Arteriosclerosis, Thrombosis, and Vascular Biology

ATVB IN FOCUS: Arterial Stiffness

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Ethnicity and Arterial Stiffness

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ABSTRACT: Early vascular aging reflects increased arterial stiffness of central blood vessels at young chronological ages and powerfully predicts cardiovascular events and mortality, independent of routine brachial blood pressure and other risk factors. Since ethnic disparities exist in routine blood pressure, in hypertension and cardiovascular outcomes, this review evaluates major studies comparing arterial stiffness through the life course between different ethnic groups or races (which have no biological definition)—in children, adolescents, young, and middle-aged adults and the very elderly. Most report that compared with white European-origin samples, populations of black African descent have increased central arterial stiffness throughout different life stages, as well as a more rapid increase in arterial stiffness at young ages. Exceptions may include African Caribbean origin people in Europe. Differences in vascular structure and function are clearest, where obesity, socioeconomic, and psychosocial factors are most marked. Few studies evaluate a wider spectrum of ethnic groups or factors contributing to these ethnic disparities. Genetic effects are not obvious; maternal risk and intergenerational studies are scarce. Nevertheless, across all ethnic groups, for given levels of blood pressure and age, some people have stiffer central arteries than others. These individuals are most at risk of vascular events and mortality and, therefore, may benefit from early, as yet untested, preventive action and treatment.

VISUAL OVERVIEW: An online visual overview is available for this article.

Key Words: age distribution ■ aortic stiffness ■ arteriosclerosis ■ blood pressure ■ ethnic groups ■ youth, African American

Arterial stiffness, measured as aortic or carotid-femoral pulse wave velocity (CFPWV), is now established as a significant independent predictor of future cardiovascular events and all-cause mortality.[1,2] An 1 m/s increase in aortic PWV corresponds to an age-, sex-, and risk factor-adjusted increased risk of 14% and 15% for cardiovascular events and mortality, respectively.[1] As aortic PWV predicts outcomes above and beyond traditional cardiovascular risk factors, including 24-hour blood pressure (BP),[3] it can be considered an intermediary outcome rather than a risk factor. These meta-analyses did not report on ethnic-specific risk, but mounting evidence supports the notion that there are ethnic disparities in arterial stiffness, which may account for discrepant cardiovascular mortality. Although such ethnic differences are thought to be explained by BP, strong evidence suggests that factors beyond BP are involved. A prime US example could be the REGARDS study (Reasons for Geographic and Racial Differences in Stroke), which compared stroke risk of individuals from African (or black) ancestry with those from European (or white) descent.[4] The impact of higher BP on stroke was 3 times greater for black than white adults—for a 10 mm Hg difference in systolic BP (SBP), increased risk was 24% for blacks but 8% for whites. Adjusting for the 2- to 3-fold excess diabetes mellitus nearly eliminated the excess.[4] Many studies support the higher stroke risk in black populations, such as the Centers for Disease Control and Prevention's Wide-Ranging Online Data for Epidemiologic Research indicating a crude rate of 52.3 stroke deaths/100 000 black versus 18.1/100 000 in white adults.[5] BP alone may not be sensitive enough to

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Nonstandard Abbreviations and Acronyms

AI	augmentation index
BMI	body mass index
BP	blood pressure
CAVI	cardio-ankle vascular index
CFPWV	carotid-femoral pulse wave velocity
CVD	cardiovascular disease
DASH	Determinants of Adolescent, Now Young Adult, Social Wellbeing, and Health
DBP	diastolic blood pressure
HELIUS	Healthy Life in an Urban Setting
NOMAS	Northern Manhattan Study
PP	pulse pressure
PWV	pulse wave velocity
REGARDS	Reasons for Geographic and Racial Differences in Stroke
SBP	systolic blood pressure

Highlights

- Early vascular aging, which reflects increased arterial stiffness at younger chronological ages, is a strong predictor of cardiovascular outcomes.
- Many studies that compare arterial stiffness between ethnic groups, spanning studies throughout the life course (including children as young as 6 years to the elderly), report ethnic disparities independent of blood pressure and other traditional cardiovascular risk factors.
- The majority of studies found that populations of African descent present with increased aortic stiffness from young ages onwards when compared to especially white populations.
- Ethnic disparities in arterial stiffness cannot yet be explained by genetic factors or by maternal risk factors, whereas obesity, socioeconomic status, and psychosocial factors were associated with increased arterial stiffness.

detect cardiovascular risk appropriately. British data for people of direct African or African Caribbean descent show less dramatic but still clear differences in stroke rates compared with whites, in part, due to competing cause from less coronary heart disease allowing more people at risk of stroke, but also likely from earlier, better BP control with a national health system.[6,7]

To clarify the potential role of arterial stiffness in ethnic-specific risk, we review studies reporting ethnic comparisons in arterial stiffness across the life course, including all ethnic or racial groups. Despite that effort, most studies compared individuals from African ancestry (referred to as black) and those from European descent (white), whereas others, such as South Asians, were underrepresented. Clearly, these categories are arbitrary, and major differences occur within such large groupings, confounded by as yet ill-defined genetic, intergenerational, and lifestyle issues referred to below.

ARTERIAL STIFFNESS THROUGHOUT THE LIFE COURSE

Large conduit elastic arteries undergo structural changes in their vessel walls with aging. Changes include fractured elastic lamellae, increasing dominance of collagen and its cross-linkages and key vascular smooth muscle cell–extracellular matrix interactions which alter vascular smooth muscle cell tone and change over time resulting in the development of arteriosclerosis or increased stiffness.[8] This biological process does not affect all individuals equally; animal and human evidence suggest that different segments of the aortic wall are affected differently,[9] which may be highly relevant to ethnic issues particularly if investigated using magnetic resonance imaging.[10] Factors such as genetic susceptibility, epigenetic imprinting during fetal life, socio-demographics, and health behaviors, including diet and physical activity, all contribute across the life course trajectory—with some individuals presenting with early vascular aging (Figure 1).[11] The concept of early vascular aging, therefore, reflects increased arterial stiffness for an individual's chronological age.[8]

The process of early vascular aging is complex. It may, therefore, be challenging to disentangle factors contributing to increased arterial stiffness in certain ethnic groups. As presented below, increased arterial stiffness is often found in ethnic groups who frequently experience lower socioeconomic status,[12] thus limited health care, less desirable diets, and lifestyle behaviors throughout the life course, including during pregnancy and, therefore, across several generations.

Heritability of arterial stiffness in both the Framingham Offspring Study[13] and a Brazilian population[14] was found to be modest, and a 2007 study between black and white populations found no ethnic difference.[15] Recently, using metabolomics, we found that higher PWV in black boys was uniquely associated with specific urinary amino acids regarded to have protective vascular functions. These amino acids play pivotal roles in collagen metabolism, glucose metabolism, and oxidative stress; and this ethnic-specific finding suggests that biosynthesis of nonessential amino acids may be upregulated to protect the vasculature against the onset of early vascular deterioration.[16] In young normotensive black and white adults with similar brachial BP, higher central SBP and central pulse pressure (PP) of black youth were independently associated with urinary amino acids that play pivotal roles in collagen metabolism and oxidative stress.[17] It remains

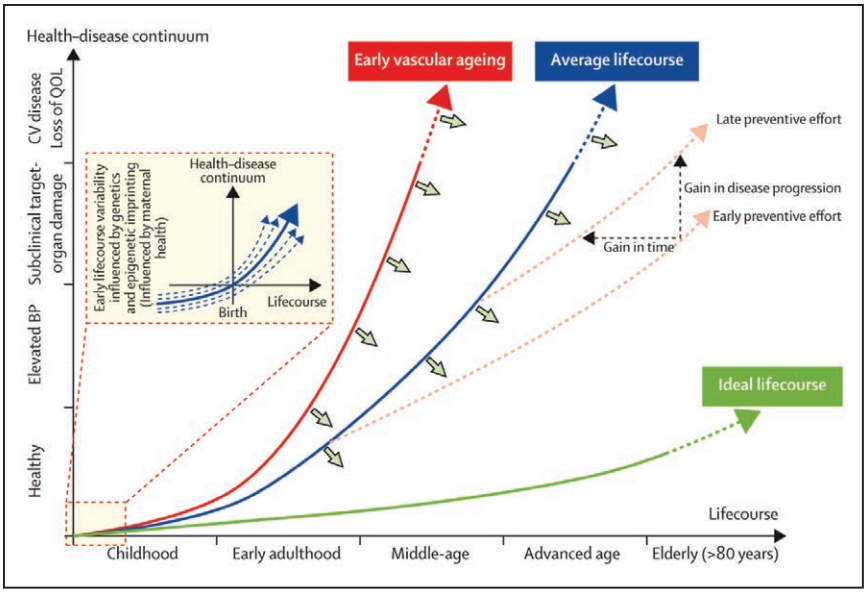

Figure 1. Genetic susceptibility, early epigenetic imprinting, and preventive efforts affecting the life course trajectory across the health-disease continuum.
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plausible that by using newer polyomics technologies, certain genes may be identified to explain unique biological pathways that regulate arterial stiffness.

ARTERIAL STIFFNESS THROUGHOUT THE LIFE COURSE—AMONG DIFFERENT ETHNICITIES

Aging, the most obvious factor contributing to cardiovascular disease (CVD), is directly associated with increased arterial wall thickness, primarily attributed to medial thickening, independently of atherosclerosis.[18] Replacement of elastic fibers by collagenous tissue reduces arterial elasticity, increasing central BP by the earlier return of reflected waves during systole.[19] These structural changes partially explain the increasing incidence of hypertension and CVD with age.[18,20,21] For detailed reviews of molecular and mechanical mechanisms, see publications by Lacolley et al[22] and Shadwick.[23]

In subsequent sections, we provide a brief overview of studies comparing arterial stiffness between ethnic groups over the life course. This is not a systematic nor exhaustive review, but we highlight key papers that included a range of arterial stiffness indices. CFPWV is regarded as a gold standard measure,[24] but studies also include PWV spanning other sections of the arterial tree (carotid-radial [which is not prognostic], carotid-dorsalis-pedis, brachial-ankle), augmentation index (AI), augmentation pressure, PP, PP amplification, cardio-ankle vascular index (CAVI), and ultrasound derived carotid β-stiffness index.

Children and Adolescents

Although arterial stiffening is a manifestation of biological aging, the onset of arterial stiffening is proposed to start at young ages due to continuous adaptations in the molecular and biomechanical makeup of blood vessels.[25] Increased aortic stiffness occurs in premature infants as measured by aortic wall thickness and vasomotor function.[26] Together with excess systemic hypertension in preterm infants,[27] low birth weight and other complications, such as bronchopulmonary dysplasia,[26] all contribute to the early onset of arterial stiffening. Explanations for higher arterial stiffness in preterm infants include impaired elastin synthesis in the aortic wall,[28] altering mechanical properties, for example, reduced arterial compliance[29] and higher pulse wave reflections.[30] Other studies investigated the impact of maternal risk factors in infants, surprisingly with an inverse possibly adaptive link between maternal BP and neonatal PWV in a multi-ethnic cohort.[31] Later studies in mainly UK European and Pakistani-origin infants, found maternal anemia weakly linked with higher infant CFPWV[31] but not with carotid-brachial PWV. Studies in children and adolescents reported higher arterial stiffness measures predominantly in black and Hispanic populations. As shown in Table 1 (Table I in the Data Supplement), most were performed in the United States comparing black and white children (with single studies from Brazil and South Africa).

The youngest study cohort investigating ethnic differences in arterial stiffness parameters was performed in black and white boys, aged 6 to 8 years from South Africa.[34] While PWV (in all regions) and intima-media thickness were highest in black compared to white boys, carotid ultrasound stiffness indices were similar between groups. In the late 1970s, findings from the Minneapolis Children's BP Study indicated that brachial PP was higher in white compared to black children (mean age 7.7 years at baseline). However, after a 9-year follow-up period, brachial PP was found to be almost 3 mm Hg higher in black adolescents when compared to their white counterparts (mean age 16.7 years).[39]

Table 1. Major Studies Investigating Arterial Stiffness in Children and Adolescents

Reference	Age, y	N	Blood Pressure (SBP/DBP mm Hg)	Arterial Stiffness; $P<0.05$*	Device	Comments and Additional Data in Supplement
Collins et al[32]; United States	Black: 15.9±2.6; White: 15.9±2.2	Black: 134; White: 71	Black: 112±9/61±6; White: 111±9/59±6	Ba-PWV (m/s) Black: 10.8±1.34*; White: 10.4±1.35	Oscillometric pressure cuffs	Unadjusted analyses PP in supplement
Ge et al[15]; United States	Men: Black: 17.5±3.1; White: 18.2±3.5 Women: Black: 17.0±3.4; White: 17.9±3.2	Men: Black: 129; White: 214 Women: Black: 160; White: 199	Men: Black: 117±11.1/59±7; White: 114±10.3/57±6.4 Women: Black: 111±10.2/61.4±6.9; White: 108±8.8/59.3±6.3	Aorto-radial PWV (m/s) Black men: 6.65±1.03*; White men: 6.38±1.08 Black women: 6.68±1.02*; White women: 6.28±0.99 Aorto-dorsalis-pedis PWV (m/s) Black men: 7.10±0.83; White men: 7.15±0.91 Black women: 7.20±0.81*; White women: 7.03±0.84	Applanation tonometry (Sphygmo-Cor)	Unadjusted analyses PP in supplement
Lefferts et al[33]; United States	Black: 10.5±0.9; White: 10.8±0.9	Black: 54; White: 53	Black: 116±10/69±6; White: 113±8/66±6	CFPWV (m/s) Black: 4.7±0.8*; White: 4.2±0.8	Applanation tonometry (AtCor Medical)	PWV adjusted for age, sex, BMI, height, MAP, and SES. PP in supplement
Mokwatsi et al[34]; South Africa	Black: 7.30±0.69; White: 7.27±0.81	Black: 40; White: 41	Black: 105±11/69.4±8.96; White: 102±7.34/62.9±7.79	Carotid-radial PWV (m/s) Black: 9.72±1.72*; White: 8.21±1.82 CFPWV (m/s) Black: 5.01±0.68*; White: 4.42±0.62 Carotid-dorsalis-pedis PWV (m/s) Black: 5.49±0.62*; White: 5.01±0.63	Complior	PWV adjusted for MAP. PP in supplement
Philip et al[35]; United States	Total population: 13.7±2.3	Black: 89; White: 100; Hispanic: 103	Normal weight: Black: 127±10.2/75±7.6; White: 121±11.3/73±7.5; Hispanic: 119±11.7/70±6 Overweight: Black: 135±14.4/77±7.9; White: 133±12.3/75±7.1; Hispanic: 128±128/72±9.7	Cardio-ankle vascular index: Black: 4.96±0.97; White: 4.95±0.9; Hispanic: 5.01±0.74 Additionally adjusted for sex Normal weight boys: Black: 5.53±0.15*; White: 5.02±0.15; Hispanic: 5.13±0.15 Overweight boys: Black: 4.1±0.17; Hispanic: 4.86±0.14*	VaSera (VS-1500) device	Adjusted for BMI Overweight was defined as BMI>85 percentile.
Shah et al[36]; United States	Black: 18.5±3.2; White: 17.9±3.1	Black: 119; White: 96	Black: 123±13/68±13; White: 121±12/66±12	CFPWV (m/s) Black: 6.96±1.30*; White: 6.21±0.87	Applanation tonometry (Sphygmo-Cor)	Diagnosis of type 2 DM Unadjusted analyses AI_{75} in supplement
Thurston et al[37]; United States	Black: 17.8±1.1; White: 17.8±0.9	Black: 81; White: 78	Black: 109±9.1/63.4/7.9; White: 107±8.6/63.1±9.1	CFPWV (m/s) Black: 5.71±1.22*; White: 5.25±1.16	Trans-cutaneous Doppler Flowmeter Model 810-A	Unadjusted analyses
Zaniqueli et al[38]; Brazil	Black: 12.0±2.8; Nonblack: 11.7±2.7	Black: 211; Nonblack: 560	Black: 104±9/62±6; Nonblack: 104±9/62±7	CFPWV (m/s) Black: 5.8±0.8*; Nonblack: 5.6±0.7	Complior	Unadjusted analyses

Data are mean ± SD unless otherwise specified. Black referring to people of African descent. AI_{75} indicates augmentation index corrected for heart rate at 75 beats per minute; Ba-PWV, brachial-ankle PWV; BMI, body mass index; CFPWV, carotid-femoral pulse wave velocity; DM, diabetes mellitus; HT, hypertension; MAP, mean arterial pressure; PP, pulse pressure; PPA, pulse pressure amplification; SBP, systolic blood pressure; and SES, socioeconomic status.

*Higher arterial stiffness.

A US study found higher CFPWV in black than white adolescents (mean age 10.7 years; n=107), with no differences in brachial or carotid PP, intima-media thickness, and central SBP after adjustment for confounders.[33] CFPWV was also higher in Brazilian black compared with white adolescents (mean age, 11.9 years; n=771).[38] A study in Memphis, Tennessee, of white, black, and Hispanic adolescents (mean age 13.7 years) measured CAVI,

Table 2. Major Studies Investigating Arterial Stiffness in Young Adults

Reference	Age, y	N	Blood Pressure (SBP/DBP mm Hg)	Arterial Stiffness; $P<0.05$*	Device	Comments† and Additional Data in Supplement
Ashraf et al[44]; United States	Black: 32±10.5; White: 28±9.9; Hispanic: 28±5.9	Black: 26; White: 26; Hispanic: 10	Black: 111.2±14.3/68.8±9.1; White: 112.3±13.8/68.4±7.9; Hispanic: 113.8±11.2/71.3±12.5	CFPWV (m/s) Black: 7.1±1.1*; White: 6.2±0.7; Hispanic: 6.5±0.7	Applanation tonometry SphygmoCor	Unadjusted analyses PP and AI_{75} in supplement
Breet et al[45]; South Africa	Black: 24.5±3.17; White: 25.2±2.86	Black: 477; White: 398	Black: 124±10/76±7; White: 120±11/71±7	CFPWV (m/s) Black: 6.31±0.04; White: 6.38±0.04	SphygmoCor XCEL	PWV adjusted for MAP PPA and AI_{75} in supplement
Cruickshank et al[12]; United Kingdom	21–23 y (range)	Black African: 132; Black Caribbean: 102; White: 107; Indian: 98; Pakistani/Bangladeshi: 111; Other: 115	Black African: 114.2/72.9; Black Caribbean: 114.5/73.7; White: 115.9/73.2; Indian: 122.9/72.5; Pakistani/Bangladeshi: 111.6/71.9; Other: 112.8/70.7	Aortic PWV (m/s) (mean; 95% CI) Black African: 6.7 (6.5–7.0); Black Caribbean: 7.2 (6.8–7.7); White: 7.3 (6.9–7.6); Indian: 7.1 (6.8–7.4); Pakistani/Bangladeshi: 7.1 (6.8–7.4); Other: 7.1 (6.8–7.4)	Arteriograph	Unadjusted analyses AI in supplement based on Faconti et al[46]
Ferreira et al[47]; Brazil	NT Black: 23±4; White: 25±6	NT Black: 23; White: 44	NT Black: 119±13/77±8; White: 120±10/78±7	CFPWV (m/s) (mean ± SE) NT Black: 7.75±0.02; White: 8.15±0.04*	Complior	Adjusted for age
	HT Black: 29±8; White: 28±7	HT Black: 14; White: 33	HT Black: 152±20/97±17; White: 151±14/94±11	HT Black: 9.30±0.17*; White: 8.88±0.02		
Heffernan et al[43]; United States	(mean ± SE)	Black: 25; White: 30	(mean ± SE)	CFPWV (m/s) (all [mean±SE]) Black: 7.3±0.3*; White: 6.0±0.2	PWA and PWV via SphygmoCor	Unadjusted analyses
	Black: 21.7±0.4; White: 23.6±0.7		Black: 131±2/76±1; White: 129±2/75±1	Carotid-radial PWV (m/s) Black: 7.6±0.2; White: 7.7±0.2	β stiffness via ultrasonography	Results confirmed after adjustment for heart rate, body fat, and cardiorespiratory fitness
				Carotid β stiffness Black: 4.4±0.3*; White: 3.8±0.1		AI_{75}, augmentation pressure, carotid PP, aortic-brachial PPA, carotid-brachial PPA, and brachial β stiffness in supplement
Liang et al[41]; United States	Men: Black: 22.8±3.7; White: 21.8±3.5	Men: Black: 119; White: 148;	Men: Black: 119.5±10.9/64.2±7.8; White: 115.9±11.0/61.1±7.4	Carotid-dorsalis-pedis PWV (m/s) Black men: 8.00±1.03*; White men: 7.83±0.86 Black women: 8.10±0.99*; White women: 7.48±0.84	Applanation tonometry SphygmoCor	Unadjusted analyses
	Women: Black: 22.7±3.5; White: 21.9±3.0	Women: Black: 164; White: 128	Women: Black: 112.5±11.9/66.4±8.7; White: 105.8±8.7/60.7±5.6			
Meyerfreund et al[48]; Brazil	Indigenous Brazilian populations Tupinikin: 37.5±15.4; Guarani: 36.3±12.4; Non-natives: 39.0±13.1	Tupinikin: 496; Guarani: 60; Non-natives: 114	Tupinikin: 123±20/77±11; Guarani: 108±14/70±10; Non-natives: 120±21/78±13	CFPWV (m/s) Tupinikin: 8.8±2.2*; Guarani: 7.5±1.4; Non-natives: 8.4±2.0*	Complior	Unadjusted analyses In this population, 25.8% of the participants had HT. PP in supplement

Data are mean ± SD unless otherwise specified. Black referring to people of African descent. AI_{75} indicates augmentation index corrected for heart rate at 75 beats per minute; Ba-PWV, brachial-ankle PWV; BMI, body mass index; CFPWV, carotid-femoral pulse wave velocity; DM, diabetes mellitus; HT, hypertensive; MAP, mean arterial pressure; NT, normotensive; PP, pulse pressure; PPA, pulse pressure amplification; SBP, systolic blood pressure; and SES, socioeconomic status.

*Higher arterial stiffness.

†Where data have shown may be referred to as 'unadjusted', adjusted values may be available in the Reference's text.

higher values indicating stiffer arteries.[35] While there were no differences in unadjusted CAVI, black boys had higher CAVI after adjusting for body mass index when compared to white and Hispanic boys with normal weight. Conversely, CAVI was lowest in obese black boys suggesting vascular adaptations to obesity in early life. Another study indicated

higher brachial-ankle PWV in black than white US adolescents (n=205, mean age, 15.9 years), with no difference in brachial PP.[32] In other American studies, socioeconomic status disparities and carotid-femoral,[36,37] as well as aorto-radial and aorto-dorsalis-pedis PWV,[15] were higher in black than white adolescents, as was AI corrected for heart rate at 75 beats per minute[36] among young patients with type 2 diabetes mellitus, indicating higher pulse wave reflections known to predict mortality and CVD events.[40]

Young Adults

Important studies investigating arterial stiffness in young adults are indicated in Table 2 (Table II in the Data Supplement). While these studies mostly compared black and white populations, there are some comparisons of Hispanics and other ethnic groups. From these various cross-sectional and longitudinal studies, there is a clear trend that black populations, particularly men, had higher arterial stiffness compared with black women, and men or women of other ethnicities. The increased arterial stiffness in black populations has, in some cases, been related to socio-demographic and psychosocial factors.[12,41] Healthy black men had higher central BP, CFPWV, carotid β-stiffness index, carotid intima-media thickness, and lower PP amplification despite younger mean age than white, 21.7 versus 23.6 years and after adjustments for heart rate, body fat, and cardiorespiratory fitness.[42] Group differences were not significant comparing brachial structure and function,[43] where routine BP is taken, confirming that early arterial alterations occur in central elastic conduit vessels. Another US study compared 3 populations; black adults (mean age 32 years) had higher AI corrected for heart rate at 75 beats per minute than Hispanic (mean 28 years) and white adults (mean 28 years), whereas PWV was also higher in the black versus white group after post hoc analysis.[44]

In important longitudinal work, Liang et al[41] reported higher carotid-dorsalis-pedis PWV over 7 years in apparently healthy, normotensive black than white Americans from late childhood through to early adulthood (Figure 2). Black men had a more prominent increase in PWV with aging than black women or white men and women. Ethnic differences persisted after adjustments for socioeconomic, anthropometric, hemodynamic, and lifestyle variables, where mean arterial pressure, waist circumference, parental marital status, and marijuana use were the major factors associated with differences in PWV.[41]

Outside the United States, in the DASH study (Determinants of Adolescent, Now Young Adult, Social Wellbeing, and Health) in London, United Kingdom, unadjusted PWVs were similar in young (21–23 years) black Caribbean and white men, but higher than in other ethnicities (black African, Pakistani/Bangladeshi, others).[12] In fully adjusted models, black African, black Caribbean, and Indian young women had lower stiffness compared to white women, with waist/height ratio, BP, and perceived racism effects showing a large impact on arterial stiffness.[12] In the same study population, unadjusted AI was higher in Caribbean, West African, Indian, and Pakistani/Bangladeshi groups compared with white adults (where some were borderline significant). After multivariate adjustments, including SBP, differences remained robust.[46] The African-PREDICT study (Prospective Study on the Early Detection and Identification of Cardiovascular Disease and Hypertension) in South Africa included only normotensive young healthy black and white adults (mean 24.4 years) and also reported no ethnic differences in CFPWV, AI corrected for heart rate at 75 beats

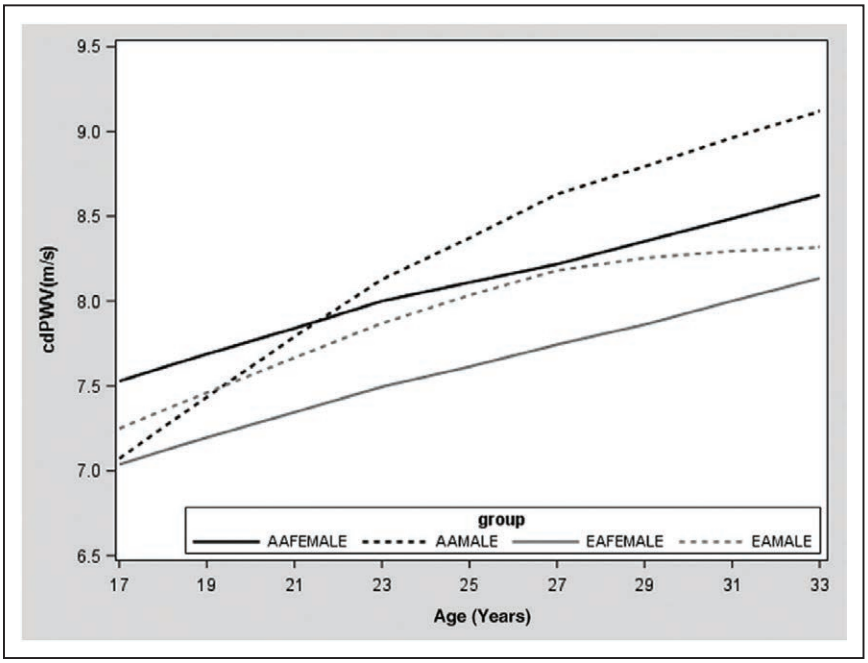

Figure 2. Mean values of raw pulse wave velocity across age for African American women (AAFEMALE), African American men (AAMALE), European American women (EAFEMALE), and European American men (EAMALE).
Reprinted from Liang et al[41] with permission. Copyright ©2019, Wolters Kluwer Health, LWW.

Table 3. Major Studies Investigating Arterial Stiffness in Middle-Aged Adults and the Elderly

Reference	Age, y	N	Blood Pressure (SBP/DBP mm Hg)	Arterial Stiffness ($P<0.05$*)	Device	Comments and Additional Data in Supplement
Brar et al[54]; Canada	South Asian: 71±5; White: 71±5	South Asian: 22; White: 22	South Asian: 139±18/68±9; White: 133±11/74±7	Ba-PWV (m/s) South Asian: 12±2; White: 11±2	…	Unadjusted analyses
						38.6% of the participants had hypertension.
				Compliance coefficient (mm^2/kPa) South Asian: 0.6±0.3*; White: 0.8±0.3		Carotid PP in supplement
Cruickshank et al[55]; United Kingdom	Community controls: African Caribbean: 58.3±5.6; European: 61.9±5.5; Gujerati (Indian): 60.5±6.8	46; 54; 74	143.2±17/82.9±9; 136.3±20/77.3±10; 139.7±24/78.6±12	Desc. Aortic PWV (m/s) 9.7±2.4; 10.1±2.2; 10.5±3.4	Doppler	Unadjusted†
						% hypertensive: NA
						Ethnic difference in mortality adjusted for systolic BP, BP treatment, and GTT status was significant, as was age and PWV.
	T2 Diabetes mellitus: African Caribbean: 58.5±6.6; European: 62.4±8; Gujerati: 58.1±8	55; 178; 127	150.1±26/84.4±13; 146.9±13/78.8±11; 141.4±22/78±10	11.4±4.1; 12.0±4; 11.6±3.9		% hypertensive: NA
de Lima Santos et al[49]; Brazil	Black: 43.1±10.7; White: 46.9±10.6; Mulatto: 43.8±10.8; Amerindian: 36.8±14.4	Black: 118; White: 538; Mulatto: 771; Amerindian: 588	Black: 135±23/90±15; White: 123±20/81±13; Mulatto: 129±22/85±14; Amerindian: 123±20/75±11	CFPWV (m/s) Black: 10.5±2.4*; White: 9.5±2.0; Mulatto: 9.6±2.2; Amerindian: 8.6±2.2	Complior	Adjusted for age, sex and MAP
						34% of the participants had hypertension (Black: 63.6%; White: 41.3%; Mulatto: 48%; Amerindian: 16.8%)
Din-Dzietham et al[50]; United States	Men: Black: 56.4±6.2; White: 56.5±5.8	Black: 268; White: 2459	Men: Black: 132.8±21.8/80.2±10.5; White: 123.1±15.9/75.7±8.1	β stiffness index	Echo-tracked systolic and diastolic carotid arterial diameters	Adjusted for sex, age, diastolic diameter, SBP, DBP linear, and squared and BMI
				Black: 11.3±0.3*; White: 10.3±0.1		
	Women: Black: 56.8±5.8; White: 56.9±6.0		Women: Black: 131.1±22.5/74.7±10.6; White: 116.2±17/66.7±8.3			28.3% of the participants had hypertension and 10% diabetes mellitus.
Goel et al[51]; United States	Black: 45±10; White: 45±10; Hispanic: 41±9	Black: 1264; White: 830; Hispanic: 450	Black: 130±18/80±10; White: 124±14/77±9; Hispanic: 120±15/75±9	Aortic arch PWV (m/s) (mean; 95% CI) Black: 4.72 (4.64–4.81)*; White: 4.25 (4.15–4.35); Hispanic: 4.48 (4.33–4.63)*	Cardiac magnetic resonance	Adjusted for age, age squared, sex, BMI, height, MAP, anti-HT medication, heart rate, cholesterol, DM, and smoking.
						45% of the black, 25% of white, and 16 % of Hispanic participants had HT, while 13% of the black, 6% of white, and 12% of Hispanic participants had DM.
						PP in supplement
Guo et al[63]; China and Sweden	Swedish: 72.5±5.5; Chinese: 75±6.5	Swedish: 3049; Chinese: 1272	Swedish: 135.7±17.3/95.7±8.7; Chinese: 143.2±21.2/76±8.9	CFPWV (m/s) Median (IQR) Swedish: 10.1 (8.8–11.8)*; Chinese: 8.9 (7.6–10.5)	SphygmoCor	Unadjusted analyses
						70.2% of Swedish and 70.1% of Chinese participants had HT, while 5.2% of Swedish and 6.7% of Chinese participants had DM.
Markert et al[56]; United States	Black: 72±9; White: 74±9; Hispanic: 68±8	Black: 317; White: 271; Hispanic: 948	Black: 144±20/84±12; White: 138±19/79±10; Hispanic: 140±20/83±11	Carotid stiffness Black: 9.24±6.21*; Whites: 8.74±6.91; Hispanic: 8.40±5.65	Stiffness derived from carotid intraluminal diameters and brachial blood pressure.	Unadjusted analyses
					Carotid ultrasound data via GE LOGIQ 700 system	70% of participants had hypertension (black: 76%; white: 61%; Hispanic 70%) and 19% had diabetes mellitus (black: 21%; white: 9%; Hispanic: 21%).
					Blood pressure via Dinamap Pro 100	

(*Continued*)

Table 3. Continued

Reference	Age, y	N	Blood Pressure (SBP/DBP mm Hg)	Arterial Stiffness ($P<0.05$*)	Device	Comments and Additional Data in Supplement
Morris et al[52]; United States	Black: 47±10; White: 49±11	Black: 386; White: 469	MAP (mm Hg) (Median [IQR]) Black: 92 (84–100); White: 88 (81–96)	CFPWV (m/s) (all [mean±SE]) Black: 7.3±0.1*; White: 7.1±0.1	SphygmoCor	Adjusted for ethnicity, sex, age, smoking, history of HT/DM, BMI, MAP, glucose and lipids
				Peripheral AI (%) Black: 21.4±1.1*; White: 15.7±1.0		28% of the participants had a history of HT (black: 37%; white: 21%) and 7% a history of DM (black: 11; white: 4%).
				Central AI (%) Black: 21.2±0.6*; White: 16.6±0.6		
Park et al[57]; United Kingdom	African Caribbean: 70.1±5.9; European: 69.7±6.2; South Asian: 69.0±6.1	African Caribbean: 169; European: 442; South Asian: 349	(mean±SE) African Caribbean: 143. 7±1.1/88±0.7; European: 141.5±0.7/84.7±0.4; South Asian: 142.4±0.8/82.8±0.5	CFPWV (m/s) (all [mean±SE]) African Caribbean:10.9±0.02; European: 11.5±0.01; South Asian: 11.3±0.01	PWV measured using Doppler probe Central hemodynamics via SphygmoCor	Adjusted for age and sex
						79% of the black, 57% of white, and 75 % of South Asian participants had HT, while 41% of the black, 19% of white, and 41 % of South Asian participants had DM.
						Central PP, PPA, and AI in supplement
Schutte et al[53]; South Africa	Black: 40.9±11.8; White: 40.4±12.9	Black: 374; White: 376	Black: 126±20.9/84.4±13.2; White: 119±15.8/78.1±9.82	Carotid-radial PWV (m/s) Black: 8.71±1.54*; White: 7.63±1.37	Complior SP	Unadjusted analyses
				Carotid-dorsalis-pedis PWV (m/s) Black: 8.16±1.51*; White: 7.82±1.15		52% of the black participants and 33% of the white participants were HT.
Snijder et al[58]; the Netherlands	Men: African Surinamese: 47.4±13.1; Ghanaian: 47.1±11.4; Dutch: 47.3±13.7; South Asian Surinamese: 45.1±13.5	Men: African Surinamese: 721; Ghanaian: 725; Dutch: 877; South Asian Surinamese: 942;	Men: African Surinamese: 127.1±15.7/80.6±11.2; Ghanaian: 137.6±17.7/87.7±12.2; Dutch: 127.4±15.4/79.1±10.3; South Asian Surinamese: 127.1±15.7/80.6±11.2;	Aortic PWV (m/s) Men: African Surinamese: 8.12±2.02; Ghanaian: 8.01±1.74; Dutch: 7.88±1.86; South Asian Surinamese: 8.22±2.20*	Arteriograph	Unadjusted analyses
						HT in men (%): African Surinamese: 46; Ghanaian: 58.8; Dutch: 33.9; South Asian Surinamese: 42.6
			Women: African Surinamese: 131.7±19/82.7±11.7; Ghanaian: 136.2±20.4/85.8±12.5; Dutch: 121±16.7/74.2±11; South Asian Surinamese: 126.6±20/78.9±12	Women African Surinamese: 8.92±2.37; Ghanaian: 9.18±2.52; Dutch: 8.28±2.45; South Asian Surinamese: 9.33±2.91*		HT in women (%): African Surinamese: 46.9; Ghanaian: 51.1; Dutch: 19.4; South Asian Surinamese: 38
						DM in men (%): African Surinamese: 9.9; Ghanaian: 10.5; Dutch: 4.7; South Asian Surinamese: 19.2
	Women: African Surinamese: 47.4±12.5; Ghanaian: 43.8±10.8; Dutch: 45.1±14.3; South Asian Surinamese: 47.0±13.4	Women: African Surinamese: 1119; Ghanaian: 948; Dutch: 920; South Asian Surinamese: 904				DM in women (%): African Surinamese: 11; Ghanaian: 7.8 Dutch: 1.4; South Asian Surinamese: 14.7

Data are mean ± SD unless otherwise specified. Black referring to people of African descent. AI_{75} indicates augmentation index corrected for heart rate at 75 beats per minute; Ba-PWV, brachial-ankle PWV; BMI, body mass index; CFPWV, carotid-femoral pulse wave velocity; DM, diabetes mellitus; HT, hypertensive; MAP, mean arterial pressure; NT, normotensive; PP, pulse pressure; PPA, pulse pressure amplification; SBP, systolic blood pressure; and SES, socioeconomic status.

*Higher arterial stiffness.

†Where data have shown may be referred to as unadjusted, adjusted values may be available in the Reference's text.

per minute, or PP amplification (adjusted for mean arterial pressure).[45]

Age and BP are well-known contributors to arterial stiffness and need to be accounted for when investigating ethnic differences. Ferreira et al[47] investigated the effects of age and BP on PWV in black and white Brazilian-born men (mean 26 years). In normotensives, white men had higher PWV than black men, whereas, in hypertensives, black men had higher PWV than white men. Furthermore, the slope of the age-adjusted PWV-SBP regression was steeper in black than white men.[47] As above, although there were no differences in arterial stiffness indices between normotensive black and white South Africans, black adults showed a steeper decline in PP amplification between ages 20 and 30,[45] which aligns with the findings in black American men. Together, these 2 studies suggest that early vascular aging manifests earlier in populations from African descent.

Middle-Aged and Elderly Populations

Arterial stiffness at older ages has been extensively investigated. As in younger populations, the following large population-based studies in different world regions consistently found that black participants had increased arterial stiffness than the comparison group(s) (Table 3 and Table III in the Data Supplement). A cross-sectional study in urban Vitoria, Brazil, included 2015 participants (aged 36–47 years) from 4 different ethnic groups: Amerindians (29.2%), white (26.7%), Mulatto (38.3%), and black (5.8%). CFPWV was higher in the black group after adjustment for traditional covariates, including age, sex, and mean arterial pressure.[49] In the US ARIC cohort (Atherosclerosis Risk in Communities), 268 black and 2459 white men and women (aged 45–64 years) with no history of CHD or stroke/transient ischemic attack were included.[50] After adjustment for cardiovascular risk factors, mean β stiffness was 9% higher for black adults (mean±SE: 11.3±0.3) than for whites (10.3±0.1). In the multi-ethnic, population-based Dallas Heart Study of white, black, and Hispanic adults (43.7 years; n=2544)[51] blacks and Hispanics, as compared to whites, displayed greater proximal aortic stiffness, assessed as aortic arch PWV or characteristic impedance, in fully adjusted models. Although blacks had a higher prevalence of numerous cardiovascular risk factors, none of these explained the ethnic differences in aortic arch PWV and characteristic impedance. In a bi-ethnic community-based sample from metropolitan Atlanta, United States (48 years; n=855),[52] CFPWV was higher in the black group compared to their white counterparts, after adjustment for traditional risk factors. These differences persisted in a subgroup completely free of conventional risk factors. A South African study[53] including black and white adults (40.7 years; n=750) also showed that carotid-radial and carotid-dorsalis-pedis PWV were elevated in black adults, in groups with normal or elevated BP.

However, in 2 UK studies, both in London and including people with testedly normal glucose tolerance from the community as well as with type 2 diabetes mellitus, ethnic differences in PWV between African Caribbeans and Europeans in similar locations were not found (Cruickshank et al[55]; Park et al[57])—Table 3. PWV was a highly significant predictor of mortality, adjusted for age, BP, and ethnicity, as was glucose tolerance status. In both studies, type 2 diabetes mellitus and glucose intolerance worsened arterial stiffening as PWV, measured directly by doppler on the descending aorta. People of Indian (South Asian), origin, Gujerati in one and Sikh in Park's, were included and had intermediate PWV values.

Among the very elderly, less data are available describing ethnic differences related to arterial stiffness. The NOMAS (Northern Manhattan Study)[56] investigated carotid artery diameter and stiffness between 1536 black, white, and Hispanic participants (70 years) also showing greater carotid stiffness among the black and Hispanic groups compared with whites.

Although the majority of studies investigating ethnic differences included black populations, other ethnic differences are also evident, specifically among South Asians. Such findings are of importance as people of South Asian ethnicity have a high prevalence of heart disease, stroke, and small vessel disease.[59] Ethnic minorities are often underrepresented in major works examining the role of arterial stiffness in CVD. Aiming to address this gap, a small Canadian study[54] cross-sectionally recruited 22 South Asian participants (71 years) and compared various arterial stiffness measures to age- and sex-matched white participants. South Asians had higher carotid PP and lower compliance coefficients indicating stiffer vessels. Similarly, central PP and AI were higher in an older (69±6.1 years) South Asian sample compared to African Caribbean and white populations from the UK SABRE study (Southall and Brent Revisited).[57] The HELIUS study (Healthy Life in an Urban Setting),[58] a large prospective cohort study on health care utilization in Amsterdam, showed similar findings. There, Dutch (n=1797), South Asian Surinamese (n=1846), African Surinamese (n=1840), and Ghanaian (n=1673) participants were included. Unadjusted PWV was higher in African and South Asian groups compared with those of Dutch descent, in agreement with known increased cardiovascular risk. Increased PWV in some groups was mainly driven by conventional risk factors, specifically high BP.

PERSPECTIVES

Collectively, most studies performing ethnic-specific comparisons in arterial stiffness report that populations of African descent (and often also Hispanic populations) have higher arterial stiffness than white populations from as young as 6[34] to 70 years of age.[56] Raised BP often accompanies arterial stiffness in black populations.[58] Yet in analyses of normotensive or healthy subgroups, increased arterial stiffness persist,[52] supported by studies in children[15,33,34] or young normotensive adults[41,43] where black participants already have elevated arterial stiffness but normal or similar BP as their comparison groups. When tracking arterial stiffness with increasing age,[39,41,45] it becomes clear that early vascular aging already occurring in adolescence or young adulthood predisposes black individuals to excess cardiovascular risk throughout the life course. Moreover, early vascular aging may be an important potentiating factor in the development of cardiovascular risk, adding to the already accelerated biological aging or weathering observed in black populations.[60]

Are specific ethnic groups genetically predisposed to develop arterial stiffness? Are socioeconomic, sociodemographic, psychological, maternal risk factors, and

health behaviors the drivers? So far, studies provide evidence for modest heritability of arterial stiffness[13,14] (with no ethnic difference[15]), and slight evidence of maternal risk factors predicting increased stiffness.[61,62] In contrast, psychosocial factors[38] such as perceived racism,[12] lower socioeconomic status,[12] and health behaviors such as obesity[12,35] do have significant impacts on arterial stiffness. Contributing factors to early vascular aging leading to excess risk remain poorly understood. There is a critical gap in studies evaluating these factors in detail, which would allow a more precise pinpointing of areas to address in the prevention and management of arterial stiffness and subsequent CVD development throughout the life course.

Identifying early vascular aging across all ethnic groups by assessment of aortic stiffness may add greater precision than BP alone to define those at risk for early onset of CVD and future events. It is certainly clear that at given ages and levels of peripheral or central BP, some individuals have stiffer vessels than others and are at higher cardiovascular risk.

ARTICLE INFORMATION

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REFERENCES

1. 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;55:1318–1327. doi: 10.1016/j.jacc.2009.10.061
2. Ben-Shlomo Y, Spears M, Boustred C, May M, Anderson SG, Benjamin EJ, Boutouyrie P, Cameron J, Chen CH, Cruickshank JK, et al. Aortic pulse wave velocity improves cardiovascular event prediction: an individual participant meta-analysis of prospective observational data from 17,635 subjects. *J Am Coll Cardiol.* 2014;63:636–646.
3. Willum-Hansen T, Staessen JA, Torp-Pedersen C, Rasmussen S, Thijs L, Ibsen H, Jeppesen J. Prognostic value of aortic pulse wave velocity as index of arterial stiffness in the general population. *Circulation.* 2006;113:664–670. doi: 10.1161/CIRCULATIONAHA.105.579342
4. Howard G, Lackland DT, Kleindorfer DO, Kissela BM, Moy CS, Judd SE, Safford MM, Cushman M, Glasser SP, Howard VJ. Racial differences in the impact of elevated systolic blood pressure on stroke risk. *JAMA Intern Med.* 2013;173:46–51. doi: 10.1001/2013.jamainternmed.857
5. Centers for Disease Control and Prevention National Center for Health Statistics. Compressed mortality file 1999-2007. CDC WONDER on-line database, compiled from compressed mortality file 1999-2007 series 20 no. 2m. 2010;2011.
6. Tillin T, Hughes AD, Mayet J, Whincup P, Sattar N, Forouhi NG, McKeigue PM, Chaturvedi N. The relationship between metabolic risk factors and incident cardiovascular disease in Europeans, South Asians, and African Caribbeans: SABRE (Southall and Brent Revisited) – a prospective population-based study. *J Am Coll Cardiol.* 2013;61:1777–1786. doi: 10.1016/j.jacc.2012.12.046
7. Harding S, Rosato M, Teyhan A. Trends for coronary heart disease and stroke mortality among migrants in England and Wales, 1979-2003: slow declines notable for some groups. *Heart.* 2008;94:463–470. doi: 10.1136/hrt.2007.122044
8. Nilsson PM, Boutouyrie P, Cunha P, Kotsis V, Narkiewicz K, Parati G, Rietzschel E, Scuteri A, Laurent S. Early vascular ageing in translation: from laboratory investigations to clinical applications in cardiovascular prevention. *J Hypertens.* 2013;31:1517–1526. doi: 10.1097/HJH.0b013e328361e4bd
9. Lacolley P, Regnault V, Avolio AP. Smooth muscle cell and arterial aging: basic and clinical aspects. *Cardiovasc Res.* 2018;114:513–528. doi: 10.1093/cvr/cvy009
10. Rezai MR, Wallace AM, Sattar N, Finn JD, Wu FC, Cruickshank JK. Ethnic differences in aortic pulse wave velocity occur in the descending aorta and may be related to vitamin D. *Hypertension.* 2011;58:247–253. doi: 10.1161/HYPERTENSIONAHA.111.174425
11. Olsen MH, Angell SY, Asma S, Boutouyrie P, Burger D, Chirinos JA, Damasceno A, Delles C, Gimenez-Roqueplo AP, Hering D, et al. A call to action and a lifecourse strategy to address the global burden of raised blood pressure on current and future generations: the Lancet Commission on hypertension. *Lancet.* 2016;388:2665–2712. doi: 10.1016/S0140-6736(16)31134-5
12. Cruickshank JK, Silva MJ, Molaodi OR, Enayat ZE, Cassidy A, Karamanos A, Read UM, Faconti L, Dall P, Stansfield B, et al. Ethnic differences in and childhood influences on early adult pulse wave velocity: the determinants of adolescent, now young adult, social wellbeing, and Health Longitudinal Study. *Hypertension.* 2016;67:1133–1141. doi: 10.1161/HYPERTENSIONAHA.115.07079
13. Mitchell GF, DeStefano AL, Larson MG, Benjamin EJ, Chen MH, Vasan RS, Vita JA, Levy D. Heritability and a genome-wide linkage scan for arterial stiffness, wave reflection, and mean arterial pressure: the Framingham Heart Study. *Circulation.* 2005;112:194–199. doi: 10.1161/CIRCULATIONAHA.104.530675
14. Alvim RO, Horimoto AR, Oliveira CM, Bortolotto LA, Krieger JE, Pereira AC. Heritability of arterial stiffness in a Brazilian population: Baependi Heart Study. *J Hypertens.* 2017;35:105–110. doi: 10.1097/HJH.0000000000001133
15. Ge D, Young TW, Wang X, Kapuku GK, Treiber FA, Snieder H. Heritability of arterial stiffness in black and white American youth and young adults. *Am J Hypertens.* 2007;20:1065–1072. doi: 10.1016/j.amjhyper.2007.05.013
16. Erasmus D, Mels CMC, Louw R, Lindeque JZ, Kruger R. Urinary metabolites and their link with premature arterial stiffness in black boys: the ASOS study. *Pulse (Basel).* 2019;6:144–153. doi: 10.1159/000492155
17. Mels CM, Delles C, Louw R, Schutte AE. Central systolic pressure and a nonessential amino acid metabolomics profile: the African Prospective study on the early detection and identification of cardiovascular disease and hypertension. *J Hypertens.* 2019;37:1157–1166. doi: 10.1097/HJH.0000000000002040
18. Lakatta EG, Levy D. Arterial and cardiac aging: major shareholders in cardiovascular disease enterprises: part I: aging arteries: a "set up" for vascular disease. *Circulation.* 2003;107:139–146. doi: 10.1161/01.cir.0000048892.83521.58
19. Laurent S. Defining vascular aging and cardiovascular risk. *J Hypertens.* 2012;30(suppl):S3–S8. doi: 10.1097/HJH.0b013e328353e501
20. Lakatta EG. So! What's aging? Is cardiovascular aging a disease? *J Mol Cell Cardiol.* 2015;83:1–13. doi: 10.1016/j.yjmcc.2015.04.005
21. Paultre F, Mosca L. Association of blood pressure indices and stroke mortality in isolated systolic hypertension. *Stroke.* 2005;36:1288–1290. doi: 10.1161/01.STR.0000166201.79222.4d
22. Lacolley P, Regnault V, Segers P, Laurent S. Vascular smooth muscle cells and arterial stiffening: relevance in development, aging, and disease. *Physiol Rev.* 2017;97:1555–1617. doi: 10.1152/physrev.00003.2017

23. Shadwick RE. Mechanical design in arteries. *J Exp Biol.* 1999;202(pt 23):3305–3313.
24. Laurent S, Cockcroft J, Van Bortel L, Boutouyrie P, Giannattasio C, Hayoz D, Pannier B, Vlachopoulos C, Wilkinson I, Struijker-Boudier H; European Network for Non-invasive Investigation of Large Arteries. Expert consensus document on arterial stiffness: methodological issues and clinical applications. *Eur Heart J.* 2006;27:2588–2605. doi: 10.1093/eurheartj/ehl254
25. Ahmadizar F, Voortman T. Arterial stiffness in childhood: a predictor for later cardiovascular disease? *Eur J Prev Cardiol.* 2018;25:100–102. doi: 10.1177/2047487317743046
26. Sehgal A, Malikiwi A, Paul E, Tan K, Menahem S. Systemic arterial stiffness in infants with bronchopulmonary dysplasia: potential cause of systemic hypertension. *J Perinatol.* 2016;36:564–569. doi: 10.1038/jp.2016.10
27. Tauzin L, Rossi P, Giusano B, Gaudart J, Boussuges A, Fraisse A, Simeoni U. Characteristics of arterial stiffness in very low birth weight premature infants. *Pediatr Res.* 2006;60:592–596. doi: 10.1203/01.pdr.0000242264.68586.28
28. Cattell MA, Anderson JC, Hasleton PS. Age-related changes in amounts and concentrations of collagen and elastin in normotensive human thoracic aorta. *Clin Chim Acta.* 1996;245:73–84. doi: 10.1016/0009-8981(95)06174-6
29. Martyn CN, Greenwald SE. Impaired synthesis of elastin in walls of aorta and large conduit arteries during early development as an initiating event in pathogenesis of systemic hypertension. *Lancet.* 1997;350:953–955. doi: 10.1016/s0140-6736(96)10508-0
30. Lurbe E, Torro MI, Carvajal E, Alvarez V, Redón J. Birth weight impacts on wave reflections in children and adolescents. *Hypertension.* 2003;41(3 pt 2):646–650. doi: 10.1161/01.HYP.0000048341.52293.7C
31. Koudsi A, Oldroyd J, McElduff P, Banerjee M, Vyas A, Cruickshank JK. Maternal and neonatal influences on, and reproducibility of, neonatal aortic pulse wave velocity. *Hypertension.* 2007;49:225–231. doi: 10.1161/01.HYP.0000250434.73119.7a
32. Collins RT, Somes GW, Alpert BS. Differences in arterial compliance among normotensive adolescent groups: Collins arterial compliance in adolescents. *Pediatr Cardiol.* 2008;29:929–934. doi: 10.1007/s00246-008-9239-7
33. Lefferts WK, Augustine JA, Spartano NL, Atallah-Yunes NH, Heffernan KS, Gump BB. Racial differences in aortic stiffness in children. *J Pediatr.* 2017;180:62–67. doi: 10.1016/j.jpeds.2016.09.071
34. Mokwatsi GG, Schutte AE, Kruger R. Ethnic differences regarding arterial stiffness of 6-8-year-old black and white boys. *J Hypertens.* 2017;35:960–967. doi: 10.1097/HJH.0000000000001267
35. Philip R, Alpert BS, Schwingshackl A, Huang X, Blakely D, Rovnaghi CR, Tran QT, Velasquez A, Arevalo A, Anand KJ. Inverse relationship between cardio-ankle vascular index and body mass index in healthy children. *J Pediatr.* 2015;167:361.e1–365.e1. doi: 10.1016/j.jpeds.2015.04.042
36. Shah AS, Dolan LM, Gao Z, Kimball TR, Urbina EM. Racial differences in arterial stiffness among adolescents and young adults with type 2 diabetes. *Pediatr Diabetes.* 2012;13:170–175. doi: 10.1111/j.1399-5448.2011.00798.x
37. Thurston RC, Matthews KA. Racial and socioeconomic disparities in arterial stiffness and intima media thickness among adolescents. *Soc Sci Med.* 2009;68:807–813. doi: 10.1016/j.socscimed.2008.12.029
38. Zaniqueli D, Alvim RO, Luiz SG, Oliosa PR, de Sá Cunha R, Mill JG. Ethnicity and arterial stiffness in children and adolescents from a Brazilian population. *J Hypertens.* 2017;35:2257–2261. doi: 10.1097/HJH.0000000000001444
39. Hlaing WM, Prineas RJ. Arterial stiffness variations by gender in African-American and Caucasian children. *J Natl Med Assoc.* 2006;98:181–189.
40. Janner JH, Godtfredsen NS, Ladelund S, Vestbo J, Prescott E. High aortic augmentation index predicts mortality and cardiovascular events in men from a general population, but not in women. *Eur J Prev Cardiol.* 2013;20:1005–1012. doi: 10.1177/2047487312449588
41. Liang X, Su S, Hao G, Snieder H, Treiber F, Kapuku G, Wang X. Determinants of pulse wave velocity trajectories from youth to young adulthood: the Georgia Stress and Heart Study. *J Hypertens.* 2019;37:563–571. doi: 10.1097/HJH.0000000000001933
42. Heffernan KS, Jae SY, Fernhall B. Racial differences in arterial stiffness after exercise in young men. *Am J Hypertens.* 2007;20:840–845. doi: 10.1016/j.amjhyper.2007.03.015
43. Heffernan KS, Jae SY, Wilund KR, Woods JA, Fernhall B. Racial differences in central blood pressure and vascular function in young men. *Am J Physiol Heart Circ Physiol.* 2008;295:H2380–H2387. doi: 10.1152/ajpheart.00902.2008
44. Ashraf AP, Fisher G, Alvarez J, Dudenbostel T, Calhoun DA, Szalai AJ, Gower BA. Associations of C-reactive protein to indices of vascular health and the influence of serum 25(OH)D status in healthy adults. *J Nutr Metab.* 2012;2012:475975. doi: 10.1155/2012/475975
45. Breet Y, Huisman HW, Kruger R, van Rooyen JM, Gafane-Matemane LF, Ware LJ, Schutte AE. Pulse pressure amplification and its relationship with age in young, apparently healthy black and white adults: the African-PREDICT study. *Int J Cardiol.* 2017;249:387–391. doi: 10.1016/j.ijcard.2017.08.070
46. Faconti L, Silva MJ, Molaodi OR, Enayat ZE, Cassidy A, Karamanos A, Nanino E, Read UM, Dall P, Stansfield B, et al. Can arterial wave augmentation in young adults help account for variability of cardiovascular risk in different British ethnic groups? *J Hypertens.* 2016;34:2220–2226. doi: 10.1097/HJH.0000000000001066
47. Ferreira AV, Viana MC, Mill JG, Asmar RG, Cunha RS. Racial differences in aortic stiffness in normotensive and hypertensive adults. *J Hypertens.* 1999;17:631–637. doi: 10.1097/00004872-199917050-00006
48. Meyerfreund D, Goncalves C, Cunha R, Pereira AC, Krieger JE, Mill JG. Age-dependent increase in blood pressure in two different Native American communities in Brazil. *J Hypertens.* 2009;27:1753–1760. doi: 10.1097/hjh.0b013e32832e0b2b
49. de Lima Santos PCJ, de Oliveira Alvim R, Ferreira NE, de Sá Cunha R, Krieger JE, Mill JG, Pereira AC. Ethnicity and arterial stiffness in Brazil. *Am J Hypertens.* 2011;24:278–284.
50. Din-Dzietham R, Couper D, Evans G, Arnett DK, Jones DW. Arterial stiffness is greater in African Americans than in whites: evidence from the Forsyth County, North Carolina, ARIC Cohort. *Am J Hypertens.* 2004;17:304–313. doi: 10.1016/j.amjhyper.2003.12.004
51. Goel A, Maroules CD, Mitchell GF, Peshock R, Ayers C, McColl R, Vongpatanasin W, King KS. Ethnic difference in proximal aortic stiffness: an observation from the Dallas Heart study. *JACC Cardiovasc Imaging.* 2017;10:54–61. doi: 10.1016/j.jcmg.2016.07.012
52. Morris AA, Patel RS, Binongo JN, Poole J, Al Mheid I, Ahmed Y, Stoyanova N, Vaccarino V, Din-Dzietham R, Gibbons GH, et al. Racial differences in arterial stiffness and microcirculatory function between Black and White Americans. *J Am Heart Assoc.* 2013;2:e002154. doi: 10.1161/JAHA.112.002154
53. Schutte AE, Huisman HW, Schutte R, Van Rooyen JM, Malan L, Malan NT, Reimann M. Arterial stiffness profiles: investigating various sections of the arterial tree of African and Caucasian people. *Clin Exp Hypertens.* 2011;33:511–517. doi: 10.3109/10641963.2011.561897
54. Brar I, Robertson AD, Hughson RL. Increased central arterial stiffness and altered cerebrovascular haemodynamic properties in South Asian older adults. *J Hum Hypertens.* 2016;30:309–314. doi: 10.1038/jhh.2015.76
55. Cruickshank K, Riste L, Anderson SG, Wright JS, Dunn G, Gosling RG. Aortic pulse-wave velocity and its relationship to mortality in diabetes and glucose intolerance: an integrated index of vascular function? *Circulation.* 2002;106:2085–2090. doi: 10.1161/01.cir.0000033824.02722.f7
56. Markert MS, Della-Morte D, Cabral D, Roberts EL Jr, Gardener H, Dong C, Wright CB, Elkind MS, Sacco RL, Rundek T. Ethnic differences in carotid artery diameter and stiffness: the Northern Manhattan study. *Atherosclerosis.* 2011;219:827–832. doi: 10.1016/j.atherosclerosis.2011.08.028
57. Park CM, Tillin T, March K, Jones S, Whincup PH, Mayet J, Chaturvedi N, Hughes AD. Adverse effect of diabetes and hyperglycaemia on arterial stiffness in Europeans, South Asians, and African Caribbeans in the SABRE study. *J Hypertens.* 2016;34:282–289. doi: 10.1097/HJH.0000000000000789
58. Snijder MB, Stronks K, Agyemang C, Busschers WB, Peters RJ, van den Born BJ. Ethnic differences in arterial stiffness the Helius study. *Int J Cardiol.* 2015;191:28–33. doi: 10.1016/j.ijcard.2015.04.234
59. Gunarathne A, Patel JV, Gammon B, Gill PS, Hughes EA, Lip GY. Ischemic stroke in South Asians: a review of the epidemiology, pathophysiology, and ethnicity-related clinical features. *Stroke.* 2009;40:e415–e423. doi: 10.1161/STROKEAHA.108.535724
60. Forrester S, Jacobs D, Zmora R, Schreiner P, Roger V, Kiefe CI. Racial differences in weathering and its associations with psychosocial stress: the CARDIA study. *SSM Popul Health.* 2019;7:003-3. doi: 10.1016/j.ssmph.2018.11.003
61. Alwan NA, Cade JE, McArdle HJ, Greenwood DC, Hayes HE, Ciantar E, Simpson NA. Infant arterial stiffness and maternal iron status in pregnancy: a UK birth cohort (Baby VIP Study). *Neonatology.* 2015;107:297–303. doi: 10.1159/000377618
62. Ng KYB, Simpson NAB, Cade JE, Greenwood DC, Mcardle HJ, Ciantar E, Alwan NA. Is infant arterial stiffness associated with maternal blood pressure in pregnancy? Findings from a UK birth cohort (Baby VIP study). *PLoS One.* 2018;13:e0200159. doi: 10.1371/journal.pone.0200159
63. Guo QH, Muhammad IF, Borné Y, Sheng GS, Persson M, Wang JG, Engström G, Li Y, Nilsson PM. Difference in the risk profiles of carotid-femoral pulse wave velocity: results from two community-based studies in China and Sweden. *J Hum Hypertens.* 2020;34:207–213. doi: 10.1038/s41371-018-0160-0