Carotid Plaque MRI and Stroke Risk
A Systematic Review and Meta-analysis

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Background and Purpose—MRI characterization of carotid plaque has been studied recently as a potential tool to predict stroke caused by carotid atherosclerosis. We performed a systematic review and meta-analysis to summarize the association of MRI-determined intraplaque hemorrhage, lipid-rich necrotic core, and thinning/rupture of the fibrous cap with subsequent ischemic events.

Methods—We performed a comprehensive literature search evaluating the association of carotid plaque composition on MRI with ischemic outcomes. We included cohort studies examining intraplaque hemorrhage, lipid-rich necrotic core, or thinning/rupture of the fibrous cap with mean follow-up of ≥1 month and an outcome measure of ipsilateral stroke or transient ischemic attack. A meta-analysis using a random-effects model with assessment of study heterogeneity and publication bias was performed.

Results—Of the 3436 articles screened, 9 studies with a total of 779 subjects met eligibility for systematic review. The hazard ratios for intraplaque hemorrhage, lipid-rich necrotic core, and thinning/rupture of the fibrous cap as predictors of subsequent stroke/transient ischemic attack were 4.59 (95% confidence interval, 2.91–7.24), 3.00 (95% confidence interval, 1.51–5.95), and 5.93 (95% confidence interval, 2.65–13.20), respectively. No statistically significant heterogeneity or publication bias was present in the 3 main meta-analyses performed.

Conclusions—The presence of intraplaque hemorrhage, lipid-rich necrotic core, and thinning/rupture of the fibrous cap on MRI of carotid plaque is associated with increased risk of future stroke or transient ischemic attack in patients with carotid atherosclerotic disease. Dedicated MRI of plaque composition offers stroke risk information beyond measurement of luminal stenosis in carotid atherosclerotic disease. (Stroke. 2013;44:3071-3077.)

Key Words: carotid arteries ■ carotid artery plaque ■ ischemic attack, transient ■ MRI ■ risk ■ stroke

Carotid stenosis severity is widely used as an imaging marker for stroke risk, with the degree of stenosis used as a key inclusion criterion in several multicenter, large randomized trials of surgery versus medical treatment of carotid atherosclerotic disease.1,2 However, recent evidence suggests that specific elements of plaque composition are stroke risk factors independent of stenosis severity.3 Moreover, recent studies have demonstrated that MRI techniques can characterize these specific components of carotid plaque accurately in vivo compared with histopathology.4,5

Given the reduction in stroke risk with advances in medical therapy during the past 2 decades, there has been increasing interest in investigating markers of plaque vulnerability to aid in selecting high-risk patients.6 However, MRI of plaque composition is a relatively new technique and individual studies have generally been small, thereby making it challenging to draw definite conclusions of the value of MRI carotid plaque characterization. Furthermore, it is unclear whether there are differences in the risk profiles of specific plaque components such as intraplaque hemorrhage (IPH), lipid-rich necrotic core (LRNC), or thinning/rupture of the fibrous cap (TRFC). In addition, it is unknown whether certain techniques for plaque characterization, such as those involving high-resolution protocols with dedicated carotid surface coils, are superior to techniques that can be performed with widely available, standard MRI neck coils. For these reasons, we performed a systematic review and meta-analysis to evaluate whether MRI of plaque composition offers stroke risk information beyond measurement of luminal stenosis in carotid atherosclerotic disease.

Methods
The methodology for this study was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement.7

Received June 19, 2013; accepted July 16, 2013.

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The online-only Data Supplement is available with this article at http://stroke.ahajournals.org/lookup/suppl/doi:10.1161/STROKEAHA.113.002551/-/DC1.

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Stroke is available at http://stroke.ahajournals.org DOI: 10.1161/STROKEAHA.113.002551

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Study Eligibility Criteria

Studies with MRI-based characterization of carotid artery plaque composition and its association with ipsilateral stroke or transient ischemic attack (TIA) were eligible. Specific inclusion criteria were: (1) English language articles; (2) studies with ≥10 subjects; (3) MRI of carotid vessel plaque composition; (4) mean follow-up >1 month after plaque imaging; (5) assessment for development of ipsilateral stroke or TIA; and (6) nonsurgical management of patients. Given the emphasis on certain plaque characteristics in the American Heart Association (AHA) classification system,3,4 we included 3 specific plaque elements in this study: (1) IPH; (2) LRNC; and (3) TRFC. Because this was not a study of the diagnostic accuracy of MRI but rather an initial evaluation to determine if MRI characterization of plaques is associated with outcomes, studies did not require histopathologic correlation of MRI findings. In cases where testing characteristics or outcome data were not clear from the article, we attempted to contact the corresponding author for additional details.

Information Search and Data Collection

A systematic search was performed on March 13, 2013, by a medical librarian searching Ovid MEDLINE, Ovid Embase, the Cochrane Library, and AHRQ website, using additional databases for related articles searching. References were screened and data extracted by a team of 3 independent readers using a predetermined data collection template. Details of search methodology, study selection, and data collection are provided in the Methods in the online-only Data Supplement.

Assessment of Risk of Bias in Studies

We adapted bias assessment criteria used in a previously published meta-analysis8 of imaging findings and stroke risk: (1) risk of outcome ascertainment bias was assessed by recording whether researchers were blinded to MRI results when stroke outcomes were assessed; (2) risk of confounding bias was assessed by recording whether potentially confounding stroke risk factors were collected and statistically analyzed; (3) completeness of follow-up data was assessed by noting the number of subjects lost to follow-up.

Statistical Analyses

All studies reporting a hazard ratio (HR) or presenting data amenable to HR calculation were included for meta-analysis. Because of the significant variation in study sizes, length of follow-up, and patient characteristics, the more conservative random-effects model was used. Heterogeneity was measured using the I² statistic. Publication bias was examined with the Begg–Mazumdar test. We performed subgroup analyses within each imaging group stratified by symptomatic versus asymptomatic disease. In the IPH subgroup, an additional subset analysis was performed stratifying studies by whether high-resolution imaging was performed with a dedicated surface carotid coil. All analyses were conducted using Stata version 12 software.

Results

Study Selection

A total of 3436 abstracts were initially screened, of which 17 potentially eligible articles were selected for further review (Figure 1). Of these 17 articles, 4 did not meet inclusion criteria when read in their entirety as they did not include patients followed up for development of stroke or TIA after specified MRI plaque testing, whereas 4 studies were excluded as they included subsets of cohorts published in larger studies ultimately selected for the systematic review. The remaining 9 studies9–17 met eligibility for the systematic review.
Qualitative Assessment and Study Characteristics
Of the 9 articles meeting eligibility for qualitative review (Table 1), all were cohort studies. Two studies were retrospective; the remaining 7 were prospective (Table 1). Three studies were conducted in Japan, 1 in the United Kingdom, and 1 each in Canada, Switzerland, and the United States. All studies had similar subject ages (mean, 69–78 years) and a similarly higher preponderance of male subjects (range, 62.7%–100%). There were considerable differences between the studies in the degree of stenosis included; 1 study focused exclusively on high-grade (≥70%) stenosis; 5 studies included moderate to high-grade (≥50%) stenosis; 3 studies included low to moderate stenosis (0%–69%). There was similar heterogeneity in patient symptoms, with 3 studies focused exclusively on patients with ≥50% stenosis. Though most current guidelines recommend carotid intervention in such patients, in one cohort the medically managed patients were either poor surgical candidates or refused surgery. The other cohort was studied in the United Kingdom at a time before which symptomatic patients with ≥50% stenosis were offered carotid endarterectomy as routine standard of care.

All studies except one12 were performed on 1.5-T MRI. For determination of LRNC or TRFC, high-resolution, multicontrast weighted dedicated carotid imaging was performed using carotid surface coils in all cases. In the IPH studies, 4 were performed using high-resolution dedicated carotid coils and 4 were performed with standard head/neck coils used for routine magnetic resonance angiography studies. MRI techniques, test results, and outcomes are summarized in Table 2. Outcomes were differentiated as ipsilateral stroke versus ipsilateral TIA in only 4 studies, whereas the remaining 5 studies used a composite outcome of ipsilateral stroke plus TIA. Detailed description of MRI testing methods as well as definitions of abnormal test results and outcome measures are provided in Table I in the online-only Data Supplement.

Assessment of Study Methods
In only 4 of 9 studies did the authors describe blinding of MRI results to researchers who assessed ischemic outcomes, whereas blinding was not reported in the remaining 5 articles. Eight of 9 studies collected and presented potentially confounding vascular risk factors, with only 1 study not.

Table 1. Overview of Patient Characteristics in Studies Evaluating the Risk of Stroke in Patients With Carotid Plaque MRI

<table>
<thead>
<tr>
<th>Study No.</th>
<th>Study First Author and Year</th>
<th>Study Design</th>
<th>No. of Medically Managed Subjects</th>
<th>No. of Carotid Arteries With Follow-up Outcome Data</th>
<th>Disease Severity (All to Proximal ICA)</th>
<th>Symptomatic (Prior TIA or Stroke)</th>
<th>Mean Follow-up, mo</th>
<th>Mean Interval Since Last Symptomatic Imaging a Surrogate for Which Plaque Element(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Takaya et al, 200610</td>
<td>Prospective cohort</td>
<td>154</td>
<td>71.1, 82</td>
<td>50%–79% Asymptomatic</td>
<td>38.2</td>
<td>No symptoms for ≤6 mo</td>
<td>IPH, LRNC, thin/ruptured FC</td>
</tr>
<tr>
<td>2</td>
<td>Yamada et al, 200710</td>
<td>Retrospective cohort</td>
<td>35</td>
<td>70, 83.2</td>
<td>45% (mean) Mixed population, no breakdown provided</td>
<td>12.0</td>
<td>Not provided</td>
<td>IPH</td>
</tr>
<tr>
<td>3</td>
<td>Singh et al, 200914</td>
<td>Prospective cohort</td>
<td>75</td>
<td>74.8, 100</td>
<td>50%–70% Asymptomatic</td>
<td>24.9</td>
<td>No symptoms for ≤6 mo</td>
<td>IPH</td>
</tr>
<tr>
<td>4</td>
<td>Sadat et al, 201010</td>
<td>Prospective cohort</td>
<td>61</td>
<td>74, N/A</td>
<td>50% (median) Symptomatic</td>
<td>16.9</td>
<td>&lt;30 d</td>
<td>LRNC, thin/ruptured FC</td>
</tr>
<tr>
<td>5</td>
<td>Kurosaki et al, 201110</td>
<td>Retrospective cohort</td>
<td>96 (full testing data only on 62 subjects)</td>
<td>77.8, 80.6</td>
<td>≥70% Symptomatic</td>
<td>9.0</td>
<td>Not provided</td>
<td>IPH</td>
</tr>
<tr>
<td>6</td>
<td>Yoshida et al, 201210</td>
<td>Retrospective cohort</td>
<td>25</td>
<td>74.2, 92</td>
<td>&lt;50% Symptomatic</td>
<td>31.3</td>
<td>Not provided</td>
<td>IPH</td>
</tr>
<tr>
<td>7</td>
<td>Mono et al, 201210</td>
<td>Prospective cohort</td>
<td>62</td>
<td>68.7, 74</td>
<td>≥50% Asymptomatic</td>
<td>18.9</td>
<td>≤6 mo (32% had stroke prior to 6 mo before imaging)</td>
<td>IPH, LRNC, thin/ruptured FC</td>
</tr>
<tr>
<td>8</td>
<td>Kwee et al, 201311</td>
<td>Prospective cohort</td>
<td>126</td>
<td>69, 62.7</td>
<td>30%–69% Symptomatic</td>
<td>12.0</td>
<td>31.5 d</td>
<td>IPH, LRNC, thin/ruptured FC</td>
</tr>
<tr>
<td>9</td>
<td>Hosseini et al, 201312</td>
<td>Prospective cohort</td>
<td>179</td>
<td>71.7, 70.9</td>
<td>≥50% Symptomatic</td>
<td>17.5</td>
<td>39.6 d</td>
<td>IPH</td>
</tr>
</tbody>
</table>

ICA indicates internal carotid artery; IPH, intraplaque hemorrhage; LRNC, lipid-rich necrotic core; N/A, data not available; TIA, transient ischemic attack; and TRFC, thinned/ruptured fibrous cap.
presenting these data. Finally, in the assessment of the completeness of follow-up, in 1 study12 2 subjects moved from the country and were lost to follow-up. No other follow-up losses were described in the remaining 8 studies.

Meta-analysis Results

Seven of 9 studies meeting inclusion for systematic review were eligible for meta-analysis. One study was not amenable for meta-analysis17 as only IPH-positive subjects were followed to outcome, whereas another study16 did not report the association between imaging findings and event rates in the form of a HR and thereby did not provide data needed for the meta-analysis. The remaining 7 studies had data that could be included in meta-analysis, including 7 studies evaluating IPH,9–15 4 studies evaluating LRNC,11–13,15 and 4 studies evaluating TRFC.11–13,15

In the IPH-characterized group, a total of 678 patients and 702 unique carotid arteries were meta-analyzed with a mean follow-up of 20.2 months. In the LRNC-characterized group, 403 patients and 406 carotid arteries with a mean follow-up of 23.8 months were meta-analyzed. Finally, in the TRFC-characterized group, a total of 363 carotid arteries and patients with a mean follow-up of 22.1 months were meta-analyzed. No significant heterogeneity or publication bias was noted in the 3 primary analyses (Table 3). We found a significant positive relationship between IPH, LRNC, and TRFC and the risk of future ischemic events (stroke plus TIA), with a random-effects HR of 4.59 (95% confidence interval [CI], 2.92–7.24), 3.00 (95% CI, 1.51–5.95), and 5.93 (95% CI, 2.65–13.29), respectively, for each specific plaque element (Figure 2).

Subset Analyses

No significant heterogeneity was found in any of the subset analyses with the exception of borderline heterogeneity (I²=68%) present in subset analysis of the 3 IPH studies using standard neck coils. A statistically significant random-effects HR was preserved in subset analyses including symptomatic versus asymptomatic subjects in studies of IPH and LRNC.

Table 2. Overview of MRI Plaque Testing Characteristics and Risk of Ipsilateral Cerebrovascular Events

<table>
<thead>
<tr>
<th>Study No.</th>
<th>Study First Author and Year</th>
<th>Plaque Element</th>
<th>No. of Arteries With Negative MRI</th>
<th>No. of Arteries With Positive MRI</th>
<th>Ipsilateral Ischemic Strokes in Negative Test Group</th>
<th>Ipsilateral Ischemic Strokes in Positive Test Group</th>
<th>All-Event (TIA/Stroke) HR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a Takaya et al, 200615</td>
<td>IPH</td>
<td>68</td>
<td>43</td>
<td>N/A</td>
<td>N/A</td>
<td>3</td>
<td>8</td>
<td>5.2</td>
</tr>
<tr>
<td>1b</td>
<td>TRFC</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>1c Kurosaki et al, 201110</td>
<td>LRNC</td>
<td>43</td>
<td>111</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
<td>11</td>
<td>4.4</td>
</tr>
<tr>
<td>2 Yamada et al, 200716</td>
<td>IPH</td>
<td>28</td>
<td>22</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>3 Singh et al, 200914</td>
<td>IPH</td>
<td>62</td>
<td>36</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>6</td>
<td>3.59</td>
</tr>
<tr>
<td>4a Sadat et al, 201013</td>
<td>TRFC</td>
<td>34</td>
<td>27</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>7.39</td>
</tr>
<tr>
<td>4b</td>
<td>LRNC</td>
<td>42</td>
<td>19</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.75</td>
</tr>
<tr>
<td>4c Kurosaki et al, 201110</td>
<td>IPH</td>
<td>30</td>
<td>31</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>5.85</td>
</tr>
<tr>
<td>5 Yoshida et al, 201217</td>
<td>IPH</td>
<td>0</td>
<td>25</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>11</td>
</tr>
<tr>
<td>7a Mono et al, 201215</td>
<td>LRNC</td>
<td>49</td>
<td>16</td>
<td>N/A</td>
<td>N/A</td>
<td>2</td>
<td>3</td>
<td>7.2</td>
</tr>
<tr>
<td>7b</td>
<td>TRFC</td>
<td>23</td>
<td>42</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
<td>4</td>
<td>1.103</td>
</tr>
<tr>
<td>7c</td>
<td>IPH</td>
<td>49</td>
<td>16</td>
<td>N/A</td>
<td>N/A</td>
<td>5</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>8a Kwee et al, 201313</td>
<td>LRNC</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>3</td>
<td>10</td>
<td>3.2</td>
</tr>
<tr>
<td>8b</td>
<td>TRFC</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2</td>
<td>11</td>
<td>5.8</td>
</tr>
<tr>
<td>8c</td>
<td>IPH</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>6</td>
<td>7</td>
<td>3.5</td>
</tr>
<tr>
<td>9 Hosseini et al, 20139</td>
<td>IPH</td>
<td>65</td>
<td>114</td>
<td>1</td>
<td>25</td>
<td>5</td>
<td>57</td>
<td>12</td>
</tr>
</tbody>
</table>

CI indicates confidence interval; HR, hazard ratio; IPH, intraplaque hemorrhage; LRNC, lipid-rich necrotic core; N/A, data not available; TIA, transient ischemic attack; and TRFC, thinned/ruptured fibrous cap.
and in studies of symptomatic subjects with TRFC. The single subset analysis not achieving statistical significance was the analysis of TRFC in asymptomatic subjects ($P = 0.268$; Table 4). Furthermore, in the IPH studies, no significant difference in HR was found when studies were stratified by whether multisequence technique with a dedicated carotid coil was used.

**Discussion**

Measurement of stenosis severity has been the primary imaging-based measure of stroke risk in carotid atherosclerotic disease and plays a critical role in existing treatment guidelines. However, histopathologic studies have demonstrated that certain plaque elements, independent of arterial narrowing, are more likely to cause symptoms and thereby are hallmarks of unstable plaque. Recent developments in MRI technology have allowed accurate discrimination between the specific histological subtypes of carotid plaque as proposed by the AHA. However, studies using MRI of plaque to predict patient outcome are relatively new, with the first such study to our knowledge published in 2006.

In our study, we found carotid plaques with IPH, LRNC, or TRFC are significantly more likely to result in ipsilateral ischemic events, with HR ranging from $\approx 3$ for LRNC to $\approx 6$ for TRFC, with this increased risk present across a wide range of stenosis severity. This is the first comprehensive meta-analysis of MRI plaque characteristics and stroke prediction, though 1 recent study did present a limited meta-analysis of IPH alongside an original patient cohort, finding a pooled odds ratio of $10.02 (95\% CI, 5.46–18.38)$ associating IPH and future stroke/TIA. In our study, we were able to calculate a HR of 4.59 with narrower CIs ($95\% CI, 2.92–7.23$) associating IPH and future stroke/TIA, with the difference between meta-analyses partly attributable to the risk metric used in our study, the HR, a potentially more useful measure of risk taking into account time to events. Further important differences in our meta-analysis of IPH data include analyzing recent studies with 188 additional patients and the inclusion of larger and longer followed cohorts published more than once in the literature. One such recent study, Mono et al, seems to contribute to the decreased effect size of IPH as a predictor of stroke compared with the previous meta-analysis. In this study, the only 1 performed on a 3-T MRI, there were 5 ischemic events in 65 patients, none of which occurred in the group with IPH present.

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**Table 4.** Study Name, HR, Lower Limit, Upper Limit, and $P$-Value for Hazard Ratio and 95% CI

<table>
<thead>
<tr>
<th>Study Name</th>
<th>HR</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>$P$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takaya 2006</td>
<td>5.20</td>
<td>1.581</td>
<td>17.153</td>
<td>0.007</td>
</tr>
<tr>
<td>Singh 2009</td>
<td>3.59</td>
<td>2.561</td>
<td>5.05</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sadat 2010</td>
<td>5.85</td>
<td>1.286</td>
<td>26.794</td>
<td>0.022</td>
</tr>
<tr>
<td>Kurosaki 2011</td>
<td>2.83</td>
<td>0.644</td>
<td>12.425</td>
<td>0.168</td>
</tr>
<tr>
<td>Kwee 2013</td>
<td>3.50</td>
<td>1.043</td>
<td>11.684</td>
<td>0.043</td>
</tr>
<tr>
<td>Hosseini 2013</td>
<td>12.00</td>
<td>4.762</td>
<td>29.943</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Mono 2013</td>
<td>0.03</td>
<td>0.000</td>
<td>86.6</td>
<td>0.999</td>
</tr>
<tr>
<td>Random</td>
<td>4.59</td>
<td>2.92</td>
<td>7.24</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

**Figure 2.** Individual forest plots of the association between MRI-determined intraplaque hemorrhage (IPH), lipid-rich necrotic core (LRNC), and thinning/rupture of the fibrous cap (TRFC), and ipsilateral cerebrovascular events determined by a random-effects model for all studies. Squares represent point estimates for effect size expressed as a hazard ratio (HR) with the size proportional to the inverse variance of the estimate. Diamond represents pooled estimate. Lines represent 95% confidence intervals (CIs).
and FC rupture, ultimately precipitating embolism. Though can develop. This in turn can further progress to surface defects development of more advanced plaque in which hemorrhage cascade of events, lipid-rich atheroma typically precedes the plaque progression in the AHA classification scheme. In this via future research, is consistent with the general sequence of intermediate HR (4.59). This rank ordering of risk, if verified showed the highest HR (5.93), with IPH demonstrating ancant difference in HR between the 3 plaque elements, though this particular subset analysis did not achieve statistical sig-
nificance. Additional studies may provide the statistical power needed to arrive at more definitive conclusions of the role of

Furthermore, our study demonstrated no statistically signifi-
cance in the studies included in this meta-analysis. Third, there is significant variation in reporting outcomes, with most studies
publication bias test only performed if minimum of 3 studies available. CI indicates confidence interval; HR, hazard ratio; IPH, intraplaque hemorrhage; LRNC, lipid-rich necrotic core; and TRFC, thinned/ruptured fibrous cap.

A statistically significant HR for all plaque elements was achieved when analysis was limited to studies of symptomatic
patients, as well as with subset analyses of IPH and LRNC in asymptomatic patients. Perhaps related to a small sample size of the 2 studies of asymptomatic patients with TRFC,12,15 this particular subset analysis did not achieve statistical signi-
ificance. Additional studies may provide the statistical power needed to arrive at more definitive conclusions of the role of TRFC in predicting ischemic events in this subgroup.

Furthermore, our study demonstrated no statistically significant difference in HR between the 3 plaque elements, though the presence of LRNC showed the lowest HR (3.00) and TRFC showed the highest HR (5.93), with IPH demonstrating an intermediate HR (4.59). This rank ordering of risk, if verified via future research, is consistent with the general sequence of plaque progression in the AHA classification scheme. In this cascade of events, lipid-rich atheroma typically precedes the development of more advanced plaque in which hemorrhage can develop. This in turn can further progress to surface defects and FC rupture, ultimately precipitating embolism.3 Though 4 of the 7 studies11–13,15 in this meta-analysis examined >1 plaque element per patient, a multiparametric testing approach addressing the significance of each plaque element as a component of a composite plaque risk profile was not performed in any study. Furthermore, given the potential dynamic nature of plaque pro-
gression over time, the possibility that plaque elements may have changed between the time of testing and stroke/TIA outcome assessment was not evaluated by any study.

Our study also highlights potential barriers to the imple-
mentation of MRI carotid plaque imaging as a routine risk stratification tool. For example, to determine the presence of LRNC and TRFC accurately, investigators used MRI protocols with multiple sequences, which generally take >30 minutes to complete and require a specialized carotid artery surface MRI coil not typically used in most clinical settings. However, in 3 studies, IPH was measured using standard, large field-of-view neck coils with a gradient echo–based protocol that takes <5 minutes.9,10,14 Prediction of future events using these gradient echo–based techniques was not significantly different from prediction using multisequence technique with a carotid coil (HR of 5.04 versus 4.41; P=0.41), though the small number of studies in this subset analysis resulted in borderline statistically significant heterogeneity suggesting that further work is needed to confirm that these techniques do in fact perform similarly. Furthermore, additional work is needed to assess the clinical utility of this tool, given that the ability to distinguish between acute intraluminal thrombus and IPH accurately is a known limi-
tation of gradient echo–based techniques of IPH classification.9

Our study illustrates important limitations of the current literature on MRI plaque characterization. First, there is significant variation in reporting outcomes, with most studies using a composite measure of stroke/TIA, thereby preventing the accurate calculation of separate HR for stroke versus TIA. Second, because detailed raw data on test results were not provided in the majority of studies, the pooled prevalence of each specific plaque element cannot be accurately calculated in the studies included in this meta-analysis. Third, there is significant variability in MRI techniques for plaque imaging, raising questions about which technique is best for risk strati-
fication, including whether quantitative volumetric analyses

### Table 4. Subgroup Analyses of Specific Plaque Element Studies

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>No. of Studies</th>
<th>HR (95% CI)</th>
<th>HR P Value</th>
<th>Heterogeneity Test of (I)</th>
<th>Publication Bias Test Statistic (I)</th>
<th>Test Between Groups P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPH studies with asymptomatic subjects</td>
<td>3</td>
<td>3.66 (2.70–4.95)</td>
<td>&lt;0.01</td>
<td>0%</td>
<td>−1</td>
<td>0.602</td>
</tr>
<tr>
<td>IPH studies with symptomatic subjects</td>
<td>4</td>
<td>5.860 (2.898–11.849)</td>
<td>&lt;0.01</td>
<td>23.20%</td>
<td>−0.33</td>
<td>0.4969</td>
</tr>
<tr>
<td>IPH studies using multisequence, carotid coil–dependent technique</td>
<td>4</td>
<td>4.40 (2.10–9.23)</td>
<td>&lt;0.01</td>
<td>0%</td>
<td>−2</td>
<td>−0.68</td>
</tr>
<tr>
<td>IPH studies using single sequence, standard neck coils</td>
<td>3</td>
<td>5.044 (2.147–11.851)</td>
<td>&lt;0.01</td>
<td>68%</td>
<td>0.33</td>
<td>0.522</td>
</tr>
<tr>
<td>LRNC studies with asymptomatic subjects</td>
<td>2</td>
<td>5.739 (1.463–22.511)</td>
<td>0.012</td>
<td>0%</td>
<td>1.08</td>
<td>0.859</td>
</tr>
<tr>
<td>LRNC studies with symptomatic subjects</td>
<td>2</td>
<td>2.410 (1.092–5.319)</td>
<td>0.028</td>
<td>0%</td>
<td>0.23</td>
<td>0.410</td>
</tr>
<tr>
<td>TRFC studies with asymptomatic subjects</td>
<td>2</td>
<td>4.54 (0.31–65.89)</td>
<td>0.268</td>
<td>3%</td>
<td>0.23</td>
<td>0.410</td>
</tr>
<tr>
<td>TRFC studies with symptomatic subjects</td>
<td>2</td>
<td>6.304 (2.581–15.395)</td>
<td>&lt;0.01</td>
<td>0%</td>
<td>0.23</td>
<td>0.410</td>
</tr>
</tbody>
</table>

Results are provided for each plaque element, stratified by study characteristics.
are needed and the differences between plaque characterization on 1.5-T versus 3-T machines. Fourth, as many studies included patients with wide ranges of stenosis, more precise composite risk estimates taking into account both stenosis and plaque characteristics will require studies with less variability in the degree of stenosis included. Fifth, as only 2 subjects in total in the meta-analysis were described as being lost to follow-up, it is unclear what systematic efforts to assure follow-up were undertaken and to what extent losses to follow-up not explicitly described may have introduced bias in the ascertainment of study outcomes. Sixth, the lack of blinding in many studies also raises concerns about ascertainment bias, particularly when evaluating subjective end points of TIA. Finally, depending on local surgical practices, those patients who undergo surgical revascularization may have plaque or vascular risk factor profiles that differ from the medically managed patients eligible for this meta-analysis, thereby potentially introducing selection bias into the nonrandomized cohort studies comprising this meta-analysis.

Despite these limits, there is sufficient evidence from our systematic review and meta-analysis to conclude that MRI characterization of the specific plaque elements of IPH, LRNC, and TRFC can provide additional measures of stroke risk not provided by simple measurement of luminal stenosis. The use of carotid plaque MRI to select high-risk groups that may benefit from surgical revascularization requires continued investigation, particularly in asymptomatic carotid stenosis, with validation that may ultimately require an ancillary cohort study of the medical management arm of 1 of the modern randomized controlled trials of medical versus surgical therapy for stroke prevention.

Sources of Funding

Dr Gupta’s effort has been supported by an Association of University Radiologists-General Electric Radiology Research Award Fellowship.

Disclosures

None.

References

Carotid Plaque MRI and Stroke Risk: A Systematic Review and Meta-analysis
Ajay Gupta, Hediyeh Baradaran, Andrew D. Schweitzer, Hooman Kamel, Ankur Pandya, Diana Delgado, Allison Dunning, Alvin I. Mushlin and Pina C. Sanelli

Stroke. 2013;44:3071-3077; originally published online August 29, 2013; doi: 10.1161/STROKEAHA.113.002551
Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0039-2499. Online ISSN: 1524-4628

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SUPPLEMENTAL MATERIAL

Carotid Artery Plaque Characterization on MRI and Stroke Risk: A Systematic Review and Meta-Analysis
Information Sources and Search:

Potentially relevant articles were found by searching the biomedical electronic databases Ovid MEDLINE(R) In-Process & Other Non-Indexed Citations and Ovid MEDLINE(R)1946 to Present, Ovid Embase and the Cochrane Library. Relevant subject headings and free text terms were used. Published, unpublished and ongoing studies were identified by searching The Cochrane Central Register of Controlled Trials and the Agency for Healthcare Research and Quality's website. Additional records were identified by employing the Related Citations feature in PubMed and the Cited Reference Search in Web of Science®. The primary search was conducted in Ovid MEDLINE. Subject headings and key words were adapted for the other databases. In both MEDLINE and Embase, a validated search filter, developed by the Health Information Research Unit at McMaster University, to sensitively detect clinically sound prognostic studies, was applied.

Ovid MEDLINE(R) In-Process & Other Non-Indexed Citations and Ovid MEDLINE(R)1946 to Present. Searched 03/13/13.
1. exp Carotid Stenosis/ 11027
2. Plaque, Atherosclerotic/ 1583
3. (carotid adj3 (athero$ or stenos$ or ulcer$ or plaque$ or narrow$ or obstruct$ or occlus$ or constrict$ or bruit$)).tw. 18774
4. (steno$ occlus$ or stenoocclus$).tw. 667
5. Plaque$.tw. 85630
6. or/1-5 104895
7. exp Magnetic Resonance Imaging/ 281263
8. magnetic resonance.tw. 190679
9. (vessel adj3 imag$).tw. 828
10. (MR or MRI or MRIs or MRA or MRDTI).tw. 210725
11. or/7-10 422480
12. exp Stroke/ 75252
13. Stroke$.tw. 133710
14. cerebrovascular.tw. 34776
15. ((brain or vascular or lacunar or venous or cerebral or isch?emic) adj2 (accident$ or infarct$ or event$ or attack$)).tw. 43254
16. (cva or cvas).tw. 1771
17. or/12-16 204222
18. 6 and 11 and 17 1704
19. limit 18 to "prognosis (maximizes sensitivity)" 520
20. (animals not (humans and animals)).sh. 3960085
21. 19 not 20 512

1. exp carotid artery obstruction/ 24029
2. atherosclerotic plaque/ 19450
3. (carotid adj3 (athero$ or stenos$ or ulcer$ or plaque$ or narrow$ or obstruct$ or occlus$ or constrict$ or bruit$)).tw. 25881
4. (steno$ occlus$ or stenoocclus$).tw. 1018
5. Plaque$.tw. 108345
6. or/1-5 142819
7. exp nuclear magnetic resonance imaging/ 472524
8. magnetic resonance.tw. 227936
9. ((vessel or plaque) adj3 imag$).tw. 2039
10. (MR or MRI or MRIs or MRA or MRDTI).tw. 271924
11. or/7-10 586858
12. exp cerebrovascular accident/ 51716
13. Stroke$.tw. 188909
14. cerebrovascular.tw. 47063
15. ((brain or vascular or lacunar or venous or cerebral or isch?emic) adj2 (accident$ or infarct$ or event$ or attack$)).tw. 59686
16. (cva or cvas).tw. 3053
17. or/12-16 274329
18. 6 and 11 and 17 3150
19. ((animal or nonhuman) not (human and (animal or nonhuman))).de. 4587047
20. 18 not 19 3084
21. limit 20 to "prognosis (maximizes sensitivity)" 2410

Cochrane Library via Wiley. Searched 03/13/13.
#1 MeSH descriptor: [Carotid Stenosis] explode all trees 525
#2 MeSH descriptor: [Plaque, Atherosclerotic] this term only 16
#3 (carotid near/3 (athero* or stenos* or ulcer* or plaque* or narrow* or obstruct* or occlus* or constrict* or bruit*)) 1330
#4 (steno* occlus* or stenoocclus*) 840
#5 Plaque* 6666
#6 (#1 or #2 or #3 or #4 or #5) 8357
#7 MeSH descriptor: [Magnetic Resonance Imaging] explode all trees 4549
#8 magnetic resonance 7074
#9 ((vessel or plaque) near/3 imag*) 138
#10 (MR or MRI or MRIs or MRA or MRDTI) 13410
#11 (#7 or #8 or #9 or #10) 16910
#12 MeSH descriptor: [Stroke] explode all trees 4179
#13 stroke* 27172
#14 cerebrovascular 6385
#15 ((brain or vascular or lacunar or venous or cerebral or isch*emic) near/2 (accident* or infarct* or event* or attack*)) 5070
#16 (cva or cvas) 335
#17 (#12 or #13 or #14 or #15 or #16) 31403
#18 (#6 and #11 and #17) from 2000 to 2013 165
Study Selection and Data Collection Process:

The title and abstract of all references were reviewed by a single reader who excluded studies that did not meet the inclusion criteria. After preliminary articles were identified, manuscripts were reviewed in their entirety by two independent readers to determine final inclusion, with disagreements resolved by a third reader as a tie-breaker. Study data was extracted by two independent readers using a predetermined data collection template. All disagreements were resolved by an independent third reader as a tie-breaker.
SUPPLEMENTAL TABLE
<table>
<thead>
<tr>
<th>Study Number</th>
<th>Study/First Author and Year</th>
<th>Plaque Element</th>
<th>Magnetic Field Strength</th>
<th>MRI Technique (for Plaque Element Under Study)</th>
<th>MRI Coil Type</th>
<th>Definition of Abnormal MRI Test Result</th>
<th>Any Quantitative Plaque Element Assessment</th>
<th>Stroke or TIA Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Takaya 2005</td>
<td>ENH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (TOF, T1W, PD, T2W, T2FST)</td>
<td>Dedicated carotid phased-array surface coil</td>
<td>Hypointense T1W and T2F A iso in core on T2. Recent ENH is hypointense on all sequences.</td>
<td>Volumetric analysis with assessment of mean areas for plaque components and wall areas.</td>
<td>Stroke: Clinical diagnosis after evaluation by vascular surgeon &amp; neurologist and confirmed to be of ischemic origin by neuroimaging. TIA: New-onset focal neurological abnormality lasting &lt;24 hours.</td>
</tr>
<tr>
<td>1b</td>
<td>靳瑞平等部 2006</td>
<td>IPH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (TOF, T1W, PD, T2W, T2FST)</td>
<td>Dedicated carotid phased-array surface coil</td>
<td>Thin or absent dark band between lumen and plaque core</td>
<td>Volumetric analysis with assessment of mean areas for plaque components and wall areas.</td>
<td>Stroke: Clinical diagnosis after evaluation by vascular surgeon &amp; neurologist and confirmed to be of ischemic origin by neuroimaging. TIA: New-onset focal neurological abnormality lasting &lt;24 hours.</td>
</tr>
<tr>
<td>1c</td>
<td>LRNC</td>
<td>ENH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (TOF, T1W, PD, T2W, T2FST)</td>
<td>Dedicated carotid phased-array surface coil</td>
<td>Iso-to-hypointense on T1W and PD</td>
<td>Volumetric analysis with assessment of mean areas for plaque components and wall areas.</td>
<td>Stroke: Clinical diagnosis after evaluation by vascular surgeon &amp; neurologist and confirmed to be of ischemic origin by neuroimaging. TIA: New-onset focal neurological abnormality lasting &lt;24 hours.</td>
</tr>
<tr>
<td>2</td>
<td>Yamada 2006</td>
<td>ENH</td>
<td>1.5T</td>
<td>3D IR T1WI MIPAGE; also 3D TOF pre- and post- gadolinium</td>
<td>Standard neck array and spine array coils</td>
<td>Carotid plaque with intensity on MIPAGE of 200% that of adjacent muscle with ROI placement</td>
<td>Plaque volume was calculated in patients with high signal intensity.</td>
<td>Clinical diagnosis for stroke/TIA</td>
</tr>
<tr>
<td>3</td>
<td>Singh 2007</td>
<td>ENH</td>
<td>1.5T</td>
<td>3D T1 FS SPGR</td>
<td>8-channel neurovascular phased-array coil</td>
<td>$S_i &gt; 50%$ adjacent muscle</td>
<td>No volumetric analysis.</td>
<td>Clinical diagnosis for stroke/TIA: determined by follow-up in clinic and by phone and by medical records evaluation</td>
</tr>
<tr>
<td>4a</td>
<td>Sidd 2010</td>
<td>ENH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (T1W, PD, T2W, T2FST, STIR)</td>
<td>Dedicated 4-channel carotid phased-array surface coil</td>
<td>FC discontinuity or catty formation in plaque (absence of low T1 signal and high STIR signal band)</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Clinical diagnosis after evaluation by vascular surgeon &amp; neurologist and confirmed to be of ischemic origin by neuroimaging. TIA: New-onset focal neurological abnormality lasting &lt;24 hours.</td>
</tr>
<tr>
<td>4b</td>
<td>LRNC</td>
<td>ENH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (T1W, PD, T2W, T2FST, STIR)</td>
<td>Dedicated 4-channel carotid phased-array surface coil</td>
<td>High signal on T1 relative to muscle, iso-to-hypointense on T2, STR. Large lipid content if &gt;25% of total volume</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Clinical diagnosis after evaluation by vascular surgeon &amp; neurologist and confirmed to be of ischemic origin by neuroimaging. TIA: New-onset focal neurological abnormality lasting &lt;24 hours.</td>
</tr>
<tr>
<td>4c</td>
<td>LRNC</td>
<td>ENH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (T1W, PD, T2W, T2FST, STIR)</td>
<td>Dedicated 4-channel carotid phased-array surface coil</td>
<td>T1 hypointense relative to muscle. Recent if high signal on all sequences; Fresh if iso-to-hypointense on T2</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Clinical diagnosis after evaluation by vascular surgeon &amp; neurologist and confirmed to be of ischemic origin by neuroimaging. TIA: New-onset focal neurological abnormality lasting &lt;24 hours.</td>
</tr>
<tr>
<td>5</td>
<td>Kawasaki 2011</td>
<td>ENH</td>
<td>1.5T</td>
<td>3D GRE black-blood T1W</td>
<td>Standard combined neck/foot coil</td>
<td>Relative intensity of &gt;1.2 times adjacent sternocleidomastoid muscle</td>
<td>No volumetric analysis.</td>
<td>Stroke/TIA: determined by 2 physicians based on combination of clinical &amp; imaging findings</td>
</tr>
<tr>
<td>6</td>
<td>Yoshida 2012</td>
<td>ENH</td>
<td>not reported</td>
<td>3D GRE black-blood T1W</td>
<td>Not specified</td>
<td>Hypointense signal relative to sternocleidomastoid muscle with ROI placement</td>
<td>No volumetric analysis.</td>
<td>Stroke/TIA: defined on clinical basis</td>
</tr>
<tr>
<td>7a</td>
<td>Nen 2012</td>
<td>LRNC</td>
<td>3T</td>
<td>High-resolution multi-contrast weighted technique (T1W, T2W, CE T1W, and T2W FS)</td>
<td>Dedicated 4-channel carotid phased-array surface coil</td>
<td>Isointense on T1F, hypointense on T2W, of variable intensity on T2W, and hypointense on CE-T1W</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Defined as focal neurologic deficit with no correlate on imaging and stroke defined as focal neurologic deficit with evidence of acute infarction on imaging</td>
</tr>
<tr>
<td>7b</td>
<td>Nen 2012</td>
<td>LRNC</td>
<td>3T</td>
<td>High-resolution multi-contrast weighted technique (T1W, T2W, CE T1W, and T2W FS)</td>
<td>Dedicated 4-channel carotid phased-array surface coil</td>
<td>Thin (dark band adjacent to lumen) missing on TOF, smooth luminal surface on all images or ruptured (dark band adjacent to lumen missing or discontinuous on TOF, signal at site of presumed rupture: hypointense on TOF, and surface irregular)</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Defined as focal neurologic deficit with no correlate on imaging and stroke defined as focal neurologic deficit with evidence of acute infarction on imaging</td>
</tr>
<tr>
<td>8a</td>
<td>Kosai 2013</td>
<td>LRNC</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (3D T1W, 3D TOF, T2W, T1W &amp; CE T1W black blood)</td>
<td>Dedicated 47 mm diameter surface coil</td>
<td>Nodular enhancement on CE T1WI; no high signal on T1W/TOF</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Defined as focal neurologic deficit with no correlate on imaging and stroke defined as focal neurologic deficit with evidence of acute infarction on imaging</td>
</tr>
<tr>
<td>8b</td>
<td>Nen 2012</td>
<td>ENH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (3D T1W, 3D TOF, T2W, T1W &amp; CE T1W black blood)</td>
<td>Dedicated 47 mm diameter surface coil</td>
<td>Disrupted/discontinuous high signal between LRNC and lumen on CE T1W</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Defined as focal neurologic deficit with no correlate on imaging and stroke defined as focal neurologic deficit with evidence of acute infarction on imaging</td>
</tr>
<tr>
<td>8c</td>
<td>Nen 2012</td>
<td>ENH</td>
<td>1.5T</td>
<td>High-resolution multi-contrast weighted technique (3D T1W, 3D TOF, T2W, T1W &amp; CE T1W black blood)</td>
<td>Dedicated 47 mm diameter surface coil</td>
<td>High signal on TOF or T1F</td>
<td>Volumetric analysis with calculation of mean areas for plaque components and wall areas.</td>
<td>Stroke: Defined as focal neurologic deficit with no correlate on imaging and stroke defined as focal neurologic deficit with evidence of acute infarction on imaging</td>
</tr>
<tr>
<td>9</td>
<td>Hinesworth 2019</td>
<td>ENH</td>
<td>1.5T</td>
<td>3D T1 GRE black-blood with FS</td>
<td>Quadrature neck array coil</td>
<td>1.5x signal hypointensity adjacent sternocleidomastoid muscle with ROI placement</td>
<td>No volumetric analysis.</td>
<td>Ischemic events determined by clinical details but confirmed by imaging.</td>
</tr>
</tbody>
</table>
**Supplemental Table I - Overview of MRI Plaque Testing and Outcome Characteristics**

N/A indicates data not available; TRFC, thinned/ruptured fibrous cap; IPH, intraplaque hemorrhage; LRNC, lipid-rich necrotic core; T, Tesla; TOF, time-of-flight; T1W, T1-weighted; T2W, T2-weighted; PD, proton density; FS, fat-saturated; IR, inversion recovery; MPRAGE, magnetization-prepared rapid acquisition with gradient echo; SPGR, spoiled gradient recalled; GRE, gradient echo; CE, contrast enhanced.
SUPPLEMENTAL REFERENCES


