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The Roles of MR Angiography, CT Angiography, and Sonography in Vascular Imaging of the Head and Neck

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Studying the cervicocranial vasculature in a noninvasive fashion has been a major focus of imaging technology for some time. Over the past two decades, a number of new imaging techniques have been developed and applied to this purpose. Some, like intravenous digital subtraction angiography, have failed to meet the test of utility despite their feasibility. By the mid-1990s, however, at least three methods of noninvasive imaging have been refined to the degree that they now rival conventional intraarterial angiography in accuracy (at least in limited segments of the anatomy). Magnetic resonance (MR) angiography, Doppler sonography, and, most recently, computed tomographic (CT) angiography are now robust techniques. MR angiography and Doppler sonography have already achieved wide popularity, while the growth of CT angiography has been limited by the relatively slow introduction of slip-ring CT technology, its dependence on intravenous bolus injection of iodinated contrast material, and the preexisting presence of two formidable rivals in the field. The actual use of these powerful new tools has been propelled most recently by the results of several clinical trials that have changed the approach to patients with carotid occlusive disease, thus greatly expanding the need for neurovascular imaging.

Cervical Carotid Imaging

The widest use of noninvasive vascular imaging techniques has been their application to the evaluation of the cervical carotid bifurcation; specifically, the screening for and evaluation of occlusive disease in this region. The concept of a diagnostic screening examination assumes the presence of a pathologic process widespread in the population that, if detected early, can be arrested or reversed, thus avoiding the otherwise likely consequences of severe morbidity and, presumably, improving outcomes, as well as (one hopes) saving money in the process. Atheromatous disease of the carotid bifurcation is just such a pathologic process. The potential consequences of stroke caused by this entity are significant. Approximately 500 000 Americans suffer from stroke each year. It is the third leading cause of death and the leading cause of disability in the United States. Approximately 40% of all ischemic strokes are due to large-vessel disease, particularly that found at the bifurcation of the internal carotid artery. The prevalence of significant carotid bifurcation stenosis in the age group at risk for stroke is approximately 5% for asymptomatic and 30% for symptomatic persons (1).

Although trials in the late 1960s and early 1970s doused the enthusiasm for surgical intervention in carotid occlusive disease, recently completed trials have demonstrated considerable improvement in the surgical morbidity and mortality of endarterectomy. Such trials have now proved the usefulness of modern carotid endarterectomy techniques as compared with the best medical therapy in the prevention of stroke. The North American Symptom-

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atic Carotid Endarterectomy Trial (NASCET) revealed an absolute risk reduction of stroke of 17% at 2 years after surgical treatment in patients with ischemic symptoms and at least a 70% diameter stenosis of the cervical carotid artery (2). In other words, for every 100 endarterectomies in this patient population, 17 strokes are prevented over the course of the next 2 years with surgical treatment as opposed to medical management alone. The data were so compelling that the trial was cut short for this particular patient population, while the data continue to accumulate in patients who have a stenosis of 30% to 69%. A second trial (the ACAS study), in asymptomatic persons with stenosis of 60% or greater, reported an absolute risk reduction of 5.8% at 5 years (3); however, there is considerable controversy over the application of this result (4–8). Part of the controversy stems from the statistically inappropriate extrapolation of the first 2 years of data gathering to the 5-year time frame (the trial ended after 2 years), the fact that only minor strokes were reduced significantly by surgery as compared with medical therapy (major strokes were not statistically affected), and that over 50 endarterectomies would have to be performed to avoid one minor stroke (9).

Needless to say, the identification of qualifying subjects for these trials was based on results of conventional angiography in the case of NASCET and on either conventional angiography or Doppler sonography in the ACAS trial. All patients in both trials had conventional angiography before surgery; the angiograms were then evaluated, and stenosis was quantified by measuring the apparent luminal diameter at the point of greatest stenosis and then comparing this to the diameter of the cervical internal carotid artery distal to the bulb (10). Since these trials have been published, interest has been refocused on noninvasive methods of identifying potentially suitable patients for endarterectomy, and the available tools have come under a great deal of scrutiny in terms of their relative capabilities and potential drawbacks.

Screening

Beyond the detection of an audible bruit with the stethoscope, a relatively insensitive and nonspecific sign, screening of carotid stenosis with noninvasive imaging has traditionally been performed with Doppler sonography because of its widespread availability, even portability, and its ability to depict morphologic characteristics of the artery, blood velocity with velocity ratios in the internal and common carotid arteries, and secondary signs of stenosis, such as spectral broadening (11). Such results have been calibrated with the percentage of stenosis as determined by conventional angiography. Although the traditional and most commonly used calibrations are not concordant with the protocol used in the NASCET and ACAS trials, more recent calibrations do address this issue (12–14). One of the biggest drawbacks of Doppler sonography has been its dependence on operator capabilities. The reproducibility of Doppler sonographic results across many centers is poor (15, 16). Continuing improvements in Doppler technology, including color Doppler and, more recently, power Doppler (17), may well lead to decreased operator dependency and improved accuracy. Finally, one of the biggest advantages of Doppler sonography is the relatively low cost of the instrument as compared with MR imagers and CT scanners. Nevertheless, given the widespread use of the technology, it has become one of the greatest expenditures in imaging for the Health Care Financing Administration (HCFA) on an annual basis, greatly outdistancing even such commonly used tests as brain CT or MR imaging (HCFA unpublished data, 1992).

Additional limitations of Doppler sonography include difficulties with calcified vessels in terms of the resultant shadowing that precludes accurate morphologic evaluation. The inability to examine the high cervical carotid and carotid siphon because of overlying bone, as well as limitations with intracranial imaging, are major disadvantages relative to conventional angiography and even MR angiography.

Partly because of the limitations of Doppler sonography, and also fueled by continued innovation, MR angiography has become a viable alternative to Doppler sonography for screening carotid stenosis. A metaanalysis of a large number of clinical trials comparing MR angiography and Doppler sonography with conventional angiography suggests comparable sensitivity and specificity in the 80% to 90% range for detection of surgically significant cervical stenosis (18). MR angiography is less hampered by problems with calcification, can portray the entire course of the carotid artery, including the intracranial portion, and can do so in the full three-dimensional morphologic format not available to Doppler sonography. In the case of a normal artery, MR angiography accurately depicts the contour of the lumen with the occasional exception of mild signal loss in the bulb, owing to flow recirculation and consequent dephasing of signal. Thus, MR angiography, like conventional angiography, provides a morphologic evaluation of the normal carotid bifurcation; however, in the presence of turbulence from stenosis, signal loss related to nonuniform flow may exaggerate or completely obscure the site of narrowing. In many ways, such signal loss is analogous to Doppler sonography in providing a functional measure of the degree of stenosis. The actual degree of stenosis at which signal loss becomes apparent depends on technical factors, particularly the echo time. For two-dimensional time-of-flight MR angiography with an echo time equal to 8.7 milliseconds, flow gaps become apparent at approximately 50% stenosis (19). For three-dimensional time-of-flight sequences, which use shorter echo times, flow gaps appear only at higher grades of stenosis. Indeed, the introduction of high-strength gradients and their consequent ability to reduce echo time may well reduce the artifactual exaggeration of stenoses seen with the MR angiographic technique. Early phantom work with this improved methodology indicates considerably improved accuracy in grading stenoses (20). Nevertheless, exact measurement of the degree of stenosis with MR angiography is still problematic.

The newest entrant into the field of carotid bifurcation screening is CT angiography, and the results of several small trials suggest that sensitivity and specificity for detection of surgical cervical carotid lesions are comparable to those of MR angiography and Doppler sonography (21). This technique tracks a bolus of contrast material after its intravenous injection through the cervical carotid artery by using continuous table motion through the CT gantry as the X-ray tube spins continuously. Timing is critical, dilution of the contrast agent through the heart chamber implies dependence on stroke volume, and there are heat-loading limitations of the X-ray tube. All these factors combine to produce certain qualifications to this technology. Most notably, only a relatively small segment of the vessel anatomy can be evaluated during a single examination.

Preoperative Evaluation

In choosing an imaging method for preoperative evaluation, a number of issues need to be considered. First, because the benefits of surgery demonstrated by the endarterectomy trials were based on a standardized method for evaluating the percentage of stenosis by conventional angiography, the issue of replacing conventional angiography with alternative methods needs to be addressed. The impetus for such replacement is the fact that conventional angiography incurs a neurologic morbidity of approximately 1%, approaching that from endarterectomy itself, thus reducing the overall benefit to the patient for detection and treatment of the disease process. Therefore, it is tempting to replace conventional angiography with one or a combination of the less invasive tests to reduce this risk (22). Several groups have explored the use of MR angiography and Doppler sonography in combination for definitive preoperative evaluation. When both tests are performed on *every* candidate, there is a reasonably high sensitivity and specificity for detection of surgically significant stenosis, although the application of the second test to only the group that tests positive on the first test leads to a lower accuracy. Approximately 16% of cases are discordant, requiring conventional angiography. A small percentage of concordant cases are "double false positives," which could lead to unnecessary surgery. Early attempts to define patient benefit in terms of morbidity and cost analysis do support the use of a combination of noninvasive tests as a replacement for conventional angiography as the definitive preoperative evaluation (23, 24).

However, the measured degree of carotid stenosis is really an *indirect* objective risk factor for ischemic stroke. Because of the collateral pathways provided by the circle of Willis and other routes, even complete carotid occlusion does not necessarily lead to diminution of regional cerebral perfusion sufficient for symptom onset and eventual infarction. In other words, it is not the flow limitation itself (from carotid stenosis) that causes morbidity; rather, it is the embolic potential of the lesion that is truly important. The vast majority of ischemic strokes from carotid bifurcation disease are due to microembolization and macroembolization of debris (be it platelet aggregates or frank thrombus) induced by the lesion. Recent power Doppler studies have documented the correlation of carotid artery bifurcation disease and symptoms caused by consequent microembolic events in the brain. The reduction of such microembolic events after treatment has also been studied with power Doppler techniques (25, 26). One could argue, therefore, that a whole new clinical trial should be undertaken that measures the "embologenic" potential of the carotid bifurcation lesion on the basis of plaque characteristics and morphology rather than diameter stenosis to select patients for surgery. This would soften the criticism that noninvasive methods are inexact in measuring stenosis.

Assessment of plaque morphology and plaque ulceration was a minor determinant of disease in the NASCET trial. However, none of the less invasive tests has so far proved to be accurate in identifying ulceration or other determinants of "embologenic" potential. Indeed, even conventional angiography is insensitive for the detection of ulceration in the carotid artery, as a number of studies have shown (27–29). Plaque characteristics, such as composition and intraplaque hemorrhage, could potentially be evaluated with high-resolution MR, sonography, or CT techniques. However, at present, such determination does not improve the predictive value of the percentage of stenosis alone (30, 31).

Were it an important parameter, volume flow in the cervical vessels could be quantified by gated phase-contrast MR angiography and by time-domain process sonography (32, 33). Although percentage of stenosis cannot be directly correlated with such data, it may ultimately prove to allow more accurate identification of those few surgical candidates in whom flow reduction seems to be the cause of symptom production (in particular, patients in whom anatomic variants or pathologic states have affected collateral pathways).

Tandem atherosclerotic stenosis of the carotid artery occurs in approximately 5% of patients with significant bifurcation stenosis. The most common second site is the paracavernous segment of the internal carotid artery, followed by the proximal common carotid artery. Accurate evaluation of this tandem site has been attempted by using MR angiography, but success has been variable in the small series reported to date (34). Again, dephasing-induced signal loss is the major hurdle for accurate evaluation of the carotid siphon: the higher-strength gradients may remove this obstacle.

Finally, in selecting patients for preoperative evaluation, it must be remembered that the vessels are only part of the pathophysiological picture. The end organ itself is important. Most surgeons and neurologists believe that assessment of the brain parenchyma before endarterectomy is useful. This is particularly true in patients who have had recent transient symptoms, because even transient symptoms may be associated with permanent pathologic infarction in a significant number of cases (35). It is well known that endarterectomy in the face of recent infarction leads to a higher risk from surgery, thus a priori knowledge of the brain's status is critical. Because MR imaging can provide information about the brain parenchyma as well as show the status of the blood vessels (with MR angiography), it may well become the most cost-effective preoperative evaluation technique in the context of carotid bifurcation disease. CT also has this potential, but the limited segment of vasculature that can be evaluated with current CT angiographic technology and the relatively lower sensitivity to ischemic insults as compared with MR imaging may diminish its cost-benefit ratio relative to MR imaging.

Intracranial Imaging

Noninvasive or minimally invasive evaluation of the intracranial vasculature is possible with either MR angiography (36) or CT angiography (37). Both methods have shown the ability to depict the brain's vasculature in terms of the presence of intracranial stenosis and collateral circulation, and both can serve as a screening examination for intracranial aneurysms. Intracranial MR angiography is capable of delineating the paracavernous carotid segment with reasonable accuracy, although the above-mentioned problem of signal loss associated with turbulence and also adjacent susceptibility effects produced by air in the sphenoidal sinus can lead to errors. MR angiography is useful for evaluating stenosis and occlusion of the proximal intracranial arteries, and source image analysis may improve accuracy (38–40). However, MR angiography is still limited in its ability to portray mild degrees of stenosis associated with vasculitis, arteriosclerosis, or vasospasm of the medium-sized and small intracranial vessels.

Early experience with CT angiography indicates that it also can show intracranial vascular narrowing, although accuracy may not equal current MR angiographic methods for grading stenosis (41). Both CT angiography and MR angiography are somewhat limited in the field of view available for intracranial vessel evaluation, this being particularly true with CT angiography given the heat-loading limitation mentioned above.

Transcranial Doppler sonography has been found to be quite useful in the noninvasive detection of intracranial vasospasm and its follow-up in the setting of subarachnoid hemorrhage (42, 43), and in the evaluation of intracranial emboli (44). It has also been proposed for evaluation of collateral flow in the circle of Willis (45). Its usefulness depends more on the signal characteristics for velocity encoding and detection of turbulence rather than on an ability to provide a true morphologic picture of the vessels. Limitations as to the available acoustic window, which result in failure rates of up to 20%, and operator dependence have also restricted its more general application (46).

Evaluation of the collateral pathways within the circle of Willis is more readily accomplished with time-of-flight MR angiography when vessel diameters of 1 mm or more are present (47). The use of selective saturation pulses in combination with MR angiography allows assessment of flow direction. Phase-contrast MR angiography can determine both flow magnitude and direction.

Intracranial aneurysms in asymptomatic persons at risk and in symptomatic patients with subarachnoid hemorrhage have been shown with both MR angiography and CT angiography (48–51). Both tests have demonstrated very good accuracy for aneurysms 5 mm and greater in diameter; accuracy is decreased for aneurysms in the 3- to 5-mm range. Initial reports have also described the accuracy of both tests in the presence of subarachnoid hemorrhage (52–54). However, given the need for accurate evaluation of aneurysmal morphology, particularly the aneurysmal neck in relation to the parent vessel, it is unlikely that either method will replace conventional angiography for preoperative examination of such patients in the near future. Widespread screening for intracranial aneurysms is not justified given the known prevalence of this disease process. However, screening with the noninvasive techniques may be indicated in certain high-risk populations (55).

Other Vascular Disorders

Several other pathologic entities that affect the extracranial carotid artery have been the target of noninvasive vascular methods, although they are less common than atherosclerotic disease (56). Of these, perhaps the most notable is cervical vessel dissection. Two percent of all first strokes are caused by dissection, and these affect a younger population than do conventional stroke syndromes. Evaluations of MR angiography and CT angiography for detection of carotid artery and vertebral artery dissection have been performed in small series (57–59), but these tests are likely to be insensitive to the subtle intimal injuries for which conventional angiography is superior. Nevertheless, MR imaging and MR angiography can show the narrowing of the vessel produced by dissection; the cross-sectional images reveal a false lumen as a crescent of abnormal signal intensity adjacent to the vascular flow void (60, 61). These techniques may be more sensitive then either CT angiography or conventional angiography in specifying dissection as the cause of compromise of the vascular lumen. The pseudoaneurysms consequent to dissection can also be detected. Fibromuscular dysplasia, one of the causes of dissection, is a subtle lesion of the vessel lumen that can only be detected by MR angiography when the changes are moderate or severe; however, mild cases that produce symptoms may be missed, as they are readily simulated by subtle artifacts of the MR angiographic techniques (62).

The use of noninvasive methods for the evaluation of vascular malformations, particularly in the brain, has received some attention in the literature. One of the advantages of MR imaging and MR angiography in combination is the ability to detect not only the nidus of a vascular malformation but also signs of past hemorrhage. Detection of such signs influences management decisions, as asymptomatic and nonhemorrhagic vascular malformations are less likely to be approached aggressively than are those that have previously bled. Certain other findings that prompt more aggressive approaches to arteriovenous malformations, such as intranidus aneurysms and venous outflow restriction, may only be detectable by conventional angiography (63)

Summary

Despite the advancements made in the field of conventional angiography, including smaller catheter size and digital image acquisition, which reduce the risk to patients to very low levels, the noninvasive technologies have made great in-roads into the diagnostic armamentarium used for evaluating cervicocranial vascular disorders. Indeed, in many academic centers, the training of residents and fellows in conventional angiographic techniques has become a problem to the point that in certain institutions only those interested in endovascular interventional techniques become well-trained in the use of conventional angiographic approaches. Such a dilemma testifies to the success of the noninvasive tools in providing adequate information for patient management. Ongoing developments in MR technology, such as high-strength gradients and high-resolution "microscopic" techniques, may further enhance the accuracy of MR imaging for depiction of vessel and plaque morphology. Improvement in X-ray tube design with greater heat-storage capacity will expand the potential for CT angiography and its ability to delineate a greater extent of the cervicocranial vascular tree. Expansion of the use of power Doppler sonography, with its capacity to show microembolic phenomena, may refine our ability to select appropriate patients for surgical (and, more recently, endovascular) intervention at the carotid bifurcation (64).

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