Original Research

Reader and Platform Reproducibility for Quantitative Assessment of Carotid Atherosclerotic Plaque Using 1.5T Siemens, Philips, and General Electric Scanners

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Purpose: To evaluate the platform and reader reproducibility of quantitative carotid plaque measurements.

Materials and Methods: A total of 32 individuals with ≥15% carotid stenosis by duplex ultrasound were each imaged once by a 1.5T General Electric (GE) whole body scanner and twice by either a 1.5T Philips scanner or a 1.5T Siemens scanner. A standardized multisequence protocol and identical phased-array carotid coils were used. Expert readers, blinded to subject information, scanner type, and time point, measured the lumen, wall, and total vessel areas and determined the modified American Heart Association lesion type (AHA-LT) on the cross-sectional images.

Results: AHA-LT was consistently identified across the same ($\kappa = 0.75$) and different scan platforms ($\kappa = 0.75$). Furthermore, scan-rescan coefficients of variation (CV) of wall area measurements on Siemens and Philips scanners ranged from 6.3% to 7.5%. However, wall area measurements differed between Philips and GE ($P = 0.003$) and between Siemens and GE ($P = 0.05$). In general, intrareader reproducibility was higher than interreader reproducibility for AHA-LT identification as well as for quantitative measurements.

Conclusion: All three scanners produced images that allowed AHA-LT to be consistently identified. Reproducibility of quantitative measurements by Siemens and Philips scanners were comparable to previous studies using 1.5T GE scanners. However, bias was introduced with each scanner and the use of different readers substantially increased variability. We therefore recommend using the same platform and the same reader for scans of individual subjects undergoing serial assessment of carotid atherosclerosis.

Key Words: carotid arteries; atherosclerosis; magnetic resonance imaging; reproducibility
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SINGLE-CENTER STUDIES have shown that in vivo MRI has considerable potential to temporally quantify changes in atherosclerotic plaque morphology (1–3). Prospective MRI studies have recently demonstrated that effective and protracted lipid-lowering therapy with simvastatin was associated with a significant regression of atherosclerotic lesions (1,2). Additionally, an observational MRI investigation (3) comparing remodeling patterns between mild and advanced carotid atherosclerotic disease found mild disease to be more associated with outward (positive) remodeling. Although alternative vessel wall imaging modalities, such as intravascular ultrasound (IVUS) or computed tomography, are also able to prospectively study changes in atherosclerotic plaques (4,5), MRI has the advantage

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that it is noninvasive and does not involve ionizing radiation.

To establish MRI as a viable clinical tool, however, the reproducibility of this modality needs to be carefully analyzed. Reproducibility of quantitative morphological measurements in MRI can be affected by several factors, such as instrumental features of the equipment, consistency in patient positioning, and the performance of the human operators analyzing images. Previous studies have reported intraplatform reproducibility of atherosclerotic plaque burden on 1.5T General Electric (GE) (6) and 1.5T Siemens scanners (7) and found the scan-rescan coefficients of variation (CV) for carotid wall volume to be 4% to 6% and 4.4%, respectively. Other studies have independently provided intra- and interreader reproducibility data (1,2). Specifically, Lima et al (2) reported intrareader and interreader intraclass correlation coefficients (ICC) to be 0.91 and 0.81, respectively.

These studies provided valuable insight for the planning of single-center studies specific to the platform evaluated. With larger clinical trials, however, multiple sites are generally required to fulfill patient recruitment goals. Consequently, platform type may vary depending on the participating institutions. Moreover, with longer trial durations, there exists the possibility of scanner upgrades or replacement and/or participant migration to a different site. In brain MR, Filippi et al (8) found that the use of different scanners significantly influenced lesion loads measured from images of patients with multiple sclerosis. As such, a complete evaluation of carotid plaque reproducibility can only be determined by assessing intra- and interplatform variation as well as intra- and interreader variability for each of the three major MRI platforms: GE, Siemens, and Philips.

The purpose of this study was to comprehensively evaluate the influence of instrumental and reader factors on the reproducibility of morphological measurements of the carotid atherosclerotic plaque. Within this goal we sought to determine: 1) intraplatform reproducibility (scan-rescan reproducibility on 1.5T Siemens and 1.5T Philips scanners); 2) interplatform reproducibility (scan on GE and rescan on Siemens or Philips scanner); 3) intrareader reproducibility; and 4) interreader reproducibility of quantitative and qualitative measurements of the atherosclerotic carotid plaque.

MATERIALS AND METHODS

Subjects

A total of 32 subjects with ≥15% stenosis as measured by duplex ultrasound were recruited from the diagnostic vascular ultrasound laboratory at the University of Washington: eight females; (the following values given are mean ± SD) age = 67.2 ± 7.7 years; height = 1.74 ± 0.1 m; weight = 85.3 ± 15.9 kg; body mass index = 28.1 ± 4.7). The study procedures and consent forms were reviewed and approved by each site's Institutional Review Board. The arterial side with greatest stenosis, referred to as the index carotid artery, was selected for evaluation. Exclusion criteria were as follows: 1) prior carotid endarterectomy on the side of the index carotid artery; 2) prior radiation therapy applied to the neck region; and 3) contraindication for MRI.

MRI Scans and MRI Scanner

Each of the 32 enrolled subjects was serially imaged within a two-week period. All subjects were imaged once on a 1.5T GE whole body scanner (Signa Horizon EchoSpeed, version 5.8; General Electric Healthcare, Milwaukee, WI, USA). A total of 16 of the subjects were imaged twice on a 1.5T Philips scanner (Philips Intera, release 10.3; Philips Medical Systems, Best, the Netherlands), and the other 16 were imaged twice on a 1.5T Siemens scanner (Siemens Magnetom Symphony, version 2002B; Siemens Medical Systems, Erlangen, Germany). During examination on the same platform, subjects were completely removed from the scanner and repositioned between the two scans.

Carotid Coil

All three coil arrays had the same geometric configurations and the same component values based on a previously described design (9). The coil for the GE scanner was assembled by a third-party vendor (Pathway MRI, Seattle, WA, USA), and the coils for the Siemens and Phillips scanners were assembled by the coil's designer at the University of Washington with parts acquired from Pathway MRI. The arrays differed to the extent that each one was terminated with a connector provided by the respective scanner manufacturer and utilized preamplifiers internal to the respective scanner.

MRI Protocol

A standardized protocol (Table 1) was used to obtain four contrast-weightings of the index carotid artery in the transverse plane: T1-weighted (T1W), proton-density-weighted (PDW), T2-weighted (T2W), and three-dimensional time-of-flight (3D-TOF) MR angiography. Fat suppression was used for the T1W, PDW, and T2W images to reduce signals from subcutaneous fat for improved definition of the total vessel area. To avoid variations in scan parameters caused by differences in heart rate between subjects, all sequences of the imaging protocol were applied without cardiac gating. The use of nongated acquisition for black-blood carotid artery imaging has been demonstrated in previous research (10) to have no significant effect on carotid artery wall measurements and image quality. Scan protocols for all scanners were designed based on our previous experience with a GE scanner (11). In the design of these protocols the imaging parameters were matched as closely as possible, although some minor variations caused by specific features of each MR scanner were unavoidable. All imaging sequences were based on standard commercially-available imaging software provided by the manufacturers.

During image acquisition, each scan was centered at the bifurcation of the index artery to maximize registration between scans. Total longitudinal coverage was 24 mm, which is generally sufficient to capture the complete carotid atherosclerotic plaque on the index side

Table 1
MRI Parameters Used in Protocol

	2D-T1W	2D-PDW	2D-T2W	3D-TOF
Readout sequence[a]	FSE or TSE	FSE or TSE	FSE or TSE	Gradient echo
TR (msec)	800	2700	2700	23
TE (msec)[b]	11/11/6	11/12/10	44/48/52	3.6/4.5/6.3
Echo train length (msec)[b]	10/9/10	12/11/12	12/11/12	—
Flip angle (degrees)[c]	90	90	90	25
Signal averages	2	2	2	2
FOV (cm)	16 × 12	16 × 12	16 × 12	16 × 12
Matrix size	256 × 192	256 × 192	256 × 192	256 × 192
Number of slices	12	24	24	24 (48)[d]
Slice thickness (mm)	2	2	2	2 (1)[d]
Interslice spacing (mm)	0	0	0	0
Flow suppression	DIR[e], TI = 330 msec	Inflow saturation (arteries and veins)	Inflow saturation (arteries and veins)	Inflow saturation (veins)
Scan time (minutes)	7[f]	3[g]	3[g]	3.5

[a]FSE (fast spin echo) and TSE (turbo spin echo) are the proprietary acronyms for a similar method available on GE (FSE) and Siemens or Phillips (TSE) scanners.
[b]Data for GE/Siemens/Phillips scanners, respectively.
[c]In FSE/TSE sequences refers to the excitation pulse.
[d]The actual and zero-interpolated number of slices and thickness are provided.
[e]Double inversion-recovery (DIR) method, where TI was calculated according to Eq. [1] in Ref. 17, assuming blood T_1 = 1200 msec.
[f]Single-slice sequential acquisition.
[g]Multislice interleaved acquisition with 12 slices per package.
FOV = field of view.

(12). After image acquisition, zero-filled interpolation was used to reduce pixel size from 0.62×0.62 mm^2 to 0.31×0.31 mm^2. Previous studies have demonstrated that this spatial resolution is sufficient to qualitatively and quantitatively evaluate carotid atherosclerotic plaques accurately and reproducibly (6,13–15).

Image Review

Identifying information including the hospital, scanner platform, and scan date was removed and the MR images were randomized by personnel at the Core Reading Center who were not involved in image interpretation. Four reviewers, all with more than 1.5 years of experience in carotid plaque imaging and blinded to subject, time point, and site information reviewed the MRI scans. Each scan was read by two reviewers to reach a consensus decision. An image-quality (IMQ) rating (5-point scale: 1 = poor, 5 = excellent) was assigned to all MR images (15) before the review. Imaging locations with an average image quality <3, typically due to subject motion or low signal to noise ratio, were excluded from the study.

To facilitate accurate identification of the American Heart Association lesion type (AHA-LT) (13,15) based on information from multicontrast MRI, cross-sectional images of each carotid artery corresponding to all the four contrast weightings obtained within a single MRI examination were matched relative to the bifurcation. The bifurcation was assigned to the location 2 mm proximal to the presence of the flow divider that separates the lumen of the common carotid artery into the two lumina of the internal and external carotid arteries. For a single exam, the maximum coverage that could be achieved was 12 locations (24 mm), as there were 12 T1W images per exam. Image locations where all four contrast weightings were not available were a priori excluded from the review (6).

To ensure identical coverage of the plaque for inter-platform or scan-rescan comparisons, an additional image-matching procedure was performed for paired image sets obtained in repeated examinations. For each of four comparisons (i.e., Siemens vs. GE, Philips vs. GE, scan-rescan on Siemens, and scan-rescan on Philips), two image sets of each patient containing all four contrast weightings matched relative to the bifurcation as described above were inspected to identify the locations covering the same anatomical region and to exclude proximal and/or distal cross-sections that were mismatched due to variations in patient's positioning (if present). This procedure enabled statistical analysis of only data corresponding to identical anatomical locations, while minimizing the number of images that had to be excluded due to mismatch between scans.

For area measurements, the lumen and outer vessel wall boundaries (total vessel area) were manually traced using a custom-designed image analysis tool Qualitative Vascular Analysis System (QVAS) (16). The total vessel area included the lumen and wall areas. The wall area for each location was calculated as the difference between the total vessel and lumen areas. Morphological measurements were obtained from T1W images acquired with double inversion-recovery (DIR) blood suppression (Table 1) because this technique provides more reliable suppression of the blood signal than the inflow saturation method (17) and, therefore, is more suitable for tracing the lumen boundary. For the determination of the modified AHA-LT, all contrast weightings were incorporated and previously established imaging criteria were applied (13,15).

To assess intrareader and interreader reproducibility, one of the two Siemens and one of the two Philips scans was randomly selected and reevaluated four weeks after the initial review.

Data Analysis

Based on repeated readings of matched scan-rescan and cross-platform image sets, the following datasets were created to investigate different types of reproducibility: 1) interplatform reproducibility between GE and a single Philips scan (or GE and a single Siemens scan), which were interpreted by the same review pair; 2) intraplatform reproducibility between the scan and rescan on one platform (Philips or Siemens), which were analyzed by the same review pair; 3) intrareader reproducibility between two readings of the same Philips (Siemens) scan by the same review pair; and 4) interreader reproducibility between two readings of the same Philips (Siemens) scan by two different review pairs.

Area measurements for each artery were calculated as the mean area per location for each artery separately (sum of all areas of one artery divided by the number of locations). The ICC was calculated to determine the level of agreement between two measurements repeated within subjects/scans in comparison to the variation in the measurements across subjects. An ICC close to 1.0 indicates that the CV is small relative to the range of values encountered. The CVs for area and volume data of lumen, wall, and total vessel were calculated as: 100%*$\sqrt{}$(within-subject variance)/mean (all measurements). The bias of Phillips or Siemens relative to GE was estimated using a linear mixed model based on the four measurements performed by the same reader. The model included a fixed effect for the platform (e.g., a dichotomous variable indicating Phillips vs. GE), used to estimate the platform bias, and random effects for the patient, platform-by-patient interaction, scan-by-patient interaction, and intrareader variance (residual term). To derive the bias for each platform relative to GE, the analysis was carried out on a GE-Phillips data set that included only patients scanned on both platforms, and, separately, on a GE-Siemens data set. Analyses were carried out in SPSS for Windows (version 12). Statistical significance was defined as a value of $P < 0.05$.

RESULTS

Image Quality

One scan performed on a GE scanner of a subject of the GE-Philips data set was excluded from analysis due to IMQ < 3. Therefore, only 15 out of 16 arteries could be used for the subanalysis of the interplatform reproducibility for GE vs. Philips. The subjects with one GE and two Philips scans achieved comparable image qualities on GE and on Philips (average IMQ = 3.3 ± 0.7 on GE vs. 3.5 ± 0.5 on Philips; $P = 0.2$), as did the subjects with one GE and two Siemens scans (average IMQ = 3.3 ± 0.4 on GE vs. 3.3 ± 0.4 on Siemens; $P = 0.7$).

Scan Coverage

In the interplatform (intraplatform) data set 330 (324) MRI locations (out of a possible 384) could be matched, resulting in a mean coverage of 2.06 ± 0.32 cm (2.03 ± 0.38 cm). For the intra- and interreader data set, the number of analyzed MR image locations was higher because the same scan was analyzed twice and therefore matching with another scan was unnecessary. Specifically, 359 MRI locations were used for the intrareader data set (mean coverage = 2.24 ± 0.36 cm) and 345 for the interreader data set (mean coverage = 2.16 ± 0.42 cm).

AHA-LT

For AHA-LT, the intrareader and intraplatform agreement was strong, with Cohen's kappa ranging from 0.74 to 0.80 (Table 2). Interplatform agreement, as measured by Cohen's kappa, was 0.71 for GE vs. Siemens and 0.67 for GE vs. Phillips. Interreader reproducibility was moderate to good with Cohen's kappa ranging from 0.56 to 0.57. Figure 1a and b shows that the relative plaque tissue intensities in a multisequence protocol are similar on 1.5T GE, Philips, and Siemens scanners.

Reproducibility of Quantitative Plaque Measurements

The ICC for intraplatform reproducibility and intra- and interreader reproducibility ranged from 0.83 to 0.99, respectively, for the lumen, wall, and total vessel areas, demonstrating strong agreement for repeated measurements. ICC for mean lumen area and total vessel area measurements had a low variation across the different types of reproducibility measured and ranged from 0.96 to 0.99. ICC for mean wall area demonstrated the largest variation and ranged from 0.83 to 0.95.

Table 3 demonstrates the CV of intraplatform reproducibility and intra- and interreader reproducibility calculated for the Siemens-GE and the Philips-GE data

Table 2
Reproducibility of Modified AHA Lesion Type Classification

AHA lesion type	Cohen's kappa			
	Intraplatform	Interplatform	Intrareader	Interreader
Siemens/GE data set (2 Siemens scans, 1 GE scan)	0.76	0.71	0.80	0.57
Philips/GE data set (2 Philips scans, 1 GE scan)	0.74	0.67[a]	0.75	0.56
Both data sets combined (32 subjects)	0.75	0.69[b]	0.77	0.56

[a]Based on 15 subjects, one GE scan had to be excluded because of IMQ <3.
[b]Based on 31 subjects, one GE scan had to be excluded because of IMQ <3.

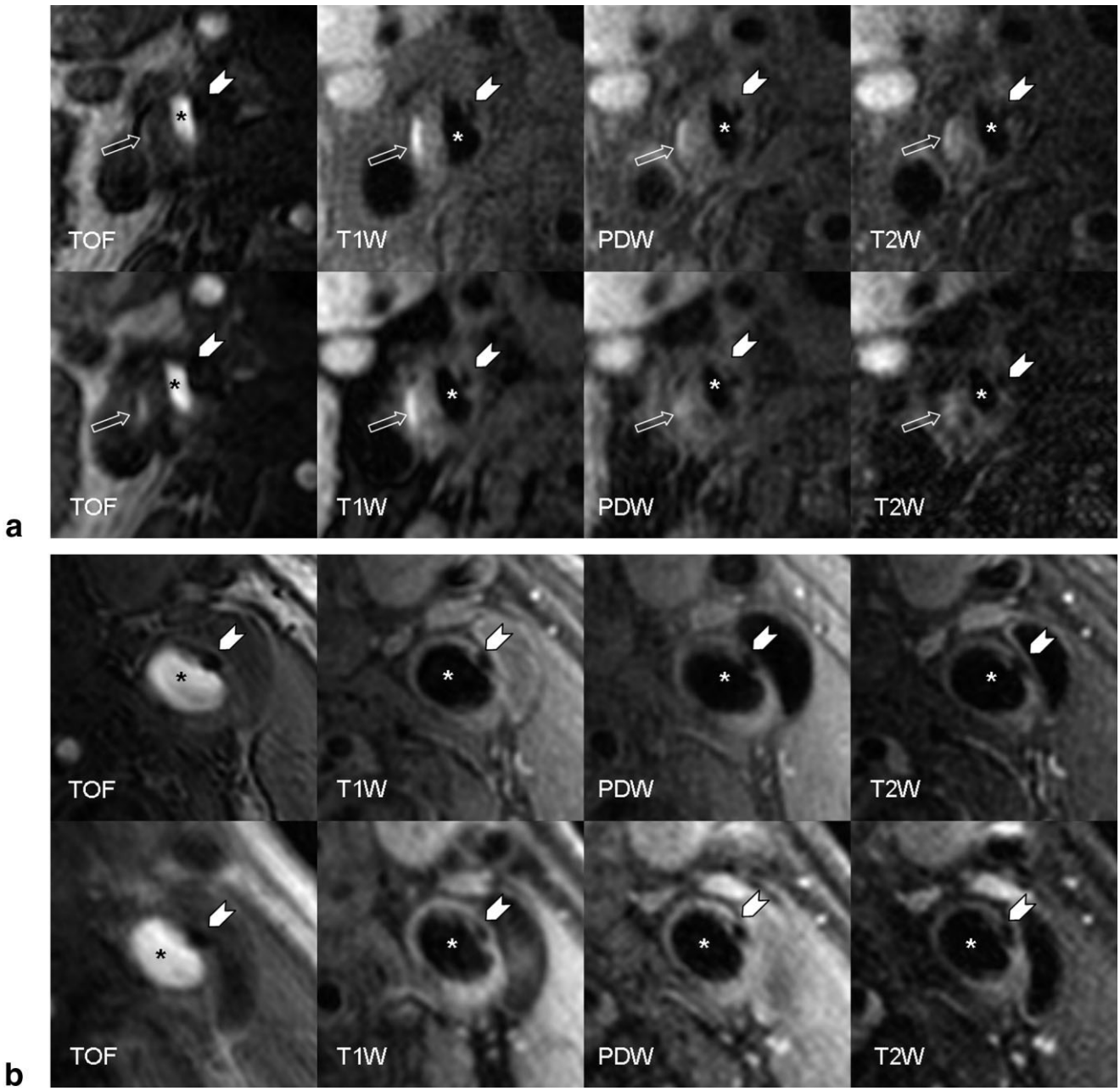

Figure 1. a: Example of a complicated AHA type VI lesion with intraplaque hemorrhage (arrow) and calcification (chevron) in the right common carotid artery of a subject who was scanned on a GE (upper row) and on a Philips (lower row) scanner. The relative tissue intensities are similar in the TOF, T1W, PDW, and T2W images on GE and on Philips. Hemorrhage (arrow) is hyperintense and calcification (chevron) is hypointense compared to the normal carotid wall in all four weightings (lumen = asterisks). **b:** Example of a calcified AHA type VII lesion in the left common carotid artery of a subject who was scanned on a GE (upper row) and a Siemens (lower row) scanner. The arrow points to a region which is hypointense on all four weightings, indicating the presence of calcification (lumen = asterisks).

set and for both data sets combined. Using the combined data sets, CV of mean lumen area ranged from 3.0% to 4.7% and was lowest for the intrareader reproducibility and highest for the intraplatform reproducibility. CV of mean wall area (total vessel area) ranged from 5.7% to 7.2% (3.0–4.4%), and was lowest for intrareader reproducibility, intermediate for the intraplatform reproducibility, and highest for the interreader reproducibility.

Interplatform Comparison of Quantitative Results

Tables 4 and 5 show the interplatform bias of quantitative results comparing GE vs. Siemens and GE vs. Philips data. On the Philips scanner the mean wall area and the mean total vessel area were 12.4% and 4.7% larger, respectively, when compared to the results from the GE scanner, and the mean lumen area was 5.3% smaller. The differences between GE and Philips for

Table 3
Coefficient of Variation Using Mean Areas*

CV	Intraplatform (scan-to-scan) (%)	Intrareader (%)	Interreader (%)
Siemens data set (16 subjects)			
Lumen	5.1	3.5	4.0
Wall	6.3	5.3	7.4
Total vessel	3.9	2.7	4.4
Philips data set (16 subjects, data with exclusion of one outlier in parentheses[a])			
Lumen	4.4 (3.9)	2.4	4.2
Wall	7.5 (5.8)	6.1	7.0
Total vessel	3.8 (3.4)	3.4	4.3
Both data sets combined (32 subjects, data with exclusion of one outlier in parentheses[a])			
Lumen	4.7 (4.5)	3.0	4.1
Wall	6.9 (6.0)	5.7	7.2
Total vessel	3.8 (3.6)	3.0	4.4

*One value per artery/subject.
[a]The differences for the measurements of the mean wall area and mean total vessel area for the outlier were both more than 4 SD above the average calculated from all other observations with the outlier excluded.
CV = coefficient of variation = 100%* √(within-subject variance)/mean (all measurements).

wall, lumen, and total vessel area were significant, with *P*-values ranging from 0.003 to 0.03. On the Siemens scanner the mean wall area and the mean total vessel area were 5.4% and 3.3%, respectively, larger when compared to the GE scanner. The differences between Siemens and GE approached statistical significance with a *P*-value of 0.052 for mean wall area and of 0.08 for mean outer wall area. No significant difference was found for mean lumen area when comparing the GE and Siemens data ($P = 0.7$). Figure 2 shows an example of a subject who was scanned on GE and Philips. When compared to the corresponding GE images the Philips images show the lumen to be smaller and the wall to appear larger. The boundaries of the different anatomical structures such as the total vessel area and the surrounding tissue—as shown by a distinct dark line surrounding the vessel—also were more pronounced on the Philips scanner than on the GE scanner. Figure 3 shows an example of a subject who was scanned on a Siemens and a GE scanner. Overall, the visual differences are less pronounced than for the GE-Philips comparison, with no visible difference in the appearance of the lumen and subtle differences in the overall signal intensity of the wall and the tissue surrounding the vessel.

DISCUSSION

This study demonstrated a high intrareader and intraplatform reproducibility for AHA-LT using a standardized multisequence protocol and surface coils of similar design. Additionally, the AHA-LT could be consistently identified across two scans from different scan manufacturers (Fig. 1a and b). This suggests that the relative tissue signal intensities and the appearance of the luminal surface in TOF, T1W, PDW, and T2W images are similar across scanners. Of critical importance, the high level of interplatform agreement for AHA-LT indicates that accurate characterization of plaque composition is possible across GE, Siemens, and Philips scanners.

Implementation of a standardized multisequence carotid imaging protocol resulted in image quality and coverage that were consistent across the different types of scanners. The average coverage of 2.06 cm across the three scans of an individual subject in the interplatform analysis suggests that this mean coverage is adequate for evaluating early carotid atherosclerotic lesions (12), as previous studies have shown that carotid lesion distribution can be determined using 16 mm (eight slices) of coverage in hypercholesterolemic subjects with mod-

Table 4
Interplatform Bias: Siemens vs. GE*

	GE (mean ± SE)	Siemens (mean ± SE)	Δ Siemens-GE (mean ± SE) (mm^2)	Δ Siemens-GE (mean ± SE) (%)	*P*-value[a]
Lumen	35.3 ± 3.3	35.5 ± 3.3	0.2 ± 0.6	0.6 ± 1.8	0.7
Wall	39.6 ± 2.0	41.8 ± 1.9	2.2 ± 1.1	5.4 ± 2.6	0.052
Total vessel	74.9 ± 4.7	77.5 ± 4.6	2.5 ± 1.4	3.3 ± 1.8	0.08
Image quality	3.2 ± 0.6	3.2 ± 0.5	n/a	n/a	.8[b]

*$N = 16$ subjects.
[a]Wald test based on linear mixed model.
[b]Paired *t*-test.
n/a = not applicable, SE = standard error.

Table 5
Interplatform Reproducibility: GE vs. Philips*

	GE (mean ± SE)	Philips (mean ± SE)	Δ Philips-GE (mean ± SE) (mm^2)	Δ Philips-GE (mean ± SE) (%)	*P*-value[a]
Lumen	35.9 ± 2.2	34.1 ± 2.1	−1.8 ± 0.7	−5.3 ± 1.9	0.01
Wall	40.3 ± 3.3	45.8 ± 3.3	5.5 ± 1.5	12.4 ± 3.4	0.003
Total vessel	76.2 ± 4.3	79.9 ± 4.2	3.7 ± 1.6	4.7 ± 2.0	0.03
Image quality	3.3 ± 0.8	3.2 ± 0.8	n/a	n/a	0.3[b]

*N = 15 subjects.
[a]Wald test based on linear mixed model.
[b]Paired *t*-test.
n/a = not applicable, SE = standard error.

erate carotid stenosis (14). Good image quality was achieved in 95 of 96 scans. The low number of exclusions shows that the standardized multisequence carotid imaging protocol can be successfully implemented on the Siemens, GE, and Philips scanners. The percentage of excluded scans was lower than in previous studies in which 5% to 22% of the subjects were excluded for insufficient image quality.(3,6,15) This might be explained by improvements in the protocol design resulted in a shorter scan time than in previous studies and by well-established procedures for technologists' training and patients' positioning (11).

This study showed excellent intra- and interreader agreement for lumen, wall and total vessel measurements, with ICCs ranging from 0.83 to 0.99. The CV for quantifying each of these parameters, however, was lower within readers than between readers (Table 3). This finding indicates that one reader should optimally review all exams for a particular research subject in order to minimize variability. Alternatively, the variability related to manual contour tracing can be substantially reduced by the use of semiautomated tools, currently under development.

Intraplatform reproducibility on Siemens and Philips scanners was comparable to previous studies on 1.5T GE scanners with ICCs ranging from 0.91 to 0.98 on Siemens and 0.94 to 0.97 on Philips scanners. Intraplatform CVs for lumen, wall, and total vessel area measurements (Table 3) ranged from 3.9% to 6.3% on Siemens and 3.8% to 7.5% on Philips. Overall, these CVs were comparable to previous studies on 1.5T GE machines, which reported CVs for mean wall area of 5.8% (6). These similarities suggest that multicenter studies that utilize a combination of the three major MRI scanner platforms are feasible.

However, our results indicate differences in some quantitative measurements of carotid atherosclerotic plaque morphology between scanner platforms. Figures 2 and 3 demonstrate the visually apparent differences between the GE and Siemens/Philips scanners. When

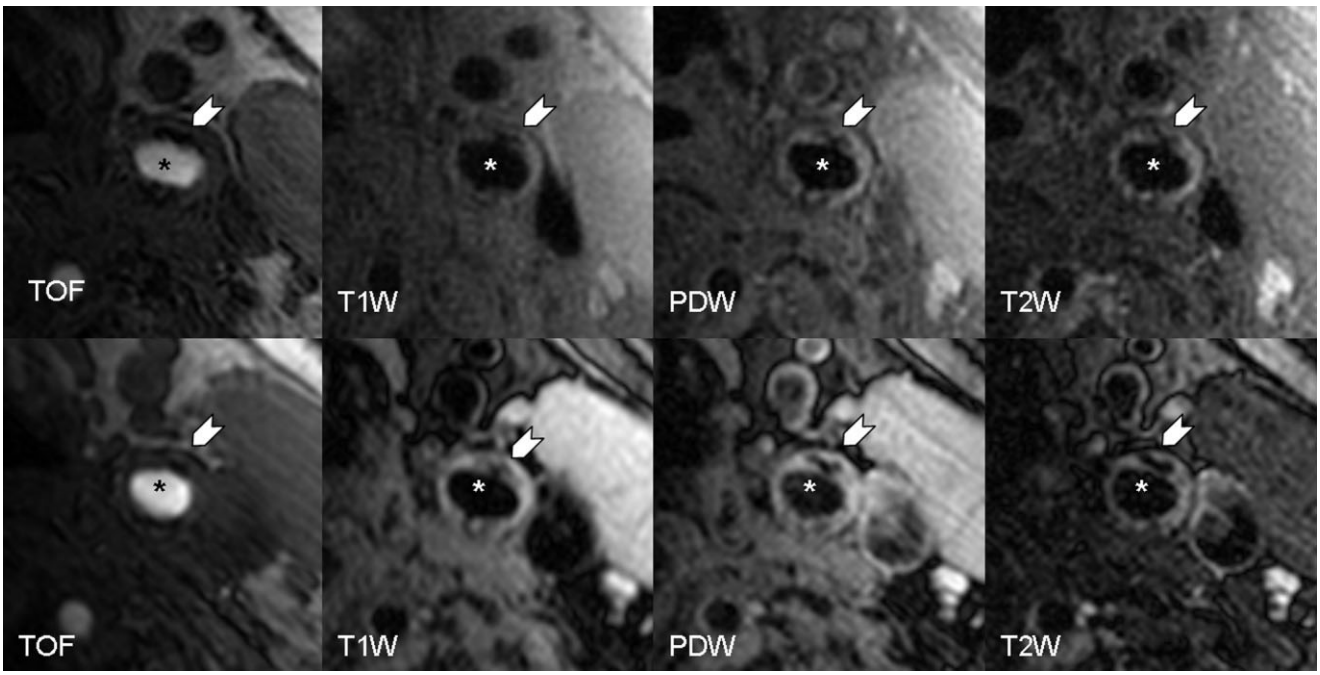

Figure 2. Example of an atherosclerotic lesion in the left common carotid artery of a subject who was scanned on a GE (upper row) and on a Philips (lower row) scanner. The lumen (asterisks) appears to be smaller on the Philips scanner than on the GE scanner and the total vessel appears larger. The boundaries between total vessel and the surrounding tissue appear different; boundaries on the Philips scanner are marked by a distinct dark line.

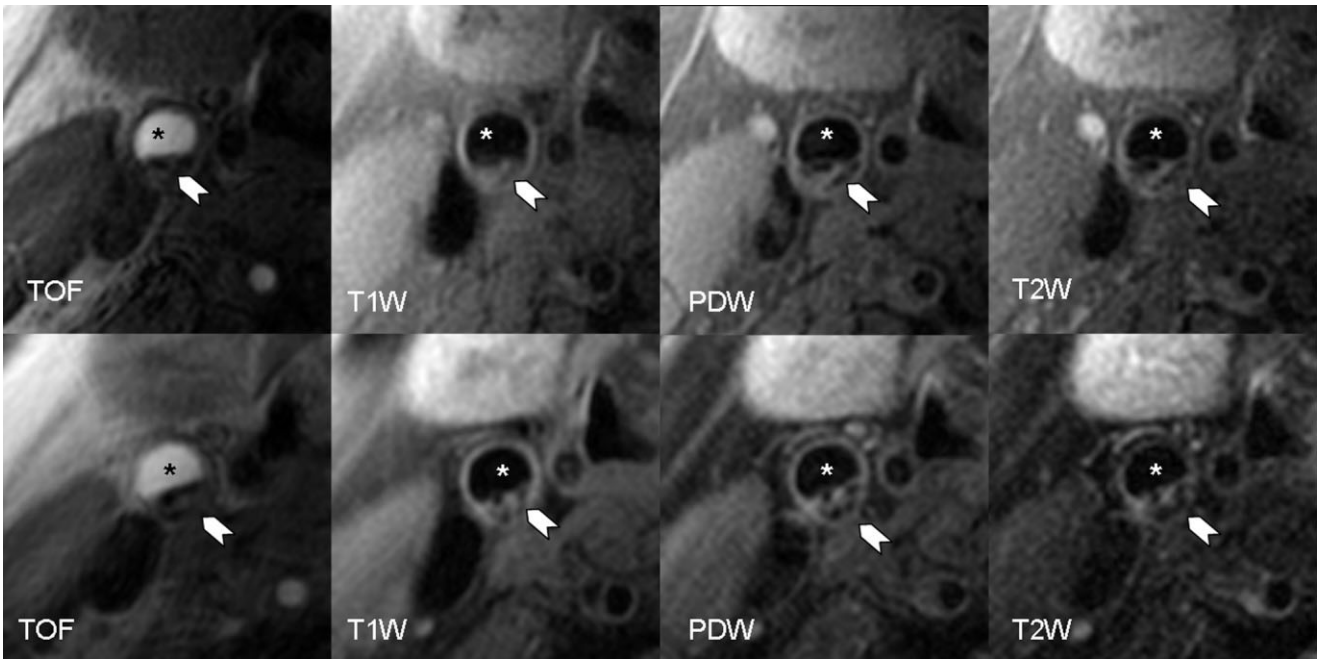

Figure 3. Example of an atherosclerotic lesion in the right common carotid artery of a subject who was scanned on a GE (upper row) and a Siemens (lower row) scanner. The arrow points to a region which is hypointense on all four weightings, indicating calcification. Overall, size and shape of the lumen (asterisks) on the two scanners appears similar. The total vessel area on the Siemens scanner appears to be better delineated from the surrounding tissue as compared to the total vessel area on the Philips scanner.

compared to the GE scanner, mean wall area was significantly larger on the Philips Scanners and approached statistical significance on the Siemens scanners, while mean lumen area was significantly smaller on the Philips scanner and statistically equal on the Siemens scanner (Tables 4 and 5). Although there is little data in the literature of the progression rate of carotid atherosclerotic plaques, a preliminary study in 68 subjects with advanced carotid atherosclerotic disease suggests an annual increase of mean wall area of 2.2% and an annual decrease of mean lumen area of 1.8% (3). In contrast to this relatively small annual increase, the magnitude of the difference of quantitative mean wall area measurements between scanner platform types was as high as 12.4%. As such, we strongly recommend that serial MRI examinations of a particular subject be performed on the same scanner platform for the duration of the study.

A significant source of variability came from the manual contours of the lumen and total vessel boundaries. This variability can be substantially reduced by the use of semiautomated tools, currently under development. This study showed the differences in quantitative measurements between GE and Siemens scanners and between GE and Philips scanners. It remains to be seen whether there are also differences between Philips and Siemens scanners. Finally, this study focused only on 1.5T MR scanners from different manufacturers. Future studies will need to evaluate possible differences between scanners of different field strengths.

Although the reason for the differences in quantitative measurements between the different scanners remains unclear, it was not due to the human operator or the image analysis software. Possible reasons for disagreement can be related to specific aspects of the pulse sequence design and hardware performance, which were beyond our control in the present study. Although our protocol design aimed to adjust basic scan parameters as close as possible between all platforms, particular implementations of pulse sequences by various manufacturers make use of different gradient structures, RF pulse shapes, and precise sequence timing parameters. Hardware performance factors may include variations in gradient calibration and eddy currents, as well as the uniformity of the RF field and the accuracy of the flip angle calibration. All these factors may result in subtle but systematic differences in flow suppression, fat suppression, actual slice thickness, and pixel size, which can be reflected by a disagreement in quantitative morphological measurements. Another reason for disagreement can be ascribed to variations in image reconstruction algorithms implemented by different vendors. Application of different (and to the user unknown) filters to the time domain data before the Fourier transform may alter effective image resolution and thus indirectly affect the results of boundary tracing on high-resolution images. While this study has employed the imaging protocol based on standard commercially available software and hardware, fine tuning of specific imaging sequences and precise hardware calibration procedures may be needed to improve cross-platform reproducibility in the future. The critical role of software and hardware factors is further supported by a recent study (18) comparing reproducibility of carotid artery measurements between scanners with different field strengths (1.5T and 3T) from the same

manufacturer (GE). While identical pulse sequences and hardware settings were implemented, there were no significant biases in morphological parameters despite the different magnetic fields used (18).

In conclusion, implementation of a standardized, multisequence, high-resolution MRI protocol enables similar image quality, arterial coverage, and tissue intensity of the carotid atherosclerotic lesion across Siemens, GE, and Philips scanners. Consequently, AHA-LT can be consistently identified across two scans from different imaging platform manufacturers. In addition, in vivo morphological measurements for each of these scanner types have a high level of intrareader and intraplatform reproducibility. However, variability increases when individuals are scanned on different scanner platforms and/or interpreted by different readers. Therefore, for serial assessments of lesion size in clinical trials, we recommend using the same platform for individual subjects, with interpretation of individual subject scans performed by the same reader.

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