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Imaging of Carotid Artery Stenosis: Clinical Efficacy and Cost-effectiveness

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PURPOSE: To determine the most accurate, safe, and cost-effective imaging protocol for selecting patients for carotid endarterectomy. **METHODS:** The actual costs of carotid angiography, ultrasound, and MR angiography were calculated. The diagnostic accuracy with different confidence levels was assessed for carotid ultrasound and MR angiography in 45 patients. The cost-effectiveness and theoretical impact on patient outcome of hypothetical screening models were compared. **RESULTS:** Ultrasound before angiography is more effective and considerably cheaper than performing angiography in all patients presenting with transient ischemic attacks (\$25 216 versus \$48 708 imaging costs per one prevented stroke). When the more costly MR angiography was used to select patients for angiography the slightly higher diagnostic accuracy did not result in a greater number of prevented strokes. As the only preoperative scrutiny, the combination of ultrasound and MR angiography would have resulted in a greater number of prevented strokes than invasive angiography (27.9 versus 23.3) but at the expense of unnecessary surgery (6.6% of all surgeries). **CONCLUSIONS:** Ultrasound followed by confirmatory angiography is a cost-effective way to image patients suspected of carotid artery stenosis. MR angiography may become cost effective and lead to a better final patient outcome only when it can reliably replace invasive angiography as the preoperative examination.

Index terms: Arteries, stenosis and occlusion; Economics; Efficacy studies

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During the last few years, the convincing results of both the North American Symptomatic Carotid Endarterectomy Trial (NASCET) (1) and the European Carotid Surgery Trial (2) have set the indications for carotid endarterectomy. At the same time, the imaging methods for carotid artery stenosis have undergone rapid development. Angiographic catheters, contrast materials, and methods have changed, and digital subtraction angiography has replaced conventional film-screen angiography at many institutions. Color-coded Doppler ultrasound has been demonstrated to depict residual lumen

more accurately than conventional ultrasound (3). Magnetic resonance (MR) angiography has emerged as an accurate tool for noninvasive evaluation of carotid stenosis (4, 5) and seems to be on the verge of being able to replace conventional invasive angiography in presurgical evaluation (6, 7).

When determining which of the imaging methods mentioned above should be used in the evaluation of carotid artery stenosis, the prime concern in clinical decision making is the diagnostic performance (sensitivity, specificity, and predictive value) of the test. However, financial aspects have become increasingly significant in all sectors of health care, and it is also important to analyze critically the clinical efficacy and cost-effectiveness of the different examinations and their combinations (8–11). Can savings be realized without adversely affecting quality? What is the ultimate benefit to patients that is derived from these examinations?

This paper reviews different carotid artery imaging methods, analyzes their clinical efficacy

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and cost-effectiveness using data from the recent literature and our own patient material, and discusses the results to choose the most accurate, safe, and cost-effective imaging protocol for selecting patients for carotid endarterectomy.

Materials and Methods

Forty-five consecutive patients with ischemic symptoms from the carotid artery territory were studied with ultrasound, MR angiography, and digital subtraction angiography. The diagnostic accuracy of ultrasound and MR angiography was calculated against that of digital subtraction angiography, and the different confidence levels of a positive diagnosis were registered. The actual costs of these three methods in our hospital were calculated. Using these data, several hypothetical imaging models were created for detecting severe carotid stenosis indicating carotid endarterectomy, and their impact on patient outcome and their cost-effectiveness were calculated in light of recent estimates of absolute risk reduction after carotid endarterectomy (1) and major complication rates after invasive angiography (12, 13). The efficacy of the method, the possible risk of serious complications, the likelihood of positive findings in a certain group of patients, and the likelihood of the finding to change the patient's outcome were considered against the cost.

Patients

The study population consisted of 45 consecutive patients who were referred by a neurologist for aortic arch and carotid artery angiography because of hemispheric or retinal transient ischemic attacks or nondisabling stroke. In addition to digital subtraction angiography, all patients underwent carotid ultrasound and MR angiography for investigational reasons (14). The practice of the neurologists was to evaluate patients with digital subtraction angiography if the symptoms were highly indicative of carotid stenosis and surgery was considered. Thus, there was no obvious embolic source from the heart or coexisting serious diseases contraindicating surgery, and the patient approved of the possible surgery. When the symptoms were more indeterminate (such as vertigo), or the patient was aged or in poor general condition, had other serious diseases or was doubtful about the possible surgery, the practice was to refer the patient for Doppler ultrasound. On the basis of hospital records, the number of carotid Doppler ultrasound examinations was three times higher than that of digital subtraction angiography during the study period of 1 year. Thirty-eight of the patients were men, and seven were women, with a mean age of 58 years (range, 34 to 72 years). Clinical auscultation revealed a carotid artery bruit unilaterally in 11 cases and bilaterally in 4 cases. Informed consent was obtained from all patients, and the study was approved by the Ethics Committee of the hospital.

Interventions

The clinical routine consists of a three-step intervention: (a) clinical examination by a neurologist, (b) imaging studies, and (c) carotid endarterectomy or conservative treatment. In the present material, we analyzed only the effects of variations of step b and assumed that steps a and c were kept constant. Thus, the neurologist selects the patients for the imaging studies on grounds similar to those by which the study population was selected: the patient had ischemic symptoms from the carotid artery territory, was otherwise fit for surgery, and approved of possible surgery. This decision was not affected by the possible presence of a carotid bruit, which is not sufficiently predictive of high-grade stenosis to be useful in selecting patients for angiography (15). Second, the complication rate associated with the surgery was assumed to be similar to that in the NASCET, leading to a constant absolute risk reduction rate achieved with carotid endarterectomy.

Carotid Artery Imaging

Each patient was evaluated with color-coded Doppler ultrasound, MR angiography, and invasive angiography within 24 hours of each other. The results of each examination were evaluated without knowledge of the results of the other examinations. All Doppler ultrasound examinations were performed by the same radiologist. An ultrasound system with a 5-MHz linear-array probe with duplex and color-coded Doppler capability was used. The internal carotid peak systolic velocity of 2.3 m/s was used as the threshold value for severe (>70%) stenosis (16).

MR angiography was performed with a 1.5-T whole-body imaging system using commercially available neck and head coils. A three-dimensional time-of-flight angiography acquisition with 64 transaxial partitions was performed at the level of the carotid bifurcations. If the right and left bifurcation were situated at different levels, two axial 3-D slabs were obtained. Parameters of 30/6/1 (repetition time/echo time/excitations), flip angle of 20°, 230-mm field of view, 160 × 256 matrix, and superior saturation band were used. The slab thickness was 5.2 to 6.4 cm, resulting in an effective section thickness of 0.8 to 1 mm. After the imaging of the brain, a double slab sagittal 3-D time-of-flight angiography of the internal carotid arteries (50/6, 25° flip angle, 32 partitions) was performed using the head coil. Angiographic projections were generated with a maximum-intensity projection algorithm and multiple-planar reconstruction images. The judgment of the stenosis degree was made after visual evaluation of the targeted maximum-intensity projection and multiple-planar reconstruction images of the bifurcations and the individual source images.

Intraarterial selective carotid angiography was performed using digital subtraction angiography equipment. Both carotid bifurcations were studied in at least two pro-

TABLE 1: Imaging models for the screening of severe carotid artery stenosis in patients with transient ischemic attacks and nondisabling stroke

Model 1	All patients undergo angiography and CT of the brain.
Model 2	All patients undergo Doppler ultrasound and CT of the brain. Angiography performed if ultrasound indicative of definite severe stenosis.
Model 3	All patients undergo Doppler ultrasound and CT of the brain. Angiography performed if ultrasound indicative of definite or possible severe stenosis, occlusion or the findings are questionable.
Model 4	All patients undergo MR angiography and MR imaging of the brain. Angiography performed if MR angiography indicative of definite severe stenosis.
Model 5	All patients undergo MR angiography and MR imaging of the brain. Angiography performed if MR angiography indicative of definite or possible severe stenosis or occlusion or the findings are questionable.
Model 6	All patients undergo detailed MR angiography and MR imaging of the brain.
Model 7	All patients undergo Doppler ultrasound Detailed MR angiography and MR imaging of the brain performed if ultrasound indicative of definite or possible severe stenosis or occlusion, or the findings are questionable. CT of the brain performed for the remaining patients.

jections, and the stenosis degree was measured according to the NASCET measurement criteria (1). There were no angiography-related major complications.

The diagnostic performance of MR angiography and Doppler ultrasound in the detection of severe stenosis was calculated from the total material of 90 carotid bifurcations, using the stenosis degree measured from the angiographic images as the standard. In addition, in both the MR angiography and ultrasound examinations the bifurcations were classified for the presence of severe (70% to 99%) stenosis with a six-category scale of confidence levels: (a) definitely not present, (b) probably not present, (c) questionable, (d) possibly present, (e) definitely present, and (f) occluded.

Different Models for the Imaging Strategies

For calculating the clinical efficacy and cost-effectiveness of the carotid artery imaging methods, several hypothetical models were created to evaluate symptomatic patients for the presence of severe carotid artery stenosis of 70% to 99% (Table 1). This threshold stenosis degree was

selected because the usefulness of surgery has been clearly demonstrated in this group of patients, whereas for patients with moderate stenosis of 30% to 69% the balance of surgical risk and benefit remains undetermined (1, 2).

In the first model, angiography is used as the only carotid artery imaging procedure for all patients. In the other models, the patients are first examined with either Doppler ultrasound or MR angiography, and only a portion of the patients undergo angiography as a confirmatory presurgical examination. Two alternatives were used in these latter models. The first possibility was that only those patients with high-probability findings (definite severe stenosis in the screening test) are referred for digital subtraction angiography, leading to a small possibility that surgery is withheld in some persons with false-negative findings. The second alternative was to refer for angiography also the lower-probability findings. Thus, the following groups were also included: (a) severe stenosis is considered possible; (b) the diagnostic quality of the examination is not optimal, and the findings are considered questionable; and (c) the carotid artery is considered occluded. It has been emphasized that contrast angiography remains the only method for reliably distinguishing those vessels with only hairline patency from total occlusions (17). The last models we used assume that the diagnostic accuracy of detailed MR angiography is considered sufficient to obviate invasive angiography, and that the patients undergo surgery on the basis of MR angiography studies. The coils and pulse sequences undergo continuous improvement; preliminary reports suggesting this approach have already been published (6, 7, 18).

Patients with transient or permanent ischemic symptoms also always undergo imaging of the brain, usually computed tomography (CT). As the CT with its additional cost becomes unnecessary if the patient undergoes MR of the brain in the same session with MR angiography, these expenses were also included in the figures. According to our experience, contrast enhancement is used in approximately 10% of these CT examinations.

Calculation of the Costs of the Examinations

The general reformation in public health care financing in our country has led to a revision in the budgeting of the hospitals. Among others, our hospital has assessed the actual expenses of the different procedures in patient care and uses these as the basis for its charges. Accordingly, the Department of Clinical Radiology has calculated the average costs of every radiologic examination on the basis of the departmental budget. The department performed 97 000 radiologic examinations in 1993 and has one MR unit, two CT machines, and three angiography laboratories. The analysis of computerized financial data and the cost assessment were performed using a computer program developed by the hospital coalition of our country. The calculated average cost of a radiologic examination consists of four separate divisions: fixed costs (examination room and equipment), material costs, personnel costs (radiologists and nursing staff), and general costs (admin-

istration and support services). Amortization of the capital costs of imaging equipment over the equipment's technological lifetime were included in the fixed costs. The components of the different expenses for the individual examinations are shown in Table 2, and the calculated costs of the radiologic examinations (1994) used in the present study, expressed as US dollars according to November 1994 rate of exchange, are given in Table 3.

When the costs of angiography were calculated, the ward expenses associated with the observation time after angiography, including room, supplies, and pharmacy, were also taken into account (Table 3). In our hospital, approximately 25% of patients referred for aortic arch and

carotid artery angiography undergo the examination on an outpatient basis and are observed for approximately 4 hours after the examination. The majority of the patients (75%) are hospitalized overnight.

Analysis of the Clinical Efficacy

First, the effect of the different imaging strategies on the final patient outcome was calculated using the data derived from the study population and from a review of the literature. Because the particular aim was to analyze therapeutic and patient-outcome efficacy, the health outcomes of patients rather than diagnostic accuracy were used as the final criterion (9–11). The term *efficacy* here overlaps partly with the idea of effectiveness (9). The following assumptions were used in the calculations: (a) the prevalence of severe stenosis in the patients referred for diagnostic imaging is the same as that in the study population; (b) the diagnostic performance of magnetic resonance angiography and ultrasound remains the same as in the study population; (c) the angiography complication rate for major stroke and death is 0.5% as reported in the recent literature (12, 13) and is not affected by the severity of stenosis; and (d) the absolute risk reduction for major stroke and death achieved by carotid endarterectomy is 10.6% as reported in the NASCET (1). Second, the costs of the imaging procedures in the different models were calculated per patient. Third, using these figures and taking into account the sensitivity of the imaging procedures, the complication rate associated with the imaging, and the risk reduction rate achieved, the price of the imaging studies necessary to prevent one stroke was finally calculated.

Results

The diagnostic performance of Doppler ultrasound and MR angiography in the detection of definite severe stenosis of 70% to 99% was first calculated from the material of the 90 carotid bifurcations of the study population (Table 4). To test the diagnostic performance of imaging models 3, 5, and 7, different criteria were used for a positive finding in Doppler ultrasound or MR angiography. The finding was interpreted as positive if the presence of severe stenosis was considered definite, possible, or questionable, or if the artery was considered occluded. Sensitivity now reached 100% for both Doppler ultrasound and MR angiography, but specificity was clearly lower (Table 4). According to the results of angiography, the mean stenosis degree in the material was 30% (range, 0% to 100%).

The theoretical patient outcome was analyzed for the different imaging models. The data

TABLE 2: Construction of the costs of some radiologic examinations

Examination	Components of the Calculated Expenses, %			
	Fixed*	Material†	Personnel‡	General§
Angiography	30	37	22	11
Doppler ultrasound	17	4	64	15
MR angiography	56	12	21	11
CT	51	2	34	13
unenhanced				
enhanced	43	14	31	12

* Expenses of the examination room and equipment.

† Expenses of all material used (eg, films, contrast material, and catheters).

‡ Expenses of the radiologists and nursing staff.

§ Expenses of the administration, support services such as typing and cleaning, and miscellaneous expenses.

TABLE 3: Calculated costs of some radiologic examinations*, including professional fees (1994)

Examination	US\$†
Digital subtraction angiography	783
Observation time‡	
outpatient	75
overnight	150
Color Doppler ultrasound	130
MR angiography, including MR imaging of the brain	
Limited§	771
Detailed	985
CT	
Unenhanced	201
Unenhanced + enhanced	393

* Imaging methods routinely used in the diagnosis of patients with transient ischemic attacks or nondisabling stroke.

† According to November 1994 rate of exchange.

‡ Charge for ward services during the observation time includes room, supplies, and pharmacy.

§ Limited MR angiography includes two or three sequences, covering the carotid bifurcations and distal portions of the internal carotid arteries.

|| Detailed MR angiography includes full preoperative evaluation and covers vessels from the aortic arch to the circle of Willis.

TABLE 4: Diagnostic performance of Doppler ultrasound and MR angiography compared with angiography in 90 carotid bifurcations*

	Sensitivity, % (95% confidence interval)	Specificity, % (95% confidence interval)	Overall Accuracy, %	Positive Predictive Value, %	Negative Predictive Value, %
Doppler ultrasound†					
Definite stenosis	92.9 (64.4–99.6)	93.4 (84.7–97.5)	93.3	72.2	98.6
Possible stenosis	100 (76.8–100)	79.0 (67.8–87.1)	82.2	46.7	100
MR angiography†					
Definite stenosis	92.9 (64.4–99.6)	94.7 (86.4–98.3)	94.4	76.5	98.6
Possible stenosis	100 (76.8–100)	82.9 (72.2–90.2)	85.6	51.9	100

* Two levels of confidence in the interpretation of severe (>70%) carotid artery stenosis.

† Doppler ultrasound and MR angiography examinations were classified for the presence of severe (70% to 99%) stenosis with a six-category scale of probability. Definite stenosis is $\geq 70\%$ stenosis definitely present; possible stenosis, $\geq 70\%$ stenosis definitely or possibly present, the findings are considered questionable, or the artery is considered to be occluded.

regarding the prevalence of severe stenoses and diagnostic accuracy of Doppler ultrasound and MR angiography, collected in the study population, were extended to a theoretical population of 1000 patients referred for a carotid imaging examination, and the number of prevented strokes was calculated.

In the first model, in which all patients undergo angiography, the diagnostic accuracy is 100%. All patients are subjected to the angiography-related major complication rate of 0.5%, resulting in 5 major strokes or deaths in a population of 1000 patients. The prevalence of severe carotid artery stenosis on the symptomatic side was 26.7% in the present material. Thus, 267 patients are supposed to undergo carotid endarterectomy. The absolute risk reduction of the patients operated on is 10.6%, leading to 28.3 prevented strokes among the patients operated on. However, 5 patients had major neurologic complications from angiography, and the net number of the prevented strokes is 23.3.

In the second model, all patients are initially examined by Doppler ultrasound and those with a definite severe stenosis on the symptomatic side are further referred for angiography. The sensitivity of Doppler ultrasound is 92.9%, and the specificity is 93.4%. Consequently, both the 248 ultrasound true-positive cases and the 48 ultrasound false-positive cases are referred for angiography; thus, 29.6% of the patients are subjected to the major angiographic complication rate of 0.5%, leading to 1.5 strokes or deaths in 1000 patients. Angiography shows a severe ipsilateral stenosis in 248 patients; 19 severe ipsilateral stenoses were missed on ultrasound. Carotid endarterectomy is performed in 24.8% of the patients, and subsequently, 26.3

strokes are prevented in the patients operated on. When the 1.5 angiography-related strokes are deducted, the net number of prevented strokes is 24.8.

In the third model, all patients are also initially examined with Doppler ultrasound, and those with a possible (see Table 4) severe stenosis on the symptomatic side are further referred for angiography and subjected to the angiography complication rate of 0.5%. The sensitivity of this model is 100%, and no severe stenoses are missed. The specificity is only 79.0%, and altogether 42.1% of the patients are referred for angiography, resulting theoretically in 2.1 strokes. Patients with angiographically severe stenoses undergo carotid endarterectomy, resulting in 28.3 prevented strokes among the patients operated on. When the angiography-related 2.1 strokes are deducted, the net number of prevented strokes is 26.2.

Analogous models with MR angiography as the initial examination were then created. In the fourth model, patients with high-probability MR angiography on the symptomatic side (28.7% of all patients) are referred for angiography, and 19 false-negative cases are missed. In a population of 1000 patients, the net number of prevented strokes is 24.9. In the fifth model, 39.2% of the patients are referred for angiography, and no severe ipsilateral stenoses are missed. The net number of prevented strokes in a population of 1000 patients is 26.3.

The sixth model presumes that the surgeons would have been ready to operate on the basis of the MR angiography alone, and no invasive angiography would have been requested. All MR angiography-positive patients (28.7%) would have been operated on, including 39 pa-

tients with false-positive MR angiography attributable to overestimation of the stenosis degree, and leaving 19 severe ipsilateral stenoses undiagnosed. Thus, surgery would have been beneficial in 248 cases according to current knowledge, and this model would theoretically have resulted in 26.3 prevented strokes among the patients operated on. However, the surgery might have been unnecessary in 39 patients who would have been subjected to the major surgical complication rate of 2.1% (1). When these additional surgery-related 0.8 strokes are deducted, the net number of prevented strokes is 25.5.

In the seventh model, all patients are initially examined with Doppler ultrasound and those with a possible (see Table 4) stenosis are further referred for detailed MR angiography to confirm the findings or to clarify uncertainties on the ultrasound. The patient would then proceed directly to endarterectomy if MR angiography indicates definite stenosis. This combination of two noninvasive tests has a sensitivity of 100%. All 267 patients with a severe stenosis are operated on, leading theoretically to 28.3 prevented strokes. However, both tests falsely overestimate the stenosis degree as severe in 2.6% of the negative cases, and possibly unnecessary surgery is performed in 19 cases, leading to 0.4 surgery-related strokes. The net number of prevented strokes is 27.9.

The calculated imaging costs per patient are shown in Table 5. When the sensitivities and confidence levels of the tests as well as the prevalence of severe stenosis, the angiographic complication rate, and the absolute risk reduction rate achieved by carotid endarterectomy were taken into account, the imaging prices per one prevented stroke were also calculated and are shown in Table 5.

Discussion

The use of carotid endarterectomy for prophylaxis against stroke has proved to be highly beneficial to patients with recent hemispheric or retinal transient ischemic attacks or nondisabling strokes and ipsilateral high-grade stenosis (70% to 99%) (1, 2). For a major or fatal ipsilateral stroke, the absolute risk reduction has been shown to be $10.6\% \pm 2.6\%$ at 2 years (1).

Hankey and Warlow in 1989 (19) analyzed the cost effectiveness of carotid imaging meth-

TABLE 5: Calculated imaging costs per patient and per one prevented stroke for the imaging models

	Costs per Patient, US\$*	Costs per Prevented Stroke, US\$*
Model 1	1135	48 708
Model 2	621	25 216
Model 3	736	28 083
Model 4	1033	41 502
Model 5	1129	42 940
Model 6	985	38 628
Model 7	673	24 107

* Costs in US\$ according to November 1994 rate of exchange.

ods. Since then, however, MR angiography has been taken into clinical practice, and the other diagnostic tools have undergone development. In addition, the clinically relevant thresholds of stenosis degree have changed. It is also noteworthy that Hankey and Warlow, in their cost-effectiveness calculations, presumed the sensitivity of ultrasound to be 100%, which is not realistic on the basis of, for example, the results of the NASCET, in which the Doppler measurements were only 59.3% sensitive and 80.4% specific for the detection of stenosis of more than 70% (20). In the present study we have also taken into account the sensitivity rates of ultrasound and MR angiography. We have also paid attention to the fact that there can be different levels of confidence in the interpretation of ultrasound and MR angiography.

In our study population, the prevalence of a severe ipsilateral stenosis was 26.7%. We realize that our study material is small, but on the basis of the recent literature, we consider this prevalence to be representative. The European Carotid Surgery Trial Collaborative Group reported that of the 2200 patients randomized to the trial, almost half had moderate stenosis; 17% had mild stenosis; and 35% had severe stenosis (2). When these figures are compared with those of the present material, it must be noted that if the referring doctor was "reasonably certain" that surgery was indicated or not indicated, the patient was not randomized to the European Carotid Surgery Trial. Hence, at least those patients with occlusions and completely normal angiograms were left out, and the percentage of severe stenoses in the total population imaged becomes lower. In their study population of 485 patients with transient hemispheric or retinal ischemic attacks or retinal infarction, Hankey and Warlow reported the

prevalence of stenosis of 75% or more to be 22% (19).

Digital subtraction angiography has replaced conventional cut-film angiography at many institutions. This seems to lead to a decreased risk of angiography-related morbidity. The cumulative incidence of persistent neurologic deficits has been shown to be 0.5% to 1% for conventional cerebrovascular angiography (12, 21). For digital subtraction angiography, the risk of major complications has been reported to be 0.09%, 0.3%, and 0.52% in three recently published studies (13, 22, 23). The overall risk of neurologic complications, including transient deficits, has been reported to be 1% to 4% for conventional angiography and 0.9% to 3.9% for digital subtraction angiography. In the present work we have used a 0.5% major complication rate in the calculations.

The diagnostic accuracy of MR angiography interpretation in the present study was comparable to the results reported in the recent literature. The sensitivity of MR angiography for the detection of severe carotid artery stenosis has been reported to vary between 89% and 100%, and the specificity of MR angiography has varied between 64% and 100% (4, 5, 17, 24, 25). The ability of MR angiography to show correctly tandem lesions needs further evaluation (7).

On review of the Doppler ultrasound data, high sensitivity and specificity (84% to 99%) and high accuracy (90% to 95%) have been reported (26), and the results of the present study are very comparable. However, color-coded Doppler ultrasound remains highly operator dependent in its sensitivity. The most important pitfalls include difficulty in distinguishing high-grade stenosis from occlusion, poor visibility associated with calcified plaques, and difficulty in demonstrating tandem lesions and common carotid artery origins.

Accurate assessment of the cost-effectiveness of interventions may have important effects on health care reform (8). Unfortunately, universally applicable costs for certain diagnostic examinations cannot be calculated, and any comparisons should therefore be made with great qualification. The costs vary inevitably between countries and from institution to institution. Also, the ratio of costs of different examinations varies. It is therefore not possible to extrapolate the results of the present study directly to any other country. In the US health care system the digital subtraction angiography

costs and overnight hospital stay charges are proportionately higher than those in the present study. The Doppler ultrasound charges for carotid atherosclerosis have been reported even to equal those of a complete MR imaging and MR angiography examination in some instances (27). The US Medicare reimbursement rate (relative value unit), however, is approximately three times higher for MR angiography (15.64 relative value unit) and almost five times higher for invasive angiography (24.13 relative value unit) than for Doppler ultrasound (4.93 relative value unit) (28).

The high economic cost of neurologic morbidity caused by misdiagnosis or delayed diagnosis must be carefully considered (29). The calculated costs of the imaging methods plus the costs of surgery (which were not assessed in the present study) could be further compared with the costs of the treatment of stroke. Asplund et al (30) calculated the average cost in Sweden from a first stroke to death as \$79 000 (using 1991 prices), including both the direct and indirect costs. When Smurawska et al (31) calculated the direct costs of acute stroke care for all first admissions in Toronto, Canada, the average cost per patient was US\$21 150.

On the basis of the present analysis, both models that include Doppler ultrasound examination before the decision to perform angiography (models 2 and 3) are considerably cheaper than those in which angiography is done for all patients. Moreover, both models were also more effective, because they managed to prevent a greater number of strokes, leading to a clear dominance in the cost-effectiveness ratio (10) when compared with angiography alone. The models using MR angiography as the initial examination were more expensive than those using ultrasound, even after taking into account the price of the CT of the brain, which could be omitted. In addition, the slightly higher diagnostic accuracy of MR angiography did not result in a higher number of prevented strokes. When we weight detailed MR angiography (with MR imaging) against invasive angiography (with CT) as the only preoperative scrutiny before carotid endarterectomy, MR angiography proved to result in a higher number of prevented strokes (25.5 versus 23.3) with a cheaper price per imaged patient (\$985 versus \$1135). However, the costs of the unnecessary operations, unfavorable for MR angiography, have not been in-

cluded in these data. They might easily reverse the ratio.

Our last model evaluates patients before surgery with a combination of two noninvasive tests, ultrasound and MR angiography. This approach has recently been proposed as a practical alternative (7). This model correctly showed all severely stenosed bifurcations, and the number of false-positive cases was lower than with MR angiography alone. Angiographically, these false-positive findings included bifurcations with 67% to 69% stenoses. The actual accuracy of digital subtraction angiography for grading stenoses has been questioned (32), and a difference of 1% to 3% in the stenosis degree may as well be within the interobserver and intraobserver variability in the angiographic stenosis measurements (33). The number of prevented strokes reached 27.9 in this model, and the calculated costs per prevented stroke were less than half of those in model (1) (\$24 107 versus \$48 708). Again, the costs of the 19 possibly unnecessary surgeries per 1000 imaged patients (6.6% of all performed operations) have not been included in the calculations.

In conclusion, the combination of ultrasound and confirmatory angiography or MR angiography are the most cost-effective ways to image patients with suspected carotid artery stenosis. At present, MR angiography is not competitive with ultrasound as an initial screening tool, if the price is considered. MR angiography may become cost-effective if it can replace invasive angiography as the preoperative examination. On the basis of its present diagnostic performance, reliance on MR angiography would lead to possibly unnecessary surgery in some cases. However, the use of MR angiography may still lead to a better final patient outcome if the avoided angiographic complication rate is taken into account.

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