25-Hydroxyvitamin D and Parathyroid Hormone Are Not Associated With Carotid Intima-Media Thickness or Plaque in the Multi-Ethnic Study of Atherosclerosis

Marc Blondon, Michael Sachs, Andrew N. Hoofnagle, Joachim H. Ix, Erin D. Michos, Claudia Korcarz, Adam D. Gepner, David S. Siscovick, Joel D. Kaufman, James H. Stein, Bryan Kestenbaum, Ian H. de Boer

Objective—Observational evidence supports independent associations of 25-hydroxyvitamin D (25-OHD) and parathyroid hormone (PTH) with cardiovascular risk. A plausible hypothesis for these associations is accelerated development of atherosclerosis.

Approach and Results—We evaluated cross-sectional and longitudinal associations of 25-OHD and PTH with carotid intima-media thickness (IMT) and carotid plaques among 3251 participants free of cardiovascular disease in the Multi-Ethnic Study of Atherosclerosis. 25-OHD and PTH were measured at baseline by mass spectrometry and immunoassay, respectively. All subjects underwent a carotid ultrasound examination at baseline and 9.4 years later (median, range 8–11.1 years). Multivariable linear and logistic regressions were used to test associations of 25-OHD and PTH with the extent and progression of IMT and the prevalence and incidence of carotid plaque. Mean (SD) 25-OHD and PTH were 25.8 ng/mL (10.6) and 44.2 pg/mL (20.2), respectively. No independent associations were found between 25-OHD or PTH and IMT at baseline (increment of 1.9 μm [95% confidence interval, −5.1 to 8.9] per 10 ng/mL lower 25-OHD; increment of 0.8 μm [95% confidence interval, −3.2 to 4.8] per 10 pg/mL higher PTH) or progression of IMT (increment of 2.6 μm [95% confidence interval, −2.5 to 7.8] per 10 ng/mL lower 25-OHD, increment of 1.6 μm [95% confidence interval, −1.9 to 5.2] per 10 pg/mL higher PTH). No associations were found with the baseline prevalence of carotid plaque or the incidence of new plaques during the study period. We did not observe any interaction by race or ethnicity (White, Chinese, Black, and Hispanic).

Conclusions—The consistent lack of association of vitamin D and PTH with carotid IMT and plaque suggests that these hormones may influence cardiovascular risk through pathways not reflected by carotid atherosclerosis. (Arterioscler Thromb Vasc Biol. 2013;33:2639-2645.)

Key Words: atherosclerosis ▪ carotid artery diseases ▪ carotid intima-media thickness ▪ mineral metabolism ▪ parathyroid hormone ▪ plaque, atherosclerotic ▪ vitamin D

Lower circulating concentrations of 25-hydroxyvitamin D (25-OHD) and higher circulating concentrations of parathyroid hormone (PTH) have been associated with an increased risk of cardiovascular events in multiple observational cohorts.1-3 There are several plausible explanations for these observations; one hypothesis is that insufficient vitamin D and excessive PTH accelerate atherosclerosis. Low circulating 25-OHD concentrations are associated with obesity, impaired glucose metabolism, hypertension, and dyslipidemia in cross-sectional studies and with incident hypertension during long-term follow-up.4-7 Inflammatory, immunomodulatory, and direct vascular effects of vitamin D have also been implicated.8-10 PTH may affect cardiovascular disease through the development of hypertension,11 left ventricular hypertrophy,12 or endothelial dysfunction.13

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Our aim was to test associations of serum 25-OHD and PTH concentrations with carotid intima-media thickness (IMT) and plaque, 2 noninvasive markers of arterial injury, including atherosclerosis, that independently predict cardiovascular disease,14 in a large community-based study. We hypothesized that participants with lower 25-OHD or higher PTH would have larger IMT measurements at baseline, more rapid IMT progression, and higher prevalence and incidence of carotid plaques.
progression during the follow-up period, and greater prevalence and incidence of carotid plaques.

**Materials and Methods**

Materials and Methods are available in the online-only Supplement.

**Results**

**Participant Characteristics**

From 6393 participants with available original IMT measurements, 3251 underwent a second ultrasound for IMT progression and had their baseline IMT remeasured using the images from the baseline ultrasound. Mean age and body mass index (SD) of these participants were 60.4 years (9.4) and 28.2 kg/m² (5.2), respectively, and 46.5% were men. They were racially/ethnically diverse, with 39.6% of White, 13.3% of Chinese, 25.8% of Black, and 21.3% of Hispanic subjects. Compared with these, participants who did not have a follow-up carotid ultrasound were older (mean age, 64.0 years) and had a greater prevalence of treated diabetes mellitus (11.5% versus 8.1%), hypertension (48.3% versus 40.6%), and current smoking (14.3% versus 11.5%). Measurements of PTH and 25-OHD were similar in these 2 groups.

Among the 3251 participants with subsequent carotid ultrasound and new readings of baseline IMT, 1033 (31.8%) had 25-OHD <20ng/mL at baseline (Table 1). Despite being younger, these participants had more cardiovascular risk factors (diabetes mellitus, hypertension, smoking, higher body mass index, higher C-reactive protein), but had higher mean estimated glomerular filtration rate, compared with participants with higher 25-OHD concentrations. Racial/ethnic differences were striking, with lower and higher 25-OHD concentrations among Black and White subjects, respectively. The proportion of 25-OHD <20 ng/mL was 15.1%, 23.7%, 60.5%, and 33.0% among White, Chinese, Black, and Hispanic participants, respectively.

Three hundred seventy participants (11.4%) had PTH ≥65 pg/mL. We observed a marked increase in the prevalence

<table>
<thead>
<tr>
<th>Table 1. Baseline Characteristics of 3251 MESA Participants</th>
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<tbody>
<tr>
<td><strong>Annualized 25-OH-Vitamin D, ng/mL</strong></td>
</tr>
<tr>
<td>&lt;20 (n=1033)</td>
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<tr>
<td><strong>Age, y</strong></td>
</tr>
<tr>
<td><strong>Male, n (%)</strong></td>
</tr>
<tr>
<td><strong>Race/ethnicity, n (%)</strong></td>
</tr>
<tr>
<td>White</td>
</tr>
<tr>
<td>Chinese</td>
</tr>
<tr>
<td>Black</td>
</tr>
<tr>
<td>Hispanic</td>
</tr>
<tr>
<td><strong>Treated diabetes mellitus, n (%)</strong></td>
</tr>
<tr>
<td><strong>Hypertension, n (%)</strong></td>
</tr>
<tr>
<td><strong>Treatment for hypertension, n (%)</strong></td>
</tr>
<tr>
<td><strong>SBP, mm Hg</strong></td>
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<tr>
<td><strong>DBP, mm Hg</strong></td>
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<tr>
<td><strong>BMI, kg/m²</strong></td>
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<tr>
<td><strong>Total cholesterol, mg/dL</strong></td>
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<tr>
<td><strong>LDL, mg/dL</strong></td>
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<tr>
<td><strong>HDL, mg/dL</strong></td>
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<tr>
<td><strong>Treatment with statins, n (%)</strong></td>
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<tr>
<td><strong>Current smokers, n (%)</strong></td>
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<tr>
<td><strong>Former smokers, n (%)</strong></td>
</tr>
<tr>
<td><strong>GFR, ml/min per 1.73 m²</strong></td>
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<tr>
<td><strong>Calcium, mg/dL</strong></td>
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<tr>
<td><strong>Phosphorus, mg/dL</strong></td>
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<tr>
<td><strong>IL-6, IU/mL</strong></td>
</tr>
<tr>
<td><strong>CRP, mg/L</strong></td>
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</tbody>
</table>

25-OHD indicates 25-hydroxyvitamin D; BMI, body mass index; CRP, C-reactive protein; DBP, diastolic blood pressure; GFR, glomerular filtration rate; HDL, high-density lipoprotein; IL-6, interleukin-6; LDL, low-density lipoprotein; MESA, Multi-Ethnic Study of Atherosclerosis; PTH, parathyroid hormone; and SBP, systolic blood pressure.
of hypertension with increasing PTH concentrations and an expected inverse correlation between PTH and glomerular filtration rate. Black and Hispanic participants were more likely to have higher PTH concentrations. The proportion of high PTH concentrations (265 ng/mL) was higher among Black and Hispanic participants (18.0% and 16.1%) than among White and Chinese participants (6.8% and 3.7%). During follow-up, the prevalence of treatment for traditional cardiovascular risk factors increased. This increase did not differ by 25-OHD or PTH status at baseline. For example, the prevalence of statin use from baseline to examination 5 did not increase more for participants with 25-OHD <20 ng/mL (18.9%) than for those with 25-OHD >30 ng/mL (23.9%).

Carotid IMT and Plaque
At baseline, the means (SD) of the common carotid artery (CCA) maximum IMT and internal carotid artery (ICA) maximum IMT were 927 μm (SD, 210 μm) and 906 μm (SD, 399 μm), respectively. Median (range) time between ultrasound examinations was 9.4 years (8.0–11.1 years). Mean (SD) changes in CCA-IMT and ICA-IMT between ultrasound examinations were 137 μm (SD, 140 μm) and 164 μm (SD, 276 μm), respectively. At least 1 carotid plaque was found among 1525 of 3246 participants at baseline (47.0%). Among participants without plaques at baseline, 698 (40.6%) had developed a carotid plaque at the time of the second ultrasound. Mean plaque scores were 1.08 (SD, 1.61) at baseline and progressed by a mean of 1.18 (SD, 1.45) during the study period.

25-OHD, IMT, and Plaque
At baseline, lower 25-OHD concentrations were associated with modestly greater CCA and ICA-IMT in demographic-adjusted analyses (Table 2, left side, model 1). However, in models further adjusted for confounders, we found no independent association of 25-OHD with CCA or ICA-IMT or their change over time (Table 2, top and middle rows, model 2). Adjustment for body mass index was responsible for most of the attenuation observed from model 1 to model 2. The precision of the null estimates ruled out clinically meaningful associations: the adjusted mean differences in baseline CCA-IMT and its change over time, per 10 ng/mL lower 25-OHD, were 1.9 μm (95% confidence interval [CI], −5.1 to 8.9) and 2.6 μm (95% CI, −2.5 to 7.8), respectively. In addition, 25-OHD concentrations were not associated with the

Table 2. Cross-Sectional and Longitudinal Associations of Serum 25-OHD Concentration With Carotid Intima-Media Thickness and Plaque

<table>
<thead>
<tr>
<th>25-OHD</th>
<th>baseline analysis</th>
<th>longitudinal analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cross-Sectional Analyses</td>
<td>Longitudinal Analyses</td>
</tr>
<tr>
<td></td>
<td>Unadjusted Mean IMT, μm (SD)</td>
<td>Adjusted Difference, μm (95% CI)</td>
</tr>
<tr>
<td>≥30.0 ng/mL</td>
<td>924 (221)</td>
<td>Ref.</td>
</tr>
<tr>
<td>20.0–29.9 ng/mL</td>
<td>923 (207)</td>
<td>1.3 (−15.1 to 17.7)</td>
</tr>
<tr>
<td>&lt;20 ng/mL</td>
<td>936 (204)</td>
<td>23.0 (5.5 to 40.5)</td>
</tr>
<tr>
<td>P value†</td>
<td>&lt;0.03</td>
<td>0.59</td>
</tr>
</tbody>
</table>

| ≥30.0 ng/mL | 907 (397) | Ref. | Ref. | 514 | 168 (285) | Ref. | Ref. |
| 20.0–29.9 ng/mL | 917 (429) | 29.7 (−7.8 to 67.3) | 19.9 (−18.9 to 58.6) | 507 | 167 (287) | 7.8 (−27.0 to 42.9) | 1.9 (−34.9 to 38.6) |
| <20 ng/mL | 890 (362) | 38.3 (−0.7 to 77.3) | 20.2 (−19.8 to 60.3) | 387 | 156 (248) | 7.2 (−31.7 to 38.8) | 2.4 (−43.7 to 38.8) |
| P value† | <0.03 | 0.25 |

<table>
<thead>
<tr>
<th>n</th>
<th>Unadjusted Prevalence (%)</th>
<th>Adjusted Odds Ratio (95%CI)</th>
<th>n</th>
<th>Unadjusted Cumulative Incidence (%)</th>
<th>Adjusted Odds Ratio (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline prevalence of carotid plaque</td>
<td>Model 3</td>
<td>Model 4</td>
<td>Baseline prevalence of carotid plaque</td>
<td>Model 3</td>
<td>Model 4</td>
</tr>
<tr>
<td>≥30.0 ng/mL</td>
<td>1048</td>
<td>47.00%</td>
<td>1.0 (ref)</td>
<td>1.0 (ref)</td>
<td>556</td>
</tr>
<tr>
<td>20.0–29.9 ng/mL</td>
<td>1140</td>
<td>48.10%</td>
<td>1.19 (0.99 to 1.42)</td>
<td>1.17 (0.98 to 1.41)</td>
<td>592</td>
</tr>
<tr>
<td>&lt;20 ng/mL</td>
<td>1024</td>
<td>44.30%</td>
<td>1.15 (0.94 to 1.41)</td>
<td>1.09 (0.88 to 1.35)</td>
<td>570</td>
</tr>
<tr>
<td>P value†</td>
<td>0.28</td>
<td>0.75</td>
<td>0.28</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

Linear model 1 adjusted for sex, race, study field center, education, income, and time between the 2 ultrasounds. Linear model 2 further adjusted for physical activity, smoking, BMI, LDL, HDL, use of statins, and GFR. Logistic model 3 adjusted for age, sex, race, site, education, income, and time between the 2 ultrasounds. Logistic model 4 further adjusted for physical activity, smoking, BMI, LDL, HDL, use of statins, and GFR. 25-OHD indicates 25-hydroxyvitamin D; BMI, body mass index; CCA-IMT, intima-media thickness of the common carotid artery; CI, confidence interval; GFR, glomerular filtration rate; HDL, high-density lipoprotein; ICA-IMT, intima-media thickness of the internal carotid artery; and LDL, low-density lipoprotein.

†Among those without carotid plaques at baseline.
†‡Among those without carotid plaques at baseline.

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prevalence and incidence of carotid plaque (Table 2, lower rows). No cross-sectional or longitudinal associations with the baseline carotid plaque score or its change over study time were observed: adjusted odds ratio per 10 ng/mL lower 25-OHD 1.00 (95% CI, 0.93–1.08; \( P=0.95 \)) and 1.05 (95% CI, 0.96–1.03; \( P=0.71 \)), respectively.

**PTH, IMT, and Plaque**

Serum PTH concentrations were not associated with baseline CCA-IMT or its change over time (Table 3, top rows). The adjusted mean difference per 10 pg/mL higher PTH was 0.8 \( \mu \)m (95% CI, 0.08–1.53), respectively. No association was found between PTH and ICA-IMT at baseline, but participants with higher PTH measurements showed nominally less progression of ICA-IMT between the 2 ultrasounds (−10.6 \( \mu \)m [95% CI, −17.9 to −5.6], \( P=0.05 \)) and 1.6 \( \mu \)m (95% CI, 0.09–3.1), respectively. There was no heterogeneity in the associations of 25-OHD and PTH with IMT or its change over time by race/ethnicity.

**Additional Analyses**

There was no heterogeneity in the associations of 25-OHD and PTH with IMT or its change over time by race/ethnicity (all \( P \) interaction >0.05; Figure). To confirm that our findings were not influenced by selection bias and, in particular, survivorship bias, we repeated cross-sectional analyses on the 6393 Multi-Ethnic Study of Atherosclerosis (MESA) participants who had baseline measurements of 25-OHD, PTH, and IMT, regardless of the presence of a second carotid ultrasound. Null results were similar, including the absence of effect modification by race/ethnicity.
associations between lower vitamin D and larger IMT. These examined selected populations (type II diabetes mellitus, HIV) and did not exclude participants with known cardiovascular disease, resulting in potential for confounding effects of PTH on the myocardium (left ventricular hypertrophy, fibrosis, calcifications) or endothelial function may be more important than the effects on arterial wall injury, at least in the carotid arteries. Vitamin D may act on cardiovascular risk through several different pathways, such as through an immune or inflammatory modulation or a direct effect on the endothelial or smooth muscle vascular cell. Of cardiovascular outcomes, lower circulating concentrations of 25-OHD have been most consistently and strongly associated with increased risk of coronary artery disease. The extent of coronary artery calcium and carotid IMT is only moderately correlated, suggesting that their pathogenesis may differ. Whether 25-OHD influences the development of coronary atherosclerosis, suggested by previous work, needs to be further explored.

Our study design and population bring important strengths to our results. Precise estimates of associations, of utmost importance given the null findings, were possible because of the large sample size and strict quality of the outcome variables. Also, Reis et al studied 654 subjects from a community-based cohort in California, with a mean age of 76 years and a high average 25-OHD (41.5 ng/mL). This study reported an independent association between vitamin D status and ICA-IMT, but not CCA-IMT, which conflicts with our results without a clear explanation. In the same study, PTH was not associated with either ICA-IMT or CCA-IMT.

Several explanations could be advanced for the lack of associations between mineral metabolism markers and carotid injury in our study. First, one measure of 25-OHD and PTH may not adequately represent the true average individual status of these hormones because of variability over time. PTH has a substantial within-subject variability, but the validity of one measure of 25-OHD is very high, with a correlation of 0.85 between 2 measurements taken 8 months in white and black American subjects. Second, carotid IMT measurement error (which would bias estimates toward the null) cannot be excluded, even with the very good intra- and inter-reader reproducibility measurements used in this study. Third, CCA-IMT may be more closely related to aging and hypertensive medial hypertrophy than atherosclerotic processes. However, ICA-IMT and carotid plaque, which yielded similar results in our analysis, are thought to represent early phenotypes of atherosclerosis. Fourth, more aggressive treatment for cardiovascular risk factors among participants with low 25-OHD or high PTH during follow-up could have attenuated the true associations, but we found that the increase in cardiovascular treatment did not differ by baseline 25-OHD or PTH status. Finally, and most likely in our opinion, our results may suggest that mineral metabolism disturbances affect cardiovascular risk through pathways distinct from carotid atherosclerosis.

Previous experimental and epidemiological evidence supports effects of PTH and 25-OHD on cardiovascular risk that do not involve carotid atherosclerosis. PTH is an independent predictor of cardiovascular mortality in the general population, but its association with incident heart failure appears much stronger than with myocardial infarction. The detrimental effects of PTH on the myocardium (left ventricular hypertrophy, fibrosis, calcifications) or endothelial function may be more important than the effects on arterial wall injury, at least in the carotid arteries. Vitamin D may act on cardiovascular risk through several different pathways, such as through an immune or inflammatory modulation or a direct effect on the endothelial or smooth muscle vascular cell. Of cardiovascular outcomes, lower circulating concentrations of 25-OHD have been most consistently and strongly associated with increased risk of coronary artery disease. The extent of coronary artery calcium and carotid IMT is only moderately correlated, suggesting that their pathogenesis may differ. Whether 25-OHD influences the development of coronary atherosclerosis, suggested by previous work, needs to be further explored.
measures. The possibility of residual confounding was reduced by the well-measured confounding variables and the lack of clinical cardiovascular disease at baseline. Survivorship bias was minimized by showing similar results for cross-sectional associations at baseline between the entire cohort and the subcohort with both ultrasound examinations. Finally, the participants’ diversity in race/ethnicity, age range, and sex broadens the generalizability of the results. Study limitations included its observational design, possible measurement error in mineral metabolism and carotid biomarkers, especially for longitudinal IMT and plaque measurements, the use of surrogate markers of carotid atherosclerosis, as well as lack of data on vitamin D supplementation.

In conclusion, data from this large, diverse cohort do not support clinically meaningful relationships of circulating 25-OHD or PTH concentrations with carotid IMT or plaque. If previously observed relationships of these biomarkers with cardiovascular events are causal, pathways other than carotid atherosclerosis are likely responsible.

Acknowledgments
We thank other investigators, the staff, and the participants of the Multi-Ethnic Study of Atherosclerosis (MESA) study for their valuable contributions. A full list of participating MESA investigators and institutions can be found at http://www.mesa-nhlbi.org.

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Disclosures
I.H. de Boer has received research funding from Abbott Laboratories. The other authors report no conflicts.

References
Lower circulating concentrations of 25-hydroxyvitamin D and higher circulating concentrations of parathyroid hormone are associated with increased risk of cardiovascular events, but potential disease pathways are poorly defined. In this study, we measured 25-hydroxyvitamin D and parathyroid hormone in 3251 participants without cardiovascular disease who underwent 2 carotid ultrasounds a mean of 9.4 years apart. 25-hydroxyvitamin D and parathyroid hormone were associated neither with the severity or progression of intima-media thickness nor with the prevalence or incidence of carotid plaques. These null results were observed among all races and ethnicities. The absence of associations suggests that the pathways mediating the increased cardiovascular risk of vitamin D and parathyroid hormone may be independent of carotid atherosclerotic processes.
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MATERIAL AND METHODS

Population
Between 2000 and 2002, the Multi-Ethnic Study of Atherosclerosis (MESA) enrolled 6814 men and women of four racial/ethnic groups (White, Black, Hispanic and Asian), aged 45-84 years. Participants, who were free of clinical cardiovascular disease, were recruited from the population near six field centers (Baltimore, Maryland; Chicago, Illinois; Forsyth County, North Carolina; New York, New York; St Paul, Minnesota; Los Angeles, California). They gave written informed consent and local institutional review boards approved the study protocol. From the 6814 MESA subjects, 3447 participants were selected for a follow-up ultrasound scan at exam 5 (2010-2011), among those who had valid baseline carotid IMT measurements and had consented to be included in MESA Air. The latter includes a subcohort of MESA to investigate associations of long-term air pollution exposure with subclinical atherosclerosis and cardiovascular disease. All images from the baseline ultrasound scan of these 3447 participants were reviewed and carotid IMT and plaques were re-measured using a strict quality protocol. We excluded 192 subjects with missing 25-OHD or PTH and 4 subjects with 25-OHD >100ng/ml (suggesting supplementation with high-dose vitamin D), leaving 3251 subjects for the main analysis (47.7% of the entire MESA cohort).

In sensitivity analyses, we also evaluated cross-sectional associations in 6737 subjects with available original IMT measurements at baseline, of whom we excluded 347 subjects with missing 25-OHD or PTH and 6 subjects with 25-OHD >100ng/ml, leaving 6393 subjects (93.4% of the cohort).

Measurements

Vitamin D / PTH
Serum 25-OHD concentrations were measured by mass spectrometry, with 25-OHD calibrated to NIST standards (interassay CV <3.4%). Serum PTH was measured by two-site immunoassay on a Beckman Access 2 automated immunoassay platform (inter-assay CV 6.1% at 30.1 pg/ml and 3.4% at 94.5 pg/ml). As season-specific thresholds for 25-OHD may be most relevant, 25-OHD was adjusted for seasonal variation using a cosinor model derived and internally validated in MESA.

Carotid artery measurements
At baseline, trained and certified sonographers from each field center performed B-mode ultrasonography of the near and far walls of the left and right internal carotid and common carotid arteries (ICA / CCA) using a Logiq 700 ultrasound system (General Electric Medical Systems) with a linear array vascular ultrasound transducer (M12L). Images were recorded on super-VHS videotapes at high resolution and frame rates using a Medical Digital Recording (MDR) device (PACSGEAR, Pleasanton, CA) and converted into DICOM compatible digital records. At exam 5, a similar protocol was performed using the same ultrasound and digitizing equipment, however images focused on the far walls of the ICA and CCA. For exam 5, the ultrasound reading center core lab at the University of Wisconsin selected reference images from exam 1
for sonographers to try to match the scanning characteristics of the initial study, including the carotid artery display depth on the screen, angle of approach, surrounding tissues and internal landmarks, degree of jugular venous distension, and ultrasound system settings. The video output was directly digitized using the same MDR settings without use of videotape.

Carotid IMT measurements were performed in triplicate at the distal 1cm of the CCA and the proximal ICA on both sides, regardless of the presence of plaque. Carotid plaque was defined as the presence of focal wall thickening at least 50% greater than that of the surrounding vessel wall or as a focal region with CIMT greater than 1.5mm that protrudes into the lumen distinctly from the adjacent boundary. Carotid plaques were evaluated from transverse and longitudinal views of the ICA, CCA and the bulb. Three trained readers from the ultrasound reading center reviewed all images at both examinations and performed all measurements. They also assessed the image quality and the matching of carotid images between the two examinations. Reader reproducibility was assessed by having all 4 readers blindly read 24 scans, chosen as 4 per field center and half each from exams 1 and 5. Intra-reader reproducibility was excellent for maximum CCA-IMT (total error of the mean [TEM] 3-4%, intra-class correlation coefficients [ICCs] 0.93-0.99) and very good for maximum ICA-IMT (TEM 8-9%; ICC 0.86-0.96). Inter-reader reproducibility was excellent for maximum CCA-IMT (TEM 2-4%, ICC 0.96) and very good for maximum ICA-IMT (TEM 5-10%, ICCs 0.86-0.88). Scan-rescan reproducibility was evaluated by 44 repeated scans from 3 sonographers, using a single reader. Pearson correlations for matched segments ranged from 0.979-0.996. Mean (SD) differences were <0.01 (<0.05) mm with no outliers on limit of agreement (Bland-Altman) analysis for matched segments.

We computed a plaque score as the total number of segments with at least one plaque present in the near or far wall of all 6 segments of the right and left carotid arteries (common, bulb, and internal carotid), ranging from 0-12.

**Covariates**

At baseline, demographic data, smoking status, medical conditions, physical activity and the use of medications, were recorded in a questionnaire. Body-mass index (BMI) and resting blood pressure were measured. Blood samples were taken from all participants at baseline for measurements of all biomarkers. Plasma HDL cholesterol was measured using CDC-standardized methods and LDL cholesterol was estimated using the Friedewald equation. We calculated the glomerular filtration rate (GFR) with the combined creatinine-cystatin C equation.

**Analyses**

For IMT, we evaluated cross-sectional and longitudinal associations of 25-OHD and PTH with CCA-IMT, ICA-IMT, and changes in IMT using linear regression. Change in IMT was restricted to participants with matching carotid segments in the two ultrasound exams (CCA: 2583/3182, ICA: 1408/2419) and the dependent variable was the difference in IMT measurements. For carotid plaque, we evaluated the prevalence of any carotid plaque at baseline and the incidence of a new plaque at the second ultrasound exam (among those free of plaques at baseline) using logistic regression. Change in the additive plaque score was evaluated using ordered logistic regression.
25-OHD and PTH were modeled as categorical exposures using commonly used thresholds: 20/30ng/ml (25-OHD)\textsuperscript{10}, 65pg/ml and tertiles (PTH)\textsuperscript{4}. The presence of non-linear trends was excluded graphically. Two-sided P values from the Wald test with robust standard errors were obtained for continuous exposures. A level <0.05 determined statistical significance.

The primary analysis was adjusted for confounders chosen prior to analyses: demographic variables, physical activity (total intentional exercise per week, in tertiles), BMI, LDL cholesterol, HDL cholesterol, GFR (continuous terms) and the use of statins at baseline. Analyses evaluating PTH were further adjusted for 25-OHD. Diabetes, hypertension and CRP were considered to be potential mediators and not included as covariates.\textsuperscript{11-13} All models were time-adjusted to account for possible differences in the time between the 2 ultrasounds.

In a subgroup analysis, we evaluated the presence of heterogeneity of the associations between race/ethnicity by adding multiplicative interaction terms of race/ethnicity with 25-OHD or PTH.

Missing covariate data were infrequent in covariates (≤2.5%) and were multiple-imputed with 5 imputed datasets using imputation by chained-equations.\textsuperscript{14} Carotid measurements, 25-OHD and PTH were not imputed.
REFERENCES


