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Coronary plaque characteristics quantified by artificial intelligence-enabled plaque analysis: Insights from a multi-ethnic asymptomatic US population

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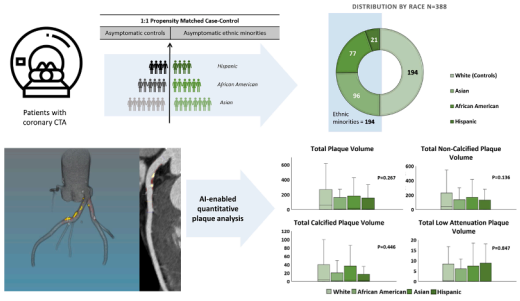
GRAPHICAL ABSTRACT



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ABSTRACT

Background: Ethnic differences in coronary atherosclerosis remain to be fully elucidated. We aimed to assess quantitative plaque characteristics from coronary CT Angiography (CCTA) in relation to ethnicity and cardiovascular risk factors in a multi-ethnic asymptomatic US population.
Methods: This cross-sectional study retrospectively evaluated 388 asymptomatic patients selected from a prospective CCTA registry. A total of 194 patients from ethnic minority groups (Asian, African American, and Hispanic) were matched by age, sex, and cardiovascular risk factors to 194 White patients. Quantitative plaque

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Ethnicity
Quantitative evaluation

volumes—including total plaque, non-calcified plaque, low-attenuation non-calcified plaque (<30 Hounsfield Units [HU]), and calcified plaque—were measured using artificial intelligence-enabled software. Pericoronary adipose tissue attenuation (PCAT) was also assessed and reported in Hounsfield Units (HU).
Results: The total study population included 388 patients (age 59.9±11.7 years, 68% male), of which 63% had coronary atherosclerosis with total plaque volumes of 149[IQR 50-438] mm^3, driven predominantly by non-calcified plaque (122, IQR 27-369) mm^3. Men presented higher volumes of all plaque components compared to women (P<0.05). In multivariable analysis adjusted for cardiovascular risk factors, only African American patients were associated with lower total plaque (β=-89.2, P=0.036), calcified (β=-26.1, P=0.015), and non-calcified plaque volumes (β=-62.7, P=0.022). African American patients were also associated with higher PCAT (β=5.8, P<0.001), along with family history of coronary artery disease (β=2.1, P=0.04).
Conclusions: Our study showed a uniformly high prevalence of atherosclerosis in this asymptomatic cohort, with lower plaque volumes of all sub-components in women. African American patients were associated with lower quantitative plaque volumes (total, non-calcified and calcified) but with higher PCAT compared to White patients; with no significant differences observed among other ethnic minorities.

1. Introduction

Coronary artery disease is one of the leading causes of morbidity and mortality worldwide, posing a significant public health challenge [1,2]. Identifying individuals at high risk for cardiovascular events is the major focus of primary prevention facilitating lifestyle changes and pharmacological interventions proven effective in enhancing life expectancy for those at risk [3].

Despite substantial advances in understanding and treating coronary artery disease, racial and ethnic differences and disparities persist [4,5]. In general, White and Black individuals have a higher prevalence of coronary artery disease compared to Hispanic and Asian individuals [6–10]. This variability is multifactorial and may be partially attributed to differences in traditional cardiovascular risk factors, comorbidities, disease pathophysiology, social determinants of health, and genetic predispositions [11]. However, these disparities are not entirely understood, in part because racial and ethnic minorities remain underrepresented in cardiovascular clinical trials [12,13].

Noninvasive coronary imaging offers a personalized approach to primary prevention by detecting coronary artery disease (CAD) in individual subjects. Coronary artery calcium is a marker of global coronary atherosclerotic burden, and has become a guideline endorsed for improving risk assessment and guiding management in primary prevention [14,15]. Coronary artery calcium has been well studied regarding ethnic differences, most extensively in the Multi-Ethnic Study of Atherosclerosis. Coronary CT angiography (CCTA) which provides information beyond coronary calcium scanning with qualitative or quantitative plaque characterization including total coronary plaque burden, plaque subtypes, and high-risk plaque features. Ethnic differences in these measurements on CCTA in asymptomatic individuals remain to be fully elucidated. Therefore, in this study, we aimed to assess quantitative plaque measures from CCTA in a multi-ethnic asymptomatic U.S. population.

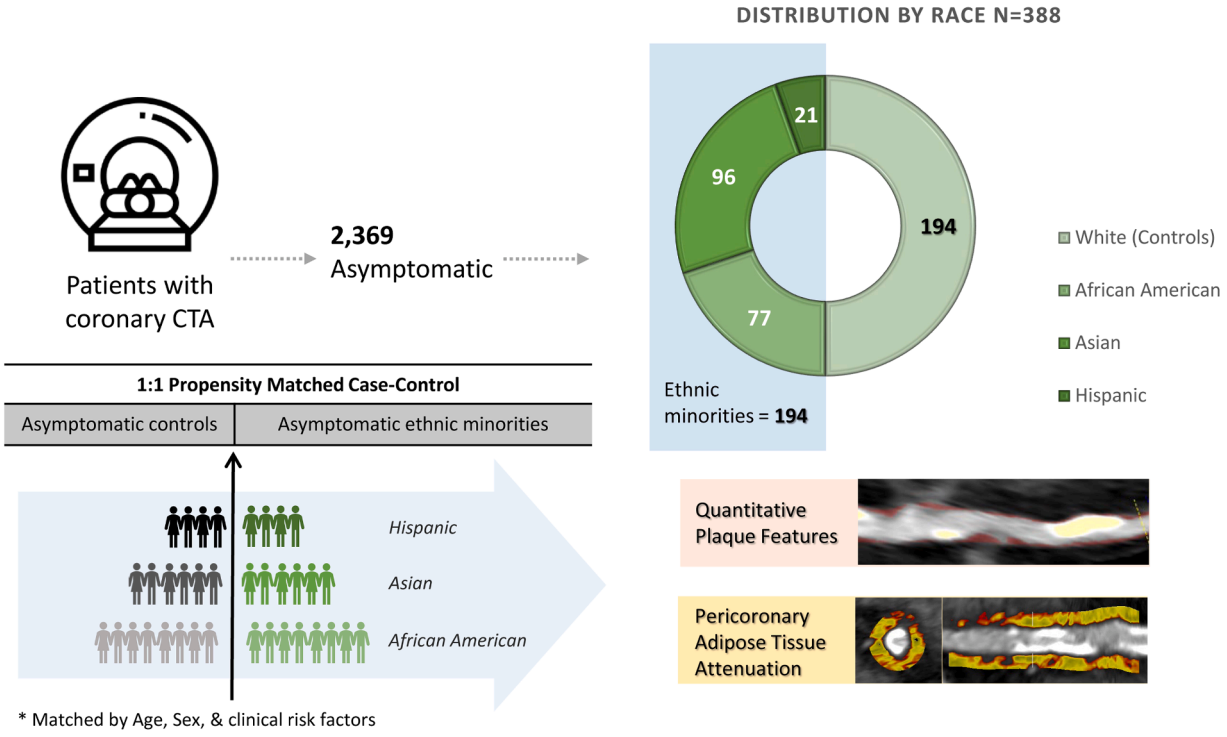

Fig. 1. Study design for Multi-ethnic Minority Study. From a cohort of 2,369 asymptomatic patients who underwent coronary computed tomography angiography, 194 individuals from minority groups were identified. These patients were matched 1:1 by age, sex, and risk factors to 194 White patients, resulting in a final study cohort of 388 patients. Quantitative analysis of plaque and pericoronary adipose tissue attenuation were performed on their coronary computed tomography angiography scans.

2. Materials and methods

2.1. Study population

This cross-sectional, observational, retrospective study aimed to evaluate quantitative plaque characteristics from coronary CTA in relation to ethnicity and cardiovascular risk factors in a multi-ethnic, asymptomatic U.S. population. We utilized data from a registry of 2,369 consecutive asymptomatic patients who underwent coronary CCTA for research or clinical indications at Cedars-Sinai Medical Center in Los Angeles, California, between January 2007 and July 2021. From these, a total of 194 patients with self-reported ethnic backgrounds as either African American, Asian, or Hispanic were identified, and propensity-matched 1:1 to 194 White patients, using previously described propensity matching technique as detailed below; a combined total of 388 patients were selected (Fig. 1). Exclusion criteria included previously known coronary artery disease and suboptimal quality of images. The study was approved by the Cedars-Sinai Medical Center Institutional Review Board, and all patients provided informed consent.

2.2. CCTA acquisition and image reconstruction

Scanning was performed using a dual-source CT scanner (Somatom Flash, or Force Siemens, Siemens Medical System, Erlangen, Germany), and according to current guidelines [16]. Prior to CCTA, all patients underwent standard electrocardiogram-gated non-contrast CT for measurement of the Agatston coronary artery score. Before scanning, metoprolol was administered to achieve a target heart rate of <70 beats/min, and 400-800μg of sublingual glyceryl trinitrate was administered. CCTA was performed after intravenous injection of 90-120 ml iodinated contrast (Omnipaque or Visipaque, GE Healthcare, Princeton, New Jersey) with an injection rate of 4-7 ml/s, followed by 50 ml of saline. CCTA scans were acquired in helical or prospective mode from 40-70% of the cardiac cycle [Prospective CareKV, tube voltage of 100 kVp (body-mass index <25 kg/m2) or 120 kVp (body-mass index 25 kg/m2)] and were reconstructed using a 512×512 matrix with 0.6 mm slice thickness.

2.3. Quantitative CCTA plaque and pericoronary adipose tissue analysis

Quantitative plaque analysis was performed on CCTA images using Artificial Intelligence (AI)-enabled, FDA-cleared software (Autoplaque 3.0, Cedars-Sinai Medical Center). Subjective image quality was assessed by expert imaging cardiologists and scored on a 4-point Likert scale (4= excellent, 3= good, 2=fair, 1=unevaluable); CCTA scans with good to excellent image quality (the upper two levels of image quality on a 4-point scale) were analyzed. Coronary plaque measurements were obtained over the entire coronary tree. Plaque quantification was performed as previously described [17]. Non-calcified plaque, low-attenuation non-calcified plaque (<30 Hounsfield Units), and calcified plaque were automatically segmented using adaptive scan-specific thresholds and manually adjusted as needed by expert reads with SCCT Level III training in CCTA (Fig. 2). Coronary plaque measurements included absolute volumes (mm3) and corresponding burdens (plaque volume × 100%/vessel volume). Pericoronary adipose attenuation was quantified around the proximal right coronary artery (10–50 mm from the ostium) within a 3 mm radius from the outer vessel wall. Pericoronary adipose tissue was defined as all voxels with CT attenuation between −190 and −30 Hounsfield units and reported as the mean attenuation within volume of interest [34].

2.4. Propensity matching

Patients representing ethnic minorities (African American, Asian, Hispanic) were propensity-score matched with White patients in a 1:1 fashion using the method of nearest neighbor without replacement. A propensity score was utilized to account for confounding variables as in prior reported studies [18,19]. An overall score was calculated for each patient using a probit model that accounted for age, sex, and cardiovascular risk factors (hypertension, hyperlipidemia, family history of

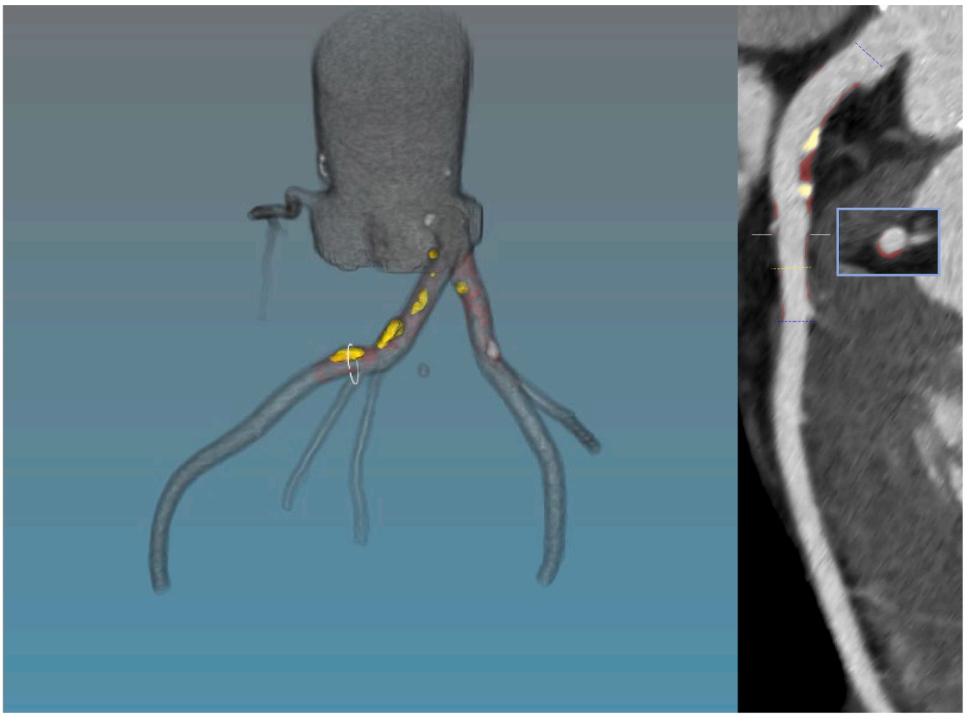

Fig. 2. The quantitative plaque analysis from cardiac computed tomography angiography of a 60-year-old African American male with a history of smoking shows atherosclerotic plaque in left anterior descending artery with non-calcified (red) and calcified (yellow)components. 3D Rendering of the coronary tree on the left, curved multiplanar reformatted image of the left anterior descending artery on the right.

premature coronary artery disease, diabetes, and smoking history). The Hosmer-Lemeshow test was applied to test the calibration and area under the curve analysis to evaluate the accuracy of the model. Standardized differences were calculated, and a value <0.1 was respected as an indicator of good balance in the covariate.

2.5. Statistical analysis

Categorical variables are presented as a number (percentage) and compared with the Chi-square test. Data were tested for normality using the Shapiro–Wilk test. Continuous variables are expressed as mean ± standard deviation or median (interquartile range) depending on the normal distribution. Global differences in quantitative plaque characteristics across ethnic groups were evaluated using analysis of variance and nonparametric tests, as appropriate. Pair-wise comparisons were performed between White and matched patients representing remaining ethnicities. Multivariable linear regression was performed to examine quantitative plaque and pericoronary adipose tissue measures with ethnicity, adjusted for age, sex, hypertension, hyperlipidemia, family history of premature coronary artery disease, diabetes, and smoking history. All variables entered into multivariable logistic regression with backward stepwise selection at a Wald p-value of 0.1. Statistical analyses were performed using STATA software (version 17; StataCorp, College Station, TX, USA). A two-sided P-value <0.05 was statistically significant.

3. Results

3.1. Study population

The total study population consisted of 388 patients with a mean age of 59.9 ± 11.7 years and 68% were male (Table 1). CCTA were obtained for suspected coronary artery disease in patients with risk factors (70%), evaluation of non-coronary artery disease (16%), pre-operative assessment (12%) or diagnosis of non-cardiac disease (2%). Within the ethnic minority cohort, 40% were African-American patients, 50% were Asian patients, and 10% were Hispanic patients. The mean body mass index amongst patients was 26.2 ± 4.8kg/m^2. Hyperlipidemia was present in 59%, hypertension in 55%, 19% had a family history of premature coronary artery disease, 16% were diabetic, and 7% were smokers. Coronary artery stenosis of any degree was present in 63% of patients. There were no significant differences in the number of diseased segments (p=0.458), or the quantitative measures of stenosis (P>0.05) across the ethnicities (Table 2).

Table 1
Baseline clinical characteristics.

Number of patients (n=388)	
Patient Characteristics	
Age, years	59.9 ± 11.7
Male sex	266 (68.4)
Body mass index, kg/m^2	26.2 ± 4.8
Hypertension	215 (55.3)
Hyperlipidemia	230 (59.1)
Diabetes	63 (16.2)
Metabolic syndrome	66 (17.0)
Family history of premature coronary artery disease	74 (19.0)
Smoking	28 (7.2)
Ethnicity	
White	194 (50.0)
African American	77 (19.8)
Asian	96 (24.7)
Hispanic	21 (5.5)
Mean ± standard deviation or number (%)	

Table 2
Comparison of quantitative measures of coronary stenosis across ethnicities.

	Ethnicity				
	White (n=194)	African American (n=77)	Asian (n=96)	Hispanic (n=21)	P-value
Any lesion (%)	121 (62.4%)	46 (59.7%)	63 (65.6%)	13 (61.9%)	**0.884**
Total diameter stenosis %	16.2 (0-35)	8.5 (0-27)	18.5 (0-33)	22.5 (0-30)	**0.216**
Contrast density drop %	20 (12-27)	18.2 (9-29)	20.5 (12-31)	19.0 (10-33)	**0.683**
Remodeling index	1.1 (0-1.4)	1.0 (0-1.3)	1.1 (0-1.4)	1.1 (0-1.2)	**0.809**

3.2. Quantitative plaque composition

The median calcium score measured in the entire population from non-contrast CT was 65.4AU (IQR 0.8 - 341.1AU). The median total plaque volume from CCTA was 29.8mm^3 (IQR 0 – 213.0mm^3), whereas the median volume of calcified plaque was 2.6mm^3 (IQR 0 – 35.1mm^3), non-calcified plaque was 0mm^3 (IQR 0 – 170.9mm^3) and low attenuation non-calcified plaque was 0 (IQR 0 -7.4) mm^3. The median total plaque burden was 8% (IQR 0 – 27.8%), calcified plaque burden was 0.9% (IQR 0 – 3.5%), non-calcified plaque burden was 0% (IQR 0 – 23.7%) and low attenuation non-calcified plaque burden was 0% (IQR 0 – 1%).

Men as compared to women had higher total (90.9mm^3 [IQR 0.0 – 374.7mm^3] vs 0.0mm^3 (IQR 0.0 – 56.3mm^3], p<0.001), non-calcified (79.2mm^3 [IQR 0.0 – 285.7mm^3] vs 0.0mm^3 [IQR 0.0 – 52.7mm^3], p<0.001), low attenuation non-calcified (1.5mm^3 [IQR 0.0 – 12.8mm^3] vs 0.0mm^3 [IQR 0.0 – 0.5mm^3], p<0.001) and calcified plaque (6.2mm^3 [IQR 0.0 – 51.4mm^3] vs 0.0mm^3 [0.0 – 8.6mm^3], p<0.001) volumes.

The global comparison of quantitative measures did not show differences between ethnicities for plaque volumes (Fig. 3) or burdens (Fig. 4). However, the pair-wise comparison between White and African American patients revealed a higher volume of non-calcified (52.6mm^3 [IQR 0-242mm^3] vs 0.0 [IQR 0-128mm^3], P=0.045mm^3) and low attenuation non-calcified plaque (1.6mm^3 [IQR 0-14mm^3] vs 0mm^3 [IQR 0-6mm^3], P=0.036). No differences in plaque burden measures were shown in pair-wise comparisons.

Gender-specific comparison of plaque volumes between ethnicities showed no differences in either men (all P>0.05) or women (P>0.05; Supplementary Table 1).

Interestingly, in multivariable linear regression adjusted for clinical parameters, only African-American participants were independently associated with less total plaque volume (β=-89.2, P=0.036), calcified plaque volume (β=-26.1, P=0.015), and non-calcified plaque volume (β=-62.7, P=0.022), but not low-attenuation plaque volume (Table 3). The results of sensitivity analysis adjusting for metabolic syndrome is presented in Supplementary Table 2.

3.3. Pericoronary coronary adipose tissue

The mean pericoronary adipose tissue attenuation in the whole cohort was -73.7 ± 7.8 HU and its global comparison between the ethnicities revealed no differences (Fig. 5). The pair-wise analysis showed, however, that African American patients (-69.4±8.1 HU) had significantly higher pericoronary adipose tissue attenuation compared to White (-75.2±8.2 HU, P<0.001) and Asian patients (-74.3±7.1 HU, P=0.002). Gender-specific comparison of pericoronary adipose tissue attenuation between ethnicities showed differences for men P<0.001), but not women (P=0.348; Supplementary Table 1). Moreover, African American patients were the only associated independently to clinical factors with increased pericoronary adipose tissue attenuation (β=5.8, P<0.001; Table 4). The results of sensitivity analysis adjusting for

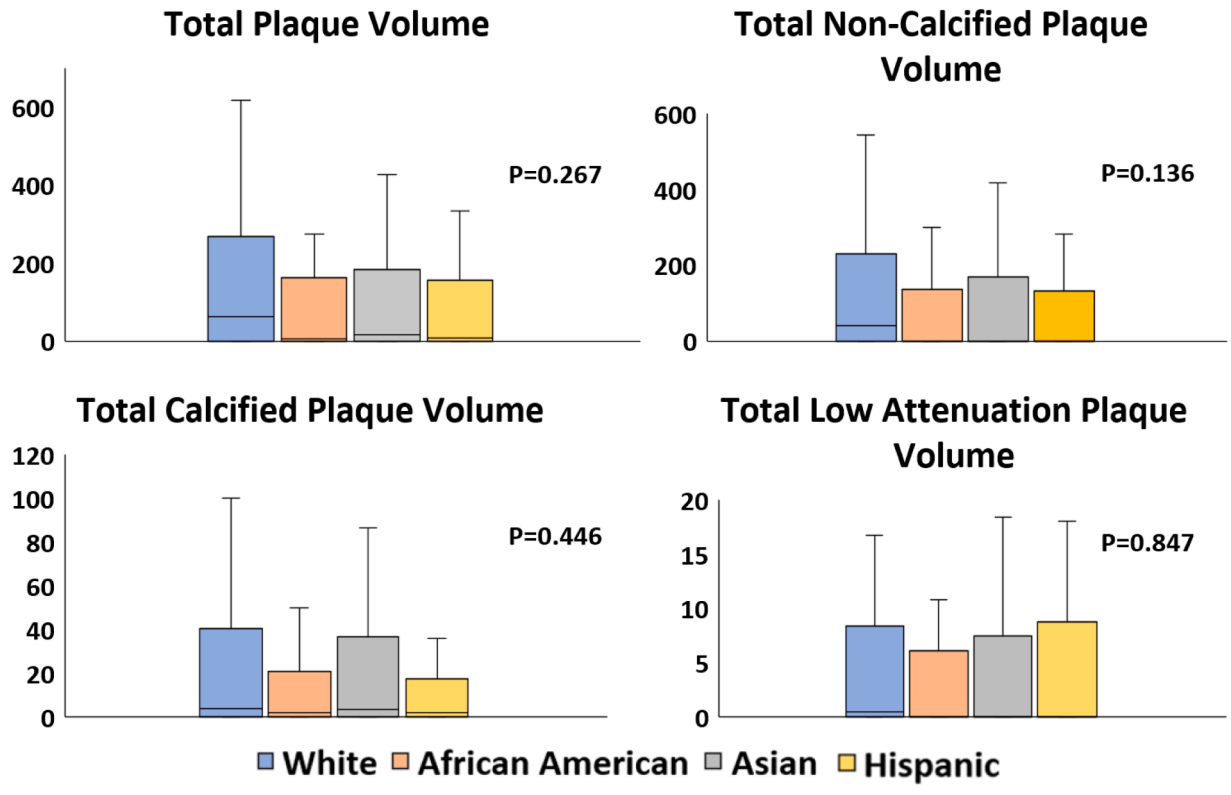

Fig. 3. Plaque Volume Comparison Across Ethnic Groups

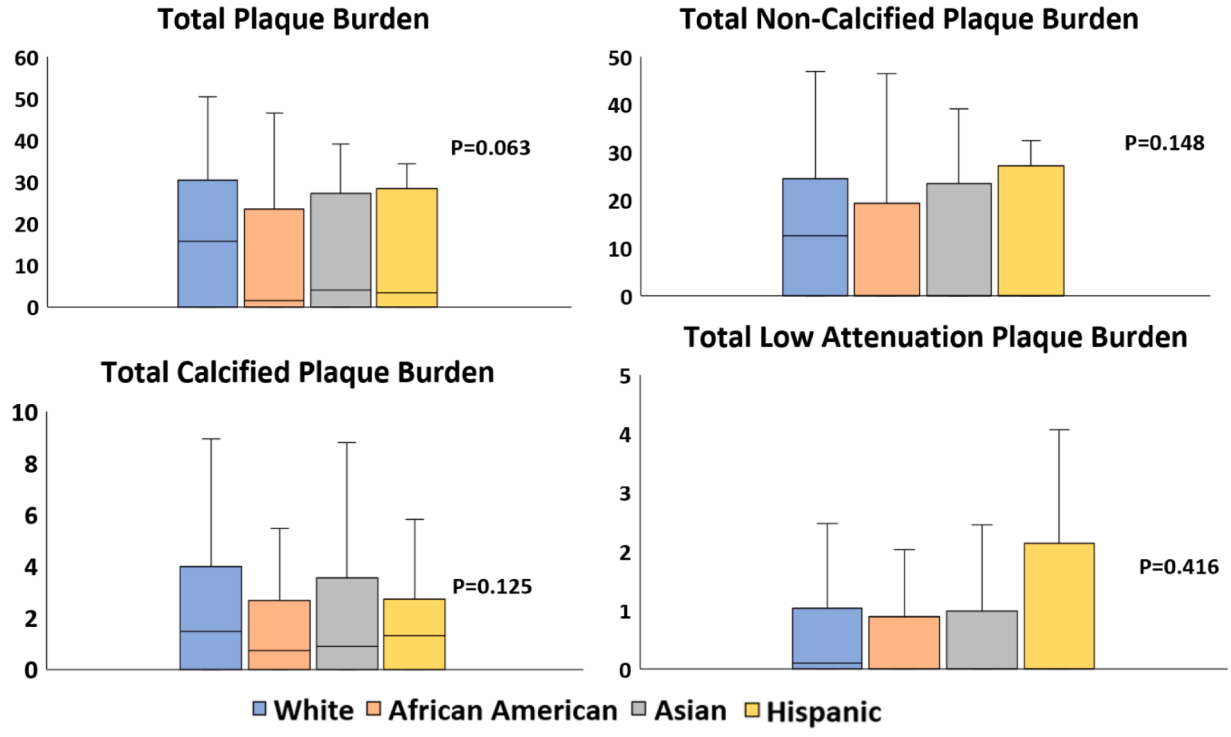

Fig. 4. Plaque Burden Comparison Across Ethnic Groups

metabolic syndrome is presented in Supplementary Table 3.

4. Discussion

The study compares quantitative measures of plaque and pericoronary adipose tissue from CCTA between asymptomatic patients of different ethnicities. We found (1) a uniformly high prevalence of atherosclerosis with (2) no significant differences in quantitative plaque or pericoronary adipose tissue characteristics across the subjects with similar cardiovascular risk profiles. Further, men presented higher

Table 3
Multivariable associations of clinical variables and ethnicities with quantitative plaque characteristics.

	Total Plaque Volume			Non-Calcified Plaque Volume			Low Attenuation Non-Calcified Plaque			Calcified plaque volume		
	B-coefficient	95% Confidence Interval	P-value	B-coefficient	95% Confidence Interval	P-value	B-coefficient	95% Confidence Interval	P-value	B coefficient	95% Confidence Interval	P-value
Age	7.5	5.1 to 9.9	<0.001	5.8	3.8 to 7.7	<.001	0.4	0.2 to 0.6	<0.001	1.9	1.2 to 2.7	<.001
Male	172.9	113.1 to 232.7	<0.001	133.4	86.1 to 180.7	<.001	9.1	4.6 to 13.5	<0.001	42.1	23.7 to 60.5	<0.001
Body mass index	6.4	0.4 to 12.4	0.036	5.7	1.1 to 10.4	0.17	0.8	0.3 to 1.2	<0.001	-	-	-
Hypertension	-	-	-	50.8	5.8 to 95.6	0.027	-	-	-	-	-	-
Hyperlipidemia	-	-	-	-	-	-	-	-	-	-	-	-
Diabetes	-	-	-	-	-	-	-	-	-	31.2	8.2 to 54.2	0.008
Family history of coronary artery disease	-	-	-	-	-	-	-	-	-	-	-	-
Smoking	-	-	-	-	-	-	-	-	-	34.1	1.9 to 66.3	0.038
White	-	-	-	-	-	-	-	-	-	-	-	-
African American	-89.2	-156.7 to -21.6	0.1	-62.7	-116.2 to -9.2	0.022	-	-	-	-26.1	-46.9 to -5.1	0.015
Asian	-	-	-	-	-	-	-	-	-	-	-	-
Hispanic	-	-	-	-	-	-	-	-	-	-	-	-

*All variables entered into multivariable logistic regression with backward stepwise selection at a Wald p-value of 0.1. The final model containing statistically significant variables is shown.

volumes of all plaque components compared to women (P<0.05). This has also been observed in the symptomatic patient population [20], indicating the need for per-patient age and sex-specific thresholds of coronary plaque for risk prediction [21].

The differences in atherosclerotic composition between the ethnicities were first described in a large autopsy series from 1965, where a higher prevalence of calcified lesions was observed in White than Black decedents [22]. However, only the widespread application of cardiac CT allowed large population-based studies identifying ethnicity-related disparities in coronary plaque composition. Calcific plaque distribution has been the best studied since coronary artery calcium scoring from non-contract CT was introduced the earliest in clinical practice. This technique was the one utilized in the landmark Multi-Ethnic Study of Atherosclerosis (MESA), which showed the highest prevalence of coronary calcification in the White population without a history of cardiovascular disease as compared to other ethnicities [23]. These findings were later confirmed in a report published by Budoff and colleagues, including 16,560 asymptomatic patients from multiple ethnicities referred for calcium scoring by physicians [24]. On the other hand, the Dallas Heart Study showed a similar prevalence of coronary artery calcium in non-contrast CT between Black and White patients, which could be potentially biased by the inclusion of patients with coronary heart disease [25]. CCTA allows noninvasive characterization of plaque composition beyond quantification of coronary calcium as well as opportunistic evaluation of pericoronary adipose tissue attenuation [26]. The Swedish Cardiopulmonary Bioimage Study that 0 coronary artery calcium score does not exclude atherosclerosis [27]. Although ethnic differences in quantitative plaque composition have been studied, the current evidence focuses on biracial comparisons. Several studies have compared the quantitative plaque composition between East Asian and Caucasian patients. Ihdayhid and colleagues found no differences in plaque volume and burden in a matched cohort of 200 patients [28]. No differences in plaque burden were also observed in a larger substudy of Progression of AtheRosclerotic PlAque DetermIned by Computed TomoGraphic Angiography Imaging (PARADIGM) [29]. A multi-ethnic comparison of quantitative plaque from CCTA is yet lacking. A pilot study comparing White and African American patients with acute chest pain showed more noncalcified disease in African American patients and more calcified disease in White individuals. [30]. Similarly to the Miami Heart Study, we show substantial prevalence of coronary plaque in asymptomatic individuals [31]. For the first time, we extend these results by including the plaque and pericoronary adipose tissue quantification with artificial intelligence in a multi-ethnic real-life US population of asymptomatic patients, with similar cardiovascular risk profiles. Although no differences in plaque composition were shown across the ethnic groups in a global comparison, pair-wise analysis showed higher non-calcified plaque volume and low attenuation plaque in Caucasian patients compared to African American patients. Moreover, African American patients were the only ethnicity associated independently of traditional risk factors with decreased volumes of all plaque components with the exception of low attenuation plaque. These observations are in line with semiquantitative comparison between Black and White individuals from a PROMISE trial who underwent CCTA for evaluation of chest pain and showed less prevalent coronary artery disease in the Black population despite a higher cardiovascular risk burden. Similarly, a Coronary CT Angiography Evaluation for Clinical Outcomes: An International Multicenter (CONFIRM) registry analysis showed African American and East Asian subjects to be less likely to present >1 non-calcified coronary segment [32]. In a recent study by Lorenzatti and colleagues, non-Hispanic White participants were also independently associated with a higher non-calcified plaque burden [33].

Asymptomatic patients who underwent CTA demonstrated a significantly higher prevalence of cardiovascular risk factors compared to the general Los Angeles population, with the most notable difference observed in the prevalence of hyperlipidemia (Supplementary Table 4).

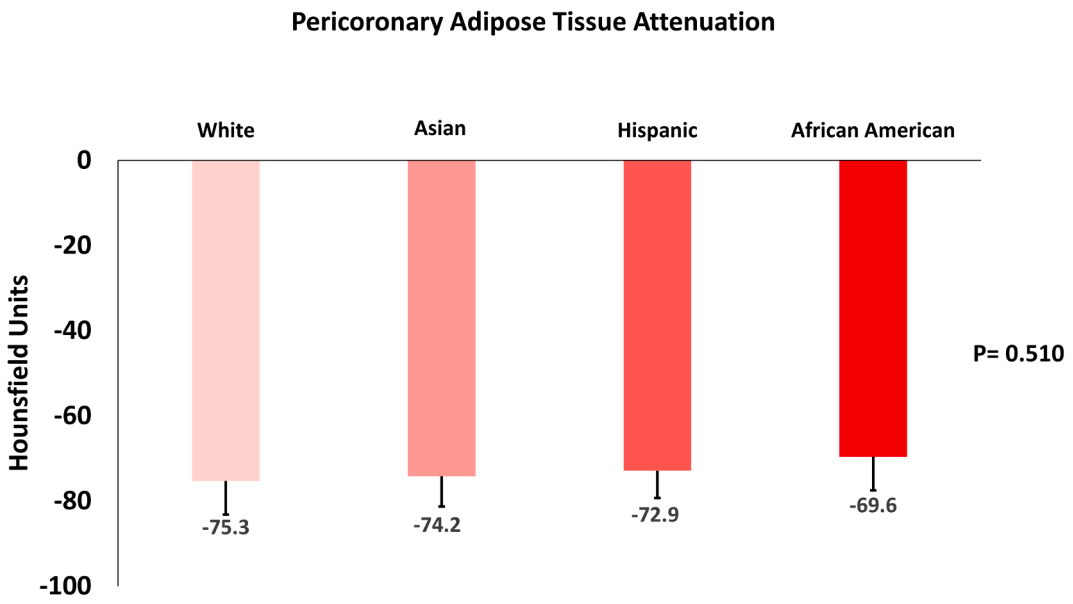

Fig. 5. Pericoronary coronary adipose tissue attenuation (in HU) comparison across ethnic groups.

Table 4
Multivariable associations of clinical variables and ethnicities with pericoronary adipose tissue attenuation.

	Pericoronary adipose tissue attenuation		
	B-coefficient	95% Confidence Interval	P-value
Age	-	-	-
Male	-	-	-
Body mass index	-0.4	-0.6 to -0.3	<0.001
Hypertension	-	-	-
Hyperlipidemia	-	-	-
Diabetes	-	-	-
Family history of coronary artery disease	2.1	0.1 to 4.1	0.04
Smoking	-	-	-
White	-	-	-
Asian	-	-	-
African American	5.8	3.8 to 7.8	<0.001
Hispanic	-	-	-

*All variables entered into multivariable logistic regression with backward stepwise selection at a Wald p-value of 0.1. The final model containing statistically significant variables is shown.

This finding aligns with the current clinical indications for CTA, which is primarily used to evaluate suspected coronary artery disease in patients with elevated risk profiles. While these differences may limit the generalizability of our results, a growing body of evidence highlights the critical role of ethnicity in shaping cardiovascular risk. Notably, African American patients in our cohort exhibited the lowest plaque volumes yet demonstrated higher attenuation of pericoronary adipose tissue compared to White and Asian patients. This finding may suggest increased pericoronary inflammation in the African American population, potentially contributing to their heightened vulnerability to subclinical atherosclerosis, as observed in 3-dimensional vascular ultrasound findings from the FAMILIA study [35]. Further research is needed to validate these observations and elucidate the underlying mechanisms driving ethnic disparities in cardiovascular health.

Our study has several limitations. First, this was a single-center study with a modest sample size, which may reduce the generalizability of the findings. Second, Hispanic patients were notably underrepresented in our study of asymptomatic individuals (5%), which may reduce the power to detect pair-wise differences for this ethnicity. This lower representation of asymptomatic Hispanic patients at our center contrasts with the higher proportion observed among symptomatic patients. Third, the hospital database follows the U.S. Census Bureau's Race and Ethnicity categorization, which does not distinguish between East and South Asian populations, limiting the ability to perform a more detailed sub-analysis. Finally, our study did not include clinical endpoints as the design was cross-sectional. Nevertheless, our study showed no significant differences between asymptomatic patients with similar cardiovascular risk profiles and may be considered hypothesis generating.

To conclude, our study showed a uniformly high prevalence of atherosclerosis in this asymptomatic patient cohort, with lower plaque volumes of all subtypes in women. African American patients were independently associated with lower quantitative plaque volumes but with higher pericoronary adipose tissue attenuation compared to White patients. No significant differences in quantitative plaque measures or pericoronary adipose tissue attenuation were observed among other ethnic minorities.

Author agreement

All authors have participated in this research and/or article preparation. All authors have approved the final article and supplementary information. All authors agree to be accountable for all aspects of the work related to the accuracy or integrity of any part of the work.

Disclosures

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CRediT authorship contribution statement

Guadalupe Flores Tomasino: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Caroline Park:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Kajetan Grodecki:** Writing – review & editing, Formal analysis, Conceptualization. **Jolien Geers:** Writing – review & editing, Formal analysis. **Donghee Han:** Writing – review & editing,

Formal analysis. **Andrew Lin:** Writing – review & editing. **Keiichiro Kuronuma:** Writing – review & editing. **Nipun Manral:** Writing – review & editing. **Emily Xing:** Writing – review & editing, Formal analysis. **Heidi Gransar:** Writing – review & editing, Formal analysis. **Sebastien Cadet:** Writing – review & editing. **Alan Rozanski:** Writing – review & editing. **Piotr J. Slomka:** Writing – review & editing, Conceptualization. **Michelle Williams:** Writing – review & editing, Conceptualization. **Daniel S. Berman:** Writing – review & editing, Conceptualization. **Damini Dey:** Writing – review & editing, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Outside the current work, Drs Berman, Slomka, and Dey received software royalties from Cedars-Sinai Medical Center and report equity in APQ Health. Drs Slomka, Berman, and Dey hold a patent (US8885905B2 in the United States and World Intellectual Property Organization patent WO2011069120A1, "Method and System for Plaque Characterization"). The other authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ajpc.2025.100929.

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