Molecular Imaging

Imaging Intraplaque Inflammation in Carotid Atherosclerosis With 18F-Fluorocholine Positron Emission Tomography–Computed Tomography
Prospective Study on Vulnerable Atheroma With Immunohistochemical Validation

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Background—18F-fluorocholine (18F-FCH) uptake is associated with cell proliferation and activity in tumor patients. We hypothesized that 18F-FCH could similarly be a valuable imaging tool to identify vulnerable plaques and associated intraplaque inflammation and atheroma cell proliferation.

Methods and Results—Ten consecutive stroke patients (90% men, median age 66.5 years, range, 59.4–69.7) with ipsilateral >70% carotid artery stenosis and who underwent carotid endarterectomy were included in the study. Before carotid endarterectomy, all patients underwent positron emission tomography to assess maximum 18F-FCH uptake in ipsilateral symptomatic carotid plaques and contralateral asymptomatic carotid arteries, which was corrected for background activity, resulting in a maximum target-to-background ratio (TBRmax). Macrophage content was assessed in all carotid endarterectomy specimens as a percentage of CD68+staining per whole plaque area (plaqueCD68+) and as a maximum CD68 percentage (maxCD68+) in the most inflamed section/plaque. Dynamic positron emission tomography imaging demonstrated that an interval of 10 minutes between 18F-FCH injection and positron emission tomography acquisition is appropriate for carotid plaque imaging. TBRmax in ipsilateral symptomatic carotid plaques correlated significantly with plaqueCD68+ (Spearman’s ρ=0.648, P=0.043) and maxCD68+ (ρ=0.721, P=0.019) in the 10 corresponding carotid endarterectomy specimens. TBRmax was significantly higher (P=0.047) in ipsilateral symptomatic carotid plaques (median: 2.0; interquartile range [Q1–Q3], 1.5–2.5) compared with the contralateral asymptomatic carotid arteries (median: 1.4; Q1–Q3, 1.3–1.6). TBRmax was not significantly correlated to carotid artery stenosis (ρ=0.506, P=0.135).

Conclusions—In vivo uptake of 18F-FCH in human carotid atherosclerotic plaques correlated strongly with macrophage infiltration and recent symptoms, thus 18F-FCH positron emission tomography is a promising tool for the evaluation of vulnerable plaques.


Key Words: atherosclerosis carotid artery diseases endarterectomy fluorocholine inflammation macrophages positron-emission tomography

Carotid endarterectomy (CEA) has been shown to prevent stroke in patients with high-grade carotid artery stenosis.1 It has, however, become increasingly clear that the degree of luminal stenosis alone is not the most optimal clinical decision parameter. Patients with almost occluded carotid arteries may remain completely asymptomatic throughout their lifetime, whereas strokes may occur in the absence of severe carotid stenosis because of outward arterial remodeling of a vulnerable plaque.2 Hence, novel targets for noninvasive imaging of...
vulnerable plaques are absolutely required for reliable patient risk stratification.

The composition and biological activity of plaques have emerged as important determinants of cerebrovascular events alongside the degree of luminal narrowing. Intraplaque inflammation plays a key role in the progression and destabilization of atherosclerotic lesions and has been proposed as a major criterion for defining a high-risk vulnerable plaque.

Positron emission tomography (PET) with the tracer 18F-fluoro-2-deoxy-D-glucose (18F-FDG) allows measurement of metabolic activity and tends to correlate with plaque macrophage infiltration, cardiovascular risk factors, Framingham Risk Score, and recent symptoms. However, 18F-FDG PET of atherosclerotic plaques remains challenging because of intense background FDG uptake that can potentially swamp any plaque signal and of some technical disadvantages, which include reduced cellular 18F-FDG uptake in hyperglycemia, the need to fast for 26 hours before 18F-FDG injection, and a lengthy waiting time of 2.5 to 3 hours between 18F-FDG injection and image acquisition to achieve an optimal vessel wall to background ratio.

The newer 18F-fluorocholesterol (18F-FCH) tracer may be an attractive alternative to 18F-FDG. Choline is a key precursor of phosphatidylcholine (lecithin), a major phospholipid component of all cellular membranes, and thus it is closely associated with cellular proliferation and activity. Radiolabeled-choline PET tracers (including 18F-FCH) are highly taken up by tumor cells and also by active and proliferating macrophages involved in inflammatory processes. A retrospective trial of tumor patients also assessing carotid atherosclerosis has shown a significantly increased choline uptake in noncalcified regions, assumed to be inflamed plaques, in comparison to the healthy vessel wall. Interestingly, in a side-by-side comparison between 18F-FCH and 18F-FDG in murine atherosclerotic lesions, choline uptake correlated with macrophage staining even better than FDG uptake. However, it is yet unknown whether 18F-FCH uptake in plaques is associated with symptoms in cardiovascular patients and histological markers of plaque vulnerability.

Therefore, in this proof-of-principle study, we prospectively investigated whether 18F-FCH PET can be used to assess vulnerable plaque macrophage infiltration and whether the degree of 18F-FCH uptake can be used to discriminate between recently symptomatic and asymptomatic lesions.

Methods

Ethical Considerations

The present article is a prospective, cross-sectional diagnostic study with patient inclusion conforming to the principles outlined in the Helsinki Declaration II. All patients gave written informed consent before inclusion in the study. The study protocol was approved by the ethical committee of the Maastricht University Medical Center (METC13-2-015), registered at the European and Dutch referral committees on research involving human subjects (EUDRACT2013-000456-17/NL43466.068.13) and in the clinical trials registry ClinicalTrials.gov (NCT01899014). Radiation exposure was licensed by the local radiation safety committee and study monitoring was performed by the Clinical Trial Center Maastricht.

Patients

The study included 10 consecutive patients after onset of acute cerebrovascular event (stroke, transient ischemic event, or amaurosis fugax) who were scheduled for CEA because of severe ipsilateral carotid artery stenosis. All patients were clinically assessed by an experienced vascular neurologist or vascular surgeon at the stroke unit or the Cardiovascular Outpatient Clinic (Maastricht University Medical Center). All patients were symptomatic at the ipsilateral side of carotid artery stenosis, defined as cerebrovascular symptoms in the ipsilateral anterior cerebral circulation or the retinal circulation, in combination with a 70% to 99% stenosis of the carotid artery, according to the North American Symptomatic Carotid Endarterectomy Trial criteria. Before enrollment, the degree of carotid stenosis on the ipsilateral and contralateral side was assessed by experienced ultrasonographers using Doppler-ultrasonography. Carotid stenosis was categorized as follows: normal, <50%, 50% to 69%, 70% to 99% stenosis, and total occlusion. Exclusion criteria included pregnancy, breastfeeding mothers, contraindications to iodinated contrast agents including known intolerance to contrast agents or impaired renal function (renal clearance <45 mL/min/1.73 m<sup>2</sup> or <60 mL/min/1.73 m<sup>2</sup> in patients with diabetes mellitus), serious clinical conditions (depression, severe heart failure New York Heart Association class III–IV, and severe pulmonary dysfunction dependent of oxygen supply), or major neurological deficits (hemiparesis, complete aphasia). Clinical history and medication use were ascertained at the time of subject enrollment. Study participants underwent carotid 18F-FCH PET-computed tomography (CT) within 14 days before CEA.

18F-FCH Positron Emission Tomography–Computed Tomography Protocol

The synthesis of 18F-FCH was based on a previously described protocol and performed according to the European directive on radiopharmaceuticals.

PET-CT (positron emission tomography–computed tomography) imaging of both carotid arteries was performed on a Gemini TF-64 PET-CT scanner (Philips Healthcare, Best, The Netherlands). Starting simultaneously with the intravenous injection of 18F-FCH (4 MBq/kg body weight), 30-minute dynamic PET imaging was performed (3-dimensional mode, 1-bed position), with field-of-view centered at the carotid artery bifurcation. Additional static PET images were taken 60 minutes post 18F-FCH injection. Then, contrast-enhanced CT images were obtained by using 90 mL of iobitridol (Supplemental Methods in the Data Supplement).

CEA and Histology Preparation

Surgeons were instructed to remove the carotid plaques in one piece. After CEA, the carotid plaques were immediately fixed in 10% buffered formalin. Carotid plaques were transversely cut in 4-mm slices, decalcified, embedded in paraffin, and transversely cut in 4-μm sections, as previously described. Adjacent 4-μm sections were subjected to immunohistological staining with monoclonal antibodies against: CD68, for identification of macrophages; human alveolar macrophage marker-56 (HAM56), for confirmatory macrophage content analysis; major histopathology complex class-II (MHC-II), for activated inflammatory cells; or IgG control (Supplemental Methods in the Data Supplement).

Coregistration of the Ipsilateral Symptomatic Carotid Plaque at PET-CT With Histology

Anatomic colocalization between corresponding PET-CT slices on the ipsilateral symptomatic side and histopathologic sections was performed by locating plaques relative to the carotid bifurcation and the narrowest carotid artery lumen as landmarks, as previously described (Supplemental Methods in the Data Supplement).

18F-FCH PET-CT Evaluation

Carotid 18F-FCH uptake, expressed as standardized uptake value (SUV), was measured at 4-mm intervals along the length of the carotid artery on a dedicated workstation with dedicated fusion software (Syngenta, Philips Healthcare). Carotid plaque was identified on contrast-enhanced CT images, defined as thickening of the vessel...
wall and calcification, and carotid stenosis grade was assessed using the North American Symptomatic Carotid Endarterectomy Trial method. On the ipsilateral symptomatic side, circular regions of interests (ROIs) were placed on consecutive axial CT images encompassing the outer carotid vessel wall at the level of the plaque (Figure 1).

On the contralateral asymptomatic side, ROIs were placed similarly along the carotid plaque when this was identified on contrast-enhanced CT. When no plaque was identified on asymptomatic sides, circular ROIs were placed on consecutive axial CT images encompassing the outer vessel wall from the internal carotid artery (8 mm cranial of the carotid bifurcation) to the level of the common carotid artery (12 mm caudal of the carotid bifurcation).

For each slice, the maximum SUV was measured as the maximum pixel activity within ROI. The maximum value of all SUVs (SUVmax) was recorded for both the symptomatic carotid plaque and the asymptomatic carotid artery. Finally, the carotid SUVmax values were corrected for blood activity by dividing by the average blood activity obtained from five circular 6-mm diameter ROIs placed in the center of the subclavian or internal jugular vein on consecutive axial CT images (SUVmean venous blood). The resulting blood-corrected values were expressed as maximum target-to-background ratio (TBRmax). PET images were reported in consensus by a nuclear medicine physician–nuclear cardiologist (>4 years of experience, >2 years of experience at quantifying carotid plaque on PET) and a nuclear medicine physician with extensive PET experience (>10 years experience) and cardiovascular interest.

Histological Analysis
Using high-resolution digital microscopy, total plaque area and CD68+ macrophage content were quantified at each 4-μm section using a computer-assisted color image analysis (QWin V3; Leica, Cambridge, England). Macrophage content was expressed as percentage of CD68+ area to total plaque area (plaqueCD68+). The maximum macrophage content was determined at the plaque section with the highest CD68+ percentage (maxCD68+).

Histological analysis was performed by a trained reader (>1 year experience in histological plaque assessment), blinded to clinical and PET data. To determine the variability of the CD68+ content measurement, the images were reanalyzed by the same observer 3 months apart in a masked manner. The intraclass correlation coefficient was 0.92 (95% confidence interval, 0.81–0.98).

Tritiated Choline Uptake Assay
Choline uptake by activated macrophages was assessed using a protocol adapted from Folco et al. Human monocytic cells (human acute monocytic leukemia cell line) were differentiated to macrophages. To induce cell activation, macrophages were incubated in RPMI1640 medium, followed by the addition of lipopolysaccharide, tumor necrosis factor-α, and interferon-γ. Nonactivated macrophages served as controls.

Cells were first washed with phosphate-buffered saline. 3H-choline was added to the cells and incubated for 30 minutes at 37°C. Cells were washed twice and detached, counted, and further assayed by liquid scintillation counting (Beckman LS 6000IC counter). The net uptake of 3H-choline is expressed as counts of choline/cell/min (Supplemental Methods in the Data Supplement).

Statistical Analysis
Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corporation, Armonk, NY). Differences in 18F-FCH activity at various time points and differences between symptomatic and asymptomatic carotid arteries were assessed by Wilcoxon signed-rank tests. The study is underpowered to assess the effect of cardiovascular risk factors and medication on choline uptake. However, in light of statin’s known anti-inflammatory effect, the available data provided an opportunity to screen for a potential
influence of statins on choline uptake. Thus, a subgroup analysis was performed, whereby 18F-FCH activity was assessed according to long-term statin use. Differences between different subgroups were assessed by using a Mann–Whitney U test. Correlations between 18F-FCH uptake and histological degree of macrophage infiltration or degree of arterial stenosis (on contrast-enhanced CT) were assessed by the Spearman rank correlation test. A two-sided \( P < 0.05 \) was considered statistically significant.

**Results**

**Baseline Characteristics**

Patient characteristics are displayed in Table 1. Median interval between last symptoms (amaurosis fugax, \( n=5 \); transient ischemic attack, \( n=2 \); and minor nondisabling stroke, \( n=3 \)) and 18F-FCH PET was 11 (Q1–Q3, 9–12) days. Median interval between 18F-FCH PET and CEA was 2 (Q1–Q3, 1–3) days.

**Carotid Artery Stenosis Grade**

Symptomatic carotid arteries had significantly higher stenosis grade than contralateral asymptomatic carotid arteries (median: 97.5%, Q1–Q3: 94.0–99.0% versus 70%, Q1–Q3: 20.0–95.0%, respectively; \( P = 0.019 \); Table 2).

**Uptake and Dynamics of 18F-FCH**

Representative PET and histological images are shown in Figure 1 and Figure I in the Data Supplement.

Expression of CD68, a pan-macrophage marker, and the macrophage activation marker MHC-II largely colocalized with 18F-FCH uptake in the symptomatic plaques, while expression of the human alveolar macrophage marker-56, as a second confirmatory macrophage marker, was more restricted (Figure 1).

Dynamic PET imaging demonstrated that background blood pool activity peaked immediately post 18F-FCH injection (median SUVmean: 9.7, Q1–Q3: 7.8–16.7). It dropped rapidly within 3 minutes (\( T_{1/2} = 3 \) minutes, median SUVmean: 1.3, Q1–Q3: 1.1–1.4) reaching a steady-state already at 10 minutes (median SUVmean: 1.03, Q1–Q3: 0.9–1.1) postinjection (Figure 2).

In both the symptomatic as well as contralateral asymptomatic plaques, dynamic PET imaging showed an initial peak activity (median SUVmax: 12.8, Q1–Q3: 12.0–16.4 and 13.1, Q1–Q3: 10.4–16.1, respectively), which was mostly attributed to the 18F-FCH bolus and which, similar to blood pool activity, rapidly dropped within 3 minutes. Activity in the symptomatic and asymptomatic carotid plaques reached a steady-state level 10 minutes post 18F-FCH injection (median SUVmax: 2.0, Q1–Q3: 1.6–2.3 and 1.5, Q1–Q3: 1.1–1.6, respectively; Figure 2).

### Table 1. Baseline Characteristics of the Included Subjects (n=10)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y (median, Q1–Q3)</td>
<td>66.5 (59.4–69.7)</td>
</tr>
<tr>
<td>Male sex</td>
<td>9 (90.0%)</td>
</tr>
<tr>
<td>Caucasian race</td>
<td>10 (100.0%)</td>
</tr>
<tr>
<td>Prior medical history</td>
<td></td>
</tr>
<tr>
<td>Ischemic cerebrovascular and/or cardiovascular disease</td>
<td>3 (30.0%)</td>
</tr>
<tr>
<td>Current or previous smoking</td>
<td>8 (80.0%)</td>
</tr>
<tr>
<td>Arterial hypertension</td>
<td>9 (90.0%)</td>
</tr>
<tr>
<td>Hyperlipidemia</td>
<td>9 (90.0%)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>3 (30.0%)</td>
</tr>
<tr>
<td>Number of cardiovascular risk factorstest</td>
<td>8 (80.0%)</td>
</tr>
<tr>
<td>2–3</td>
<td>2 (20.0%)</td>
</tr>
<tr>
<td>Concurrent neurological symptoms</td>
<td></td>
</tr>
<tr>
<td>Minor stroke, transient ischemic attack, or amaurosis fugax</td>
<td>10 (100%)</td>
</tr>
<tr>
<td>Medication</td>
<td></td>
</tr>
<tr>
<td>Antiplatelet agent</td>
<td>10 (100.0%)</td>
</tr>
<tr>
<td>Antihypertensive agent</td>
<td>7 (70.0%)</td>
</tr>
<tr>
<td>Statin*</td>
<td>10 (100.0%)</td>
</tr>
</tbody>
</table>

Data are presented as numbers and percentages between brackets, unless otherwise indicated. Q1–Q3 indicates interquartile range.

*\( n=4 \), duration >6 months.

### Table 2. Carotid Artery Stenosis Grade of Ipsilateral Symptomatic and Contralateral Asymptomatic Carotid Arteries in All Subjects (n=10)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Ipsilateral Symptomatic Carotid Artery</th>
<th>Contralateral Asymptomatic Carotid Artery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaque stenosis on contrast-enhanced CT (median, Q1–Q3)</td>
<td>97.5% (94.0–99.0%)</td>
<td>70.0% (20.0–95.0%)</td>
</tr>
<tr>
<td>Carotid plaque on Doppler ultrasonography</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absence of plaque</td>
<td>0 (0%)</td>
<td>2 (20.0%)</td>
</tr>
<tr>
<td>&lt;50% stenosis</td>
<td>0 (0%)</td>
<td>2 (20.0%)</td>
</tr>
<tr>
<td>50% to 69% stenosis</td>
<td>0 (0%)</td>
<td>2 (20.0%)</td>
</tr>
<tr>
<td>70% to 99% stenosis</td>
<td>10 (100.0%)</td>
<td>3 (30.0%)</td>
</tr>
<tr>
<td>Occlusion</td>
<td>0 (0%)</td>
<td>1 (10.0%)</td>
</tr>
<tr>
<td>18F-FCH PET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TBRmax (median, Q1–Q3)</td>
<td>2.00 (1.46–2.49)</td>
<td>1.39 (1.27–1.61)</td>
</tr>
<tr>
<td>SUVmean venous blood (median, Q1–Q3)</td>
<td>1.03 (0.98–1.14)</td>
<td>0.98 (0.90–1.09)</td>
</tr>
<tr>
<td>CD68+ immunohistochemistry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PlaqueCD68+, % (median, Q1–Q3)</td>
<td>5.6% (2.3–8.7%)</td>
<td>NA</td>
</tr>
<tr>
<td>MaxCD68+, % (median, Q1–Q3)</td>
<td>10.5% (4.9–15.4%)</td>
<td>NA</td>
</tr>
<tr>
<td>Total plaque area, mm² (median, Q1–Q3)</td>
<td>129.5 (85.7–171.3)</td>
<td>NA</td>
</tr>
</tbody>
</table>

Data are presented as numbers and percentages between brackets, unless otherwise indicated. CT indicates computed tomography; 18F-FCH PET, 18F-fluorocholine positron emission tomography; NA, not assessed; Q1–Q3, interquartile range; SUV, standard uptake value; and TBRmax, maximum target-to-background ratio.
Correlation Between 18F-FCH Uptake in Symptomatic Carotid Plaques and Histology

CD68+ macrophage content varied markedly between patients (Table 2). TBRmax in symptomatic carotid plaques 10 minutes post 18F-FCH injection correlated strongly with the plaqueCD68+ macrophage content ($\rho=0.648$, $P=0.043$) and maxCD68+ ($\rho=0.721$, $P=0.019$; Figure 3).

In vitro tritiated-choline experiments showed that the choline uptake rate increases >5-folds in human monocyte-derived macrophages under proinflammatory stimulation compared with the unstimulated cells (median: 1.1, Q1–Q3: 0.8–1.2 versus 0.2, Q1–Q3: 0.1–0.3 nmol/cell/h, respectively; $P=0.009$).

Comparison of Symptomatic Carotid Plaques With Contralateral Asymptomatic Arteries

TBRmax 10 minutes post 18F-FCH injection was significantly higher ($P=0.047$) in the symptomatic carotid plaques (median: 2.0, Q1–Q3: 1.5–2.5) compared with the contralateral arteries (median: 1.4, Q1–Q3: 1.3–1.6; Figure 4). 18F-FCH uptake was not significantly related to carotid artery stenosis grade, for both the symptomatic ($p=0.506$, $P=0.135$) and asymptomatic side ($p=0.413$, $P=0.207$).

As statin therapy was initiated after the index event, 6 patients were on statins <15 days, whereas 4 patients with a history of cardiovascular disease were on statins >6 months. Our results showed a tendency toward a lower choline uptake in patients >6 month under statin-treatment compared with those <15 days under therapy (TBRmax median: 1.6, Q1–Q3: 1.2–1.9 versus 2.3, Q1–Q3: 1.3–2.6, respectively; $P=0.055$). No such difference was observed at the asymptomatic side.

Discussion

Here we have demonstrated that 18F-FCH PET is a valuable tool for imaging of vulnerable atherosclerotic plaques. Irrespective of the degree of carotid artery stenosis, 18F-FCH uptake significantly correlated with plaque macrophage content, a measure of plaque inflammation and vulnerability, and could distinguish between recently symptomatic vulnerable plaques and asymptomatic plaques.

Choline is an essential precursor of phospholipids, a key substrate of cell membranes.6 Hence, high membrane turnover in proliferating and in active cells is closely associated with an increased choline metabolism.17–19 Radiolabeled-choline tracers are already used in clinical PET imaging of different cancers17 and are under evaluation for imaging of different inflammatory conditions.18,19 We showed enhanced 18F-FCH uptake in human carotid plaques early after onset of a cerebrovascular event compared with a low uptake in asymptomatic plaques. Previous reports, limited to a retrospective analysis of patients who underwent PET imaging for prostate cancer, have described choline uptake in the aorta and carotid arteries.22,23,29 As choline uptake was found mainly in noncalcified vessel wall areas,22 these reports raised the possibility of choline uptake in vulnerable atherosclerotic plaques. However, no clear conclusion could

Figure 2. Dynamic tracer uptake. Graph showing 18F-FCH uptake in the blood pool and in the ipsilateral symptomatic carotid plaques during the first 60 minutes after tracer injection (n=10). After 18F-FCH injection, 18F-FCH blood pool activity dropped rapidly ($T_{1/2}=3$ minutes), whereas the activity in the symptomatic and asymptomatic carotid plaques stabilized rapidly already at 10 minutes postinjection. 18F-FCH indicates 18F-fluorocholine, and SUV, standardized uptake value.

Figure 3. Correlation of tracer uptake and immunohistochemistry. Graphs showing the correlation between TBRmax in symptomatic carotid plaques 10 minutes after 18F-fluorocholine injection and plaqueCD68+ (A) and maxCD68+ (B) of the 10 corresponding carotid endarterectomy specimens. TBRmax indicates maximum target-to-background ratio.
be drawn from these reports because of their retrospective nature and lack of histological validation.

Another novel aspect of the present study is the correlation between $^{18}$F-FCH uptake in symptomatic human plaques with immunohistological analysis of plaque vulnerability, as a gold standard. The level of $^{18}$F-FCH uptake in the symptomatic carotid plaques strongly correlated with the degree of intraplaque CD68$^+$ macrophage content, a surrogate marker of intraplaque inflammation and vulnerability. This finding is in agreement with previous experimental animal data showing a high choline uptake in inflamed plaques,20,21 which strongly correlates with the amount of active intraplaque macrophages.20 The enhanced choline uptake may be explained by high macrophage proliferation present in symptomatic CEA specimens,30 or by enhanced choline transporter expression and choline kinase activity, as seen under inflammatory conditions.31 Furthermore, choline kinase activity is significantly increased by hypoxia or under stimulation with tumor necrosis factor-$\alpha$,32 which are both present in vulnerable plaques3 and may hence explain high $^{18}$F-FCH uptake.

Interestingly, in a mouse model of atherosclerosis it has been demonstrated that vulnerable plaque detection is more sensitive with $^{18}$F-FCH than with FDG (84% versus 64%).20 The PET tracer FDG, a biological glucose analogue, has been extensively evaluated for measuring intraplaque inflammation in atherosclerotic plaques.6–12 However, because FDG is taken up by any metabolically active tissues, including those surrounding atherosclerotic plaques (such as fat, muscles, and lymph nodes), concerns have been raised about the specificity of this tracer for imaging inflammatory cells. Indeed, Davies et al32 showed that in vivo FDG uptake in atherosclerotic lesions of rabbit aorta does not correlate with macrophage density. They reported no significant difference in FDG uptake between rabbits with highly inflamed aortic walls, those with low levels of inflammation, or controls.32 Moreover, recent clinical data on FDG PET showed an inconsistent correlation between FDG uptake and intraplaque inflammation, ranging from significantly high,7 medium,33 to very poor correlation coefficients.34 Conversely, a high degree of choline uptake in macrophage-rich areas of murine atherosclerotic lesions has been observed with choline in autoradiographic studies,20 suggesting that $^{18}$F-FCH may provide a more specific tracer to assess active macrophage infiltration. However, no definitive conclusion on the relative specificity of the aforementioned tracers can be drawn until a direct head-to-head comparison is performed.

In terms of technical advantages for imaging atherosclerotic plaques by PET, $^{18}$F-FCH may provide significant advantages over $^{18}$F-FDG. First, no period of fasting before injection is required. Second, $^{18}$F-FCH clears from the blood rapidly, with little change in biodistribution pattern >10 minutes post injection.24 Accordingly, our dynamic PET imaging data showed that blood pool activity dropped rapidly within 3 minutes, and that carotid plaque activity reached a steady state already after 10 minutes post $^{18}$F-FCH injection. Thus, $^{18}$F-FCH has a much shorter circulation time compared with $^{18}$F-FDG (10 minutes versus 2.5 hours). These advantages of $^{18}$F-FCH PET would increase patient comfort and throughput. Third, for diabetic patients, $^{18}$F-FCH uptake is not affected by prescan blood glucose levels that could hamper $^{18}$F-FDG uptake in these patients.14,15

A potential drawback to the use of $^{18}$F-FCH is that it is not yet FDA registered or approved despite its use in clinical oncological imaging. Yet whereas $^{18}$F-FCH is not yet available in the US, it is increasingly used throughout Europe, although to a lesser clinical extent and at higher prices compared with FDG. A concern is that despite having a much lower background uptake than FDG, the intense normal choline uptake in the salivary glands and oral mucosa may interfere with choline uptake at carotid bifurcation or in the internal carotid artery. We observed no such interference in the present study.

Future prospective studies are needed to investigate whether $^{18}$F-FCH PET can predict future strokes and improve risk stratification in patients with carotid atherosclerosis. In addition, the value of $^{18}$F-FCH uptake compared with other imaging markers of vulnerable plaques should be determined. These techniques include $^{18}$F-NaF PET for active plaque microcalcifications,16,17 $^{18}$F-labeled Arginine-Glycine-Aspartic acid (RGD) peptides PET for intraplaque microvascularization,17 and magnetic resonance imaging to visualize intraplaque hemorrhage, fibrous cap status, lipid-rich necrotic core size, and microvessel density.18 As it remains unclear whether inflammation, microcalcification, or other vulnerable plaque features are the best for predicting clinical events, a double $^{18}$F-NaF and $^{18}$F-FCH PET assessment or combined $^{18}$F-FCH PET-magnetic resonance imaging are interesting imaging approaches to be tested in future clinical studies. The present article was conceived as a proof-of-principle study and, therefore, its results cannot be extrapolated to a general population with carotid artery disease. Moreover, we acknowledge our study involves a relatively small number of patients. Hence, the effects of other possible determinants on $^{18}$F-FCH uptake, including injected $^{18}$F-FCH dose, medication, and renal function, could not be investigated as
they warrant larger prospective trials. Moreover, we did not perform a direct comparison between 18F-FCH and 18F-FDG PET, which is the current imaging standard for noninvasive assessment of inflammation in atherosclerosis. The added radiation dose from PET and CT remains an important concern. However, the total effective radiation dose in our patients was well below 10 mSv and comparable to a standard cardiac FDG PET-CT scan.

In conclusion, the present study provides proof of concept that 18F-FCH PET of human carotid atherosclerotic plaques can distinguish between recently symptomatic and asymptomatic plaques and that 18F-FCH uptake strongly correlates with degree of macrophage infiltration, a marker of plaque vulnerability. Our proof-of-principle study shows that 18F-FCH PET can be a valuable tool to identify vulnerable carotid plaques and needs to be investigated in larger prospective studies.

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Given limitations of conventional ¹⁸F-fluoro-2-deoxy-D-glucose positron emission tomography-computed tomography (¹⁸F-FDG PET-CT) imaging, the main inflammation-sensitive molecular imaging agent used for clinical molecular imaging of atherosclerosis, the search for new tracers with improved pharmacokinetics or specificity are important. The present article hypothesizes that ¹⁸F-fluorocholine (¹⁸F-FCH) PET imaging is a valuable imaging tool for the identification of intraplaque inflammation and identification of vulnerable plaques. As proof-of-principle, the article describes the use of ¹⁸F-FCH PET-CT for diagnosing carotid vulnerable plaques in patients with symptomatic carotid stenosis. The present data provide evidence that ¹⁸F-FCH PET-CT imaging can be used to detect vulnerable, inflamed atherosclerotic plaques in symptomatic patients. A major advantage of this modality over that of conventional ¹⁸F-FDG PET imaging is that ¹⁸F-FCH quickly clears from blood without any necessary glucose modulation and it accumulates in inflamed atherosclerotic plaques to achieve a reasonable target to background ratio in a short time. This demonstration makes ¹⁸F-FCH an attractive imaging tracer compared with ¹⁸F-FDG that could allow for high throughput diagnostic imaging in clinics. The present study highlights the important potential clinical utility of the tracer studied.
Vulnerable Atheroma With Immunohistochemical Validation

Imaging Intraplaque Inflammation in Carotid Atherosclerosis With $^{18}$F-Fluorocholine Positron Emission Tomography—Computed Tomography: Prospective Study on


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SUPPLEMENTAL MATERIAL

Supplemental Methods

\[^{18}\text{F-}\text{FCH PET-CT protocol}\]

The synthesis of \(^{18}\text{F-FCH}\) was based on a previously described protocol\(^1\) and performed according to the EU directive on radiopharmaceuticals.

PET-CT imaging of both carotid arteries was performed on a Gemini TF-64 PET-CT scanner (Philips Healthcare, Best, the Netherlands) with 4.8-mm PET resolution (full width at half maximum). Patients were not required to fast prior to \(^{18}\text{F-FCH PET-CT}\). A restraining band was used to fix patients' heads to minimize head movement during PET acquisition. An initial low-dose CT scan was obtained in the cranio-caudal direction from the skull base to the upper mediastinum (120 kVp, 30 mAs, pitch 1.5, and 1s per rotation) prior to PET imaging. Subsequently, starting simultaneously with the intravenous injection of \(^{18}\text{F-FCH}\) (4 MBq/kg body weight), 30-minute dynamic PET imaging was performed (3-dimensional [3D] mode, 1-bed position), with field-of-view centered at the carotid artery bifurcation. After a second low-dose CT scan, additional static PET images were taken 60 minutes post \(^{18}\text{F-FCH}\) injection (3D mode, 1 bed position, 5-minute acquisition time). Following PET scanning, contrast-enhanced CT images were obtained by using 90 mL of iobitridol, collimation of 64x0.625 mm, 120 kVp, 175 mAs, 0.5-second tube rotation, pitch 0.671, and image reconstruction with 250x250 FOV, 512x512 matrix, and 0.7-mm slice thickness. Both dynamic and static PET acquisitions were reconstructed using the BLOB-OS-TF reconstruction algorithm (2 mm voxel size). The dynamic PET acquisition was reconstructed in 24 successive time frames of increasing duration (8x15 s; 6x30 s; 5x1 min; 5x4 min). PET images were corrected for attenuation, scatter, randoms, dead-time, and radioactive decay. Radiation exposure per study was \(<10\text{ mSv}\).
CEA and histology preparation

Surgeons were instructed to remove the carotid plaques in one piece (performed by conventional (n=2) or eversion (n=8) technique). After CEA, the carotid plaques were immediately fixed in 10% buffered formalin. Carotid plaques were transversely cut in 4-mm slices grouped by distance relative to the carotid bifurcation, decalcified, embedded face up in paraffin, subsequently transversely cut in 4-μm sections, and mounted on gelatin-coated glass slides, as previously described. Adjacent 4-μm sections were subjected to epitope retrieval by pepsin digestion and immunohistochemically stained for 30 minutes with monoclonal antibodies against: CD68 (1:100 in TBS-1%BSA-0.1% tween, DAKO M0814), for identification of macrophages; HAM56 antibody (1:50, DAKO ABIN966509), for confirmatory macrophage content analysis; major histopathology complex class II (MHC-II)(1:100, AKO ABIN370813), for activated inflammatory cells; or IgG control. All sections were further incubated with biotinylated sheep anti-mouse (RPN 1001v1, Amersham) followed by streptavidin-biotin amplification complex conjugated to horseradish peroxidase (Vectastain ABC kit PK4000, Vector) to visualize macrophages with 3,3'-diaminobenzidine (DAB, DAKO) as a brown precipitate. Quantitative morphometry was done using Qwin (Leica) to quantify CD68-positive area/total plaque area in all sections per patient.

Coregistration of the ipsilateral symptomatic carotid plaque at PET-CT with histology

Anatomic colocalization between corresponding PET-CT slices on the ipsilateral symptomatic side and histopathologic sections was performed by locating plaques relative to the carotid bifurcation and/or the narrowest carotid artery lumen as landmark, as previously described. The carotid bifurcation was defined as the apex of the luminal flow divider between the internal and external carotid arteries, as identified on contrast-enhanced CT or in
excised specimens. Locations of plaque regions on PET-CT data were recorded along axial images at 5-mm intervals and referenced according to the distance from the flow divider. Matched cross-sections were compared quantitatively for $^{18}$F-FCH TBR and CD68 as an immunohistochemical marker.

*Tritiated choline uptake assay*

Choline uptake by activated macrophages was assessed using a protocol adapted from Folco *et al.*$^{#3}$ Human monocytic cells (THP-1) were differentiated to macrophages. To induce cell activation, macrophages were incubated in RPMI1640 containing 1% human serum for 18h, followed by the addition of LPS, TNF-$\alpha$, and IFN-$\gamma$ at final concentrations of 10 ng/ml each. Non-activated macrophages served as controls.

Cells were first washed with phosphate-buffered saline. $^3$H-choline was added to the cells (final concentration, 100 $\mu$M for each; specific activity of 0.5 $\mu$Ci per sample for $^3$H-choline), and incubated for 30 min at 37$^\circ$C. After the removal of the incubation buffer, cells were washed twice with ice-cold RPMI 1640 and detached from the culture wells. Cells were counted and further assayed by liquid scintillation counting (Beckman LS 6000IC counter). The net uptake of $^3$H-choline is expressed as counts of choline/cell/min.
Supplemental Figure

Figure I.
Supplemental Figure Legend

**Figure I.** Representative $^{18}$F-FCH PET-CT images and corresponding histology of an ipsilateral symptomatic and contralateral asymptomatic carotid plaque of a 67-year-old patient who experienced left-sided stroke 7 days prior to PET imaging. (A) Diagnostic contrast-enhanced CT shows a significant stenosis in the left internal carotid artery due to a soft plaque, whereas no atherosclerotic plaque can be seen on the contralateral internal carotid artery. Regions of interest (ROIs, white outlining) drawn around the outer border of the vessel walls were placed along the right carotid stenosis and along the contralateral carotid artery, respectively. (B) CT, inset on the symptomatic plaque. (C) No clear “hotspot”, only a light FCH uptake can be visually detected in the ROI drawn onto the left symptomatic carotid plaque. The activity recorded for both symptomatic and contralateral asymptomatic carotid arteries were corrected for venous blood background activity in the jugular veins, resulting in a TBRmax of 1.23 and TBRmax 1.15, respectively. (D) Corresponding immunohistochemistry sections indicating CD68$^+$ (D), MHC-II$^+$ (E), and HAM56$^+$ (F) cells (all in brown).

Supplemental References


#3 Folco EJ, Sheikine Y, Rocha VZ, Christen T, Shvartz E, Sukhova GK, Di Carli MF and Libby P. Hypoxia but not inflammation augments glucose uptake in human