Visualization of Local Changes in Vessel Wall Morphology and Plaque Progression in Serial Carotid Artery Magnetic Resonance Imaging

Ronald van ’t Klooster, PhD; Martine T.B. Truijman, MD; Anouk C. van Dijk, MD; Floris H.B.M. Schreuder, MD; M. Eline Kooi, PhD; Aad van der Lugt, PhD; Rob J. van der Geest, PhD

Carotid atherosclerosis is an important cause of ischemic stroke. Assessment of plaque composition in addition to degree of luminal stenosis can be used to identify patients with increased risk of stroke and assess disease progression. Magnetic resonance imaging (MRI) is an excellent noninvasive imaging technique to assess vessel wall morphology and plaque composition, with good accuracy and reproducibility.\(^1\) Serial MRI of the carotid artery is used in several studies which focus on measuring the natural history of carotid artery plaques in symptomatic\(^1\) and asymptomatic\(^2\) patients and effects of lipid-lowering therapy using statins.\(^3,4\) The current standard to analyze serial MRI scans is to compare volume measurements based on manual segmentations of the vessel wall and plaque components. Before comparing the scans, the scans have to be aligned to each other on a slice level. Different approaches exist to align scans from different time points. One study aligns the scans by centering the image stack at each time point over the plaque,\(^1\) and another study uses the baseline scan as a reference at the follow-up session to ensure targeting the same arterial segment.\(^4\) Alternatively, postprocessing can be used to match the axial images from different time points according to their distance to the carotid bifurcation.\(^2,3\) Furthermore, comparison between time points is hindered by inconsistent repositioning of the artery from scan to scan in conjunction with thick image slices. Balu et al.\(^5\) studied the influence of subresolution multisequence MRI protocol consisted of 5 magnetic resonance sequences: 3D time of flight, 2D T1-weighted (T1w) turbo spin echo, 2D T2w turbo spin echo, 3D inversion recovery–turbo field echo, and postcontrast 2D T1w turbo spin echo. Fifteen transverse adjoining slices of 2 mm each, with an in-plane reconstructed pixel size of 0.3×0.3 mm, covering the entire plaque were acquired.

Description of the Innovation

Patient

A 71-year-old man was admitted to the hospital because of loss of strength and sensation of the left arm on awakening. An MRI of the brain revealed several small cortical ischemic lesions in the region of the right middle cerebral artery. Carotid ultrasound showed an ipsilateral carotid artery plaque with ≈30% luminal reduction. A minor stroke of the right hemisphere was diagnosed. The patient was included in a large prospective multicenter study to improve diagnosis of mild to moderate carotid plaques (Plaque At RISK study).\(^6\) The institutional Medical Ethical Committee approved the study, and the patient gave written informed consent. The patient was followed up for 2 years, during which he did not experience new ischemic events.

Magnetic Resonance Imaging

Carotid MRI examinations were performed 35 days after the event and after 2 years as previously described.\(^6\) The high-resolution multisequence MRI protocol consisted of 5 magnetic resonance sequences: 3D time of flight, 2D T1-weighted (T1w) turbo spin echo, 2D T2w turbo spin echo, 3D inversion recovery–turbo field echo, and postcontrast 2D T1w turbo spin echo. Fifteen transverse adjoining slices of 2 mm each, with an in-plane reconstructed pixel size of 0.3×0.3 mm, covering the entire plaque were acquired.

Image Analysis

The magnetic resonance images at baseline and follow-up were manually segmented by delineating the lumen, outer wall, calcifications, lipid-rich necrotic core (LRNC), and intraplaque of local differences between time points, providing intuitive insight into the disease progression of an individual patient.
hemorrhage (IPH) according to previously published criteria. Per definition, IPH was always located within the LRNC. Information from all MRI sequences was taken into account during the delineation process. The precontrast T1w images of both time points including segmentations are shown in Figure 1 and demonstrate a slice offset between time points at the bifurcation. The offset was manually corrected by applying a through-plane translation of 1 slice to the follow-up image. To reduce the effect of the high anisotropy of the data on the measurements, the T1w images and segmented vessel wall boundaries were interpolated to a slice thickness of 0.5 mm. The vessel wall boundaries were visually inspected and corrected after interpolation. The interpolated vessel wall boundaries are used in the next section for the calculation of the vessel wall thickness (VWT) and the creation of 3D meshes. The segmentations of the plaque components were not interpolated.

### Automated Image Registration

The baseline and follow-up T1w images were aligned to each other using an automated image registration framework which was optimized for carotid artery MRI scans. After registration, point correspondence between the lumen of the baseline and the follow-up image was obtained, that is, for each point on the lumen boundary in the baseline image, the corresponding point on the lumen boundary in the follow-up image is known.

### Visualization Using 3D Surface Meshes

The interpolated lumen and outer wall segmentations were converted into 3D surface meshes. For each point on the lumen mesh, the distance to the nearest point on the outer wall mesh was calculated resulting in a local VWT measure. The VWT is color coded on the lumen mesh to provide a 3D visualization. The VWT analysis was repeated for the follow-up segmentation.

By using the point correspondence between the baseline and follow-up lumen, differences in measurements between baseline and follow-up can be visualized by color coding this difference on the baseline luminal surface mesh. Similarly, increase or decrease of plaque components can be visualized by color coding the lumen surface. Presence of a plaque component was indicated on a lumen mesh point when a plaque component was present between that lumen mesh point and its closest point on the outer vessel wall. Nearest neighbor interpolation was used to extract this information from the manual segmentations.

### Results of Pilot Testing

First, volume- and area-based comparison between baseline and follow-up was performed. Lumen volume at baseline was 1.525 and 1.507 mL at follow-up, vessel wall volume was 1.634 versus 1.577 mL, calcification volume was 0.017 versus 0.015 mL, and LRNC was 0.378 versus 0.444 mL. The external carotid artery was excluded from the volume- and area-based measurements. Figure 2 shows the slice-based area measurements of the lumen, outer vessel wall, calcifications, and LRNC of the manually aligned baseline and follow-up slices. The volume and area measurements demonstrate a mixed result; a consistent increase in LRNC was observed, whereas the other components showed a small decrease and little variation between baseline and follow-up.

Figure 3 shows the 3D visualization of VWT at baseline and follow-up, change in VWT, and progression or regression of LRNC with or without IPH over time. All metrics are color coded on the lumen surface, and appropriate color maps are chosen. A bipolar color map was chosen for Figure 3C in which gray corresponds to no change, blue to a decrease, and red to an increase in VWT. The strong red regions indicate a clear increase in VWT.

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**Figure 1.** T1-weighted imaging slices obtained at baseline (A: rows 1 and 2) and at 2-year follow-up (B: rows 3 and 4) with manually defined vessel wall and plaque segmentation results overlaid. Only the first 14 proximal slices (of 15) are shown. Through-plane misalignment between the 2 scans can readily be observed based on the location of the carotid bifurcation (slice T1-S10 of the baseline scan corresponds to slice T2-S9 of the follow-up scan). Red indicates lumen; green, outer vessel wall; orange, calcification; yellow, lipid-rich necrotic core; and blue, intraplaque hemorrhage.

**Figure 2.** Comparative visualization of slice-based area measurements for baseline (solid line) and 2-year follow-up (dashed line) after application of manual alignment of the 2-year follow-up images to the baseline scan. Slice numbering is based on the baseline image data. Red indicates lumen area; green, vessel wall area; orange, calcification area; yellow, lipid-rich necrotic core (LRNC) area.
The absence of strong blue regions suggests accurate registration between baseline and follow-up. The increase in VWT is positively correlated with the presence of LRNC (Figure 3D). The 3D visualizations are interactive which allows the clinician to explore the results using zoom and rotation.

The change in VWT was quantified for locations inside the vessel wall which were thickened (VWT >1 mm) and grouped into locations without and with LRNC (with or without IPH; Figure 4). The mean change and SD in VWT was $-0.02\pm0.41$ mm for thickened vessel wall and $0.36\pm0.52$ mm for the LRNC locations. Wilcoxon rank-sum test demonstrated a significant difference between both groups ($P<0.001$).

Conclusions

We introduced a new method to analyze and present serial MRI data of the carotid artery vessel wall. Three-dimensional image registration is used to obtain point correspondence between images from different time points, which enables assessment of local changes in plaque morphology. Three-dimensional visualization techniques are applied to present changes in vessel wall morphology using difference maps which are color coded on a mesh of the lumen segmentation of the baseline image and related to the presence of different atherosclerotic plaque components in the vessel wall. The bipolar color map of the difference map as shown in Figure 3C allows the clinician to differentiate between small and substantial changes in VWT between time points. Moreover, the presented tool can be used to demonstrate a significant increase in VWT over time for locations with LRNC with or without IPH. Both observations could not be deducted from the traditional volume or area measurements.

The 3D visualizations provide an interactive and intuitive way to represent measurements extracted from the original image data. The visualizations as presented in this work provide insight in the change in VWT and progression or regression of different plaque components. Other measurements, for example, changes in degree of stenosis, can be visualized using a similar methodology. These new visual data analysis tools provide clinicians with a detailed view of atherosclerotic disease progression of individual patients and can potentially improve understanding of the effect of changes in plaque components on local plaque progression/regression. Compared with conventional slice-wise comparison, which can only partly account for interscan misalignment, the presented approach based on 3D registration may potentially have a positive impact on measurement reproducibility. Further research on a larger cohort of patients and multiple readers is warranted to investigate this aspect.

To conclude, the presented method to analyze and visualize changes over time for carotid artery MRI is an improvement over the traditional volume-based analysis as it provides a detailed view of local differences between baseline and follow-up scans and increased insight into the disease progression of an individual patient.

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Disclosures

Dr van der Lugt receives a research grant from GE Healthcare for testing magnetic resonance sequences for plaque imaging. The other authors report no conflicts.

References


Key Words: atherosclerosis ◼ carotid arteries ◼ computer-assisted follow-up studies ◼ computer-assisted image interpretation ◼ image processing ◼ magnetic resonance imaging ◼ stroke
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表5. FDA, HC和EMA药物标签中的药物相互作用比较

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Clinical and Research Innovations

颈动脉磁共振成像中血管壁局部形态和斑块进展的可视化成像

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初步实验结果

首先，完成了基线和随访图像间基于体积和面积的比较。基线管腔体积是1.525ml，而随访图像为1.507ml。管壁体积分别是1.634ml和1.577ml，钙化体积分别是0.017ml和0.015ml，而LRNC是0.378ml和0.444ml。颈外动脉未做基于体积和面积的测量。图2示手动对齐基线和随访层面后，基于层面管腔、外壁、钙化、LRNC面积测量值比较结果。体积和面积测量结果是一个混杂的结果；在基线和随访图像中，LRNC可见一致增加，而其它成分少量减少或没有变化。图3示基线和随访图像VWT的3D图像，VMT的改变，以及全程含或不含IPH的LRNC进展或逆转。所有测量值在管腔表面用颜色编码，从而呈现适宜的颜色图。图3C中显示的差异双极彩图允许临床医生区分不同时间的VWT变化。而且可用于验证每个患者治疗前和治疗后LRNC的位置改变。

3D显像提供了一个直观的方式展示从原始影像数据中提取的测量结果。该工作的3D显像能够洞察VWT变化和不同斑块成分进展或逆转。其他测量值，如狭窄程度的变化也可类似方法来显像。这些新的3D可视化分析工具是临床医生提供一个详细视野，以更好地理解每个患者的疾病进展情况。传统层面的比较只能部分解决不同扫描图像间的错配，而现在基于3D显像的方法对测量具有很好的可重复性。

结论

我们引入了一个新方法分析和展示颈动脉层面MRI数据。三维图像配准用于不同时间点获取图像的层面对应关系，使得评估斑块形态的局部变化成为可能。3D显像技术用不同的彩色图展示血管壁形态的变化，用颜色编码基线图像中管腔形态的变化点。对血管壁不同动脉粥样硬化斑块成分的变化，通过不同的颜色编码技术进行显像。这段期间的变异性通过多读取程序提供了额外的观察结果。这会为其他研究者提供一个实用的工具。