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Determinants of carotid-femoral Pulse wave velocity in adolescents

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Declaração de Integridade

Declara-se que o conteúdo desta dissertação é original e que todo o material de terceiros foi devidamente referenciado de acordo com as normas académicas vigentes. Afirma-se, ainda, que os autores não possuem qualquer conflito de interesse atual ou potencial, incluindo conflitos financeiros, pessoais ou relacionais com pessoas ou organizações que possam influenciar os resultados ou interpretações do trabalho.

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RESUMO

Introdução: A velocidade de onda de pulso carotídeo-femoral (VOP) é a medida gold standard da rigidez arterial central e um preditor de eventos cardiovasculares em adultos, com crescente relevância nas populações pediátricas. Embora a VOP aumente naturalmente com a idade, fatores de risco cardiometabólicos podem acelerar este processo. A crescente prevalência da obesidade infantil aumenta as preocupações relativamente às consequências vasculares a longo prazo. Contudo, a forma como a rigidez arterial evolui da infância para a adolescência e o contributo independente de fatores como adiposidade, a pressão arterial e a resistência à insulina durante este período permanecem pouco compreendidos. Este estudo comparou a VOP carotídeo–femoral entre adolescentes sem excesso de peso e com excesso de peso/obesidade, avaliou a sua progressão desde uma idade pré-púbere até ao início da adolescência e identificou determinantes independentes de rigidez arterial.

Métodos: Este estudo longitudinal incluiu 118 participantes da coorte Geração XXI (Porto, Portugal) avaliados aos 8–9 e aos 13–14 anos de idade. A VOP carotídeo-femoral foi medida em ambos os momentos utilizando um dispositivo portátil validado. Foram recolhidos dados antropométricos, pressão arterial de consultório e amostras de sangue em jejum para análise do perfil lipídico, glicose e insulina; a resistência à insulina foi estimada através do HOMA-IR. A classificação do índice de massa corporal (IMC) foi realizada de acordo com os critérios da Organização Mundial da Saúde.

Resultados: A VOP aumentou significativamente da infância para a adolescência (5,01 ± 0,47 para 6,30 ± 1,05 m/s; $p<0,001$). Aos 13–14 anos, os adolescentes com excesso de peso/obesidade apresentaram VOP significativamente superior aos pares sem excesso de peso. A VOP aos 13-14 anos correlacionou-se positivamente com o IMC, z-score do IMC, pressão arterial sistólica e diastólica e glicemia em jejum. Nos modelos ajustados, a VOP aos 8–9 anos ($\beta=0,39$; $p=0,039$) e o z-score do IMC aos 13–14 anos ($\beta=0,33$; $p<0,001$) permaneceram preditores independentes da VOP aos 13-14 anos.

Conclusões: A rigidez arterial no início da adolescência parece ser influenciada pela trajetória vascular estabelecida desde a infância, bem como, pela adiposidade concomitante, sendo a VOP aos 8–9 anos e o z-score do IMC preditores independentes. Estes resultados apoiam o rastreio vascular precoce e intervenções de gestão do peso durante períodos de desenvolvimento críticos para otimizar a saúde cardiovascular a longo prazo.

Palavras-chave: Velocidade da onda de pulso; Rigidez arterial; Adolescência; Obesidade infantil; Risco cardiovascular.

ABSTRACT

Background: Carotid–femoral pulse wave velocity (PWV) is the gold standard measure of central arterial stiffness and a predictor of cardiovascular events in adults, with growing relevance in pediatric populations. Although PWV increases naturally with age, cardiometabolic risk factors may accelerate this process. The rising prevalence of childhood obesity heightens concerns regarding long-term vascular consequences. However, how arterial stiffness evolves from childhood to adolescence and the independent contributions of adiposity, blood pressure, and insulin resistance during this period remain poorly understood. This study compared carotid–femoral PWV between non-overweight and overweight/obese adolescents, evaluated its progression from prepubertal age to early adolescence, and identified independent determinants of arterial stiffness.

Methods: This longitudinal study included 118 participants from the Generation XXI cohort (Porto, Portugal) assessed at ages 8–9 and 13–14 years. Carotid–femoral PWV was measured at both time points using a validated portable device. Anthropometric data, office blood pressure, and fasting blood samples for lipid profile, glucose, and insulin were collected; insulin resistance was estimated using the HOMA-IR. Body mass index (BMI) classification followed the World Health Organization growth references.

Results: PWV increased significantly from childhood to adolescence (5.01 ± 0.47 to 6.30 ± 1.05 m/s; $p<0.001$). At 13–14 years, overweight/obese adolescents had significantly higher PWV than non-overweight peers. PWV at 13-14 years correlated positively with BMI, BMI z-score, systolic and diastolic blood pressure, and fasting glucose. In adjusted models, PWV at 8–9 years ($\beta=0.39$; $p=0.039$) and BMI z-score at 13–14 years ($\beta=0.33$; $p<0.001$) remained independent predictors of PWV at 13-14 years.

Conclusions: Arterial stiffness in early adolescence reflects both vascular tracking from childhood and concurrent adiposity, with PWV at 8–9 years and BMI z-score emerging as independent predictors. These findings support early vascular screening and weight management interventions during key developmental periods to optimize long-term cardiovascular health.

Keywords: Pulse wave velocity; Arterial stiffness; Adolescence; Childhood obesity; Cardiovascular risk.

ABBREVIATIONS

BMI, body mass index

BP, blood pressure

HDL, high-density lipoprotein

HOMA-IR, homeostasis model assessment index

IMT, intima-media thickness

LDL, low-density lipoprotein

PWV, pulse wave velocity

SD, standard deviation

WHO, World Health Organization

TABLE OF CONTENTS

AGRADECIMENTOS i
RESUMO ii
ABSTRACT iii
ABBREVIATIONS iv
LIST OF TABLES vi
INTRODUCTION 1
METHODS 2
RESULTS 5
DISCUSSION 6
REFERENCES 10

LIST OF TABLES

Table I - Demographic, anthropometric, and cardiovascular variables in non-overweight and overweight/obese adolescents aged 13–14 years. 13
Table II - Evolution of carotid–femoral pulse wave velocity (PWV) between 8–9 and 13–14 years according to weight-status trajectory...... 14
Table III - Spearman correlations between carotid-femoral pulse wave velocity (PWV) and cardiovascular risk determinants. 15
Table IV - Independent determinants of carotid-femoral pulse wave velocity (PWV)... 16

INTRODUCTION

Pulse wave velocity (PWV) is recognized as an indicator of arterial stiffness, with carotid–femoral PWV being widely accepted as the gold standard for assessing aortic stiffness[1,2]. Although PWV naturally increases with age due to vascular aging, conditions such as arterial hypertension and diabetes mellitus can accelerate this process, promoting early vascular changes[3]. In adults, PWV is recognized as a robust predictor of cardiovascular events and all-cause mortality [4,5] .In recent years, the relevance of PWV in the pediatric population has gained increasing attention, as early vascular alterations may precede the clinical manifestation of cardiovascular disease[3,6,7]. Therefore, assessing PWV in children and adolescents may help identify individuals at higher lifetime cardiovascular risk[8].

Obesity is a public health concern with increasing prevalence affecting individuals across all age groups[9]. In recent decades, the rise in obesity during childhood and adolescence has been particularly concerning, largely driven by sedentary lifestyles and unhealthy dietary patterns[10,11]. This condition is associated with various health complications, including insulin resistance, dyslipidemia, and elevated blood pressure (BP). In the pediatric population, excess weight has been linked to the early onset of several cardiovascular risk factors and the development and progression of atherosclerosis[7,8,12].

Several studies have shown that obese children exhibit higher PWV compared to their non-overweight counterparts[13], suggesting that obesity adversely affects arterial elasticity and pulse wave propagation, thereby increasing long-term cardiovascular risk. Although most studies confirm this association, some authors have reported contradictory findings, with some failing to identify a correlation or even suggesting an inverse relationship between weight and PWV[14]. These inconsistencies are often interpreted as reflecting a transient vasodilatory adaptation that may occur in the early phases of obesity.

In addition to body weight, factors such as elevated BP and metabolic alterations, including insulin resistance, also appear to contribute to arterial stiffness at young ages[15–17]. However, the available evidence remains limited and heterogeneous[18]. Therefore, further research is needed to clarify how excess weight and metabolic disturbances interact in the development of arterial stiffness during adolescence.

In the present study, we aimed to compare carotid–femoral PWV between non-overweight and overweight/obese adolescents, and to evaluate the change of this arterial stiffness marker from prepubertal age (8–9 years) to early adolescence (13-14 years). Additionally, we sought to examine the contribution of other cardiometabolic risk factors to arterial stiffness during adolescence.

METHODS

Study design and sample

The present study is a follow-up of the ObiKid project, a cross-sectional study nested within the Generation XXI birth cohort (Porto, Portugal; n = 8,647) [19,20]. ObiKid was designed to investigate the influence of childhood obesity and related comorbidities on kidney health in children aged 8–9 years. Participant selection was based on Generation XXI members who attended a follow-up visit at 7 years of age (n = 6,889). Those with anthropometric data and blood samples available (n = 4,590) were eligible for ObiKid. From these, a subsample of 313 children underwent further evaluation at 8–9 years of age as part of the original ObiKid assessment. The screening and recruitment procedures have been previously described in detail [21].

For the current project (Obikid 2.0), all individuals who had participated in the 8–9-year evaluation were invited for a follow-up assessment at 13–14 years of age. Among these, 18 declined participation, 41 could not be contacted, and 77 were unable to schedule visits within the recruitment period, largely due to COVID-19–related constraints. No participants met the predefined clinical exclusion criteria (genetic, renal, or metabolic diseases). However, four adolescents were excluded due to chronic medication that could influence BP, glucose, or lipid metabolism. Additionally, 55 participants were removed from the analysis due to incomplete data, specifically carotid–femoral PWV measurements. A total of 118 adolescents met all criteria and were included in the final sample for this study.

Data collection and variable definition

Both study visits, at 8-9 years of age and during adolescence, took place at the Public Health and Forensic Sciences and Medical Education Department, Faculty of Medicine - University of Porto. Anthropometric measurements and general physical examinations were performed, according to standard procedures and as previously reported. Body mass index (BMI) was calculated (kg/m²), and BMI-for-age values were classified into 2 categories: (1) non-overweight [≤+1 standard deviation (SD)], (2) overweight (>1SD and ≤+2SD) /obesity (>2SD), according to the World Health Organization (WHO) reference data for BMI z-score [22].

Carotid–femoral PWV analysis was performed, at both time points, by a single trained cardiopneumology technician using a portable device (Micro Medical, model PulseTrace PWV PT4000, Kent, UK). After a 5-minute rest in the supine position, the distance between carotid and femoral arteries was assessed as the distance of suprasternal notch to the umbilicus and from the umbilicus to the femoral arterial measuring point, minus the distance from the suprasternal notch to the carotid artery measuring point. Electrocardiogram registry was performed simultaneously, allowing the software to calculate the time from the peak of the R-wave to the foot of the pulse

wave at the carotid and femoral arteries, respectively. The digital volume pulse waveform was required to fill two-thirds of the display with minimal noise or artefact to be accepted, and three PWV measurements were obtained and averaged for analysis.

Office BP assessment was performed with validated oscillometric sphygmomanometers (Elite 92125; Medel, Parma, Italy) using an adequately sized cuff placed on the right arm, by a trained nonphysician interviewer. Measurements were obtained three times at 5-minute intervals, and the mean of the second and third evaluations was used for analysis.

Laboratory procedures

A venous blood sample was collected from all participants, after an overnight fast of at least 8 hours. Standard blood analyses, including lipid profile (total cholesterol, high-density lipoprotein (HDL) cholesterol, low-density lipoprotein (LDL) cholesterol, triglycerides), glucose, insulin, were performed at the Clinical Pathology Department of Centro Hospitalar Universitário São João, Porto. Insulin resistance was determined using the homeostasis model assessment index (HOMA-IR).

Ethics

The ObiKid study was approved by the Ethics Committee of Centro Hospitalar Universitário de São João, E.P.E., and Faculty of Medicine of the University of Porto. The study complies with the Declaration of Helsinki, the guidelines for the ethical conduct of medical research involving children and the current national legislation. Written informed consent was obtained from parents (or legal substitutes), and verbal assent was obtained from the adolescents for the participation and biological sample collection.

Statistical analysis

Statistical analysis was performed using IBM® SPSS® Statistics 27.0. Variables are presented as mean ± standard deviation (SD), number (%), or median (percentile 25^{th}-75^{th}, P25–P75), as appropriate. Between-group differences in continuous variables were evaluated using Student's *t*-test. Bivariate associations were assessed with Spearman correlation coefficient. A two-sided p value < 0.05 was considered statistically significant. A multivariable linear regression model was developed to identify independent determinants of carotid–femoral PWV. Sex, age (in months), BMI, and BP parameters, which are known to influence PWV, were forced into the model. Additional variables with $p < 0.30$ in bivariate analysis were considered candidate predictors. PWV measured at 8–9 years was included in regression models to explore vascular tracking from childhood to adolescence. All eligible variables were initially entered, and a backward stepwise elimination procedure was applied, sequentially removing non-significant predictors until only covariates that remained significant after adjustment were retained in the final model.

To explore the influence of weight-status changes on arterial stiffness, participants were categorized into four trajectory groups based on their weight status at 8–9 years and 13–14 years: persistently non-overweight, persistently overweight/obese, overweight/obese to non-overweight, and non-overweight to overweight/obese. Differences in PWV between time points within each trajectory group were assessed using paired t-tests.

RESULTS

A sample of 118 adolescents (54.2% male), aged 13–14 years, was analyzed in this study. Demographic, anthropometric, and cardiovascular variables are presented in Table I according to BMI category (non-overweight, n = 77; overweight/obese, n = 41). Regarding laboratory variables, adolescents with overweight/obesity displayed significantly lower HDL-cholesterol levels and higher HOMA-IR values, whereas total cholesterol, LDL cholesterol, and triglycerides did not differ significantly between groups (**Table I**).

The mean carotid–femoral PWV increased significantly from childhood to adolescence in the overall sample (5.01 ± 0.47 m/s vs. 6.30 ± 1.05 m/s, $p < 0.001$, at 8-9 and at 13-14 years of age, respectively). A similar trend was observed when weight-status trajectories between the two age points was considered, with PWV increasing significantly in all subgroups, including adolescents who remained non-overweight, those who remained overweight/obese, and those who changed BMI category between assessments **(Table II)**.

The correlations between PWV and cardiovascular risk variables are presented in **Table III**. Significant positive correlations were observed between PWV and anthropometric measures, including BMI, BMI z-score, and weight at both 8–9 and 13–14 years of age. PWV also showed strong positive correlations with systolic and diastolic BP levels. Among biochemical markers, PWV was inversely correlated with HDL cholesterol, while a positive correlation was found with fasting glucose.

After adjustment for sex and age, the multivariable linear regression model identified PWV at 8–9 years and BMI z-score as independent predictors of carotid–femoral PWV at 13–14 years (**Table IV**). Specifically, higher PWV at 8–9 years was associated with a 0.39 m/s increase in PWV at 13–14 years (95% CI: 0.02 to 0.76; $p = 0.039$), while each unit increase in BMI z-score was associated with a 0.33 m/s higher PWV at 13–14 years (95% CI: 0.18 to 0.49; $p < 0.001$).

DISCUSSION

In this longitudinal study of a well-characterized sample of non-overweight and overweight/obese adolescents, we identified early-life and concurrent determinants of arterial stiffness in early adolescence. Carotid–femoral PWV increased significantly from childhood to adolescence across all weight-status trajectories, and PWV at 13–14 years was independently associated with both prior PWV measured at 8–9 years and BMI z-score. These findings reinforce that arterial stiffness in early adolescence reflects a combination of vascular tracking from childhood and adiposity-related influences, highlighting that vascular characteristics established early in life may persist across developmental stages.

We found significantly higher PWV levels in overweight and obese adolescents, as we had already reported in a previous evaluation of the same group at 8-9 years[23]. These results support the hypothesis that excess body weight contributes to early vascular changes, reflecting both structural and functional alterations in the arterial wall. Our findings are consistent with previous evidence reporting a positive association between adiposity and arterial stiffness in youth[13,24]. Nonetheless, some studies have presented divergent findings, reporting lower PWV values among overweight or obese individuals, or even no association between obesity and arterial stiffness. One of these studies reported that, although obese adolescents exhibited increased intima-media thickness (IMT), they presented lower PWV compared with lean subjects [14]. This has been interpreted as a compensatory vasodilatory response occurring in the initial stages of obesity, likely driven by increased metabolic demand. The divergent results observed in that study by Dangardt and colleagues may largely stem from sample differences [14]. Their age range (10–18 years) encompasses multiple pubertal stages, unlike our more homogeneous 13–14-year-old cohort, which means that a single mean PWV value in their analysis cannot meaningfully represent any specific developmental phase.

In our cohort, carotid–femoral PWV increased significantly from childhood to early adolescence across all weight-status trajectories. This consistent increase, observed in participants who maintained normal weight, those who remained overweight/obese, and those who changed weight category, suggests that a substantial component of PWV progression reflects normal developmental arterial stiffening. This pattern suggests that, alongside normal age-related arterial stiffening, individual differences in vascular properties established earlier in life may persist over time. However, although within-group changes were assessed, the small number of participants in certain trajectories did not allow reliable comparisons between groups. Consequently, while all groups exhibitend significant increases, we could not establish whether certain weight-status

patterns corresponded to a faster progression of arterial stiffness. This limitation restricts our ability to fully clarify the cumulative impact of obesity on PWV progression.

Although longitudinal research in this area is still limited, the few available studies suggest that adiposity trajectories play a significant role in vascular development. The Avon Longitudinal Study of Parents and Children (ALSPAC) demonstrated that higher and sustained fat mass index throughout childhood and adolescence is associated with elevated PWV in late adolescence, whereas those who reduced their fat mass exhibited PWV values comparable to peers who were never overweight[25]. These findings support the notion that obesity-related vascular alterations may be at least partially reversible during this developmental period, and that weight reduction may mitigate early arterial remodeling. Additionally, the five-year follow-up by Dangardt et al. (2013) found that persistent adiposity across childhood and adolescence is associated with a steeper increase in arterial stiffness over time[26]. Taken together, these findings highlight adolescence as a critical period for interventions targeting obesity to optimize long-term vascular health.

Another relevant finding of our study is that PWV at 8–9 years was an independent predictor of PWV at 13–14 years. This finding supports the concept of vascular tracking, whereby individuals tend to maintain their relative position within the distribution of arterial stiffness over time. This suggests a degree of stability in arterial stiffness across childhood and early adolescence, with children who present higher values at younger ages tending to maintain a less favorable vascular profile later. Such tracking phenomena have been previously described for several cardiovascular risk factors in youth, including BP and adiposity, suggesting that early-life cardiovascular profiles may persist into later stages of development. This observation reinforces the clinical importance of early vascular assessment. Nevertheless, longitudinal evidence on PWV trajectories in pediatric populations remains limited, and further studies with repeated intermediate measurements are needed to clarify how early-life vascular characteristics evolve across developmental stages and interact with other cardiometabolic parameters.

In our sample, systolic and diastolic BP were strongly associated with PWV in univariate analysis, in line with observations from previous pediatric studies[7,27,28]. However, this association was no longer present after multivariate adjustment. Several studies in youth have documented significant associations between BP indices and arterial stiffness, supporting BP as an important hemodynamic contributor to vascular function in childhood and adolescence[3,16,28]. Nonetheless, some of these associations tend to weaken once BMI or metabolic factors are taken into account[3,7]. Within this context, a plausible explanation for the absence of an independent association in our analysis is that BP, sex, and adiposity are highly interrelated during adolescence; therefore, when entered simultaneously into adjusted models, the independent contribution of BP may be attenuated.

In addition, we did not detect an independent association between PWV and HOMA-IR. This contrasts with some reports, particularly a study conducted in male adolescents which identified HOMA-IR as an independent determinant of arterial stiffness even after adjustment for adiposity[17]. However, our findings are consistent with other investigations showing that this association often disappears once adiposity and BP are included in the models[18]. More recent pediatric data, including findings from the SHIP AHOY study, also failed to demonstrate an independent relationship between HOMA-IR and PWV[29]. Differences in methodology across studies, such as the use of brachial–ankle instead of carotid–femoral PWV as well as variations in metabolic profiles and sample characteristics, may contribute to these discrepancies[18]. Notably, insulin resistance has been shown to relate more strongly and consistently to peripheral (brachial–ankle) rather than central (carotid–femoral) PWV, which may further explain inconsistent findings across vascular segments[1]. Overall, current evidence suggests that insulin resistance may play a modest role in determining central arterial stiffness once adiposity and hemodynamic load are accounted for, which aligns with our results.

Strengths and limitations

The use of a large sample of adolescents, all of similar age and assessed through a detailed evaluation of cardiovascular risk markers, provides a solid foundation for interpreting the results. The measurement of PWV at two points - during childhood and again in early adolescence - also offers valuable insight into the early progression of arterial stiffness.

The study also benefits from the use of standardized measurement protocols, which helped ensure consistent data collection, as well as from the analytical adjustment for key confounders, strengthening the internal validity of the results. Additionally, the assessment of arterial stiffness through carotid–femoral PWV, considered the gold standard, provides a reliable and validated measure of large-artery stiffness. Beyond its strong validation in the literature, carotid–femoral PWV is non-invasive, low-cost, and feasible in pediatric settings, making it a practical tool for large-scale evaluations of vascular health.

One of the main limitations of this study relates to the fact that, although PWV was assessed at two time points, the absence of intermediate measurements limits the ability to delineate the trajectory of arterial stiffening in greater detail or to identify potential periods of accelerated change. In addition, as previously stated, although PWV evolution within weight-status groups was described, PWV trajectories could not be robustly compared across weight-status groups, as some groups included a limited number of participants, precluding a reliable assessment of between-group differences. As a result, we could not assess whether prolonged exposure to excess weight is associated with steeper increases in PWV. Additionally, variability in the estimation of the carotid–

femoral path length may occur, particularly in individuals with higher adiposity, where overestimation is more likely [1]. However, the fact that all measurements were performed by a single trained cardiopneumology technician helps to minimize this potential source of bias.

Conclusions

In conclusion, our findings indicate that arterial stiffness in early adolescence is shaped by both early-life vascular characteristics and contemporaneous adiposity. The independent association between PWV measured in childhood and carotid–femoral PWV at 13–14 years supports the concept of early-life vascular tracking, while the contribution of BMI z-score emphasizes the modifiable role of excess adiposity in early arterial stiffening. Together, these results highlight the importance of early identification of children at increased vascular risk and support the potential value of early lifestyle interventions aimed at preventing or attenuating the progression of arterial stiffness during critical developmental periods.

REFERENCES

1. Townsend RR, Wilkinson IB, Schiffrin EL, et al. Recommendations for Improving and Standardizing Vascular Research on Arterial Stiffness: A Scientific Statement From the American Heart Association. *Hypertension*. 2015;66(3):698-722. doi:10.1161/HYP.0000000000000033

2. Salvi P, Scalise F, Rovina M, et al. Noninvasive Estimation of Aortic Stiffness Through Different Approaches: Comparison with Intra-Aortic Recordings. *Hypertension*. 2019;74(1):117-129. doi:10.1161/HYPERTENSIONAHA.119.12853

3. Stoner L, Kucharska-Newton A, Meyer ML. Cardiometabolic Health and Carotid-Femoral Pulse Wave Velocity in Children: A Systematic Review and Meta-Regression. *J Pediatr*. 2020;218:98-105.e3. doi:10.1016/j.jpeds.2019.10.065

4. Liu K, Lin Z, Chen Y, Hong H. Elevated pulse wave velocity as a marker of arterial stiffness and its association with mortality in US adults. *Sci Rep*. 2025;15(1):23026. Published 2025 Jul 2. doi:10.1038/s41598-025-07198-w

5. Vlachopoulos C, Aznaouridis K, Stefanadis C. Prediction of cardiovascular events and all-cause mortality with arterial stiffness: a systematic review and meta-analysis. *J Am Coll Cardiol*. 2010;55(13):1318-1327. doi:10.1016/j.jacc.2009.10.061

6. Kodithuwakku V, Breslin M, Hersant J, et al. Establishing Reference Values for Pulse Wave Velocity in Young People: The Youth Vascular Consortium. *Hypertension*. 2025;82(7):1234-1245. doi:10.1161/HYPERTENSIONAHA.125.25007

7. Lona G, Hauser C, Köchli S, et al. Association of blood pressure, obesity and physical activity with arterial stiffness in children: a systematic review and meta-analysis. *Pediatr Res*. 2022;91(3):502-512. doi:10.1038/s41390-020-01278-5

8. de Ferranti SD, Steinberger J, Ameduri R, et al. Cardiovascular Risk Reduction in High-Risk Pediatric Patients: A Scientific Statement From the American Heart Association. *Circulation*. 2019;139(13):e603-e634. doi:10.1161/CIR.0000000000000618

9. World Health Organization. International Classification of Diseases for Mortality and Morbidity Statistics (11th Revision) [Internet]. Geneva: WHO; 2024 [cited 2025 Nov 20]. Available from: https://icd.who.int/browse/2024-01/mms/en

10. Zhang X, Liu J, Ni Y, et al. Global Prevalence of Overweight and Obesity in Children and Adolescents: A Systematic Review and Meta-Analysis. *JAMA Pediatr*. 2024;178(8):800-813. doi:10.1001/jamapediatrics.2024.1576

11. Kansra AR, Lakkunarajah S, Jay MS. Childhood and Adolescent Obesity: A Review. *Front Pediatr*. 2021;8:581461. Published 2021 Jan 12. doi:10.3389/fped.2020.581461

12. Kelly AS, Barlow SE, Rao G, et al. Severe obesity in children and adolescents: identification, associated health risks, and treatment approaches: a scientific statement from the American Heart Association. *Circulation*. 2013;128(15):1689-1712. doi:10.1161/CIR.0b013e3182a5cfb3

13. Cote AT, Phillips AA, Harris KC, Sandor GG, Panagiotopoulos C, Devlin AM. Obesity and arterial stiffness in children: systematic review and meta-analysis. *Arterioscler Thromb Vasc Biol*. 2015;35(4):1038-1044. doi:10.1161/ATVBAHA.114.305062

14. Dangardt F, Osika W, Volkmann R, Gan LM, Friberg P. Obese children show increased intimal wall thickness and decreased pulse wave velocity. Clin Physiol Funct Imaging. 2008;28(5):287–293. doi:10.1111/j.1475-097X.2008.00806.x

15. Genovesi S, Tassistro E, Lieti G, et al. Wall Properties of Elastic and Muscular Arteries in Children and Adolescents at Increased Cardiovascular Risk. *J Clin Med*. 2023;12(21):6919. doi:10.3390/jcm12216919

16. Liang X, Su S, Hao G, et al. Determinants of pulse wave velocity trajectories from youth to young adulthood: the Georgia Stress and Heart Study. *J Hypertens*. 2019;37(3):563-571. doi:10.1097/HJH.0000000000001933

17. Lee JW, Lee DC, Im JA, Shim JY, Kim SM, Lee HR. Insulin resistance is associated with arterial stiffness independent of obesity in male adolescents. Hypertens Res. 2007;30(1):5–11. doi:10.1291/hypres.30.5

18. Urbina EM, Gao Z, Khoury PR, Martin LJ, Dolan LM. Insulin resistance and arterial stiffness in healthy adolescents and young adults. *Diabetologia*. 2012;55(3):625-631. doi:10.1007/s00125-011-2412-1

19. Alves E, Correia S, Barros H, Azevedo A. Prevalence of self-reported cardiovascular risk factors in Portuguese women: a survey after delivery. *Int J Public Health*. 2012;57(5):837-847. doi:10.1007/s00038-012-0340-6

20. Larsen PS, Kamper-Jørgensen M, Adamson A, et al. Pregnancy and birth cohort resources in europe: a large opportunity for aetiological child health research. *Paediatr Perinat Epidemiol*. 2013;27(4):393-414. doi:10.1111/ppe.12060

21. Correia-Costa L, Afonso AC, Schaefer F, et al. Decreased renal function in overweight and obese prepubertal children. *Pediatr Res*. 2015;78(4):436-444. doi:10.1038/pr.2015.130

22. de Onis M, Onyango AW, Borghi E, Siyam A, Nishida C, Siekmann J. Development of a WHO growth reference for school-aged children and adolescents. *Bull World Health Organ*. 2007;85(9):660-667. doi:10.2471/blt.07.043497

23. Correia-Costa A, Correia-Costa L, Caldas Afonso A, et al. Determinants of carotid-femoral pulse wave velocity in prepubertal children. *Int J Cardiol*. 2016;218:37-42. doi:10.1016/j.ijcard.2016.05.060

24. Hudson LD, Rapala A, Khan T, Williams B, Viner RM. Evidence for contemporary arterial stiffening in obese children and adolescents using pulse wave velocity: A systematic review and meta-analysis. *Atherosclerosis*. 2015;241(2):376-386. doi:10.1016/j.atherosclerosis.2015.05.014

25. Dangardt F, Charakida M, Georgiopoulos G, et al. Association between fat mass through adolescence and arterial stiffness: a population-based study from The Avon Longitudinal Study of Parents and Children. *Lancet Child Adolesc Health*. 2019;3(7):474-481. doi:10.1016/S2352-4642(19)30105-1

26. Dangardt F, Chen Y, Berggren K, Osika W, Friberg P. Increased rate of arterial stiffening with obesity in adolescents: a five-year follow-up study. *PLoS One*. 2013;8(2):e57454. doi:10.1371/journal.pone.0057454

27. Haley JE, Woodly SA, Daniels SR, et al. Association of Blood Pressure-Related Increase in Vascular Stiffness on Other Measures of Target Organ Damage in Youth. *Hypertension*. 2022;79(9):2042-2050. doi:10.1161/HYPERTENSIONAHA.121.18765

28. Stabouli S, Kollios K, Nika T, Chrysaidou K, Tramma D, Kotsis V. Ambulatory hemodynamic patterns, obesity, and pulse wave velocity in children and adolescents. *Pediatr Nephrol*. 2020;35(12):2335-2344. doi:10.1007/s00467-020-04694-1

29. Price JJ, Urbina EM, Carlin K, et al. Cardiovascular Risk Factors and Target Organ Damage in Adolescents: The SHIP AHOY Study. *Pediatrics*. 2022;149(6):e2021054201. doi:10.1542/peds.2021-054201

Table I - Demographic, anthropometric, and cardiovascular variables in non-overweight and overweight/obese adolescents aged 13–14 years.

		WHO BMI z-score classification		
		Non-overweight (n = 77)	Overweight/Obese (n = 41)	p
Demography and anthropometry				
Age (months)		170.8 ± 2.2	170.9 ± 2.1	0.748
Male sex		44 (57.1%)	20 (48.8%)	0.390
Weight (Kg)		53.8 ± 6.7	72.3 ± 11.7	< 0.001
Height (cm)		165.1 ± 7.8	165.3 ± 7.8	0.907
BMI (kg/m^2)		19.7 ± 1.9	26.4 ± 3.1	< 0.001
	BMI z-score	0.01 ± 0,79	1.82 ± 0.54	< 0.001
Blood pressure				
Systolic BP (mmHg)		110.8 ± 9.5	117.8 ± 10.8	< 0.001
	Systolic BP z-score	-0.07 ± 0.90	0.61 ± 0.91	< 0.001
Diastolic BP (mmHg)		71.9 ± 7.5	76.85 ± 9.8	0.003
	Diastolic BP z-score	0.65 ± 0.67	1.08 ± 0.87	0.003
Laboratorial parameters				
Total cholesterol (mg/dL)		149.0 ± 32.4	145.4 ± 25.7	0.541
LDL cholesterol (mg/dL)		85.2 ± 24.9	87.1 ± 21.8	0.679
HDL cholesterol (mg/dL)		52.1 ± 9.0	46.4 ± 7.0	0.001
Triglycerides (mg/dL)		67.3 ± 27.2	65.7 ± 25.3	0.748
HOMA-IR		2.23 (1.68-3.19)	2.97 (1.98-3.61)	0.026
Fasting insulin (µIU/dL)		11.19 (7.93-14.73)	13.60 (9.48-17.70)	0.021
Fasting glucose (mg/dL)		86.8 ± 5.8	86.6 ± 6.9	0.905

The values presented are mean ± standard deviation, median (25th-75th percentiles), or n (%). The BMI classes are according to the WHO classification for BMI z-score values [22].

BMI- body mass index; BP, blood pressure; LDL- low-density lipoprotein; HDL- high-density lipoprotein; HOMA-IR – homeostasis model assessment of insulin resistance

Table II - Evolution of carotid–femoral pulse wave velocity (PWV) between 8–9 and 13–14 years according to weight-status trajectory.

Weight-status trajectory (8-9 to 13-14 years)	PWV at 8-9 years (m/s)	PWV at 13-14 years (m/s)	p
Total sample	5.01 ± 0.47	6.30 ± 1.05	p < 0.001
Persistently non-overweight	4.95 ± 0.48	6.09 ± 0.90	p < 0.001
Persistently overweight/obese	5.14 ± 0.48	6.72 ± 1.26	p < 0.001
Overweight/obese to non-overweight	4.94 ± 0.42	6.04 ± 0.90	p < 0.001
Non-overweight to overweight	4.94 ± 0.49	6.54 ± 0.33	p = 0.006

The values are presented as mean ± standard deviation.

Table III - Spearman correlations between carotid-femoral pulse wave velocity (PWV) and cardiovascular risk determinants.

	PWV (m/sec)	
	Spearman correlation coefficient (ρ)	**p**
Age (months)	-0.035	0.708
PWV (8-9)	0.238	**0.009**
BMI (8-9)	0.248	**0.007**
BMI z-score (8-9)	0.282	**0.002**
Weight (8-9)	0.195	**0.034**
BMI	0.221	**0.016**
BMI z-score	0.276	**0.003**
Weight	0.268	**0.003**
Systolic BP	0.385	**<0.001**
Systolic BP z-score	0.321	**<0.001**
Diastolic BP	0.319	**<0.001**
Diastolic BP z-score	0.340	**<0.001**
Total cholesterol (mg/dL)	-0.164	**0.077**
LDL cholesterol (mg/dL)	-0.060	0.534
HDL cholesterol (mg/dL)	-0.297	**0.001**
Triglycerides (mg/dL)	-0.006	0.949
Fasting glucose (mg/dL)	0.259	**0.005**
Fasting insulin (µIU/dL)	0.080	0.402
HOMA-IR	0.123	**0.196**

The values presented are Spearman's ρ and p value.

BMI, body mass index; BP, blood pressure; LDL, low-density lipoprotein; HDL, high-density lipoprotein; HOMA-IR, homeostasis model assessment of insulin resistance

Table IV - Independent determinants of carotid-femoral pulse wave velocity (PWV)

	Pulse wave velocity (m/sec)	
	Adjusted β (95% CI)	**p**
PWV (8-9)	0.391 (0.020 to 0.762)	0.039
BMI z-score	0.332 (0.177 to 0.487)	<0.001

The values presented are adjusted linear regression coefficients (β) and 95% confidence intervals, estimated with pulse wave velocity as dependent variable. The final model presented is adjusted for all variables in the table and additionally for sex and age.

BMI, body mass index; HOMA-IR, homeostasis model assessment of insulin resistance

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