Accuracy and utility of three-dimensional contrast-enhanced magnetic resonance angiography in planning carotid stenting

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Background: **Contrast-enhanced magnetic resonance angiography (CE-MRA) is a proven diagnostic tool for the evaluation of carotid stenosis; however, its utility in planning carotid artery stenting (CAS) has not been addressed. This study assessed the accuracy of three-dimensional CE-MRA as a noninvasive screening tool, compared with digital subtraction angiography (DSA), for evaluating carotid and arch morphology before CAS.**

Methods: **In a series of 96 CAS procedures during a 2-year period, CE-MRAs and DSAs with complete visualization from the aortic arch to the intracranial circulation were obtained before CAS in 60 patients. Four additional patients, initially considered potential candidates for CAS, were also evaluated with CE-MRA and DSA. The two-by-two table method, receiver operating characteristic curve, and Bland-Altman analyses were used to characterize the ability of CE-MRA to discriminate carotid and arch anatomy, suitability for CAS, and degree of carotid stenosis.**

Results: **The sensitivity and specificity of CE-MRA were, respectively, 100% and 100% to determine CAS suitability, 87% and 100% to define aortic arch type, 93% and 100% to determine severe carotid tortuosity, and 75% and 98% to detect ulcerated plaques. CE-MRA had 87% sensitivity and 100% specificity for the detection of carotid stenosis ≥80%. The accuracy of CE MRA to determine optimal imaging angles and stent and embolic protection device sizes was >90%. The operative technique for CAS was altered because of the findings of preoperative CE-MRA in 22 procedures (38%). The most frequent change in the operative plan was the use of the telescoping technique in 11 cases (18%). CAS was aborted in four patients (5%) due to unfavorable anatomy identified on CE-MRA, including prohibitive internal carotid artery tortuosity (n = 1), long string sign of the internal carotid artery (n = 2), and concomitant intracranial disease (n = 1). Among patients considered suitable for CAS by CE-MRA, technical success was 100%, and the 30-day stroke/death rate was 1.6%.**

Conclusions: **Contrast-enhanced magnetic resonance angiography of the arch and carotid arteries is accurate in determining suitability for CAS and may alter the operative technique. Certain anatomic contraindications for CAS may be detected without DSA. Although CE-MRA is less accurate to estimate the degree of stenosis, it can accurately predict imaging angles, and stent and embolic protection device size, which may facilitate safe and expeditious CAS. (J Vasc Surg 2007;46:257-64.)**

Digital subtraction angiography (DSA) is still considered the gold standard for the evaluation of atherosclerotic lesions of the carotid arteries. This procedure is, however, invasive and carries a small but definite risk of complications, including cerebrovascular thromboembolicevents.[1] Noninvasive methods such as magnetic resonance angiography (MRA), computed tomography angiography (CTA), and duplex ultrasound imaging (DUI) have been evaluated as possible alternatives to DSA.

Overall, previous observational studies comparing DSA and contrast-enhanced MRA (CE-MRA) have consistently revealed a strong correlation of the degree of carotid stenosis estimated with these two diagnostic modalities, despite an occasional tendency toward overestimation reported with CE-MRA.[2-6] Although CE-MRA has been widely used to corroborate the degree of carotid stenosis determined with DU before performing carotid endarterectomy (CEA), to our knowledge, its utility in planning carotid angioplasty and stenting (CAS) has not been assessed.

Carotid stenting with cerebral embolic protection is currently performed primarily for the treatment of carotid stenosis in high-risk surgical patients; that is, those with significant comorbidities or a hostile neck from previous surgical procedures or radiation.[7-10] The role of CAS for the treatment of carotid stenosis among low-risk patients has not been defined, and although recent randomized clinical trials have reported inferior outcomes after CAS,[11,12] its usefulness will only be established once the results of larger and rigorous clinical trials become available.[13,14]

Because the learning curve for CAS is prolonged and challenging, patient selection is critical to minimize adverse outcomes.[15,16] Unfavorable anatomic variations are the main limiting factor during CAS.[17,18] As a consequence, it has been suggested that during the early experience with

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the procedure, DSA should be obtained beforehand to anticipate the difficulty of the case and to select the appropriate techniques and tools.[19] Alternative preoperative imaging studies, such as CE-MRA, which is capable of assessing from the aortic arch to the intracranial circulation, could be used in preparation for CAS.

This study was designed to assess the accuracy of three-dimensional (3D) CE-MRA as a noninvasive screening tool, compared with DSA, for evaluating carotid and arch morphology of patients with carotid stenosis being considered for CAS.

METHODS

During a 2-year period from September 2004 to September 2006, 96 CAS procedures were performed in 90 men and two women at high risk or with contraindications for CEA.[17,20] Indications included moderate (≥50%) symptomatic carotid stenosis or severe (≥80%) asymptomatic carotid stenosis determined with DUI. CE-MRA and DSA were obtained in 82 patients before CAS. In 60 patients, CE-MRA imaged the aortic arch, the complete course of the extracranial carotid arteries, and the intracranial circulation. Four additional patients, initially considered potential candidates for CAS, were also evaluated with CE-MRA and DSA. Data from this group of 64 patients, in whom aortic arch, cervical, and intracranial carotid CE-MRA and DSA was obtained for preoperative work-up before CAS, were prospectively entered into a database designed for this anatomic study, which was approved by the local Institutional Review Board.

CE-MRA was performed with an Avanto 1.5-T magnet machine (Siemens, Bala Cynwyd, Pa) using a 3D subtracted fast gradient-echo sequence and turbo fast low-angle shot sequence (4/1.6 repetition time msec/echo time msec; flip angle, 20°; matrix, 120-128 × 128-256). A total dose of 20 mL of gadolinium-based contrast material (ProHance; Bracco Diagnostics, Princeton, NJ) was injected into an antecubital vein. A bolus test preceded imaging acquisition with scan delay automatically calculated to optimize aortic arch imaging.

The MRA studies were processed with a maximum-intensity-projection algorithm to display 3D projections of each carotid bifurcation. For the 3D CE-MRA, the maximum-intensity-projection algorithm was used after subtracting the sequence that showed the best arterial enhancement. MRI analysis software with magnification and precise cursor placement was used for diameter measurements. CE-MRA images were further evaluated using 3D reconstruction on a Vitrea workstation (Vital Images, Plymouth, Minn) to determine carotid tortuosity and optimal angles of projections and views to image the aortic arch, great vessels, intracranial circulation, and target lesions.

Baseline and postoperative angiograms and all CAS procedures were performed with an OEC/GE Model 9800 mobile C-arm (OEC, Salt Lake City, Utah) or fixed angiographic units (AXIOM Artis dTA, Siemens, Malvern, Pa or Allura Xper FD10, Philips, Bothell, Wash). Baseline DSA studies were performed concurrently with the CAS procedure.

Angiographic projections that demonstrated the most severe degree of stenosis were selected. Measurements of angiographic carotid stenosis (percentage by diameter) in both CE-MRA and DSA images were performed according to North American Symptomatic Carotid Endarterectomy (NASCET) methodology.[21] A signal void on MRA was assumed to represent a >70% stenosis.[22]

CE-MRA and DSA images were further evaluated for the presence of plaque ulcers, occlusion, and other significant stenoses from the aortic arch to the circle of Willis. The presence of a plaque ulcer was confirmed when an ulcer niche was clearly seen (ie, a crater penetrating into a stenotic plaque).

Aortic arch morphology and elongation (types I, II, and III),[23] and carotid lesion length and carotid tortuosity were also evaluated. Common carotid artery (CCA) and internal carotid artery (ICA) tortuosity was graded according to the vascular angulation from the proximal center line flow (absent, 0°; mild, <30°; moderate, 30° to 60°; severe, >60°).[24,25]

CE-MRA images were further used to estimate imaging angles, target lesion suitability for CAS, changes in CAS technique, and stent and embolic protection device (EPD) sizes. Suitability for CAS was determined according to aortic arch morphology, ICA/CCA tortuosity, and target lesion characteristics. CAS suitability was defined as the expectation of delivering an EPD and stent to the target site according to the clinicians' experience and the current practice with CAS systems commercially available in the United States.

Procedural details and CAS protocols at our institution have been described in detail.[19] Briefly, the sequential over-the-wire technique was primarily used. Several types and models of cerebral protection device were used to prevent distal embolization: Abbott Accunet filter (ACCULINK System, Abbott Vascular, Santa Clara, Calif), FilterWire EZ system (Boston Scientific, Natick, Mass), and Angioguard Filter (Cordis, Warren, NJ). Three self-expanding stents were used: Acculink carotid stent (Acculink System, Abbott Vascular, Santa Clara, Calif), Carotid Wallstent (Boston Scientific Corp, Natick, Mass), and PRECISE carotid stent (Cordis, Warren, NJ).

Descriptive statistics for categoric variables are presented as relative frequencies (percentages). Continuous variables were expressed as medians and interquartile ranges (IQR). For the purpose of this study, matched and paired carotid lesion and vessel-based evaluations and comparisons of CAS suitability and aortic arch and carotid morphologic measures as assessed in CE-MRA and DSA images were performed. Spearman rank correlation coefficients (Spearman ρ) with 95% confidence intervals (CI) of angiographic carotid stenosis and vessel size measurements were calculated. The two × two table method, receiver operating characteristic (ROC) curve, and Bland-Altman analyses were further used to characterize the ability of CE-MRA to discriminate carotid and arch anatomy, suit-

Table. Accuracy of contrast-enhanced magnetic resonance angiography to detect aortic arch and carotid morphology, disease, and device sizes before carotid artery stenting using digital subtraction angiography as reference standard (n = 64)*

Variable	*No.*	*Sensitivity, % (95% CI)*	*No.*	*Specificity, % (95% CI)*	*No.*	*PPV, % (95% CI)*	*No.*	*NPV, % (95% CI)*
Severe ICA stenosis (80%-99%)	46	87 (75-95)	11	100 (72-100)	46	100 (100-100)	11	71 (36-83)
CAS suitability	60	100 (94-100)	4	100 (40-100)	60	100 (94-100)	4	100 (40-100)
Aortic arch type (I vs II/III)	39	87 (73-95)	19	100 (82-100)	39	100 (91-100)	19	76 (55-91)
Bovine aortic arch configuration	26	100 (87-100)	37	100 (91-100)	26	100 (87-100)	37	100 (91-100)
Aortic arch imaging angle (45°-60°)	52	100 (93-100)	11	92 (62-99)	52	98 (90-100)	11	100 (72-100)
Tortuosity (moderate to severe)								
ICA	14	93 (68-99)	49	100 (93-100)	14	100 (77-100)	49	98 (88-100)
CCA	3	75 (19-99)	60	100 (94-100)	3	100 (29-100)	1	98 (91-110)
Carotid plaque ulceration	12	75 (47-93)	46	98 (89-100)	12	92 (64-99)	46	92 (81-98)
ICA string sign	1	100 (25-100)	62	100 (94-100)	1	100 (25-100)	62	100 (94-100)
Stent								
Diameter (6-8 mm vs 7-10 mm)	26	96 (81-100)	25	96 (80-99)	26	96 (81-100)	25	96 (80-99)
Length (>0 mm)	25	68 (50-82)	22	96 (78-100)	25	96 (80-99)	22	64 (46-80)
EPD (diameter >4.5 mm)	10	83 (52-98)	46	100 (92-100)	10	100 (69-100)	2	96 (86-99)

CI, Confidence interval; *PPV,* positive predictive value; *NPV,* negative predictive value; *CAS,* carotid angioplasty and stenting; *ICA,* internal carotid artery; *CCA,* common carotid artery; *EPD,* embolic protection device.

*Accuracy parameters and exact confidence intervals were computed with a binomial proportion for one-way tables using the F distribution method.

ability for CAS, and degree of carotid stenosis using DSA as the reference standard. Computation of binomial proportion and exact confidence limits for one-way tables was performed using the F distribution method. Findings were considered statistically significant if the resulting value *P* was <.05. The SAS 9.1 (SAS Institute, Cary, NC) and MedCalc 8.1.0.0 (MedCalc Software, Mariakerke, Belgium) software programs were used for data analyses.

RESULTS

Aortic arch, cervical, and intracranial carotid CE-MRA and DSA imaging data were available for comparison in 60 CAS procedures (59 men and 1 woman) and four additional high-risk men that were ultimately considered not suitable for CAS. The median age of the study population was 64 years (IQR, 60 to 72 years). Fifty-nine percent of the cases were asymptomatic, and 41% were symptomatic. CE-MRA was performed a median of 8 days (IQR, 1 to 16 days) before DSA. Indications for CAS included high surgical risk due to severe comorbidities in 28 (44%), hostile neck (previous CEA, radical neck dissection, radiation, permanent tracheostomy) in 15 (23%), high or low primary or concomitant lesion (lesion above C2 or below the clavicle) in 12 (19%), and contralateral ICA occlusion in 9 (14%). Fifty-three patients (88%) underwent CAS with the Abbott Accunet filter, five (8%) with FilterWire EZ system, and two (4%) with Angioguard filter. Abbott Acculink carotid stents (Abbott Vascular, Santa Clara, Calif) were used in 50 procedures (83%), Carotid Wallstents (Boston Scientific Corp, Natick, Mass) in six (10%), and PRECISE carotid stents in 4 (7%).

Technical success was achieved in all 60 cases (100%) deemed suitable for CAS from CE-MRA findings, and results were satisfactory (residual stenosis, <20%). In all instances in which CAS was not considered suitable by CE-MRA and DSA, the procedure was not attempted. In this series, no strokes occurred during or after CAS. One patient died at home 7 days after uneventful CAS, presumably from a myocardial infarction. Thus, the overall 30-day stroke/death rate was 1.6%.

Quality analysis of CE-MRA images allowed examination either without artifacts (92%) or with artifacts (8%) that did not hinder interpretation. No CE-MRA studies were considered uninterpretable. The accuracy parameters of vessel-based evaluation with CE-MRA using DSA as the reference standard are summarized in the Table. Only in three instances was signal void found on CE-MRA, and this was considered to represent 70% stenosis.

Quantitative analysis of the degree of carotid stenosis using CE-MRA and DSA revealed significant correlation (Spearman $\rho = 0.76$; 95% CI, 0.63 to 0.85; $P < .001$; Fig 1). CE-MRA had 85% sensitivity (95% CI, 72% to 93%) to detect severe carotid stenosis and 100% specificity (95% CI, 69% to 100%), according to ROC curve analysis with an area-under-the-curve value of 0.92 (95% CI, 0.83 to 0.98). Bland-Altman analysis revealed that CE-MRA measured a lower percentage of carotid stenosis (bias, −4.4%; limits of agreement, − 22% to 13%; Fig 2). None of the CE-MRA studies resulted in the degree of stenosis being overestimated, whereas underestimation occurred in eight lesions that involved a stenosis ≥80% by DSA.

CE-MRA had 100% sensitivity and 100% specificity of to determine CAS suitability and a bovine configuration of the aortic arch. The sensitivity and specificity of CE-MRA were, respectively, 93% and 100% to determine moderate to severe ICA tortuosity, 75% and 100% for CCA tortuosity, 87% and 100% to estimate the type of aortic arch (type I vs types II and III), and 75% and 98% to detect ulcerated plaques. Correlation was excellent between CE-MRA and DSA for ICA diameter (Spearman $\rho = 0.91$; 95% CI, 0.85

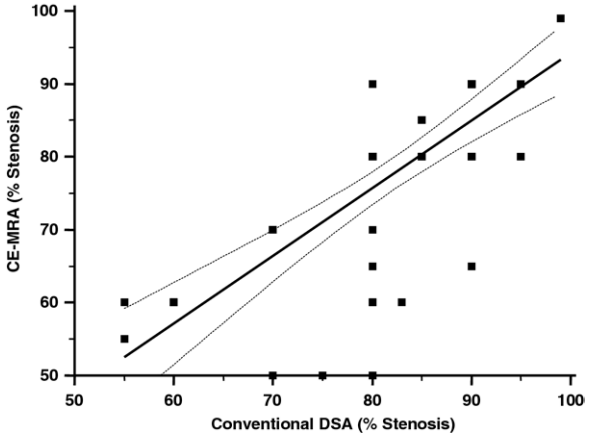

Fig 1. Scatter plots of the percentage (%) of carotid stenosis using North American Symptomatic Carotid Endarterectomy criteria for contrast-enhanced magnetic resonance angiography *(CE-MRA)* vs digital subtraction angiography *(DSA)* revealed significant correlation (Spearman ρ = 0.76; 95% confidence interval, 0.63 to 0.85; $P < .001$). The *dashed lines* indicate 95% confidence limits; the *solid line* is the line of equality.

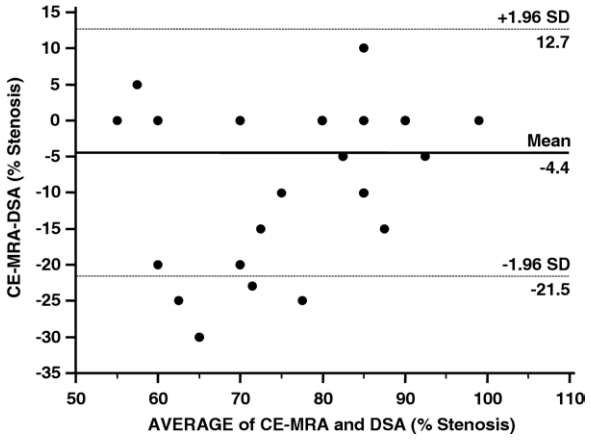

Fig 2. Bland-Altman plots reveal good agreement between measurement methods even though contrast-enhanced magnetic resonance angiography *(CE-MRA)* measured a lower percentage of carotid stenosis (*dashed lines* indicate 95% confidence limits; *solid line,* bias) than digital subtraction angiography *(DSA)*.

to 0.95; $P < .001$), distal CCA diameter (Spearman ρ = 0.92; 95% CI, 0.86 to 0.95; $P < .001$), and lesion length (Spearman ρ = 0.87; 95% CI, 0.77 to 0.92; $P < .001$) As determined by vessel size measurements, the accuracy of CE MRA to predict stent and embolic protection device (EPD) sizes was >90% (Table).

The accuracy of CE-MRA to predict the optimal DSA working projection of the aortic arch (ie, the degree of left anterior oblique angulation) was 100%. The operative technique for CAS was altered because of the findings of preoperative CE-MRA in 22 procedures (38%). The most frequent change was the use of the telescoping technique in 11 CAS procedures (18%). This technique, in which the sheath or guiding catheter are advanced over a hydrophilic guidewire and a diagnostic catheter into the CCA,[19] was primarily used when CE-MRA and DSA revealed that the target lesion was located in the distal CCA (n = 6), the external carotid artery was occluded (n = 2), or for severe arch tortuosity (types II and III; n = 3). The use of different types of stents based on CE-MRA findings occurred in seven CAS procedures (11%), and the use of different guiding or diagnostic catheters in six (9%). In five patients (8%), CE-MRA revealed proximal common carotid (n = 4) and innominate (n = 1) lesions that were verified with DSA and required proximal balloon angioplasty and stent placement. Four patients (6%) were not treated with CAS because of unfavorable anatomy identified on CE-MRA and confirmed with DSA, including prohibitive ICA tortuosity (n = 1) that precluded the use of an EPD, long string sign of the ICA (n = 2), and concomitant intracranial disease (n = 1).

DISCUSSION

The results of our study indicate that although CE-MRA may not be as accurate as DSA to determine the degree of carotid stenosis, it does provide very accurate information about aortic arch and carotid morphology that may facilitate and alter the procedural protocol and technique for CAS. Moreover, certain anatomic contraindications for CAS may be detected with CE-MRA, obviating the need for DSA. Certain procedural details, such as imaging angles, vessel size measurements, and stent and EPD size, which may facilitate safe and expeditious CAS, can be accurately predicted preoperatively with CE-MRA.

CE-MRA, CTA, and DUI are noninvasive methods that have been evaluated as possible alternatives to DSA, which is still considered the gold standard, to determine the degree of carotid stenosis. Because of the definite risk of local and systemic complications associated with carotid DSA, many surgeons proceed with CEA with the sole evaluation provided by DUI. CE-MRA has, however, often been used to corroborate the degree of carotid stenosis determined with DUI before CEA. Overall, most observational studies evaluating the utility of CE-MRA to assess the degree of carotid stenosis have consistently revealed a strong correlation with DSA as the reference standard, although an occasional tendency toward overestimation has been reported with CE-MRA.[2-6,26] Of interest, no overestimations of ICA stenosis were noted on CE-MRA in our series; conversely, 7 of 53 severe (≥80%) stenoses were underestimated.

Previous observational studies reporting overestimations have included a wide range of ICA stenosis, with a significant number of lesions with mild (<50%) stenosis.[2-6] The absence of overestimations in this study may be explained by the preferential inclusion of patients with severe (80% to 99%) carotid stenosis (53/64 lesions [83%]). Moreover, the use of ideal DSA imaging angles and projections predicted with CE-MRA instead of the conventional two-view DSA and more conservative estimation of the

degree of ICA stenosis, given the previously reported tendency for overestimation, may also account for the lack of overestimations.

Underestimations of the degree of carotid stenosis with CE-MRA, on the other hand, probably occurred because of the presence of a signal void in all these lesions, which is usually assumed by most neuroradiologists to represent a >70% stenosis according to previous studies.[22,27] In our data set, the degree of stenosis was entered arbitrarily as 70% when a signal void was observed; such carotid stenoses, however, proved to be >80% with DSA in all cases.

CE-MRA has been frequently used to corroborate the degree of carotid stenosis determined with DUI before CEA, but to our knowledge, its specific utility in planning CAS has not been reported. Because of the greater number of projections available and higher spatial resolution that allows routine evaluation from the aortic arch to the circle of Willis, 3D CE-MRA has become our diagnostic imaging modality of choice to evaluate patients before CAS. Compared with previous pulse sequences to perform MRA, such as time-of-flight angiography, CE-MRA provides higher image resolution, larger imaging fields, nearly complete absence of motion and flow-related artifacts, shorter acquisition times, and enhanced postprocessing and subtraction algorithms that can depict aortic arch and carotid morphology in great detail.[28]

Although CTA has been used to assess patients before CAS,[29] the use of ionizing radiation and potentially nephrotoxic iodinated contrast agents make it less attractive in routine clinical practice. Moreover, because CAS may be required urgently, particularly in symptomatic patients, avoiding a second large dose of iodinated contrast material within a short time span may be desirable.

Obviously, CTA should be the primary assessment in patients with pacemakers, implants, and metallic stents. Octogenarians and patients with heavily calcified plaques may also be preferentially evaluated with CTA because it allows enhanced visualization of vessel walls and plaques. Because recent reports have revealed that gadolinium compounds have been linked to the development of nephrogenic systemic fibrosis in patients with renal insufficiency, the use of gadolinium-based contrast agents in this patient population is not currently defined.[30] Of note, no specific instances of nephrogenic systemic fibrosis have been associated with the use of gadoteridol (ProHance, Bracco Diagnostics, Princeton,NJ), the contrast agent used for CE-MRA in our series.

The safety and efficacy of CAS are primarily related to patient selection, materials used, and operator experience. Although both medical and anatomic factors may influence the outcome of any carotid intervention, aortic arch and carotid morphology are of utmost importance in patient selection. In our study, CE-MRA had high diagnostic accuracy in the evaluation of the type of aortic arch and carotid tortuosity, the main limiting anatomic factors for CAS.

The preoperative noninvasive identification of the type of aortic arch and associated carotid tortuosity resulted in a substantial change in our CAS technique in 38% of the procedures. The use of the telescoping technique for advancing a sheath or guiding catheter into the distal CCA and the selection of a different diagnostic catheter or guidewire were frequently determined preoperatively in patients with type II and III aortic arches or carotid tortuosity, or both, on the basis of the CE-MRA findings.

These procedural changes certainly resulted in the avoidance of excessive catheter and wire manipulations in the aortic arch and the CCAs. As demonstrated by Hammer et al,[31] cerebral embolization may primarily originate from the aortic arch, because embolic lesions are frequently found outside the vascular territory of the target ICA. One patient in our series was not treated with CAS because of severe ICA tortuosity noted on CE-MRA. Therefore, our data show that preoperative decisions can be based on aortic arch and carotid morphology determined with CE-MRA, avoiding patients with difficult anatomy and minimizing catheter manipulations. Although all CAS procedures in the current series were supervised by an experienced interventionalist who had performed >100 CAS procedures, the primary operators of most of the cases were vascular surgery fellows with no prior training in carotid interventions. CE-MRA findings allowed accurate planning of most of the CAS procedures by the trainees with the staff vascular surgeon. In this regard, preoperative carotid and arch CE-MRA could potentially contribute to accelerate the learning curve for CAS, particularly in academic centers.

In our series, all CAS procedures were performed with distal filter protection devices because these were the only EPDs commercially available in the United States during the study period. CE-MRA was highly accurate in determining the ICA diameter at the level of the potential EPD deployment location, which resulted in a very accurate prediction of the size of filter to be used. Moreover, ICA tortuosity was also successfully assessed with CE-MRA for potential difficulties in advancing an EPD. As noted, one patient did not undergo CAS owing to prohibitive tortuosity of the proximal ICA that prevented safe placement of any filter EPD. As new EPDs are introduced, particularly occlusive systems with reversal of flow, the importance of preoperative evaluation of collateral intracranial circulation and carotid tortuosity with CE-MRA may be essential to identify patients that may not tolerate CAS with temporary complete ICA occlusion.

The CE-MRA findings resulted in a different type of stent being used for CAS in seven patients (8%). Five were symptomatic and had evidence of deep carotid plaque ulcerations with high-grade stenosis. Two of these patients underwent plaque composition analysis with intravascular ultrasound imaging that confirmed large areas of necrotic core with ruptured overlying thin fibrous cap. Because of the potential increased risk of cerebral embolic events among patients with carotid stenosis and ulcerated plaques,[32] closed-cell stents were used and postdilatation was avoided to prevent the potential squeezing of plaque material through the interstices of the stent. Conversely,

three patients with significant proximal ICA tortuosity underwent CAS with more flexible open-cell nitinol stents that may accommodate better to tortuous vessels. CE-MRA also accurately predicted stent size required for most lesions based on lesion length and vessel diameter measurements, which may be helpful in materials selection, particularly in settings with limited resources.

CONCLUSION

Our results show that CE-MRA is an effective preoperative imaging study in planning CAS because it provides complete and accurate anatomic assessment from the aortic arch to the intracranial circulation that may be particularly useful during the early experience with CAS. Moreover, procedural details such as optimal working projections and imaging views, vessel size, and EPD and stent configurations can be accurately predicted with CE-MRA. This may result in shorter operative and fluoroscopy times and fewer catheter and wire manipulations that may improve technical success and outcomes. Because most patients in this study were men, our results should be interpreted with caution in relation to women; indeed, the accuracy of CE-MRA in planning CAS for women remains to be determined.

Finally, future developments such as the introduction of newer contrast agents that may enhance signal intensity and further refinements in high-spatial-resolution MRI to evaluate plaque morphology and composition will certainly make CE-MRA and MRI of the carotid plaque and brain the technique of choice for the evaluation of patients before CAS because most diagnostic information will be obtainable in a single comprehensive noninvasive imaging study.

AUTHOR CONTRIBUTIONS

Conception and design: CT, JM
Analysis and interpretation: CT, ER, RV, GC
Data collection: CT, ER, SM
Writing the article: CT, ER, SM, RV, GC, JM
Critical revision of the article: CT, ER, SM, RV, GC, JM
Final approval of the article: CT, ER, SM, RV, GC, JM
Statistical analysis: CT, ER
Obtained funding: CT
Overall responsibility: CT

REFERENCES

1. Hessel SJ, Adams DF, Abrams HL. Complications of angiography. Radiology 1981;2:273-81.
2. Enochs WS, Ackerman RH, Kaufman JA, Candia M. Gadolinium-enhanced MR angiography of the carotid arteries. J Neuroimaging 1998;4:185-90.
3. Scarabino T, Carriero A, Giannatempo GM, Marano R, De MP, Bonomo L, et al. Contrast-enhanced MR angiography (CE MRA) in the study of the carotid stenosis: comparison with digital subtraction angiography (DSA). J Neuroradiol 1999;2:87-91.
4. Randoux B, Marro B, Koskas F, Duyme M, Sahel M, Zouaoui A, et al. Carotid artery stenosis: prospective comparison of CT, three-dimensional gadolinium-enhanced MR, and conventional angiography. Radiology 2001;1:179-85.
5. Hathout GM, Duh MJ, El-Saden SM. Accuracy of contrast-enhanced MR angiography in predicting angiographic stenosis of the internal carotid artery: linear regression analysis. AJNR Am J Neuroradiol 2003;9:1747-56.
6. Anzalone N, Scomazzoni F, Castellano R, Strada L, Righi C, Politi LS, et al. Carotid artery stenosis: intraindividual correlations of 3D time-of-flight MR angiography, contrast-enhanced MR angiography, conventional DSA, and rotational angiography for detection and grading. Radiology 2005;1:204-13.
7. Veith FJ, Amor M, Ohki T, Beebe HG, Bell PRF, Bolia A, et al. Current status of carotid bifurcation angioplasty and stenting based on a consensus of opinion leaders. J Vasc Surg 2001;2:S111-6.
8. Ohki T, Veith FJ, Grenell S, Lipsitz EC, Gargiulo N, Mckay J, et al. Initial experience with cerebral protection devices to prevent embolization during carotid artery stenting. J Vasc Surg 2002;6:1175-85.
9. Ohki T, Roubin GS, Veith FJ, Iyer SS, Brady E. Efficacy of a filter device in the prevention of embolic events during carotid angioplasty and stenting: An ex vivo analysis. J Vasc Surg 1999;6:1034-42.
10. Yadav JS, Wholey MH, Kuntz RE, Fayad P, Katzen BT, Mishkel GJ, et al. Protected carotid-artery stenting versus endarterectomy in high-risk patients. N Engl J Med 2004;15:1493-501.
11. Ringleb PA, Allenberg J, Bruckmann H, Eckstein HH, Fraedrich G, Hartmann M, et al. 30 day results from the SPACE trial of stent-protected angioplasty versus carotid endarterectomy in symptomatic patients: a randomised non-inferiority trial. Lancet 2006;9543:1239-47.
12. Mas JL, Chatellier G, Beyssen B, Branchereau A, Moulin T, Becquemin JP, et al. Endarterectomy versus stenting in patients with symptomatic severe carotid stenosis. N Engl J Med 2006;16:1660-71.
13. Hobson RW. CREST (Carotid Revascularization Endarterectomy versus Stent Trial): background, design, and current status. Semin Vasc Surg 2000;2:139-43.
14. Asymptomatic Carotid Surgery Trial-2 (ACST - 2). MRC asymptomatic carotid surgery trial (ACST) collaborative group. http://www.acst.org.uk/index.htm. Accessed December 30, 2006.
15. Lin PH, Bush RL, Peden EK, Zhou W, Guerrero M, Henao EA, et al. Carotid artery stenting with neuroprotection: assessing the learning curve and treatment outcome. Am J Surg 2005;6:850-7.
16. Verzini F, Cao P, De RP, Parlani G, Maselli A, Romano L, et al. Appropriateness of learning curve for carotid artery stenting: an analysis of periprocedural complications. J Vasc Surg 2006;6:1205-11.
17. Yadav JS, Roubin GS, King P, Iyer S, Vitek J. Angioplasty and stenting for restenosis after carotid endarterectomy. Initial experience. Stroke 1996;11:2075-9.
18. Ouriel K, Hertzer NR, Beven EG, O'hara PJ, Krajewski LP, Clair DG, et al. Preprocedural risk stratification: identifying an appropriate population for carotid stenting. J Vasc Surg 2001;4:728-32.
19. Ohki T, Timaran CH, Yadav JS. Technique of Carotid Angioplasty and Stenting. In: Moore WS, editor. Vascular and endovascular surgery: a comprehensive review. 7th ed. Philadelphia, Pa: Saunders Elsevier; 2006. p. 355-82.
20. Gray WA, Hopkins LN, Yadav S, Davis T, Wholey M, Atkinson R, et al. Protected carotid stenting in high-surgical-risk patients: the ARCHeR results. J Vasc Surg 2006;2:258-68.
21. Taylor DW. Beneficial Effect of Carotid Endarterectomy in Symptomatic Patients with High-Grade Carotid Stenosis. N Engl J Med 1991; 7:445-53.
22. Huston J, Nichols DA, Luetmer PH, Rydberg CH, Lewis BD, Meyer FB, et al. MR angiographic and sonographic indications for endarterectomy. AJNR Am J Neuroradiol 1998;2:309-15.
23. Myla SV. Carotid access techniques: an algorithmic technique. Carotid Interv 2001;2-12.
24. Lin SC, Trocciola SM, Rhee J, Dayal R, Chaer R, Morrissey NJ, et al. Analysis of anatomic factors and age in patients undergoing carotid angioplasty and stenting. Ann Vasc Surg 2005;6:798-804.
25. Setacci C, de DG, Chisci E, Setacci F, Pieraccini M, Cappelli A, et al. Is carotid artery stenting in octogenarians really dangerous? J Endovasc Ther 2006;3:302-9.
26. Johnston DC, Eastwood JD, Nguyen T, Goldstein LB. Contrast-enhanced magnetic resonance angiography of carotid arteries: utility in routine clinical practice. Stroke 2002;12:2834-8.

27. Serfaty JM, Chirossel P, Chevallier JM, Ecochard R, Froment JC, Douek PC. Accuracy of three-dimensional gadolinium-enhanced MR angiography in the assessment of extracranial carotid artery disease. AJR Am J Roentgenol 2000;2:455-63.
28. Mitra D, Connolly D, Jenkins S, English P, Birchall D, Mandel C, et al. Comparison of image quality, diagnostic confidence and interobserver variability in contrast enhanced MR angiography and 2D time of flight angiography in evaluation of carotid stenosis. Br J Radiol 2006;939: 201-7.
29. The Value of 3D-CT Angiographic Assessment Prior to Carotid Stenting. Available at: http://www.vascularweb.org/CONTRIBUTIONPAGES/AnnualMeeting/Abstracts/2006/WyersTheValueof3D-CTAngiographicAssessment.html. Accessed January 8, 2007.
30. Chewning RH, Murphy KJ. Gadolinium-based contrast media and the development of nephrogenic systemic fibrosis in patients with renal insufficiency. J Vasc Interv Radiol 2007;3:331-3.
31. Hammer FD, Lacroix V, Duprez T, Grandin C, Verhelst R, Peeters A, et al. Cerebral microembolization after protected carotid artery stenting in surgical high-risk patients: results of a 2-year prospective study. J Vasc Surg 2005;5:847-53.
32. Hatsukami TS, Ferguson MS, Beach KW, Gordon D, Detmer P, Burns D, et al. Carotid plaque morphology and clinical events. Stroke 1997; 1:95-100.

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DISCUSSION

Dr William Jordan (Birmingham, Ala). First, I want to congratulate Dr Timaran and his colleagues with his presentation of this important treatment algorithm for carotid artery stenting. In their series, he has demonstrated the utility of using additional imaging of contrast-enhanced MRA to direct the planning of the procedures specifically related to the aortic arch morphology, the location of the stenosis, and the course of the distal carotid artery. The proximal and distal arterial anatomy is not well imaged with duplex ultrasound, thus making the adjunctive step of MRA a helpful one to discover some anatomic limitations that might make carotid stenting difficult.

The authors presented a very respectable clinical series of 60 patients, with only one death and no strokes. The stroke rate clearly represents fine work that rivals some of the best reports in the literature and clearly exceeds some of the early reports of 9% stroke rates in the mid-90s. Currently, stroke rates are reported in the 3% to 6% range, with the most scientifically valid randomized clinical trials of EVA 3S and SPACE reporting rates of 6%, which brings to light the first question. You had no strokes in your series, and one presumed cardiac death. Can you provide us with a glimpse of your carotid experience? This report represents two thirds of your total cases. Did you do 30 cases first and then embark on MRA to assist in case planning? Specifically, how many cases did you accomplish prior to the series to reach the rate of no strokes?

When we look at our series from UAB in the 90s, we found our learning curve to be almost 300 patients before the stroke rate plunged from 9% to 3%. Some experts have suggested a learning curve of 50 cases before one can be considered an experienced carotid interventionalist. My personal experience, which suggests learning from other nonsurgical "experts," would place the learning curve well below the 50 cases that some have suggested or even 30 cases in some of the randomized protocols. I would appreciate your comment on that principle of learning curve.

Second, I suspect many carotid interventionalists would suggest the MRA is not required once you gained that initial experience. That is, an arteriogram will define the anatomic limitations that would direct you to what catheter guide to use to cannulate the vessel of interest. Additionally, the duplex scan should define the location of stenosis, whether it is proximal or distal to the external origin, and the initial angiogram can define the distal and the proximal morphology to determine the best protection device. Said more plainly, can't you simply figure this out when you get there rather than spending a few thousand dollars on a MRA prior to the procedure?

Finally, I suspect you are using this MRA to aid in the planning process during your learning curve. This tool can help you decide whether to take this patient to the next step of an angiogram and stenting; therefore, the MRA would be a nice planning tool to limit the length or slope of your learning curve, particularly if you can limit all strokes by avoiding complex anatomy as you have done in this series. So, was the additional anatomic information really needed to be a contrast enhanced MRA?

What about those patients that have a pacemaker or defibrillator? You know, those are being implanted almost as fast as carotid stents these days. It seems that CT angio could provide the same information and, actually, why not simply a time-of-flight MR scan or a noncontrast CT scan? We can get lots of information this way.

Once again, let me congratulate you on your presentation and the elegant statistical analysis that your manuscript accomplishes on using this mechanism, but let me remind the rest of here today that we as vascular surgeons remain the single discpline that can offer both modalities of carotid surgery and stenting for a more balanced approach of treating carotid disease. Thank you for providing me a copy of the manuscript in a timely fashion well before the meeting and for the privilege of the floor to discuss this paper.

Dr Carlos Timaran: I was fortunate to perform a fair amount of carotid stenting cases during my fellowship training prior to joining UT Southwestern. I did my fellowship with Drs Ohki and Veith at Montefiore Medical Center, and I was probably able to perform about 50 carotid stenting cases as the primary operator and another 50 or 60 cases as the assistant. Obviously, training and experience give you some advantage, but I still believe you have to plan these cases thoroughly because you never know what you are going to encounter anatomically.

Of note, it is curious that I only began to use CE-MRA for planning carotid stenting when I joined UT Southwestern, primarily because the patients that were referred for carotid interventions already had MRAs, which were usually of excellent quality. Clearly, I was really pleased to see such MRA images. I was also able to do all kinds of 3D reconstructions and manipulations of the images using software, which prompted me to obtain CE-MRAs in everybody considered for carotid stenting. Indeed, we currently do it for almost everybody, except for those patients that have contraindications for MRI, including patients with pacemakers or defibrillators. Again, we try to get it in every patient, and despite our increasing experience, we have not changed our practice.

Initially, we did it primarily because we had limited resources, so CE-MRA allowed us to know if we needed to get extra materials that we did not have in our shelves. Currently, we have almost everything that is available for carotid stenting, but we still obtain CE-MRA for different reasons. I think it is very important, particularly in teaching institutions, to go over these cases in detail prior to the actual procedures with trainees because this may result in a more expeditious procedure with decreased catheter and wire manipulation of the aortic arch and the carotid arteries.

I think that if you get CE-MRA prior to carotid stenting with excellent imaging, the learning curve may actually be shortened because you do not have to do as many cases to learn different alternatives. In fact, MRAs can certainly allow you to plan these procedures more effectively. Obviously, carotid duplex gives you a lot of information, but I prefer to see the images and do the 3D reconstructions myself. Moreover, if you have a symptomatic patient, you are going to have to image the brain anyway, and CE-MRA does not add much time or effort to a regular brain MRI.

Finally, MRI is a rapidly evolving imaging technique, and recent studies have shown that plaque composition can actually be assessed with carotid coils. Thus, I think MRI is going to be probably the tool of choice to evaluate carotid stenosis because brain MRI, aortic arch and carotid MRA, and plaque composition will all be obtained in one setting. For patients with contradictions for MRI, CTA is the best option as well as for patients with heavy calcification and octogenarians. For the latter, CTA is particularly important because it is imperative not only to image the arch but also to assess the vessel wall as plaque at this level can be the source of emboli during carotid stenting in elderly patients.

INVITED COMMENTARY

Christopher J. Kwolek, MD, *Boston, Mass*

Dr Timaran and his colleagues have provided us with a timely article discussing the potential use of magnetic resonance angiography (MRA) in the preprocedural evaluation of patients undergoing carotid angioplasty and stenting (CAS). This has become more relevant given the recent publication of several trials which call into question the efficacy of CAS compared with CEA for stroke prevention. Discussion of these papers has once again brought out the importance of careful patient selection, appropriate physician training and experience, along with careful preprocedural planning to minimize the risk of complications associated with CAS.

MRA may prove useful in identifying individual anatomic factors such as the presence of ulcerated plaque, arch type, and severe tortuosity. However, suitability for stenting is based not only on anatomic factors, but also the individual physician's experience and the types of protection devices available. In addition, some institutions may prefer computed tomography angiograms (CTA) as a more readily available or easier to interpret form of noninvasive arterial imaging.

The current study is also limited in its generalized applicability given the fact that only one woman and no patients over the age of 80 were included in the evaluation. It is now well recognized that octogenarians comprise a high risk subset of patients undergoing CAS.

Future studies will hopefully elucidate which patients will benefit most from preprocedural MR angiogram. In addition, it will be important to justify the additional cost associated with this procedure, since many centers report excellent results without using MRA. Perhaps, it will be most useful for operators early in their learning curve or in certain high risk groups of patients who may have more complex anatomy such as those over the age of 80.