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Renal MR and CT angiography: current concepts

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Abstract

During the past decade, noninvasive CTA and MRA imaging techniques have replaced catheter angiography for evaluation of the renal arteries. This article reviews techniques for optimizing renal MRA and CTA, assesses the advantages and limitations of MRA and CTA, and provides the current indications for renal vascular imaging including renal artery stenosis screening. New and future developments in these rapidly evolving techniques are also discussed.

Key words: CTA—Renal artery—MRA—Vascular—Stenosis

Diagnostic evaluation of the renal vasculature is a common imaging request. Although renal artery duplex sonography is often the first examination performed, there are a number of well-recognized limitations, not the least of which is the challenge of optimally visualizing these vessels in large patients. Catheter angiography has been the traditional gold standard for renal artery evaluation; however, improvements in spatial resolution and image quality of cross-sectional techniques have allowed MR and CT angiography to replace this invasive examination in most circumstances. CTA, for example, has been revolutionized by the introduction of multidetector row CT. Current 64-channel CT systems permit rapid acquisition of large volumes of submillimeter data with isotropic resolution allowing three-dimensional data to be reconstructed in any plane. MRA has also benefited from a number of recent developments, including improvements in gradient hardware and the recent introduction of parallel imaging, both of which permit reduced acquisition times and improved spatial resolution. A wide range of functional techniques are now available, which may help us to identify patients who would or would not benefit from renal artery revascularization.

Renal MRA and CTA are well suited for noninvasive imaging evaluation of the renal arteries and veins, and have been widely applied to clinical practice for several years. This article reviews the current state-of-the art of renal MRA and CTA.

Current techniques will be discussed, along with common pitfalls, artifacts and limitations. The wide range of clinical applications and future imaging trends of both techniques will be illustrated, with particular emphasis on the diagnosis of renal artery stenosis (RAS).

Technical considerations

CTA

CTA has evolved from acquisition by single spiral detector scanners to multichannel helical CT (including 4, 8 and 16 detectors) examinations. More recently, 64-multichannel CT systems have become available. Improvements in the CT technology using submillimeter acquisitions combined with subsecond gantry rotation allow CTA examinations to be obtained more rapidly with improved temporal and spatial resolution in the x, y and z axes. In 1994, Galanski et al. [1] noted a sensitivity of 100% and specificity of 94% in the evaluation of significant RAS for renal vascular hypertension. More recent studies have noted improved specificity [2] which reflects the continued advancements in CT image resolution with current CT techniques systems providing 0.4 mm isotropic resolution.

Accurate evaluation of the renal arteries by CTA requires adequate IV access for administration of iodinated IV contrast at a rate of 3–5 cc/s. Limited precontrast CT images can be obtained for localization purposes, or a dedicated precontrast CT of the kidneys can be acquired to exclude renal stone disease and/or to evaluate precontrast density measurements of renal masses. Optimal CTA acquisitions are obtained using thin (<1 mm) collimation with the creation of overlapping submilli-

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meter reconstructions for use in the postprocessing imaging analysis. Bolus timing techniques can be used for optimal opacification of the renal arterial vasculature.

The major current advantages of CTA compared to MRA are improved spatial resolution and decreased total examination time for acquisition when compared to MR angiography. CTA of the renal arteries using the 64-channel technology and including complete evaluation of the abdominal aorta, mesenteric vasculature, iliac vessels, and renal arteries can be performed in 5–10 s with submillimeter spatial resolution. An additional advantage may include the ability to determine the extent of atheromatous calcification, which cannot be depicted by MRA. The main limitation of CTA is radiation exposure and the necessity for administration of an iodinated contrast material especially in patients with decreased renal function or severe allergic reaction. Radiation dose requirements for CTA can be optimized by the application of automatic tube current modulation techniques. Finally, CTA does not provide functional information with regard to altered flow dynamics or elevated pressure gradients in the renal artery as can be demonstrated by renal artery duplex sonography, phase contrast MRI, and catheter angiography.

MRA

The renal MRA methodology continues to evolve, a reflection of both technical improvements in gradient hardware and pulse sequence development as well as accumulating clinical experience. While early studies emphasized inflow methods such as 2D and 3D time-of-flight noncontrast sequences, the dominant technique today is 3D contrast-enhanced MRA [3–11]. This consists of a 3D fast spoiled gradient echo sequence performed in conjunction with intravenous bolus injection of a gadolinium-based contrast agent. Acquisition is coordinated with the arrival of the contrast bolus in the abdominal aorta and renal arteries. This technique relies on the indirect paramagnetic effect of the contrast agent to reduce the T1 relaxation time of adjacent water protons. The typical CE MRA sequence also has the effect (through relatively high flip angles and short repetition times (TRs) of suppressing background tissue not exposed to gadolinium. Additional background suppression can be achieved by adding fat suppression pulses to the sequence (at a small cost in additional imaging time) or by subtracting the contrast-enhanced sequence from a precontrast mask acquisition (this method can generate misregistration artifacts in patients whose breath holding is not consistent between the two acquisitions).

Three-dimensional CE renal MRA is an attractive technique for a number of reasons: acquisition times are short enough to be encompassed within a reasonable breath hold, thereby greatly reducing or eliminating respiratory motion artifact. The short acquisition time is also helpful in preventing or minimizing venous contamination from the relatively rapid renal circulation. The reliance on gadolinium for image contrast reduces or eliminates many of the well-known artifacts associated with time-of-flight and phase contrast techniques. Three-dimensional data acquisition coupled with excellent background suppression means that 3D reconstruction is relatively straightforward using any of the currently available methods such as maximum intensity projection or volume rendering. The relative invisibility of calcium, while to some extent a limitation, can also be advantageous in allowing clear visualization of the renal artery lumen in patients with extensive arterial calcification. MRA is generally considered a safe alternative to CTA or conventional angiography in patients with renal insufficiency.

Limitations of 3D CE renal MRA have to do with fundamental constraints on acquisition time imposed by the requirement for data acquisition during the first pass of the contrast bolus. Since spatial resolution is typically related to the number of phase encoding steps acquired in two dimensions, higher spatial resolution images require longer acquisition times. Additionally, as spatial resolution improves, voxel size decreases, and SNR diminishes—eventually the reduced SNR can compromise image quality. In general, spatial resolution in renal 3D CE MRA has been considered adequate to detect significant ($>50\%$) stenosis of main renal arteries; it is limited in the detection of stenoses in small accessory vessels, and has reduced sensitivity for the detection of subtle fibromuscular dysplasia. The typical voxel size for renal MRA in clinical practice today probably ranges between 1.5 mm^3 and 3 mm^3: this resolution, while adequate for evaluation of main renal arteries, is significantly lower than the resolution achieved by conventional angiography as well as state-of-the-art multidetector row CTA. Although flow-related artifacts are minimized with 3D CE MRA, they can occur, and can occasionally lead to the overestimation of stenoses. The lack of visible calcium may be advantageous as noted above; however, it is also a limitation, since this information is useful to physicians contemplating renal artery stent placement or percutaneous transluminal angioplasty. General limitations of MRI include a small percentage of patients unable to undergo examinations because of claustrophobia or gadolinium contrast agent allergy. Patients with pacemakers, AICD devices, and certain aneurysm clips and implanted electronic devices are excluded from MRI.

Applications of renal MRA and CTA

Renal artery stenosis

Atherosclerotic RAS is the most common cause of secondary hypertension, and it is estimated that RAS ac-

counts for 5% of all patients with hypertension and 10–30% of hypertensive patients with known or suspected atherosclerotic cardiovascular disease [12, 13]. In addition, renovascular disease is the primary cause of renal insufficiency in approximately 15% of patients >50 years of age who develop end-stage renal disease [14].

The consequences of significant RAS can be severe; screening patients in this group rests on the assumption that revascularization (surgical, percutaneous angioplasty, or renal stent placement) is an effective therapy. Surprisingly, the evidence is not conclusive. The Dutch RAS intervention cooperative study (DRASTIC), for example, a prospective randomized study of medical therapy versus percutaneous transluminal angioplasty concluded that PTA showed no advantage over medical therapy [15]. The Scottish and Newcastle study followed 55 patients randomized to PTA or medical therapy. No patient was cured. PTA resulted in a modest reduction in systolic blood pressure in those patients with bilateral RAS [16]. On the other hand, data from a multicenter registry on renal artery stenting in over 1000 patients over a 4-year period show a beneficial effect on blood pressure control [17]. The preponderance of evidence seems to support the view that blood pressure is better controlled with fewer medications after successful revascularization.

Preservation or improvement of renal function has also become an important indication for renal revascularization. Here as well the evidence is not overwhelming. The results of 10 descriptive studies of the effect of renal revascularization on renal function were recently reviewed: renal function improved in 26%, remained stable in 48%, and deteriorated in 26% of stented patients [18]. Another recent prospective study on the effect of renal artery stenting on renal function in patients with renal insufficiency demonstrated that patients with declining but not stable renal function benefited from stenting [19]. Taken together, these results suggest that renal revascularization may be most beneficial in patients with progressive renal failure.

General screening of hypertensive patients for RAS is not warranted since the overall prevalence is low and additionally many patients with RAS can be managed effectively with medication. Patients likely to benefit from revascularization and therefore candidates for renal MRA or CTA include those with refractory hypertension, progressive azotemia, and acute renal failure on angiotensin converting enzyme (ACE) inhibitors, recurrent flash pulmonary edema, and candidates for salvage therapy in the recent onset of end-stage renal disease [20–22].

MRA has been evaluated more extensively than CTA for the assessment of RAS, probably because many patients with renovascular disease also have compromised renal function and are therefore at higher risk for receiving iodinated contrast. The majority of studies have concluded that renal MRA and CTA are highly accurate in most cases (Figs. 1, 2, 3). Tan et al. [23] recently published a meta-analysis of 39 studies, 25 of which met the inclusion criteria. The sensitivity and specificity of gadolinium-enhanced MRA were 97% and 85%, respectively. The authors concluded that renal contrast-enhanced MRA could replace conventional angiography in most patients with suspected RAS. A second meta-analysis (Boudewijn et al. [24]) evaluated multiple modalities, with 5/22 CTA studies meeting the inclusion criteria, 16/39 MRA studies, 24/58 sonography studies, 14/25 captopril renal scintigraphy. The area under the ROC curves for the diagnostic modalities was 0.99 for CTA and contrast-enhanced MRA, 0.93 for sonography, and 0.92 for captopril renal scintigraphy. The authors concluded that MRA and CTA were preferred for noninvasive evaluation of renovascular hypertension.

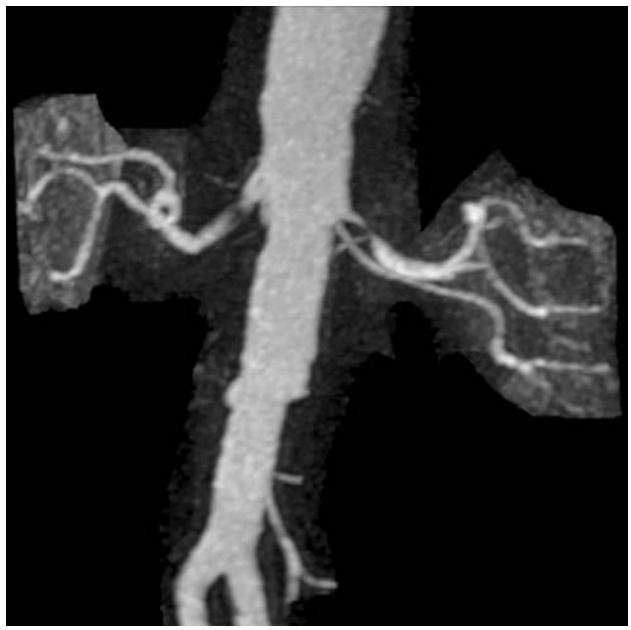

Fig. 1. Subvolume maximum intensity projection image from contrast-enhanced renal MRA demonstrating severe stenosis of both left and right main renal arteries as well as an accessory left renal artery. Both lesions were confirmed angiographically.

Recently, however, several authors have questioned the accuracy of renal MRA and CTA. Most notable is the result of the RADISH trial conducted from 1998 to 2001 and published in 2004 [25]. This was a well-designed multicenter trial which evaluated 356 patients who underwent CTA, MRA, and conventional angiography. Twenty percent of patients had clinically relevant RAS (defined as >50%). Only moderate interobserver agreement was found (k values 0.59–0.64 for CTA and 0.4–0.51 for MRA). The combined sensitivity and specificity were 64% and 92% for CTA and 62% and 84% for MRA.

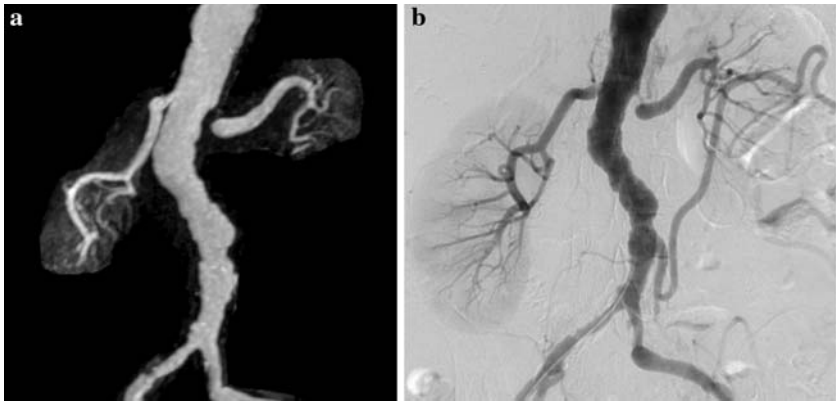

Fig. 2. Subvolume MIP image from contrast-enhanced renal MRA (**A**) reveals severe stenosis of the proximal left renal artery. There is excellent correlation with the conventional angiogram (**B**).

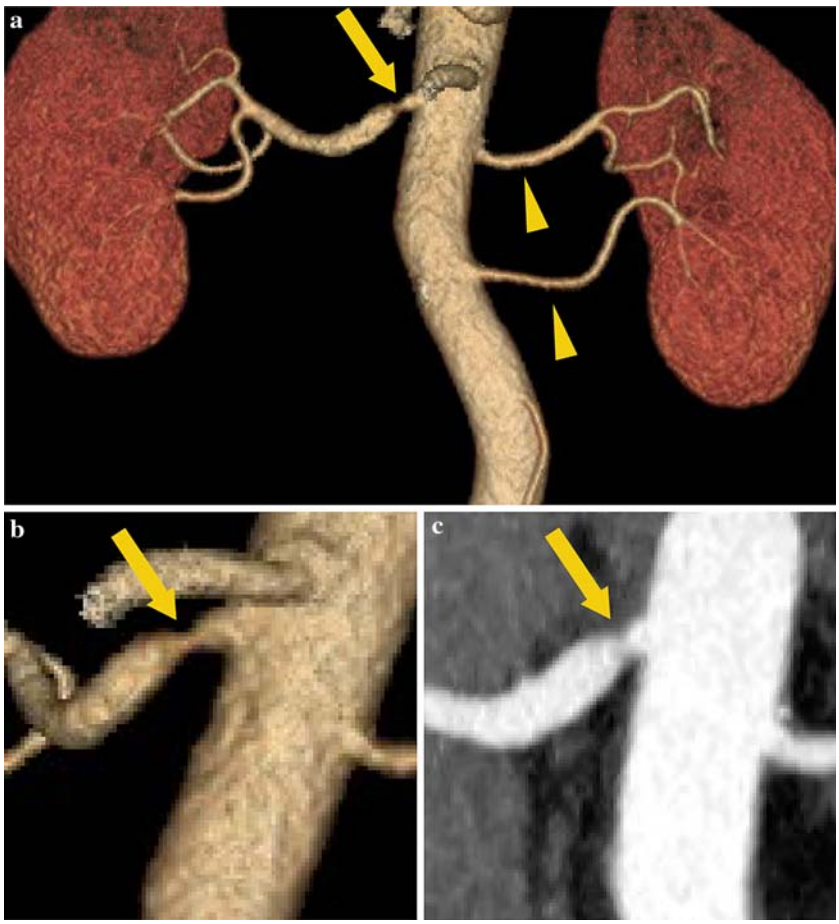

Fig. 3. CTA of renal arterial stenosis. Volume-rendered (**A** and **B**) and MIP (**C**) images of the renal arteries demonstrate high grade stenosis at the origin of the single renal artery and two widely patent left renal arteries (*arrowheads*).

The authors concluded that CTA and MRA are not reproducible or sensitive enough to rule out RAS in hypertensive patients, and that conventional angiography remains the diagnostic method of choice.

A number of criticisms have been leveled at the RADISH study, including the relatively low incidence of RAS, and the very high incidence of fibromuscular dysplasia (38% of all patients with RAS), well known as a problematic diagnosis for both MRA and CTA. The imaging technique can be criticized as well—the spatial resolution achieved was not optimal when the study was conducted, and would certainly not be optimal today. It is also worth noting that conventional angiography is an imperfect gold standard. Eccentric stenoses can be over or underestimated depending on the acquired projections, and interobserver agreement, while significantly better than CTA and MRA, is far from ideal.

Relatively poor performance of MRA and/or CTA in some cases can be attributed to a number of factors. One of the most important considerations is spatial resolution. Average renal artery diameters are in the range of 4–5 mm, and accessory arteries are considerably smaller.

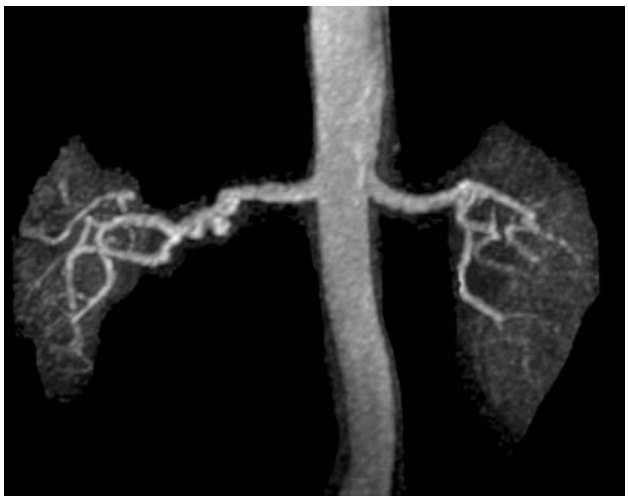

Fig. 4. MRA of fibromuscular dysplasia. Subvolume MIP image from contrast-enhanced renal MRA reveals extensive beading of the mid and distal right renal artery.

Accurate visualization and measurement of renal artery diameters require a sufficient number of pixels spanning the renal. This issue is especially problematic for MRA. Although voxel dimensions in much of the renal MRA literature range between 1.5 mm and 3 mm, it is now possible to obtain isotropic voxels on the order of 1 mm or slightly less. Achieving such high spatial resolution with MRA will probably require parallel imaging in most cases as well as a carefully positioned volume to cover the renal arteries as efficiently as possible [26, 27]. CTA has made considerable improvements in spatial resolution with the introduction of multidetector CTA and state-of-the-art systems now routinely obtain submillimeter isotropic resolution with short acquisition times (Fig. 3).

While spatial resolution is improving in both CTA and MRA, it remains problematic in the evaluation of accessory renal arteries, and in the cases of fibromuscular dysplasia, where lesions often involve segmental arteries, and can be quite subtle (Figs. 4, 5). The high accuracy of renal MRA and CTA in most studies can be at least in part attributed to the relatively low prevalence of FMD, as well as the circumstance that at least 80% of atherosclerotic lesions causing renovascular hypertension occur in the ostia, where the arteries are relatively large.

Temporal resolution is a related problem. It has been shown that the renal arteries move significantly during respiration, and that this motion increases with the distance from the aorta [28, 29]. An additional consideration is the pulsatility of the aorta and renal arteries during the cardiac cycle. Both CTA and MRA are acquired during suspended respiration; however, many patients have limited pulmonary function, and may not sustain a breath hold for the required length. Respiratory motion artifact results in image blurring which when severe can render an examination uninterpretable. Unfortunately, there is often a direct correspondence between acquisition time and spatial resolution, so that high spatial resolution acquisitions require relatively long breath holds and are therefore more susceptible to respiratory motion artifact. Motion artifact is less problematic with state-of-the-art CTA, since acquisition times are generally shorter than MRA. Time-resolved renal MRA has been advocated by some authors: a variety of techniques, including projection reconstruction, parallel imaging, and k-space acquisition strategies in which the low spatial frequencies are fully sampled, while peripheral k-space is undersampled and interpolated [30, 31]. These techniques may not be applicable to all patients, but they can be quite useful in selected cases, and particularly in patients with limited respiratory capacity (Fig. 6).

Data analysis is another important aspect of renal MRA and CTA which can affect accuracy and reliability. Most studies assess severity of disease by measuring the percent stenosis, i.e. one minus the ratio of the stenotic and normal renal artery diameters. While this one-dimensional measurement is easily translated to and from conventional angiography, it ignores the three-dimensional aspect of MRA and CTA data. Schoenberg et al. [26], using data from high spatial resolution renal MRA, recently demonstrated that cross-sectional area measurements of stenotic arteries could routinely be obtained, and that these data had significantly less interobserver variability than simple diameter measurements.

A few problems are unique to either MRA or CTA. Renal arteries are often heavily calcified in the regions of stenosis (Fig. 7); while the presence of calcification is useful information in planning interventional therapy, it can be problematic when attempting to visualize the arterial lumen and accurately determine the percent stenosis. This is a problem unique to CTA, since calcium is usually invisible on MRA. The presence of stents, on the other hand, is more detrimental to MRA than CTA. Metallic susceptibility artifact from most renal artery stents completely obscures the lumen, so that determination of in-stent stenosis is impossible. Recently, ''MR-visible'' stents have been introduced by a few manufacturers [32–34]. Visualization of the arterial lumen is possible in this limited case; however, optimal depiction of the lumen requires high flip angles, which can be problematic in other ways (high flip angles generally necessitate a longer TR, resulting in longer acquisition times).

In summary then, the preponderance of data indicates that renal MRA and CTA are highly accurate in the detection of significant RAS, and can be safely used as a noninvasive alternative to conventional diagnostic angiography. Recent dissenting views, however, emphasize that much work remains to be done, particularly with regard to improving spatial and temporal resolution.

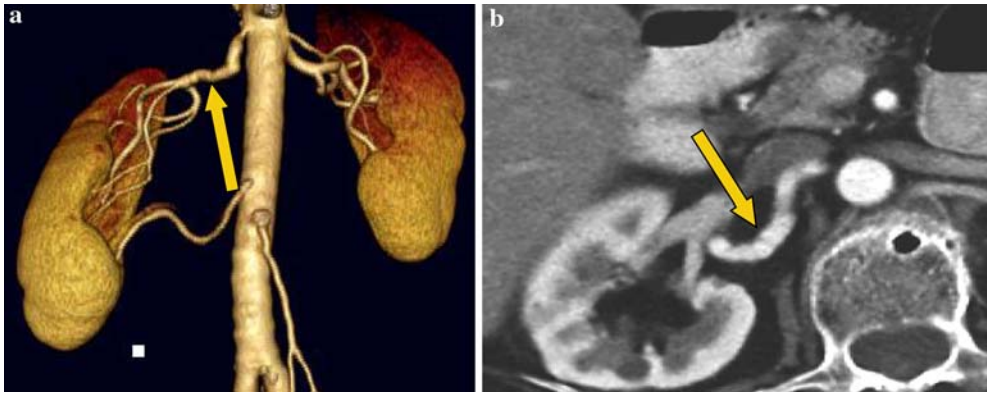

Fig. 5. CTA of renal arterial fibromuscular dysplasia. Volume-rendered (**A**) and axial CT (**B**) of the renal arteries demonstrate web-like narrowing of the mid-segment of a renal artery consistent with fibromuscular dysplasia.

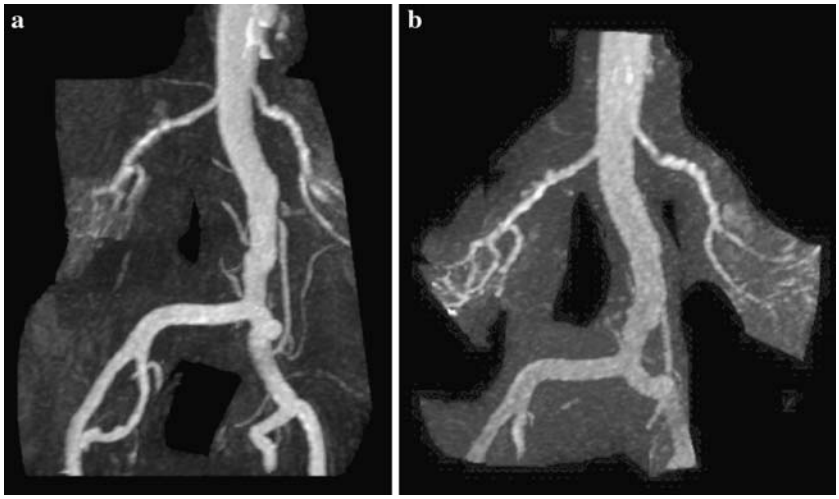

Fig. 6. Time-resolved renal MRA. MIP image from conventional MRA (*left*) and optimal arterial frame MIP from time resolved TRICKS (time-resolved imaging of contrast kinetics) sequence. The beaded appearance of the renal arteries in this patient with bilateral FMD is better appreciated with the TRICKS sequence (temporal resolution approximately 3 s) compared with the 20 s conventional acquisition, perhaps because subtle motion of the renal arteries during the longer conventional acquisition results in blurring of the lesions.

Renal cell carcinoma

Renal cell carcinoma is often incidentally detected at early stages on routine abdominal sonography and CT; however, a significant percentage of patients present with advanced disease. Tumor thrombus involving in the renal vein or IVC is discovered in 4–10% of patients, and roughly half of these have extension to the intrahepatic IVC or right atrium [35]. The extent of tumor thrombus is an important factor in determining the surgical approach as well as the uppermost extension of possible resection.

CT and to a lesser extent MRI are routinely used to stage renal cell carcinoma. Evaluation of venous extension is particularly well suited to CTA and MRA (Figs. 8, 9). Generally, the technique is similar to arterial-phase methods; in this case, one or more additional phases are acquired to allow contrast to opacify the venous system and optimize visualization of the renal veins and IVC. Arterial phase data are also useful: patients with very hypervascular tumors (Fig. 10) and extensive arterio-venous shunting may benefit from embolization prior to surgical resection in order to minimize intraoperative bleeding. Additionally, the presence of significant RAS in the opposite kidney may be detected and treated to prevent postoperative renal insufficiency.

A recent study evaluated the performance of CT and MR in 23 patients with renal cell carcinoma and suspected IVC thrombus. CT detected thrombus with a sensitivity and specificity of 0.93 and 0.8, while two readers for MR had sensitivities of 1.0 and 0.85 and a specificity of 0.75 [36]. Other authors have reported sensitivities of up to 100% for MRI in the detection of caval thrombus [37–39], and studies comparing MRI to early generation spiral CT favored MRI. The distinction between the two techniques is probably less clear today, since high spatial resolution CT data can be obtained with isotropic resolution and reconstructed in any plane without loss of resolution. MR does offer added flexibility: when venous return is slow, for example, a large number of postcontrast acquisitions can be obtained to optimize venous contrast without regard to the cumulative radiation dose. A number of additional bright and dark blood pulse sequences are available for the assessment of the IVC and renal veins without intravenous contrast. MRI on the other hand generally has lower spatial resolution than CT, and total examination times are longer, which can occasionally be problematic in very ill patients.

Fig. 7. Atheromatous calcification in the abdominal aorta and at the renal ostia. CTA and MRA of the abdominal aorta and renal arteries in the same patient. **A** CTA with extensive atheromatous calcification throughout the abdominal aorta and at the origin of the left renal ostia (*arrowhead*). **B** MRA shows luminal opacification which is unobscured by atheromatous calcification.

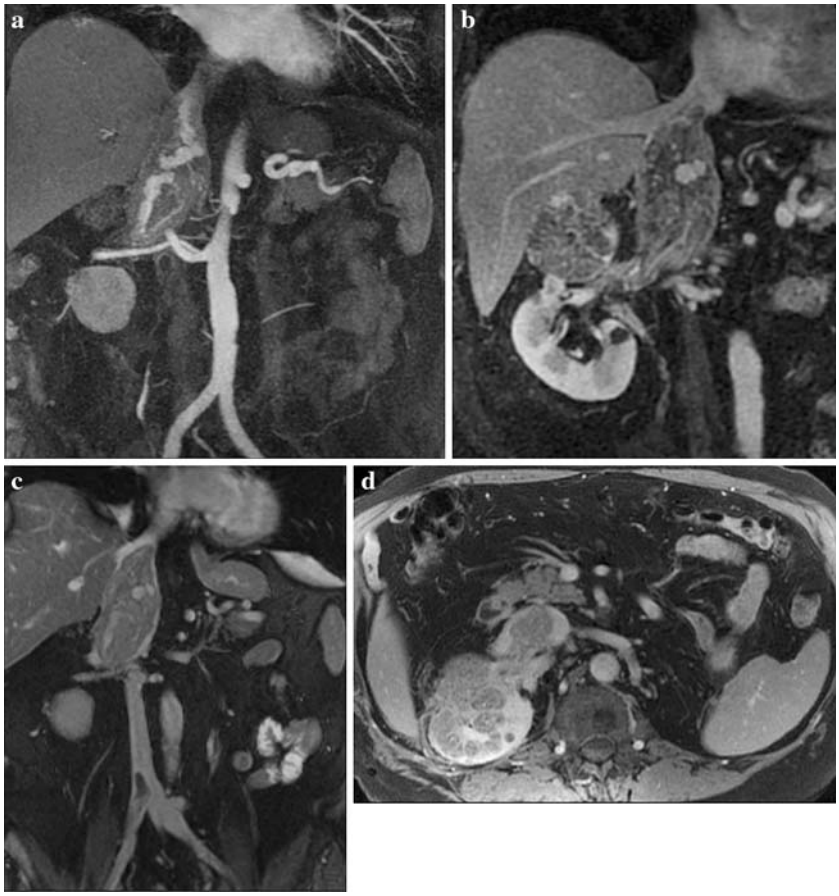

Fig. 8. Versatility of MRI in staging renal cell carcinoma. Coronal arterial phase (**A**) image from 3D fat-saturated SPGR sequence revealing two right renal arteries as well as enhancing tumor vascularity in the IVC. Venous phase image from same sequence (**B**) reveals large upper pole right renal mass with thrombus expanding the right renal vein and IVC. Coronal image from a noncontrast fat-saturated steady state free precession sequence (**C**) depicts additional bland thrombus in the IVC at the bifurcation. Axial postcontrast fat saturated SPGR image (**D**) again reveals large renal mass with renal vein and IVC tumor thrombus.

Renal transplantation

The prevalence of end-stage renal disease in the United States is increasing at a rate of more than 8% per year, and the number of patients on waiting lists for kidney transplants has more than quadrupled in the past two decades [40–42]. Since the supply of cadaveric kidneys has increased only slightly, living donor transplantation has become an important alternative. Living donor transplantation recipients have better graft function and survival when compared with cadaveric graft recipients, perhaps because the surgery can be performed electively, and the cold ischemia time is reduced [41].

The increasing prevalence of living renal donors and the recent trend toward laparoscopic nephrectomy has paralleled advances in preoperative imaging evaluation of potential renal donors. In the past, living renal donors have undergone preoperative evaluation using catheter-directed renal angiography, excretory urography, and occasional additional diagnostic examinations. Today,

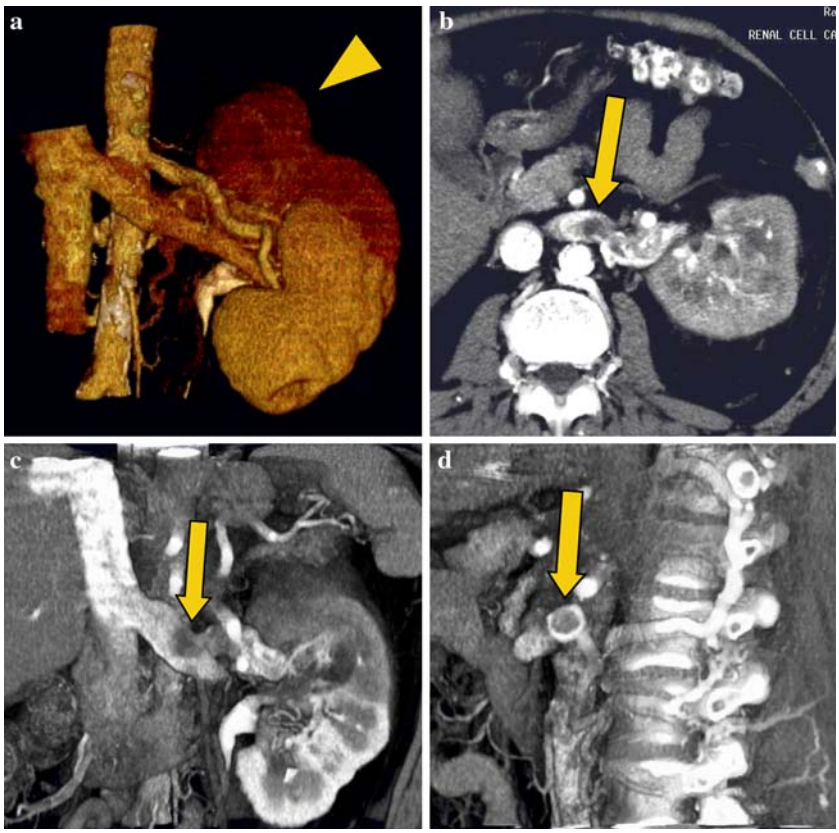

Fig. 9. Renal cell carcinoma with renal vein thrombus. CTA of the abdominal aorta and left kidney. Volume rendered CTA (**A**) demonstrates a hypervascular mass in the upper pole of the solitary left kidney. Axial (**B**), coronal (**C**), and sagittal (**D**) CT images of the left renal vein demonstrate the extent of nonocclusive venous thrombus.

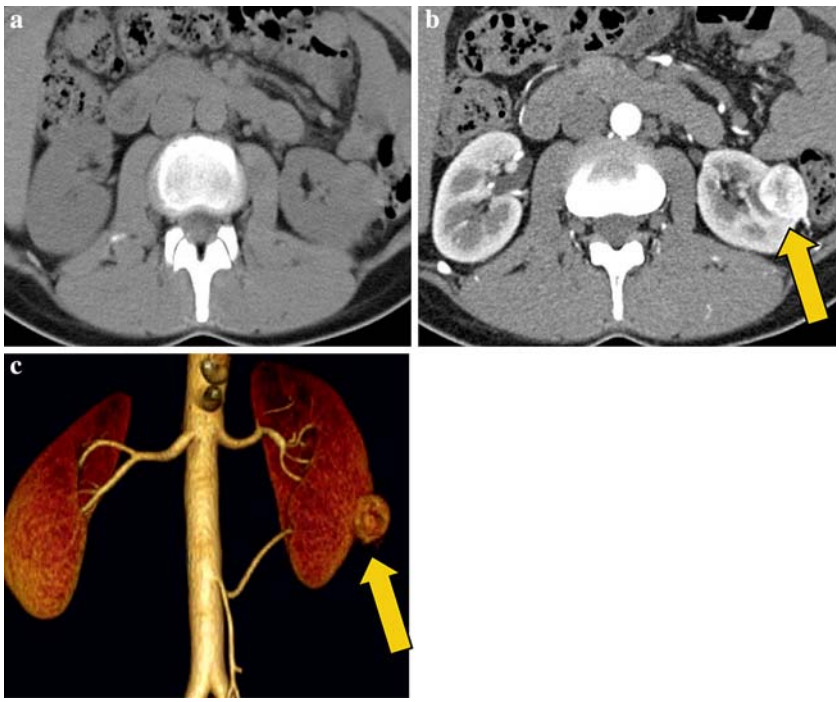

Fig. 10. CTA of hypervascular renal cell carcinoma. Unenhanced CT (**A**), arterial phase contrast enhanced CTA (**B**), and VR CTA (**C**) of the abdominal aorta and renal arteries reveal a hypervascular mass (*arrows*) in the lower pole of the left kidney consistent with surgically proven renal cell carcinoma.

complete evaluation is accurately performed using comprehensive multichannel CT combining CTA (>97% accuracy), CT venography (accuracy 96–100%), and urographic images in one diagnostic examination. The arterial and venous phase images can be sent to post-processing workstations to reconstruct specific views demonstrating renal anatomy and anatomic variants. The postprocessed images can be made available on the

same day to the referring nephrologist and transplant surgeon for preoperative planning. In addition, the display of the 3D CTA during preoperative consultation provides an excellent educational tool for patients. Important renal donor CT information includes: (a) renal arterial branching pattern; (b) number of renal arteries and veins; (c) Anomalous renal artery and/or venous anatomy; and (d) Renal parenchymal and extrarenal abnormalities.

Advantages of CTA of living renal donors include faster examinations, higher spatial resolution, and the ability to detect calcium including small renal calculi. Additionally, CT urography is at a more advanced stage of development than MR urography, with more widespread acceptance in the radiology and clinical community. MR on the other hand offers the advantage of no radiation or contrast exposure, with generally similar results to CT. A number of studies have evaluated MRA and CTA in comparison with the gold standard of conventional angiography. Both techniques fared extremely well, detecting accessory arteries at a rate comparable to conventional angiography, and often with superior performance in defining venous anatomy [42–49].

In the postoperative renal transplant recipient, sonography is usually the initial examination for evaluation of vascular complications. MRA and CTA are useful problem-solving techniques when sonography is inconclusive. Both MRA and CTA can assess arterial and venous anastomoses as well as identify renal infarctions, collecting system abnormalities, and perirenal fluid collections. A recent series on MRA in 31 patients with suspected posttransplantation complications detected vascular findings in 48%, including both arterial and venous stenosis and thrombosis [50]. Additional nonvascular complications were detected in a high percentage of patients.

Miscellaneous applications

Several other uncommon conditions can be evaluated with renal MRA and/or CTA. Renal artery aneurysms are usually incidental findings in patients whose kidneys or renal arteries are imaged for other indications (Figs. 11, 12). The clinical relevance of renal artery aneurysms is uncertain; however, there is a definite risk of aneurysm rupture, which increases with aneurysm diameter. Both MRA and CTA are safe, noninvasive modalities for characterization and surveillance [51]. Arteriovenous malformations are unusual causes of hematuria in young adults, and their treatment can be quite problematic. MRA and CTA are both able to demonstrate large feeding arteries and draining veins without a focal mass, confirming the diagnosis (Fig. 13). A large number of vasculitides can involve the renal arteries. The role of MRA and CTA in detecting renal vasculitis is uncertain. While sequellae of vasculitis such as peripheral infarcts are easily demonstrated with either CT or MRI, the tendency of many of these entities to involve medium and small sized renal arteries implies that very high spatial resolution is required to detect lesions with acceptable sensitivity.

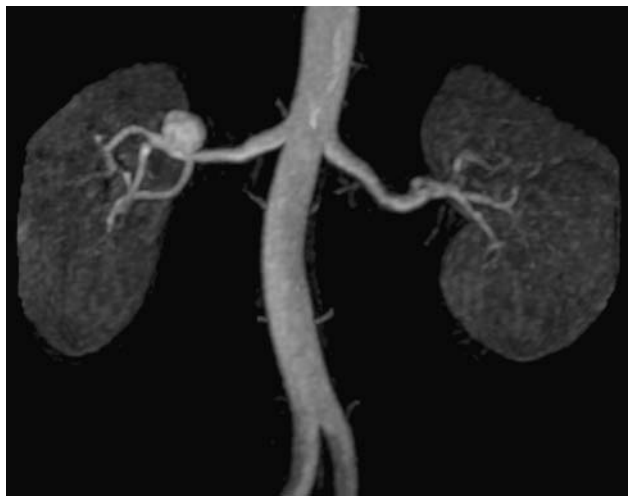

Fig. 11. Renal artery aneurysm. Subvolume MIP image from renal MRA reveals a large aneurysm at the right renal hilum.

Pitfalls and artifacts

CTA

State-of-the-art CT angiography of the renal arteries is acquired in a single breath hold and accurately timed using bolus tracking techniques. These advancements have virtually eliminated motion and partial volume artifacts. The main pitfall of current CT angiography is accurate assessment of the size of the true lumen given adjacent atheromatous calcifications. Future image acquisitions may be possible with synchronous acquisition as dual energy which will allow automated subtraction techniques using CT data.

MRA

A number of pitfalls and artifacts have been described regarding 3D CE MRA in general and renal MRA in particular. Problems with the coordination of data acquisition and arrival of the contrast bolus are common: if the scan is initiated too early, insufficient contrast is present in the arteries, and the resulting images are either uninterpretable or SNR is suboptimal. Additionally, ringing artifact can occur when the arterial concentration of contrast changes rapidly during acquisition of the central portion of k-space [52]. This usually occurs when scanning is begun before the peak of the contrast bolus has arrived in the renal arteries. Scanning too late is often just as problematic; in this case SNR is also poor, and extensive venous

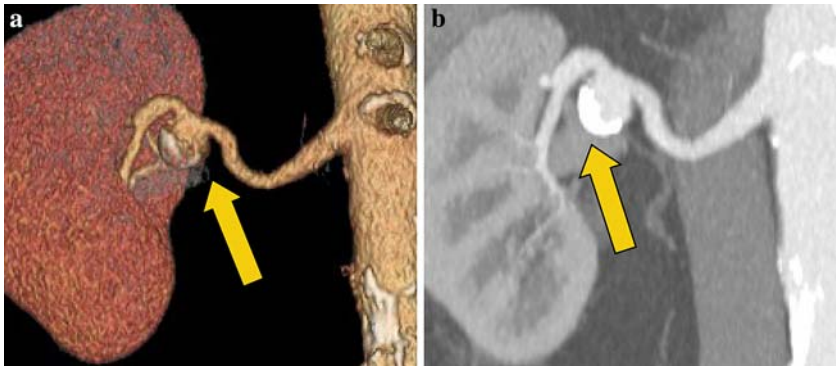

Fig. 12. Renal artery aneurysm. Volume rendered CTA (**A**) and maximum intensity projection CTA (**B**) of the right renal artery demonstrates a 1.5 cm partially calcified aneurysm arising from the distal main right renal artery inferiorly.

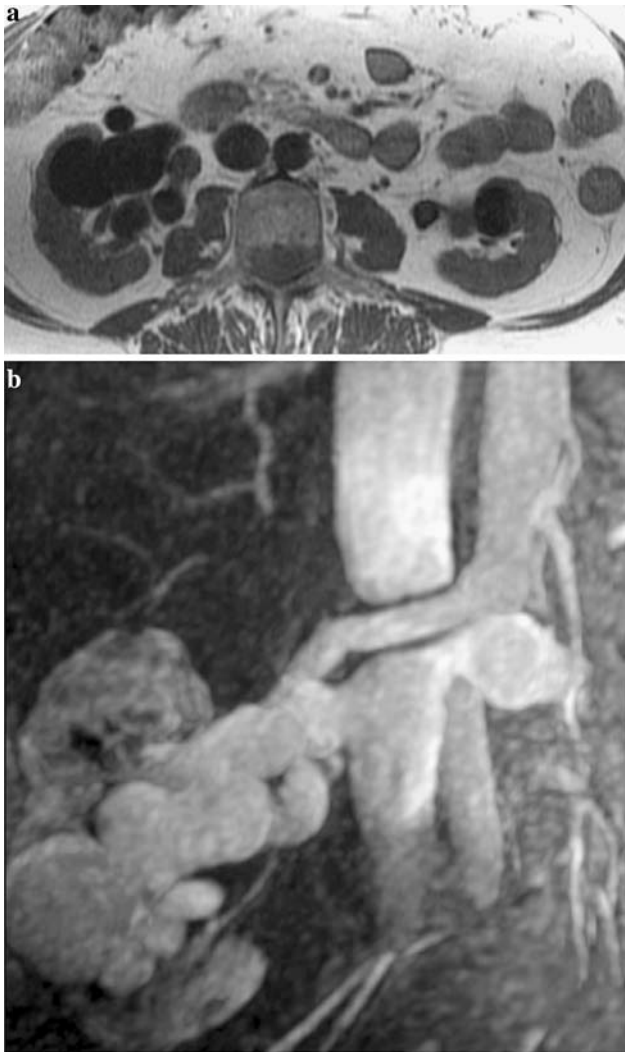

Fig. 13. Renal arteriovenous malformation. Breath-held T1-weighted fast spin echo image (**A**) and venous phase reformatted image from 3D MRA (**B**) reveal massively dilated right renal artery and massively dilated veins, consistent with arteriovenous malformation. A left sided AV malformation was also present and is less well seen on these images.

contamination can limit visualization of the renal arteries. Motion artifact has been discussed in other sections. The combination of subtle motion artifact and volume averaging in voxels containing both vessel and background tissue can lead to an irregular beaded appearance of the renal arteries which can easily be attributed to FMD [53]. Bilateral symmetry, involvement of multiple additional vessels as well as the presence of ghosting artifact outside of the arteries are all clues to this artifact.

Undisclosed renal artery stents can be misinterpreted as severely stenotic or occluded vessels. Clues to the presence of stents include signal dropout in the region of the stent. This can be easily appreciated on in- and out-of-phase spoiled gradient echo images, where susceptibility blooming is most prominent on the in-phase image due to its longer TE.

Evaluation of renal MRA or CTA data should always occur at the workstation, with access to full and subvolume MIP images, reformatted images in multiple projections, and source images. As noted above, the most accurate and reproducible measurements of RAS are obtained by assessing the cross-sectional area of the vessel. Interpretation of renal MRA or CTA based solely on MIP images is not recommended: not only can stenoses be over or underestimated, but also parenchymal lesions and other findings are easily missed.

Renal MRA is most commonly performed for RAS, and naturally vascular lesions are the predominant findings in the vast majority of cases. Incidental lesions are not uncommon in this population; however, it is useful to obtain a few additional sequences to allow assessment of the adrenal glands and renal parenchyma (single shot fast spin echo and in and out of phase spoiled gradient echo acquisitions, for example). Adrenal adenomas are common and can be characterized easily without the need for additional testing. Renal parenchymal lesions should be detected and characterized on renal MRA without the requirement for an additional examination (Fig. 14). The detection of incidental findings on CTA is also aided by obtaining one or more additional acquisitions: a nephrographic phase acquisition will improve the detection of small renal masses as well as allow characterization of incidentally detected lesions in the liver and other organs.

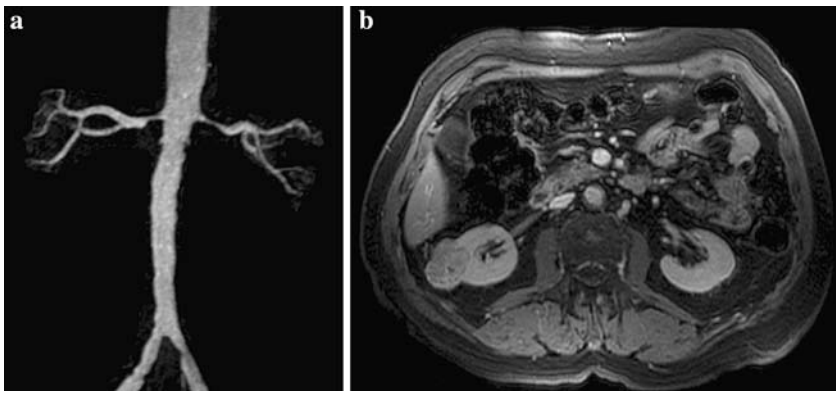

Fig. 14. Incidental renal cell carcinoma. Patient with severe bilateral renal artery stenosis on MRA (**A**) also had an incidental enhancing renal cell carcinoma in the right kidney seen on postcontrast fat-saturated SPGR sequence (**B**).

Future directions

MRA

Even if one accepts the proposition that renal MRA and CTA are highly accurate in the detection of RAS, it remains true that renal revascularization is unsuccessful or even detrimental in a subset of patients. The ideal diagnostic test then would not only be able to detect significant RAS but also determine which patients would benefit from revascularization and which patients would be best treated medically. Standard contrast-enhanced MRA and CTA offer a number of clues to assess the functional status of the kidneys as well as to evaluate the functional severity of the stenosis, including loss of cortical-medullary differentiation on T1-weighted precontrast images, renal atrophy, and poststenotic dilatation [54].

In addition to these relatively straightforward observations, MR and to a lesser extent CT offer additional functional techniques which allow additional assessment of the kidneys or renal arteries. Signal drop-out in 3D phase contrast MRA, for example, is related to intravoxel dephasing caused by disordered, chaotic flow in the region of a severe stenosis. The presence of this signal drop-out tends to correlate with a significant pressure gradient, and this technique has been advocated by many authors [55, 56].

Two-dimensional cine phase contrast sequences, allowing velocity and flow measurements throughout the cardiac cycle, are also potentially very useful. Loss of the characteristic early systolic peak, for example, is a good indication of a hemodynamically significant stenosis. A recent multicenter study reported that the combined approach of 3D CE MRA and cine PC velocity profile analysis yielded the lowest interobserver variability and excellent agreement with conventional angiography [57]. Several other parameters can also be assessed with cine phase contrast techniques, including resistive and pulsatility indices and renal arterial and venous blood flow. Renal blood flow is not typically expected to be reduced until RAS becomes quite severe; however, flow measurements can be obtained in conjunction with captopril administration in analogy with renal scintigraphy. Another interesting approach is to combine functional flow data from cine PC measurements with anatomic information from 3D CE MRA to construct a computational fluid dynamic model of the renal artery. Yim et al [58] recently demonstrated that the accurate prediction of pressure gradients could be obtained using CFD methods Renal perfusion can be assessed with either MR or CT [59–62].

Blood oxygen level dependent (BOLD) imaging depends on contrast generated by changing levels of paramagnetic deoxyhemoglobin: a decrease in intrarenal T2 during hypoxia is a reflection of increasing concentrations of deoxyhemoglogin. Recently, multiecho T2*-weighted gradient echo sequences have been employed to generate maps of renal relaxivity (R2*). This approach was recently used to demonstrate changes in intrarenal oxygenation during acute reduction of renal blood flow in an animal model [63].

Parallel imaging, in which half or fewer of the usual number of lines of k-space are collected and the missing data are reconstructed using spatial information inherent in the signals received from different phased array elements, has rapidly gained widespread acceptance in the clinical radiology community [64, 65]. Parallel imaging has the major virtue of reducing acquisition times while preserving spatial resolution. Recently, Schoenberg et al. [26] demonstrated that parallel imaging could be used in renal MRA to improve spatial resolution while maintaining a reasonable acquisition time: the authors achieved resolution on the order of 1 mm^3 [26]. While the benefits of spatial resolution are obvious, parallel imaging can also be employed to reduce acquisition times while preserving spatial resolution—this is an attractive option in patients with limited breath hold capacity. Limitations of parallel imaging include significant loss in SNR, which is especially problematic when used in pursuit of higher resolution: in this case SNR loss is compounded by smaller voxel size. Strategies to minimize this effect include the use of contrast agents with higher relaxivity as well as higher magnetic field strengths. Parallel imaging techniques are somewhat

artifact-prone, although as reconstruction algorithms improve some of these problems will likely be alleviated.

High field systems, in particular 3 T, are gaining clinical acceptance. Since SNR is directly proportional to magnetic field strength, a theoretical doubling of SNR could occur when switching from 1.5 T to 3 T. Practical considerations will probably limit this benefit somewhat; however, a significant gain in SNR is likely. Since the SNR gain occurs with little cost in acquisition time, the coupling of high field MRI with parallel imaging is very attractive, with the potential for high spatial resolution with excellent SNR [27].

Several blood pool contrast agents are currently undergoing evaluation for clinical use. These agents are attractive by virtue of their improved contrast compared with conventional extravascular agents as well as by their long intravascular half lives. By removing the constraint of data acquisition during the first pass of the contrast bolus, much longer acquisitions can be contemplated, with corresponding gains in both spatial resolution and SNR. If long acquisitions are performed, however, very effective compensation for respiratory motion will be needed (respiratory triggering or navigator gating, for example). An additional problem is the task of separating arterial from venous anatomy. Some vessel segmentation strategies show great promise, but these tasks often become more difficult as the severity of vascular disease increases. Blood pool contrast agents also greatly simplify the process of obtaining quantitative renal perfusion data.

Steady state free precession sequences have proved valuable in cardiac and coronary artery imaging. Recently, several investigators have applied these techniques to the renal arteries, with promising results [66, 67]. These bright-blood sequences are typically performed without intravenous contrast, and navigator-gated sequences, in a manner analogous to intravascular contrast agents, can be acquired with high SNR and high spatial resolution. These techniques are currently investigational and have not been widely applied to the clinical setting.

MRA versus CTA

MR and CT angiography have unique advantages and disadvantages. MRA does not require ionizing radiation or the use of an iodinated contrast agent; MRA is therefore an attractive alternative in patient populations with borderline renal function as well as those who are particularly sensitive to radiation. Young patients, pregnant patients, and patients likely to undergo multiple follow-up examinations are all candidates for MRA based on radiation considerations alone. A large percentage of patients with suspected renovascular hypertension also have borderline or reduced renal function. These patients are at increased risk for nephrotoxicity with iodinated contrast agents, and are also candidates for MRA. Renal MRA is also preferred in patients with severe allergies to iodinated contrast agents.

On the other hand, candidates who may proceed directly to CTA include those with pacemakers, AICD devices, or other noncompatible MR devices. Patients with severe claustrophobia are much more likely to complete renal CTA than MRA. Patients with limited breath hold capacity might fare better with renal CTA in a 64-channel systems and a very short acquisition time instead of an MRA requiring a longer total examination time and longer breath holds.

When very high spatial resolution is required, state-of-the-art multichannel CT is generally preferred, and the cases where this might be particularly important include examination of segmental renal arteries for FMD or vasculitis. Relatively high spatial resolution approaching CTA can be achieved with MRA, but this generally requires careful attention to technique, the use of parallel imaging, and potential problems with imaging artifacts and low SNR.

CT angiography is probably used in more institutions for screening potential renal donors than MRA. Reasons for this preference include wider availability, visualization of calcium (for the detection of renal calculi), faster examinations, and better urographic images. Spatial resolution is occasionally important for detecting very small accessory arteries; however, both CTA and MRA are very successful at this in most studies.

Staging renal cell carcinoma is another indication which both techniques perform quite well. MR might have a slight advantage in visualization of venous thrombus: a number of techniques, both contrast-enhanced and noncontrast, are available, and MR therefore offers greater flexibility, particularly when venous return is relatively slow and venous contrast is limited. Nevertheless, both CT and MR are highly successful in accurately staging renal cell carcinoma.

Conclusions

Renal MRA and CTA are effective tools in answering most clinical questions regarding the renal vasculature. Each technique has unique advantages and limitations as outlined above, and under ideal circumstances both techniques would be readily available, with the choice determined only by clinical need.

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