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Haemodynamic characterisation of primary hypertension in children and adolescents

Short Title: Haemodynamics of hypertension in children

Ye Li¹ PhD

Haotian Gu¹ PhD

Manish D Sinha^{1,2*} PhD

Phil Chowienczyk^{1*} BSc

1. King's College London British Heart Foundation Centre, London, UK
2. Department of Pediatric Nephrology, Evelina London Children's Hospital, UK

*joint senior authors

Correspondence:

Prof PJ Chowienczyk, Department of Clinical Pharmacology, St Thomas' Hospital, Lambeth Palace Road, London SE1 7EH, UK

Tel: + 44 207 1884642, Fax: + 44 207 4012242, E-mail:

phil.chowienczyk@kcl.ac.uk

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Abstract

Background: Primary hypertension in children is often characterised by high pulse pressure that could be due to increased ventricular ejection velocities and volumes and/or increased arterial stiffness. The objective of this study was to examine the contributions of cardiac (ventricular ejection) and vascular (systemic vascular resistance, arterial stiffness and pressure wave reflection) properties to primary hypertension in children and adolescents.

Methods and Results: Children aged 8 – 18 years referred to a tertiary centre for evaluation of hypertension and found to have primary hypertension (n=31) were compared with normotensive controls of similar age (n=50). Peripheral (brachial) and central (carotid) blood pressure waveforms and carotid-femoral pulse wave velocity were measured by tonometry. Left ventricular (LV) outflow tract velocities and ejection volumes were measured by echocardiography. Wave separation and wave intensity analysis was used to assess pressure wave propagation. Increased mean arterial pressure in hypertensive children (90 ± 15 vs. 76 ± 10 mmHg in hypertensive vs. normotensive children, $P < 0.001$) was explained by increased heart rate and cardiac output (5.3 ± 2.0 vs. 4.5 ± 1.2 l/min, means \pm SD, adjusted for age and sex, $P < 0.05$) rather than increased systemic vascular resistance (18.0 ± 4.6 vs. 19.3 ± 7.3 mmHg.min/ml, $P = 0.374$). A more marked increase in pulsatility (peripheral pulse pressure 66 ± 21 vs. 46 ± 12 mmHg, $P < 0.001$) was explained by increased proximal aortic stiffness (PWV: 3.3 ± 1.4 vs. 2.5 ± 0.8 m/s, $P < 0.005$) and increased LV ejection velocity (1.33 ± 0.24 vs. 1.21 ± 0.18 m/s, $P < 0.05$).

Conclusions: Cardiac overactivity characterised by increased heart rate and LV ejection velocities and increased proximal PWV may be the main cause of primary hypertension in children.

Key words:

Arterial pressure, primary hypertension, cardiovascular disease, cardiac output, hemodynamics

Clinical Perspective

- Hypertension in children with primary hypertension is predominantly due to overactivity of the heart (increased heart rate and increased ejection velocities) and increased proximal aortic stiffening.
- Given the tracking of hypertension from children to adults, the finding of a cardiac/aortic rather than peripheral vascular cause of primary hypertension has implications for the aetiology of hypertension both in children and adults.
- It also has implications for the best treatment in children: clinical trials of interventions designed to reduce cardiac overactivity should be considered.

Introduction

Hypertension is one of the most important global public health problems but its aetiology, particularly in children, is still poorly understood. In children and young adults hypertension often takes the form of isolated systolic hypertension with a wide pulse pressure.¹ High pulse pressure is also seen in old age where it has been attributed to stiffening of large elastic arteries limiting the cushioning of blood ejected by the left ventricle by the arterial tree and possibly other haemodynamic effects.² Arterial stiffening is well recognised as part of an age-related degenerative process.³ In children a degenerative process seems unlikely but other mechanisms of arterial stiffening could occur and there may be other causes of increased pulse pressure such as an increase in ventricular ejection or increased pressure wave reflection.

The aim of the present study was to characterise central arterial haemodynamics and to investigate the mechanisms of primary hypertension in children and adolescents, specifically, to examine the contributions of cardiac (left ventricular ejection velocities and volumes) and vascular (systemic vascular resistance, arterial stiffness and pressure wave reflection) properties to hypertension.

Methods

Study Population

Data used in this study will be made available to any researcher for the purposes of reproducing the results reported or use in other studies.

Children and adolescents (subsequently referred to as “children”) up to age 18 with primary hypertension referred to the paediatric hypertension clinic of the Evelina London Children’s Hospital, UK were consecutively recruited to a prospective observational study investigating the relationship of target organ damage to blood pressure (BP). Age-matched healthy children were recruited contemporaneously from the local community. Hypertension was defined as average systolic or diastolic BP $\geq 95^{\text{th}}$ percentile (equivalent to z score ≥ 1.645) or if the patient was on antihypertensive therapy, according to definitions of hypertension in the Fourth report on the diagnosis, evaluation, and treatment of high blood pressure in children and adolescents.⁴ Children with chronic kidney disease or other causes of secondary hypertension were excluded from the study. Additional exclusion criteria included those with congenital heart disease, cardiac arrhythmias, and inability to obtain high-quality cardiovascular measurements. The institutional ethics committee approved the study, children

gave their assent and all parents gave written informed consent. Anthropometric, clinical and laboratory data were collected on the day of the research investigations. Healthy children underwent all examinations except for venesection.

Blood pressure, arterial tonometry and pulse wave velocity

Hemodynamic measurements were made with children in a supine position in a quiet environment. Peripheral systolic and diastolic BP were measured in triplicate by a trained observer by auscultation using a calibrated aneroid sphygmomanometer and an appropriate-size arm cuff according to the British and Irish Hypertension Society guidelines. Given the age-related change in BP throughout childhood, all peripheral BP measurements were expressed as z-scores (the number of standard deviations above or below a population mean assigned a value of zero).⁴ Radial and carotid pressure waveforms were obtained by applanation tonometry performed by an experienced operator using the SphygmoCor system (AtCor, Australia). Approximately 10 cardiac cycles were ensemble averaged. Waveforms that did not meet the in-built quality control criteria in the SphygmoCor system were rejected. Peripheral systolic and diastolic BP was used to calibrate radial waveforms and thus to obtain a mean arterial pressure (MAP) through the integration of the radial waveform. Carotid waveforms were calibrated from MAP and diastolic brachial blood pressures on the assumption of the equality of these pressures at central and peripheral sites.⁵ Carotid-femoral PWV (PWVcf) was calculated from sequential recordings of the carotid and femoral artery pressure waveforms using the same SphygmoCor device and transducer. The difference in time of pulse arrival between the two sites referenced to the R-wave of the electrocardiogram was taken as the transit time. The path length between these two sites was estimated from the distance between the sternal notch and femoral artery at the point of applanation and PWV calculated as the quotient of path length and transit time. All measurements were made in triplicate, and mean values were used for analysis.

Left ventricular outflow tract flow velocity and ejection volumes

Ultrasound imaging was performed by an experienced operator using the Philips IE33 or Epiq ultrasound system (Philips Healthcare, Andover, USA). Flow velocity in the left ventricular outflow tract was recorded using pulsed wave Doppler obtained from an apical 5-chamber view. Flow velocity measurements were averaged over at least 3 cardiac cycles. The internal diameter of the left ventricular outflow tract (LVOT) was measured in the parasternal long-axis view and LVOT area calculated assuming circularity. Direct measurements of time-

resolved left ventricular volume, end-diastolic volume (EDV) and end-systolic volume (ESV) were also measured using the Philips QLab analysis package (Philips Healthcare, Andover, USA) from 2D apical views.

Waveform post-processing

BP pressure waveforms obtained by tonometry and LVOT flow velocity waveforms were processed offline using custom software written in MATLAB (MathWorks, Natick, USA) to characterise waveform morphology, perform forward and backward waveform separation and hence determine reflection coefficients.

BP pressure wave morphology

The first (P1) and second (P2) systolic shoulders/peaks and end-systolic (Pes) points of the carotid pressure waveform and their timings (T1, T2 and Tes) relative to the upstroke of the pressure waveform (Figure 1) were identified as the first and second local minima of the first derivative of the carotid pressure curve and confirmed by visual inspection by an observer blinded to the results. Pulsatile components of pressure at these points (PP1, PP2 and PPeS) were obtained by subtracting diastolic BP from P1, P2 and Pes. Augmentation pressure (AP) was taken as the difference between P2 and P1. Augmentation index (AIx) was defined as $AP/cPP \times 100\%$.

Flow and volume measurements

Aortic flow velocity was multiplied by the LVOT cross-sectional area to obtain flow, which was integrated over time to obtain the stroke volume (SV_{flow}) and cardiac output (CO) as the product of SV and heart rate (HR). SV was also obtained as the difference between left ventricular end-diastolic and end-systolic volumes (SV_{vol}). Ejection volumes (V1 and V2) corresponding to times T1 and T2 were obtained by integration of the aortic flow waveform from the start of systole to T1 and T2.

Forward and backward pressure wave decomposition and wave intensity analysis

Pressure wave decomposition was performed using Parker's time-domain approach⁶, based on conservation of mass and momentum, to obtain forward (P_f) and backward (P_b) pressure components of central pulse pressure so that: $P_f + P_b = P - P_d$, where P is total pressure and P_d is the diastolic pressure. P_f and P_b are given by:

$$P_f = \frac{1}{2} \sum [(dP + \rho cdU)] \quad (1)$$

$$P_b = \frac{1}{2} \sum [(dP - \rho cdU)] \quad (2)$$

Where U is flow velocity, ρ is blood density, and c is proximal aortic pulse wave velocity which was estimated using the method of the sum of squares (PWVss).⁷ Reflection index, (R_{index}) was defined as the ratio of amplitude of backward to that of forward wave.

Wave intensity, the flux of wave energy per unit area is calculated as $dI=dPdU$ and can be separated into forward and backward components:

$$dI_{\pm} = \frac{1}{4\rho c} (dP \pm \rho cdU)^2 \quad (3)$$

Wave intensity is positive for forward waves and negative for those that are travelling in a backward direction. Total wave energy can be obtained by integrating equation (3) with respect to time.

Determinants of steady state and pulsatile components of BP

The contributions of cardiac and arterial properties to the steady state component of BP in hypertensive vs. normotensive children was assessed by comparing the percentage difference between MAP in hypertensive and normotensive children with that of CO and SVR using the relation $MAP = CO \times SVR$. Cardiac and arterial contributions to greater PP1 (which in most children was equal to the central pulse pressure) in hypertensive vs. normotensive children were assessed by comparing the difference in PP1 in hypertensive vs. normotensive children with that of PWVss and U1, since previous work has shown that, to a first approximation, for similar LVOT/proximal aortic geometry, PP1 is proportional to $PWVss \times U1$.⁸

Statistics

Subject characteristics are presented as means \pm SD. Comparison of haemodynamic variables between hypertensive and normotensive groups was made using one-way analysis of covariance (ANCOVA), with age and gender included as covariates. Results are presented as adjusted values (means \pm SE). Comparison of variables between untreated hypertensive and normotensive subjects was also performed. Analysis was performed using SPSS version 25 (SPSS Inc., Chicago, Illinois) and $P < 0.05$ was taken as significant.

Results

Subject characteristics

Table 1 shows the characteristics of children with hypertension (n=31) and normotensive controls of similar age (n=50). The proportion of male children was greater in the hypertensive compared to the normotensive group and hypertensive children were taller and heavier, but with similar body mass index (BMI). Fifty eight percent of children with hypertension had isolated systolic hypertension (ISH) and 42% systolic-diastolic hypertension. Sixty four percent were taking anti-hypertensive medication.

Peripheral and central BP, and aortic PWV

As per definition, those with hypertension had significantly higher peripheral BP with systolic and diastolic BP 30 ± 3 and 9 ± 3 mmHg respectively greater in the hypertensive compared to normotensive groups, so that there was a more marked increase in pulsatility rather than mean BP. Central BP pressure components and PWV are summarized in table 2. Average values of P1 were greater than those of P2 in normotensive and hypertensive groups so that AP and AIx were negative. Both P1 and P2 were greater in hypertensive children compared to normotensive children but the difference was proportionately greater for P1 than P2 so that AP and AIx were similar in the 2 groups. Pulsatile components of central BP were all significantly greater in hypertensive compared to normotensive children with the greatest difference being for PP1 (table 2). Both P1 and P2 occurred earlier in systole in hypertensive compared to normotensive children with values of T1 and T2 15 ± 6 and 16 ± 5 ms lower respectively in hypertensive compared to normotensive children. The rate of initial pressure rise (PP1/T1) was therefore markedly greater in hypertensive compared to normotensive children (table 2). PWVcf was similar in both group, proximal aortic but PWVss was higher in hypertensive compared to normotensive children (3.3 ± 0.20 vs. 2.5 ± 0.16 m/s, $P=0.004$).

LVOT flow, stroke volume, cardiac output and systemic vascular resistance

Flow waveform characteristics are presented in Table 3. Compared with normotensive children, children with hypertension had significantly higher maximal flow velocity (U_{\max}) and mean flow velocity (U_{mean}). Despite the earlier timing, T1 of P1 and U1, values of U1 were greater in hypertensive compared to normotensive children. Values of U2, V1 and V2 also tended to be greater in hypertensive compared to normotensive children (Figure 2) but the differences were not statistically significant. Stroke volumes calculated by integration of

the flow waveform and from LV volumes were slightly greater in hypertensive children ($3.2\pm 5.3\%$ and $3.5\pm 5.5\%$ greater for SV_{flow} and SV_{vol} respectively) compared to normotensive children, but the differences were not significant (table 3). Due to both greater SV and heart rate (by 8 ± 3 bpm) in hypertensive children mean CO was 0.8 ± 0.30 L/min ($18.1\pm 8.1\%$) greater in hypertensive compared to normotensive children. The percentage difference between CO in hypertensive compared to normotensive children was similar to that of mean arterial pressure, so that SVR was similar in normotensive and hypertensive children (18.0 ± 0.87 versus 19.3 ± 1.1 mmHg.min/ml, $P=0.374$, table 3).

Wave separation and intensity analysis

The average central pressure and the corresponding decomposed forward and backward pressure waveforms in normotensive and hypertensive children are presented in figure 3. The peak amplitudes of the forward and backward pressure waves and of values of individual forward and backward components of pressure at characteristic points on the pressure waveform (P1, P2, and Pes) and timings of these are shown in table 4. Both peak forward and backward amplitudes were greater in hypertensive compared to normotensive children. P1 and P2 were determined mainly by the forward wave in both hypertensive and normotensive children and components of the forward wave for these values were greater in hypertensive compared to normotensive children. Reflection index calculated as the ratio of the maximal amplitude of the backward to forward wave was similar in hypertensive and normotensive children as were the ratios of the backward to forward components of P1, P2 and Pes.

Wave intensities and timing of wave intensity components are shown in table 5. All wave intensity components including amplitudes and area of forward and backward wave intensities except the amplitude of the backward expansion wave were greater in hypertensive compared to normotensive children. Size of the forward expansion wave, indicative of a braking action of the left ventricle on forward pressure wave propagation was particularly marked in the hypertensive group (table 5). The peak of the backward expansion wave arrived earlier in hypertensive children (table 5) but timings of other waves were not significantly different between normotensive and hypertensive children (table 5).

Cardiac and arterial contributions to the difference in steady state and pulsatile components of BP between hypertensive and normotensive children

The greater MAP in hypertensive compared to normotensive children was explained by greater CO rather than SVR (figure 4). Greater PP1 in hypertensive compared to

normotensive children was explained by a combination of greater PWV_{ss} and greater early ejection velocities (figure 4).

Influence of treatment and adjustment for height and body surface area on differences between hypertensive and normotensive children

Results were not materially altered when comparisons were made between untreated hypertensive and normotensive children (Tables S1-S5). Differences between hypertensive and control groups in key haemodynamic measures (CO, SV, SVR, U1, PWV_{ss}, PWV_{cf}) were similar irrespective of whether the comparison was adjusted for age, sex, height and body surface area and (in the case of PWV) MAP, HR and LVOT cross-sectional area (Table S6). In sub-sample analysis in boys alone, similar differences between hypertensive and control groups were seen but not all differences that were significant in the whole sample reached statistical significance in the sub-sample due to the smaller sample size of the latter. Correction for body surface area but not height did attenuate the difference between CO in the hypertensive and normotensive groups, consistent with greater mass being a driver of increased CO.

Discussion

To the best of our knowledge, this is the first comprehensive characterisation of central haemodynamics in children with primary hypertension. There are two major findings. Firstly, increased MAP, the steady state component of BP, in hypertension is due to an increase in HR and CO rather than increase in SVR. Secondly, the increased pulsatility of BP in children with primary hypertension, which is more marked than that of MAP, is explained by a combination of increased proximal aortic stiffness (as measured by PWV_{ss}) and increased LV ejection velocity. These findings are consistent with and extend previous studies in adolescents and in young adults. Chirico et al measured CO by echocardiography in adolescents with primary hypertension and found elevated BP to be explained by increased CO rather than SVR.⁹ Arterial properties were not measured in the study by Chirico et al but, in the ENIGMA population study on young adults, CO (by inert-gas rebreathing) and PWV were measured and elevated BP was explained by increased SV and PWV rather than increased SVR.¹⁰ The present study extends the findings of the ENIGMA study with respect to proximal PWV as a determinant of pulsatility in primary hypertension in young adults to children and also identifies increased LV ejection velocity as an additional determinant of pulsatility in such children.

Measurement of flow velocity in addition to pressure allowed us to perform a comprehensive wave separation and intensity analysis which confirmed that the main difference between hypertensive and normotensive children was an increase in the forward compression wave indicative of a hyperkinetic state. Whilst backward wave components were also increased this was likely secondary to the increase in the forward wave. Increased pressure wave “reflection” usually inferred from pressure wave morphology (e.g. from AIx, which is now recognised to be influenced by ventricular dynamics as well as by reflection) has been implicated in systolic hypertension in adults. However, in the present study, we found no evidence of increased reflection as measured by AIx or by the ratio of backward to forward wave components in hypertensive children.

When considering the primary haemodynamic alteration in children with hypertension it is important to consider whether the increased proximal PWV we observed was a primary phenomenon or secondary to the increased MAP. Pressure dependence of PWV due to distension of the arterial wall transferring wall stress to stiffer elements within the wall is well recognised. In adults, acute modulation of transmural pressure (equivalent to an acute increase in MAP) or direct modulation of MAP using vasoactive drugs increases PWV_{cf} and

intra-thoracic PWV (which theoretically is more closely related to PWVss) over a range of approximately 0.5 to 1.0 m/s per 10 mmHg.^{11, 12} In the present study the difference between PWVss in the hypertensive and control groups was 0.8 m/s and that for MAP 14 mmHg giving ratios of 0.6 m/s per 10 mmHg. Thus, the increase in PWV could be secondary to the increased MAP. Statistical adjustment for MAP did not alter the difference in proximal PWV between hypertensive and normotensive subjects but this adjustment could have been limited by the relatively small number of subjects. The findings of the present study that primary hypertension in children is mainly a phenomenon arising from overactivity of the heart and proximal aorta is in stark contrast to the established view of primary hypertension as being a condition caused by increased resistance of the microvasculature. Given the tracking of BP from childhood to adulthood¹³ this calls into question the focus on the microvasculature as the main cause of primary hypertension in adults.^{14, 15} It is possible that microvascular dysfunction occurs through re-modelling secondary to increased MAP or pulsatility as proposed by Folkow.^{14, 16} Furthermore it suggests that therapies such as beta-adrenergic antagonists that reduce cardiac activity may be more effective in children than in adults.

Our study did not address the underlying aetiology of the haemodynamic determinants of hypertension. However, increased sympathetic activity has been suggested as the underlying cause for primary hypertension in children, particularly when hypertension is associated with obesity.¹⁷ Sympathetic activity was not measured in the present study but increased sympathetic activity would be entirely consistent with the increased heart rate and increased ventricular ejection velocities we observed. It could also contribute to the elevated proximal PWV independent of effects of MAP. In the present study BMI was similar in hypertensive and normotensive groups and increased sympathetic activity could be an important cause of primary hypertension in non-obese children. Renal sodium handling is likely to be another important cause of the difference between hypertensive and normotensive children. The current study did not directly measure sympathetic activity nor address renal sodium handling and, as such, does not fully characterise what is likely to be a complex and heterogeneous phenotype.

There are a number of other important limitations to our study. We studied a relatively small number of hypertensive children and were not able to meaningfully stratify our analysis by age and sex. Further studies are required to characterise hypertension in different age groups and according to other characteristics. Many of our hypertensive children were on some anti-hypertensive treatment and although adjustment for treatment or analysis in untreated children made no difference to our conclusions, further studies on a larger group of

untreated children are indicated. Non-invasive measurements of haemodynamics are inevitably subject to experimental error and measurements of peripheral and central BP are subject to calibration error. Our method of calibration of carotid waveforms by MAP derived from radial tonometry and brachial and diastolic BP is subject to error due to brachial to radial amplification.¹⁸ Whilst these errors may have influenced absolute values of BP, they are unlikely to have influenced values in the hypertensive relative to the normotensive group which was the main focus of the present study.

In conclusion, the present study suggests that primary hypertension in children results from cardiac overactivity characterised by increased heart rate and LV ejection velocities and increased proximal aortic stiffness.

Disclosures

None

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Table 1 Characteristics of normotensive and hypertensive children

Characteristic*	Normotensive (n=50)	Hypertensive* (n=31)	P value
Age (years)	14±3	15±3	0.150
Gender, male/female	23/27	22/9	0.028
Height (cm)	158±13	166±14	0.015
Weight (kg)	53.5±17.4	64.0±18.6	0.012
BMI (kg/m ²)	21.0±5.1	22.8±4.9	0.113
BMI z-score	0.22±1.2	0.67±0.92	0.069
Heart rate (bpm)	73±11	81±15	0.010
SBP (mmHg)	107±13	137±17	<0.001
SBP z-score	-0.21±0.97	2.2±1.5	<0.001
DBP (mmHg)	62±11	71±16	0.004
DBP z-score	-0.26±0.95	0.44±1.4	0.009
MAP (mmHg)	76±10	90±15	<0.001
Anti-hypertensive drugs (n, %)		20, 64.5	<0.001

BMI, body mass index; SBP, peripheral systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure. *Values are numbers, % or means±SD. *Values are adjusted for age and sex. Z-scores represent the number of standard deviations from values in a reference population.⁴

Table 2 Central hemodynamics: pressure wave morphology and pulse wave velocity

Measure	Normotensive (n=50)	Hypertensive* (n=31)	P value
Central systolic pressure points and timing			
P1 (mmHg)	90.0±1.7	111.6±2.0	<0.001
P2 (mmHg)	88.9±1.8	108.0±2.2	<0.001
Pes (mmHg)	80.6±1.9	95.4±2.3	<0.001
T1 (ms)	120±4	105±5	0.041
T2 (ms)	225±3	209±4	0.005
Tes (ms)	309±3	298±4	0.031
Central pulse pressures			
PP1 (mmHg)	28.0±1.7	39.7±2.1	<0.001
PP2 (mmHg)	26.9±1.5	37.1±1.8	<0.001
PPes (mmHg)	18.7±1.1	24.5±1.3	0.001
Augmentation pressure and index			
AP (mmHg)	-1.0±0.99	-2.6±1.2	0.322
AIx (%)	-3.6±2.4	-4.1±3.0	0.913
Pulse wave velocities			
PWV _{ss} (m/s)	2.5±0.16	3.3±0.20	0.004
PWV _{cf} (m/s)	5.9±0.18	5.9±0.19	0.802

P1, blood pressure at the first systolic shoulder; P2, blood pressure at the second systolic shoulder; Pes, end-systolic blood pressure; T1, timing of first systolic shoulder of central pressure; T2, timing of second systolic shoulder of central pressure; Tes, timing of the end-systolic blood pressure; PP1, pulse pressure at P1; PP2, pulse pressure at P2; PPes, pulse pressure at Pes; AP, augmentation pressure; Aix, augmentation index; PWV_{ss}, pulse wave velocity by sum-of-squares; PWV_{cf}, carotid-femoral pulse wave velocity. *Values are adjusted for age and sex.

Table 3 Central hemodynamics: LVOT flow velocity, flow, stroke volume and cardiac output

Measure	Normotensive (n=50)	Hypertensive* (n=31)	P value
LVOT flow velocity			
U _{max} (m/s)	1.21±0.03	1.33±0.04	0.032
U _{mean} (m/s)	0.29±0.01	0.35±0.02	0.005
U ₁ (m/s)	1.13±0.03	1.26±0.04	0.010
U ₂ (m/s)	0.75±0.03	0.86±0.04	0.051
LVOT area and ejection volumes			
LVOT area (cm ²)	2.53±0.07	2.52±0.08	0.924
V ₁ (ml)	24.1±1.7	22.3±2.1	0.529
V ₂ (ml)	50.3±2.1	50.6±2.6	0.921
SV _{flow} (ml)	62.5±2.6	64.4±3.1	0.648
SV _{vol} (ml)	50.0±1.7	51.7±2.1	0.532
CO (L/min)	4.5±0.23	5.3±0.27	0.029
SVR(mmHg.min/ml)	18.0±0.87	19.3±1.1	0.374

U_{max}, peak of flow velocity; U_{mean}, mean of flow velocity; U₁, flow velocity at T1; U₂, flow velocity at T2; LVOT area, left ventricular outflow tract area; V₁, ejection volume at T1; V₂, ejection volume at T2; SV_{flow}, stroke volume obtained by integration of LVOT flow; SV_{vol}, stroke volume obtained from ventricular dimensions; CO, cardiac output; SVR, systemic vascular resistance.

*Values are adjusted for age and sex.

Table 4 Forward and backward pressure wave decomposition

Measurement	Normotensive	Hypertensive*	P value
Amplitudes of pressure components			
Max Pf (mmHg)	25.2±1.6	37.0±2.0	<0.001
Max Pb (mmHg)	9.3±0.53	11.5±0.65	0.012
P1f (mmHg)	24.7±1.6	36.1±1.9	<0.001
P1b (mmHg)	3.3±0.36	3.6±0.45	0.632
P2f (mmHg)	20.4±1.3	29.8±1.6	<0.001
P2b (mmHg)	6.5±0.62	7.3±0.76	0.466
Pesf (mmHg)	11.2±0.71	15.8±0.88	<0.001
Pesb (mmHg)	6.7±0.56	7.5±0.69	0.338
Reflection index and backward/forward ratios			
Rindex	0.39±0.02	0.34±0.03	0.177
R _{P1}	0.15±0.02	0.10±0.02	0.097
R _{P2}	0.35±0.03	0.26±0.04	0.134
R _{Pes}	0.73±0.10	0.50±0.13	0.160
Timing of pressure components			
Tarrival (ms)	99±8	92±10	0.585
TmaxPf (ms)	117±5	121±6	0.603
TmaxPb (ms)	342±8	323±10	0.175

Max Pf, peak value (amplitude) of forward pressure wave; Max Pb, peak value (amplitude) of backward pressure wave; P1f, forward component of P1; P1b, backward component of P1; P2f, forward component of P2; P2b, backward component of P2; Pesf, forward component of end-systolic pressure; Pesb, backward component of end-systolic pressure; Rindex: reflection index; R_{P1}, ratio of P1b to P1f; R_{P2}, ratio of P2b to P2f; R_{Pes}, ratio of Pesb to Pesf; Tarrival, arrival time of backward pressure wave; TmaxPf, timing of peak value of forward pressure wave; TmaxPb, timing of peak value of backward pressure wave. *Values are adjusted for age and sex.

Table 5 Wave intensity analysis

Measurement	Normotensive	Hypertensive*	P value
Amplitudes of wave intensity components			
F _{comp} (W/m ²)	91.5±10.2	166.3±12.6	<0.001
B _{comp} (W/m ²)	6.0±1.2	11.6±1.5	0.006
F _{exp} (W/m ²)	15.1±1.9	27.7±2.3	<0.001
B _{exp} (W/m ²)	4.8±1.5	6.7±1.9	0.454
Areas of wave intensity components			
F _{comp} area (J/m ²)	3.5±0.35	6.1±0.42	<0.001
B _{comp} area (J/m ²)	0.22±0.03	0.34±0.03	0.004
F _{exp} area (J/m ²)	0.88±0.10	1.6±0.12	<0.001
B _{exp} area (J/m ²)	0.39±0.04	0.64±0.05	<0.001
Timing of wave intensity components (maximal amplitude)			
TF _{comp} (ms)	30±1	29±1	0.439
TB _{comp} (ms)	88±10	95±12	0.696
TF _{exp} (ms)	284±6	272±7	0.227
TB _{exp} (ms)	306±25	207±31	0.018

F_{comp}, peak value (amplitude) of forward wave intensity; B_{comp}, peak value (amplitude) of backward wave intensity; F_{exp}, peak value of forward expansion wave intensity; B_{exp}, peak value of backward expansion wave intensity; F_{comp} area, area of forward wave intensity; B_{comp} area, area of backward wave intensity; F_{exp} area, area of forward expansion wave intensity; B_{exp} area, area of backward expansion wave intensity; TF_{comp}, timing of peak of forward wave intensity; TB_{comp}, timing of peak of backward wave intensity; TF_{exp}, timing of peak of forward expansion wave intensity; TB_{exp}, timing of peak of backward expansion wave intensity. *Values are adjusted for age and sex.

Figure Legend

Figure 1: Central (carotid) pressure waveform. A) pressure at first systolic shoulder (P1) and second systolic shoulder (P2). B forward (dashed line) and backward (dotted line) wave components that summate to equal total pressure (solid line). Reflection index (Rindex) is defined as the ratio of the magnitude of backward wave (Pb) to that of forward wave (Pf). Pulse pressures at P1, P2 and Pes are denoted by PP1, PP2 and PPeS and can be divided into forward and backward components: $PP1 = PP1f + PP1b$.

Figure 2: Average left ventricular flows and volumes in normotensive and hypertensive children.

Figure 3: Average central pressure and corresponding decomposed forward and backward pressure waveforms in children. A) normotensive children and B) hypertensive children. Solid lines show the measured pressure, dashed lines show the forward pressure, and dotted lines show the backward pressure.

Figure 4: Major haemodynamic measures in normotensive (NT) and hypertensive (HT) children. A) mean arterial pressure (MAP), B) cardiac output (CO), C) systemic vascular resistance (SVR), D) Central pulsatile pressure at the first systolic shoulder (PP1), E) proximal aortic pulse wave velocity (PWV), F) left ventricular outflow velocity at the first systolic shoulder. Percentages refer to differences between normotensive (NT) and hypertensive children.

SUPPLEMENTAL MATERIAL

Table S1 Characteristics of normotensive and hypertensive children: comparison of values in untreated hypertensive and normotensive children

Characteristic*	Normotensive (n=50)	Hypertensive (n=13)	P value
Age (years)	14±3	14±3	0.616
Gender, male/female	23/27	6/7	0.992
Height (cm)	160±13	163±13	0.723
Weight (kg)	53.5±17.4	59.1±16.2	0.352
BMI (kg/m ²)	21.0±5.1	22.7±5.3	0.334
BMI z-score	0.22±1.2	0.76±0.90	0.115
Heart rate (bpm)	73±11	83±18	0.011
SBP (mmHg)	107±13	133±19	<0.001
SBP z-score	-0.21±0.97	2.1±1.8	<0.001
DBP (mmHg)	62±11	72±13	0.003
DBP z-score	-0.26±0.95	0.66±1.4	0.004
MAP (mmHg)	76±10	91±15	<0.001

BMI, body mass index; SBP, peripheral systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure. *Values are numbers, % or means±SD.

Table S2 Central hemodynamics: pressure wave morphology and pulse wave velocity: comparison of values in untreated hypertensive and normotensive children

Measure	Normotensive (n=50)	Hypertensive* (n=13)	P value
Central systolic pressure points and timing			
P1 (mmHg)	89.8±1.4	110.0±2.6	<0.001
P2 (mmHg)	89.0±1.6	109.3±3.0	<0.001
Pes (mmHg)	80.8±1.6	96.3±3.0	<0.001
T1 (ms)	120±4	103±8	0.085
T2 (ms)	224±3	209±6	0.035
Tes (ms)	309±3	303±6	0.452
Central pulse pressures			
PP1 (mmHg)	27.7±1.4	38.0±2.7	0.001
PP2 (mmHg)	26.9±1.4	37.3±2.7	0.001
PPes (mmHg)	18.7±1.1	24.3±2.0	0.017
Augmentation pressure and index			
AP (mmHg)	-0.79±0.82	-0.68±1.5	0.952
Aix (%)	-3.0±2.2	-2.5±4.2	0.914
Pulse wave velocities			
PWVss (m/s)	2.5±0.14	3.2±0.27	0.029
PWVcf (m/s)	5.8±0.14	5.4±0.26	0.217

P1, blood pressure at the first systolic shoulder; P2, blood pressure at the second systolic shoulder; Pes, end-systolic blood pressure; T1, timing of first systolic shoulder of central pressure; T2, timing of second systolic shoulder of central pressure; Tes, timing of the end-systolic blood pressure; PP1, pulse pressure at P1; PP2, pulse pressure at P2; PPes, pulse pressure at Pes; AP, augmentation pressure; Aix, augmentation index; PWVss, pulse wave velocity by sum-of-squares; PWVcf, carotid-femoral pulse wave velocity. *Values are adjusted for age and sex.

Table S3 Central hemodynamics: LVOT flow velocity, flow, stroke volume and cardiac output: comparison of values in untreated hypertensive and normotensive children

Measure	Normotensive (n=50)	Hypertensive* (n=13)	P value
LVOT flow velocity			
U _{max} (m/s)	1.21±0.03	1.36±0.05	0.015
U _{mean} (m/s)	0.30±0.01	0.38±0.02	<0.001
U ₁ (m/s)	1.13±0.03	1.30±0.05	0.005
U ₂ (m/s)	0.76±0.03	0.96±0.06	0.007
LVOT area and ejection volumes			
LVOT area (cm ²)	2.45±0.06	2.25±0.12	0.145
V ₁ (ml)	23.4±1.4	18.7±2.6	0.118
V ₂ (ml)	48.6±1.8	46.4±3.3	0.547
SV _{flow} (ml)	60.6±2.3	61.7±4.3	0.827
SV _{vol} (ml)	48.4±1.7	47.7±3.3	0.859
CO (L/min)	4.4±0.17	5.0±0.32	0.079
SVR(mmHg.min/ml)	18.4±0.70	18.9±1.3	0.732

U_{max}, peak of flow velocity; U_{mean}, mean of flow velocity; U₁, flow velocity at T1; U₂, flow velocity at T2; LVOT area, left ventricular outflow tract area; V₁, ejection volume at T1; V₂, ejection volume at T2; SV_{flow}, stroke volume obtained by integration of LVOT flow; SV_{vol}, stroke volume obtained from ventricular dimensions; CO, cardiac output; SVR, systemic vascular resistance. *Values are adjusted for age and sex.

Table S4 Forward and backward pressure wave decomposition: comparison of values in untreated hypertensive and normotensive children

Measurement	Normotensive (n=50)	Hypertensive* (n=13)	P value
Amplitudes of pressure components			
Max Pf (mmHg)	25.1±1.4	36.4±2.6	<0.001
Max Pb (mmHg)	9.3±0.54	11.2±1.0	0.111
P1f (mmHg)	24.5±1.4	35.3±2.6	0.001
P1b (mmHg)	3.2±0.31	2.7±0.59	0.462
P2f (mmHg)	20.5±1.2	31.0±2.3	<0.001
P2b (mmHg)	6.4±0.60	6.3±1.1	0.920
Pesf (mmHg)	11.2±0.72	16.3±1.4	0.001
Pesb (mmHg)	6.7±0.55	6.8±1.0	0.922
Reflection index and backward/forward ratios			
Rindex	0.39±0.02	0.32±0.05	0.204
R _{P1}	0.14±0.02	0.09±0.03	0.134
R _{P2}	0.34±0.04	0.22±0.07	0.128
R _{Pes}	0.74±0.11	0.41±0.21	0.186
Timing of pressure components			
Tarrival (ms)	101±8	102±16	0.940
TmaxPf (ms)	118±5	124±9	0.523
TmaxPb (ms)	342±8	353±15	0.531

Max Pf, peak value (amplitude) of forward pressure wave; Max Pb, peak value (amplitude) of backward pressure wave; P1f, forward component of P1; P1b, backward component of P1; P2f, forward component of P2; P2b, backward component of P2; Pesf, forward component of end-systolic pressure; Pesb, backward component of end-systolic pressure; Rindex: reflection index; R_{P1}, ratio of P1b to P1f; R_{P2}, ratio of P2b to P2f; R_{Pes}, ratio of Pesb to Pesf; Tarrival, arrival time of backward pressure wave; TmaxPf, timing of peak value of forward pressure wave; TmaxPb, timing of peak value of backward pressure wave. *Values are adjusted for age and sex.

Table S5 Wave intensity analysis: comparison of values in untreated hypertensive and normotensive children

Measurement	Normotensive (n=50)	Hypertensive* (n=13)	P value
Amplitudes of wave intensity components			
F _{comp} (W/m ²)	92.8±9.1	168.1±17.2	<0.001
B _{comp} (W/m ²)	6.0±1.1	11.6±2.0	0.016
F _{exp} (W/m ²)	15.7±1.8	28.6±3.5	0.002
B _{exp} (W/m ²)	5.0±1.6	7.4±2.9	0.469
Areas of wave intensity components			
F _{comp} area (J/m ²)	3.6±0.30	6.1±0.57	<0.001
B _{comp} area (J/m ²)	0.22±0.03	0.36±0.05	0.009
F _{exp} area (J/m ²)	0.89±0.09	1.7±0.17	<0.001
B _{exp} area (J/m ²)	0.40±0.04	0.70±0.07	<0.001
Timing of wave intensity components (maximal amplitude)			
TF _{comp} (ms)	30±1	29±2	0.814
TB _{comp} (ms)	87±10	117±19	0.177
TF _{exp} (ms)	284±5	293±10	0.420
TB _{exp} (ms)	300±27	211±50	0.122

F_{comp}, peak value (amplitude) of forward wave intensity; B_{comp}, peak value (amplitude) of backward wave intensity; F_{exp}, peak value of forward expansion wave intensity; B_{exp}, peak value of backward expansion wave intensity; F_{comp} area, area of forward wave intensity; B_{comp} area, area of backward wave intensity; F_{exp} area, area of forward expansion wave intensity; B_{exp} area, area of backward expansion wave intensity; TF_{comp}, timing of peak of forward wave intensity; TB_{comp}, timing of peak of backward wave intensity; TF_{exp}, timing of peak of forward expansion wave intensity; TB_{exp}, timing of peak of backward expansion wave intensity. *Values are adjusted for age and sex.

Table S6 Influence of adjustment for age, sex, height, body surface area and other factors on key haemodynamic measures

	Normotensive (n=50)	Hypertensive (n=31)	Difference (%)	P value
CO (L/min)				
Unadjusted	4.3±0.18	5.4±0.36	25.6	0.004
Age + Sex	4.5±0.23	5.3±0.27	17.8	0.029
Boys only + Age	4.6±0.40	5.5±0.38	19.6	0.125
Age + Sex + Height	4.5±0.23	5.3±0.28	17.8	0.036
Age + Sex + BSA	4.6±0.21	5.1±0.25	10.9	0.087
CI (L/min/m²)				
Unadjusted	2.9±0.91	3.2±1.7	10.3	0.073
Age + Sex	2.8±1.2	3.2±1.4	14.3	0.071
SV_{flow} (ml)				
Unadjusted	60.4±2.6	67.5±3.7	11.8	0.108
Age + Sex	62.5±2.6	64.4±3.1	3.0	0.648
Boys only + Age	68.2±4.8	69.5±4.5	1.9	0.838
Age + Sex + Height	62.7±2.6	64.2±3.1	2.4	0.713
Age + Sex + BSA	63.7±2.3	62.8±2.8	-1.4	0.826
SVR (mmHg.min/ml)				
Unadjusted	18.4±0.69	18.7±1.3	1.6	0.835
Age + Sex	18.0±0.87	19.3±1.1	7.2	0.374
Boys only + Age	17.4±1.4	17.4±1.3	0	0.998
Age + Sex + Height	18.0±0.88	19.3±1.1	7.2	0.347
Age + Sex + BSA	17.8±0.85	19.6±1.0	10.1	0.204
U1 (m/s)				
Unadjusted	1.13±0.03	1.26±0.04	11.5	0.008
Age + Sex	1.13±0.03	1.26±0.04	11.5	0.010
Boys only + Age	1.11±0.05	1.23±0.05	10.8	0.101
Age + Sex + Height	1.13±0.03	1.26±0.04	11.5	0.009
PWV_{ss} (m/s)				
Unadjusted	2.5±0.12	3.4±0.25	36.0	0.001
Age + Sex	2.5±0.16	3.3±0.20	32.0	0.004
Boys only + Age	2.8±0.28	3.3±0.27	17.9	0.253
Age + Sex + MAP + HR	2.5±0.17	3.3±0.22	32.0	0.013
Age + Sex + MAP + HR + LVOT area	2.5±0.17	3.3±0.22	32.0	0.014
PWV_{cf} (m/s)				
Unadjusted	5.7±0.17	6.1±0.22	7.0	0.145
Age + Sex	5.9±0.18	5.9±0.19	0	0.802

Boys only + Age	6.0±0.24	6.1±0.20	1.7	0.948
Age + Sex + MAP + HR	6.0±0.22	5.8±0.23	-3.3	0.691
Age + Sex + MAP + HR + LVOT area	5.9±0.20	5.9±0.21	0	0.823

BSA, body surface area; CO, cardiac output; CI, cardiac index; SV, stroke volume; SVR, systemic vascular resistance; PWVss, pulse wave velocity by sum-of-squares; PWVcf, carotid-femoral pulse wave velocity; LVOT, left ventricular outflow tract.* Adjusted for age.