Combined $^{18}$F-FDG PET-CT and DCE-MRI to Assess Inflammation and Microvascularization in Atherosclerotic Plaques

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**Background and Purpose**—Hallmarks of vulnerable atherosclerotic plaques are inflammation that can be assessed with $^{18}$fluorine-fluorodeoxyglucose positron emission tomography/computed tomography, and increased neovascularization that can be evaluated by dynamic contrast–enhanced-MRI. It remains unclear whether these parameters are correlated or represent independent imaging parameters. This study determines whether there is a correlation between inflammation and neovascularization in atherosclerotic carotid plaques.

**Methods**—A total of 58 patients with transient ischemic attack or minor stroke in the carotid territory and ipsilateral carotid artery stenosis of 30% to 69% were included. All patients underwent positron emission tomography/computed tomography and dynamic contrast–enhanced-MRI of the carotid plaque. $^{18}$Fluorine-fluorodeoxyglucose standard uptake values with target/background ratio were determined. Neovascularization was quantified by the mean (leakage) volume transfer constant $K_{\text{trans}}$. Spearman rank correlation coefficients between target/background ratio and $K_{\text{trans}}$ were calculated.

**Results**—Images suitable for further analysis were obtained in 49 patients. A weak but significant positive correlation between target/background ratio and mean $K_{\text{trans}}$ (Spearman $\rho=0.30$ [$P=0.035$]) and 75th percentile $K_{\text{trans}}$ (Spearman $\rho=0.29$ [$P=0.041$]) was found.

**Conclusions**—There is a weak but significant positive correlation between inflammation on positron emission tomography/computed tomography and neovascularization as assessed with dynamic contrast–enhanced-MRI. Future studies should investigate which imaging modality has the highest predictive value for recurrent stroke, as these are not interchangeable.

**Clinical Trial Registration**—URL: http://www.clinicaltrials.gov. Unique identifier: NCT00451529.

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**Key Words:** atherosclerosis ▪ imaging ▪ inflammation ▪ magnetic resonance imaging ▪ neovascularization ▪ plaque, atherosclerotic ▪ positron-emission tomography ▪ vascular diseases
Methods

Patients
Patients with recent (<3 months) amaurosis fugax, transient ischemic attack or minor stroke in the carotid territory and ipsilateral carotid plaque causing a mild to moderate (30%–69%) stenosis at Doppler ultrasonography,10 were eligible for inclusion. Cardiovascular risk factors and the use of medication were assessed by a questionnaire.11 The study was approved by the institutional Medical Ethical Committee. All patients gave written informed consent.

Imaging
PET-CT examination and the multisequence MRI have in detail been described previously.12 Parameters of the DCE-MRI protocol have been published as well.9

Image Analysis
The analysis of the PET-CT images was performed using a dedicated workstation.12 To determine the target/background ratio (TBR), the standard uptake values were normalized to blood 18F-FDG activity by dividing them by the mean standard uptake value of blood as measured in the internal jugular vein (Figure). TBR is considered to be a reflection of arterial FDG uptake and reflective of underlying macrophage activity.13

Plaque morphology was manually assessed using dedicated vessel wall analysis software (VesselMASS; LUMC, The Netherlands).12 The operator was blinded for the PET-CT results. Quantification of neovascularization was done using a custom-made Matlab program (Matlab version 7.5; The Mathworks, Natick, MA), using the Patlak model and a generalized vascular input function.9,14 The mean \( K^{trans} \) per patient was determined. In addition, histogram analysis was performed to determine the 75th percentile \( K^{trans} \), which is more reflective for hot spots with high \( K^{trans} \) values (Figure).

Statistical Analysis
To correlate TBR with \( K^{trans} \), Spearman rank correlation coefficient was calculated using SPSS version 20 (SPSS Inc, Chicago, IL). Relation between clinical characteristics, TBR and \( K^{trans} \), was explored by univariate linear regression analysis. A \( P \) value of <0.05 was considered statistically significant.

Results
In total 58 patients were included. Nine of them had to be excluded, because of poor DCE-MRI quality. Patients underwent PET-CT 36.7±19.4 days and DCE-MRI 33.7±19.6 days after their last neurological symptoms. Mean time interval between both examinations was 2.9±5.5 days.

For the 49 patients analyzed, clinical characteristics and their relation between \( K^{trans} \) and 18F-FDG are displayed in Table 1. The mean TBR was calculated as 1.45±0.26. The morphological parameters of the plaque as determined with MRI are given in Table 2. The mean and 75th percentile \( K^{trans} \) were determined as 0.11±0.03 and 0.15±0.04 min⁻¹, respectively. A positive weak correlation between TBR and \( K^{trans} \) was found

Table 1. Cardiovascular Risk Factors of the 49 Analyzed Patients and the Results of the Univariate Linear Regression Analysis With TBR and Mean \( K^{trans} \)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>No (%)</th>
<th>TBR</th>
<th>95% CI</th>
<th>P Value</th>
<th>Mean ( K^{trans} )</th>
<th>Standardized Coefficient</th>
<th>95% CI</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>29 (59)</td>
<td>0.13</td>
<td>−0.08 to 0.22</td>
<td>0.87</td>
<td>0.12</td>
<td>−0.01 to 0.02</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Age, y, mean±SD</td>
<td>65.3±8.8</td>
<td>−0.02</td>
<td>−0.01 to 0.01</td>
<td>0.91</td>
<td>−0.19</td>
<td>−0.00 to 0.00</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Smoking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>12 (25)</td>
<td>−0.11</td>
<td>−0.24 to 0.11</td>
<td>0.44</td>
<td>0.05</td>
<td>−0.02 to 0.02</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Former</td>
<td>20 (41)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypertension</td>
<td>42 (86)</td>
<td>−0.30</td>
<td>−0.42 to −0.01</td>
<td>0.04</td>
<td>−0.13</td>
<td>−0.03 to 0.01</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>11 (22)</td>
<td>−0.16</td>
<td>−0.27 to 0.08</td>
<td>0.26</td>
<td>−0.10</td>
<td>−0.03 to 0.01</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>History of ischemic heart disease</td>
<td>8 (16)</td>
<td>−0.23</td>
<td>−0.35 to 0.04</td>
<td>0.12</td>
<td>−0.09</td>
<td>−0.03 to 0.02</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Use of statins before event</td>
<td>18 (37)</td>
<td>−0.20</td>
<td>−0.26 to 0.05</td>
<td>0.17</td>
<td>0.02</td>
<td>−0.02 to 0.02</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>Use of statins after event</td>
<td>46 (94)</td>
<td>−0.22</td>
<td>−0.54 to 0.07</td>
<td>0.12</td>
<td>0.10</td>
<td>−0.02 to 0.04</td>
<td>0.49</td>
<td></td>
</tr>
</tbody>
</table>

CI indicates confidence interval; and TBR, target/background ratio.
(mean $K^{trans}$, Spearman $\rho$ of 0.30 [P=0.035]; 75th percentile $K^{trans}$, Spearman $\rho$ of 0.29 [P=0.041]). No significant correlations between TBR and $K^{trans}$ in relation to the morphological parameters were observed.

**Discussion**

The purpose of this study was to investigate the relation between inflammation (PET-CT) and neovascularization (DCE-MRI) in carotid atherosclerotic plaques. We demonstrated that higher FDG uptake is weakly associated with increased microvasculature within the plaque. Cyran et al\textsuperscript{15} also showed positive correlation between the mean TBR and the extraction fraction of DCE-MRI. Both imaging modalities provide information about hallmarks of plaque vulnerability, but it is unknown whether these imaging features are interchangeable or provide additive information. This study proves that, in symptomatic patients with mild to moderate (30%–69%) stenosis, PET-CT and DCE-MRI features of the plaque are related with each other, although the information provided is not interchangeable. This is expressed in the relative low correlation coefficient ($\rho$ of 0.30; $P<0.05$). However, we have not studied the use of these techniques for treatment decision making. Further studies should determine the clinical usage of inflammation and neovascularization for the individual patient’s management.

**Conclusions**

There is a weak but significant positive correlation between inflammation on PET-CT and neovascularization as assessed with DCE-MRI. Future studies should investigate that which imaging modality has the highest predictive value for recurrent stroke, as these are not interchangeable.

**Acknowledgments**

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**Table 2. Correlations Between TBR, mean $K^{trans}$, and Plaque Morphology as Assessed on MRI**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean±SD</th>
<th>TBR</th>
<th>Spearman $\rho$</th>
<th>$P$ Value</th>
<th>$K^{trans}$</th>
<th>Spearman $\rho$</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total lumen volume, mm$^3$</td>
<td>889.21±290.56</td>
<td>0.04</td>
<td>0.70</td>
<td>$-0.03$</td>
<td>0.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total wall volume, mm$^3$</td>
<td>979.84±333.31</td>
<td>0.05</td>
<td>0.73</td>
<td>$-0.20$</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total vessel volume, mm$^3$</td>
<td>1869.05±508.16</td>
<td>0.04</td>
<td>0.78</td>
<td>$-0.09$</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean wall thickness, mm</td>
<td>1.46±0.42</td>
<td>0.04</td>
<td>0.79</td>
<td>$-0.17$</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max wall thickness, mm</td>
<td>3.99±1.43</td>
<td>0.26</td>
<td>0.07</td>
<td>0.05</td>
<td>0.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized wall thickness</td>
<td>0.52±0.09</td>
<td>0.13</td>
<td>0.37</td>
<td>$-0.19$</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TBR indicates target/background ratio.

**Disclosures**

None.

**References**

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