95th	105	106	107	109	111	113	114	67	68	69	70	71	72	73
	BP 99th	113	114	115	117	119	121	122	73	74	75	76	77	78	79
5	Height (cm)	104	105	108	111	114	117	119	104	105	108	111	114	117	119
	BP 90th	102	103	105	107	109	111	112	65	66	67	68	69	70	71
	BP 95th	107	107	109	111	113	115	116	68	69	70	71	72	73	74
	BP 99th	115	116	117	119	121	123	124	74	75	76	77	78	79	80
6	Height (cm)	108	111	115	120	124	126	127	108	111	115	120	124	126	127
	BP 90th	105	106	107	109	112	113	114	66	67	68	69	70	71	72
	BP 95th	109	110	112	114	116	118	119	69	70	71	72	73	75	75
	BP 99th	118	118	120	122	124	126	127	75	76	77	78	79	81	81
7	Height (cm)	115	117	121	124	128	131	134	115	117	121	124	128	131	134
	BP 90th	108	109	110	112	115	116	117	68	68	69	71	72	73	73
	BP 95th	112	113	115	117	119	121	122	71	72	73	74	75	76	77
	BP 99th	121	121	123	125	127	129	130	77	78	79	80	81	82	83
8	Height (cm)	120	122	126	130	133	136	139	120	122	126	130	133	136	139
	BP 90th	111	112	113	115	117	119	120	69	70	71	72	73	74	75
	BP 95th	115	116	118	120	122	124	124	72	73	74	75	76	77	78
	BP 99th	123	124	126	128	130	132	133	78	79	80	81	82	83	84
9	Height (cm)	124	127	131	134	138	143	145	124	127	131	134	138	143	145
	BP 90th	113	114	116	118	120	122	123	70	71	72	73	74	75	76
	BP 95th	118	119	120	122	124	126	127	74	74	75	76	78	79	79
	BP 99th	126	127	128	130	132	134	135	80	80	81	82	84	85	85
10	Height (cm)	131	133	136	140	146	150	152	131	133	136	140	146	150	152
	BP 90th	115	116	118	120	122	124	125	71	72	73	74	75	76	77
	BP 95th	120	121	122	124	126	128	129	75	75	76	77	78	80	80
	BP 99th	128	129	130	132	134	136	137	81	81	82	83	84	86	86
11	Height (cm)	136	138	142	147	152	158	160	136	138	142	147	152	158	160
	BP 90th	117	118	119	121	123	125	126	72	73	74	75	76	77	78
	BP 95th	121	122	124	126	128	129	130	75	76	77	78	79	80	81
	BP 99th	129	130	132	134	136	138	139	81	82	83	84	85	86	87
12	Height (cm)	142	145	150	155	160	164	167	142	145	150	155	160	164	167
	BP 90th	118	119	120	122	124	126	127	73	73	74	75	76	78	78
	BP 95th	122	123	125	127	129	131	131	76	76	77	78	80	81	81
	BP 99th	130	131	133	135	137	139	140	82	82	83	84	86	87	87
13	Height (cm)	148	151	155	160	164	168	170	148	151	155	160	164	168	170
	BP 90th	119	120	121	123	125	127	128	73	74	75	76	77	78	79
	BP 95th	123	124	125	128	130	131	132	76	77	78	79	80	81	82
	BP 99th	131	132	134	136	138	140	141	82	83	84	85	86	87	88
14	Height (cm)	152	155	159	163	168	172	175	152	155	159	163	168	172	175
	BP 90th	120	121	122	124	126	128	129	74	74	75	77	78	79	79
	BP 95th	124	125	127	129	131	133	133	77	78	79	80	81	82	83
	BP 99th	132	133	135	137	139	141	142	83	84	85	86	87	88	89
15	Height (cm)	153	156	160	164	169	173	175	153	156	160	164	169	173	175
	BP 90th	122	122	124	126	128	130	131	75	76	77	78	79	80	81
	BP 95th	126	127	128	130	133	134	135	78	79	80	81	82	83	84
	BP 99th	134	135	137	139	141	143	143	84	85	86	87	88	89	90
16	Height (cm)	155	157	160	164	170	174	176	155	157	160	164	170	174	176
	BP 90th	125	126	127	129	131	133	134	77	78	79	80	81	82	83
	BP 95th	129	130	132	134	136	137	138	80	81	82	83	84	85	86
	BP 99th	137	138	140	142	144	146	147	86	87	88	89	90	91	92
17	Height (cm)	155	158	162	166	171	175	177	155	158	162	166	171	175	177
	BP 90th	130	131	132	134	137	138	139	80	81	82	83	84	85	86
	BP 95th	134	135	137	139	141	143	144	83	84	85	86	87	88	89
	BP 99th	143	143	145	147	149	151	152	89	90	91	92	93	94	95

however, at 15–17 years, differences diverged up to 11 mmHg, with the oscillometric sample showing lower values. In boys, age-specific differences in the 95th percentile of DBP at the 50th height percentile range from 1 to 3 mmHg, with lower values in the oscillometric sample; at older ages, differences peak at 6 mmHg. In girls, differences are smaller, ranging from 0 to 1 mmHg, but at 15–16 years, they increase to as much as 6 mmHg, with the oscillometric values being lower. It is important to note that the predicted BP percentiles for each method are based on individuals who differ not only in measurement methodology but also in geographical location and setting, among other factors.

Fourth, it is relevant that the 95th percentile at age 13 in both sexes is close to 130/80 mmHg coinciding with the American Academy of Paediatrics recommend threshold, and at age 16 years or older, boys show SBP around 140 and DPB ranges from 82 to 88 mmHg in both methods at median height according to the recommend threshold of the ESH.

The largest normative BP database used for children and adolescents (National High Blood Pressure Education Program) is based on auscultatory measurements [2,34,35] of a variety of studies obtained during

Table 5
Auscultatory systolic and diastolic blood pressure values for boys by age and height percentiles.

		SBP							DBP						
		Height percentile							Height percentile						
Age		5th	10th	25th	50th	75th	90th	95th	5th	10th	25th	50th	75th	90th	95th
3	Height (cm)	91	93	95	98	100	103	105	91	93	95	98	100	103	105
	BP 90th	101	101	103	105	107	109	109	65	65	67	68	69	70	70
	BP 95th	105	106	107	109	112	113	114	68	69	70	71	73	73	74
	BP 99th	113	114	116	118	120	121	122	75	75	76	78	79	80	80
4	Height (cm)	98	100	105	108	110	111	119	98	100	105	108	110	111	119
	BP 90th	103	103	105	107	109	111	112	65	66	67	68	69	70	71
	BP 95th	107	108	110	112	114	115	116	69	69	70	72	73	74	74
	BP 99th	116	116	118	120	122	124	124	75	75	77	78	79	80	80
5	Height (cm)	104	106	109	112	115	118	120	104	106	109	112	115	118	120
	BP 90th	105	106	107	109	111	113	114	66	67	68	69	70	71	71
	BP 95th	109	110	112	114	116	117	118	69	70	71	72	74	74	75
	BP 99th	118	118	120	122	124	126	126	76	76	77	79	80	81	81
6	Height (cm)	111	112	116	120	123	127	128	111	112	116	120	123	127	128
	BP 90th	107	108	109	111	113	115	116	67	68	69	70	71	72	73
	BP 95th	111	112	114	116	118	119	120	70	71	72	74	75	76	76
	BP 99th	120	120	122	124	126	128	129	77	77	79	80	81	82	82
7	Height (cm)	116	119	121	125	129	131	133	116	119	121	125	129	131	133
	BP 90th	109	110	111	113	115	117	118	68	69	70	71	72	73	74
	BP 95th	113	114	116	118	120	121	122	72	72	73	75	76	77	77
	BP 99th	122	122	124	126	128	130	130	78	78	80	81	82	83	83
8	Height (cm)	121	123	127	130	134	138	140	121	123	127	130	134	138	140
	BP 90th	111	112	113	115	117	119	120	69	70	71	72	74	74	75
	BP 95th	115	116	118	120	122	123	124	73	73	74	76	77	78	78
	BP 99th	124	124	126	128	130	132	132	79	80	81	82	83	84	85
9	Height (cm)	125	127	131	136	139	143	145	125	127	131	136	139	143	145
	BP 90th	113	113	115	117	119	121	121	70	71	72	73	75	75	76
	BP 95th	117	118	119	122	124	125	126	74	74	75	77	78	79	79
	BP 99th	125	126	128	130	132	133	134	80	81	82	83	84	85	86
10	Height (cm)	129	131	136	140	144	149	152	129	131	136	140	144	149	152
	BP 90th	114	115	117	119	121	123	123	71	72	73	74	76	76	77
	BP 95th	119	120	121	123	125	127	128	75	75	76	78	79	80	80
	BP 99th	127	128	130	132	134	135	136	81	82	83	84	85	86	86
11	Height (cm)	136	138	142	146	151	155	157	136	138	142	146	151	155	157
	BP 90th	116	117	119	121	123	124	125	72	73	74	75	76	77	78
	BP 95th	121	122	123	125	127	129	130	75	76	77	79	80	81	81
	BP 99th	129	130	132	134	136	137	138	82	82	84	85	86	87	87
12	Height (cm)	140	142	148	152	157	163	166	140	142	148	152	157	163	166
	BP 90th	118	119	121	123	125	127	127	73	73	75	76	77	78	78
	BP 95th	123	124	125	127	129	131	132	76	77	78	79	80	81	82
	BP 99th	131	132	134	136	138	139	140	83	83	84	86	87	88	88
13	Height (cm)	146	149	153	160	165	171	175	146	149	153	160	165	171	175
	BP 90th	121	121	123	125	127	129	130	74	74	75	77	78	79	79
	BP 95th	125	126	128	130	132	133	134	77	78	79	80	81	82	83
	BP 99th	133	134	136	138	140	142	142	83	84	85	86	88	88	89
14	Height (cm)	152	156	162	168	173	179	181	152	156	162	168	173	179	181
	BP 90th	123	124	126	128	130	131	132	75	75	76	78	79	80	80
	BP 95th	128	128	130	132	134	136	137	78	79	80	81	82	83	84
	BP 99th	136	137	138	140	142	144	145	84	85	86	88	89	90	90
15	Height (cm)	159	162	167	174	178	183	187	159	162	167	174	178	183	187
	BP 90th	126	127	129	131	133	134	135	76	77	78	79	81	81	82
	BP 95th	131	131	133	135	137	139	139	80	80	81	83	84	85	85
	BP 99th	139	140	141	143	145	147	148	86	87	88	89	90	91	91
16	Height (cm)	165	167	172	176	181	185	188	165	167	172	176	181	185	188
	BP 90th	130	130	132	134	136	138	138	78	79	80	82	83	84	84
	BP 95th	134	135	136	138	140	142	143	82	82	84	85	86	87	87
	BP 99th	142	143	145	147	149	150	151	88	89	90	91	92	93	94
17	Height (cm)	167	170	175	179	184	188	191	167	170	175	179	184	188	191
	BP 90th	134	134	136	138	140	142	142	82	82	83	85	86	87	87
	BP 95th	138	139	140	143	145	146	147	85	86	87	88	89	90	91
	BP 99th	146	147	149	151	153	154	155	91	92	93	95	96	97	97

the 1970s and 1980s, including 63.000 American children from 1 to 17 years [2]. The 2017 Guidelines of the American Academy of Paediatrics (AAP) [5] use those tables, including only normal weight, up to 13 years old, defining HTN based on the 95th specific age, sex and height percentile. At 13 years a fix cut off was stabilized using 130/80 mmHg as the threshold to define HTN.

When our data were compared with the AAP values differences at the 50th height percentile, the age-specific differences in 95th percentiles of SBP in the auscultatory sample ranged from to 2 to 8 mmHg in boys, and from 2 to 9 mmHg in girls. In general, values were higher in the HyperChildNET cohort. For DBP differences range from 1 to 4 mmHg in boys and 0 to 5 mmHg in girls. The differences in height were minimal, ranging from 1 to 3 cm in boys and 1 to 4 cm in girls. The minimal height differences at the 50th percentile suggest that height variations do not explain differences in BP levels. The two compared cohorts are not similar in terms of the years in which the studies were performed (1970ies and 1980ies in the USA/ 2000–2022 in Europe) and place the measurements were taken (USA/ 8 European countries) which could suggest variations in characteristics such as ethnic group, family history, dietary patterns, and other risk factors that may influence blood pressure levels.

There have been several attempts to provide paediatric reference values in Europe [12–15], that do not fulfil the desirable criteria foremost standardized BP measurement either using the auscultatory or oscillometric method with good validation, sampling a sufficiently large age range and reference values presentation by age, sex and height percentile simultaneously. It was in 2011 when Neuhauser and coworkers [16] published the KiGGS study using an oscillometric device validated in children, including 12.199 non-overweight children 3 to 17 years old and percentiles were expressed as sex, age and height percentiles covering the limitations of the previous studies. Differences between Neuhauseŕs study and the present show that, at the 50th height percentile, age-specific differences in the 95th percentile of SBP in the oscillometric sample ranged from 1 to 5 mmHg in boys, with HyperChildNET study reporting higher values. In girls, the values ranged from 0 to 5 mmHg higher in the HyperChildNET cohort. For DBP, differences range from 0 to 1 mmHg in both sexes, generally being higher in HyperChildNET. Height differences with the Neuhauseŕs study were not significant, ranging from 1 to 4 cm in both sexes, with HyperChildNET study height percentiles being slightly lower.

Even though the present study was not developed to obtain references values like the Neuhauseŕs study, the information obtained with a large number of healthy European normal weight subjects may contribute to a better knowledge using oscillometric validated devices in clinical and home settings and furthermore giving information on the auscultatory method.

The present study has to be interpreted within the context of its strengths and limitations. Among the strengths, the study included almost 40.000 healthy normal weight children and adolescents, aged 3 - 17 years, coming from eight European countries, measuring BP with a standardized methodology according to the ESH Paediatric Guidelines [4] performed by trained personal and in which BP values for the auscultatory and oscillometric methods with at least two measurements were obtained. This is especially relevant when considering the quality of the data. Blood pressure percentiles were predicted using a standard methodology, linear regression models, that optimally adjust for the relationship between BP levels, height, and age by sex. The current study could serve as a seed for a platform.

Among the limitations of the study is that even though the oscillometric devices used in the present study were validated in children and adolescents [25–30] they are coming from different manufactures. The potential differences in the BP values using monitors from different manufacturers could be minimised considering the large number of children included in the oscillometric group (24.390).

Another limitation is that the included cohorts are cross-sectional, performed between 2000 and 2022, and in some cohorts, BP was measured at school or in the office. Even though not all age groups have the same number of subjects, each group still had a substantial number, and the sample's age distribution closely resembles that of the paediatric population in Europe, except the younger age groups.

5. Conclusion

The progressive increment of BP in children across age is largely influenced by height.

In boys blood pressure values still increase after 13 years old, while in girls the BP increment after this age was lower. A first exploration suggests differences in SBP and DBP among the two used methods are minimal except in the oldest age group. The present study provides useful information about BP in European healthy normal weight children and adolescents by using the oscillometric method, the most used in Europe right now both in the clinical and out of office setting.

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Declaration of competing interest

None of the authors declares a conflict of interest.

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Supplementary materials

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