Renal Imaging: Core Curriculum 2019

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Renal imaging has become a fundamental part of clinical care for patients with kidney disease. Imaging strategies for the kidney have been evolving during the past hundred years and have been even more rapidly changing during the past couple of decades due to the development of modern computed tomographic techniques, magnetic resonance imaging, and more sophisticated ultrasonographic techniques, such as contrast-enhanced ultrasonography. Applying the correct radiologic study for the clinical situation maximizes the diagnostic accuracy of the imaging, and a judicious choice between techniques helps limit radiation dose and potential adverse events. This Core Curriculum outlines the imaging modalities currently in use in radiology departments and is divided into 3 sections: (1) a review of the development of renal imaging and an outline of modalities available to the nephrologist, (2) imaging strategies for select clinical situations, and (3) a discussion of some potential adverse events from imaging, including effects of iodinated contrast on kidney function, risks of gadolinium-based contrast agents in kidney failure, and potential risks of imaging techniques that use ionizing radiation.

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Introduction

Evaluation of the urinary tract was one of the first experimental applications of radiology and contrast administration. More than 100 years later, imaging has developed into a fundamental part of the evaluation of nephrology and urology patients. We have evolved from glass tubes emitting weak x-rays and faint silver-based contrast agents at the turn of the last century to a multitude of modalities, including traditional radiographic techniques, scintigraphy with nuclear medicine agents, ultrasonography, computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET). Contrast agents and our understanding of their effects in the kidney (and elsewhere) have also evolved over time. However, the role of imaging has only just begun; high-resolution imaging, functional imaging, and molecular imaging promise that the evolution of renal imaging during the next century will be just as rapid as the first hundred years.

This Core Curriculum article looks at renal imaging in two complementary ways. First, a brief overview of current imaging technologies introduces the "cast of characters" in the radiology department. Then we review select clinical scenarios with a discussion of how the different imaging technologies can be used to best effect. Finally, we close with a discussion of contrast nephropathy, nephrogenic sclerosing fibrosis (NSF), radiation dose, and future directions for renal imaging.

Part 1: Imaging Modalities

***Case**: A 65-year-old man presents with a history of diabetes and poorly controlled hypertension despite the use of three antihypertensives. The patient has multiple comorbid conditions, including body mass index of 45 kg/m² and ischemic heart disease requiring a pacemaker. He also has lumbar stenosis and has undergone multilevel laminectomies with placement of extensive fusion hardware. His kidney function decreased after administration of the third antihypertensive and you suspect renal artery stenosis. As you consider an imaging study to confirm the diagnosis, the patient mentions that he is concerned about receiving radiation.*

Question 1: Which of these imaging techniques uses nonionizing radiowave frequencies for imaging?

a) Ultrasonography with microbubbles
b) Ultrasonography with Doppler
c) Contrast-enhanced CT angiography (CTA)
d) Contrast-enhanced MR angiography (MRA)

For the answer to the question, see the following text.

Radiography (X-ray)/Intravenous Urography/Retrograde Pyelography

These techniques are grouped together because they are similar in how they generate their images. X-rays are sent from an x-ray tube through a patient to a detector, either in a single high-energy burst (a "spot radiograph") or as a continuous low-energy series of images (fluoroscopy). Both techniques can be used during a single study.

Before the invention of ultrasonography and CT, these techniques were the primary way to anatomically image the kidney. Plain radiography (sometimes referred to as a "plain film," although this has become an antiquated term since radiographic film is rarely used anymore) has a limited ability to characterize the kidney, ureters, and bladder. The similarity in density between the renal parenchyma and surrounding structures prevents tissue contrast and the kidney is obscured. Renal stones and calcifications can be detected, as well as gas in the collecting system or within the kidney, but overall, plain radiography is a suboptimal way of evaluating the genitourinary system.

To compensate for the lack of tissue contrast on plain radiography, iodine-based contrast was administered intravenously, which would then flow through the renal vasculature and filter into the collecting system. This was the basis for the intravenous (IV) urogram (also known as an IV pyelogram), which was a revolutionary technique when it was developed in the late 1920s and was the primary method of imaging the kidneys for decades. Retrograde pyelography uses similar technology, but instead of administering the iodinated contrast intravenously, a catheter is placed into the ureter and contrast is administered retrograde into the ureter, outlining the collecting system. It can create exquisite imaging of the renal calyces, pelvis, and ureters, but renal abnormalities usually had to be inferred from various mass-effect patterns. A comparison of an IV urogram image and a retrograde pyelogram image can be seen in Figure 1.

Renal angiography uses the same x-ray technology as the previously mentioned modalities, but the iodinated contrast for the images is introduced directly into the renal artery through an arterial catheter, rather than administered from a peripheral vein (see the Evaluation of Renal Hypertension/Renal Artery Stenosis section for an image). The rate and volume of contrast administration is better controlled using this technique. Renal angiography was a valuable diagnostic tool in the era before CT; currently, it is reserved almost exclusively for planning and performing transcatheter interventions.

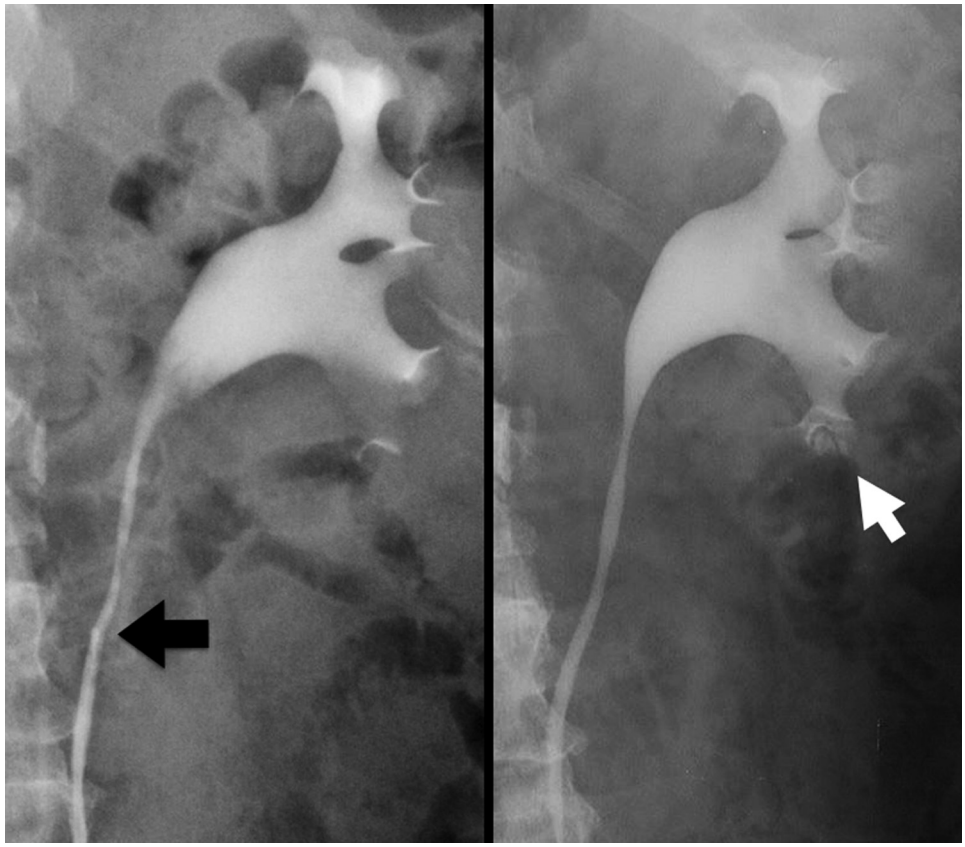

Figure 1. Comparison of a retrograde pyelogram and an intravenous urogram (IVU) in a patient receiving follow-up for low-grade urothelial carcinoma of the bladder. (Left) Retrograde pyelogram. Contrast is administered from a ureteral catheter (tip is at the black arrow) and fills the renal pelvis. To optimally fill the calyces, the patient has to be turned into different positions. (Right) In contrast, the patient's IVU. The radiograph is timed for when the contrast enters the collecting system. This patient has tubular ectasia with a "paint brush" appearance of some of the tips of the medullary pyramids (such as at the white arrow). A retrograde study would not be able to reliably evaluate a parenchymal abnormality in the renal pyramid.

The use of many of these techniques declined when later generations of CT technology were able to produce high-quality CT urograms or CT angiograms, and they are rarely, if ever, performed in the modern era. Even so, the spatial resolution obtained with a high-quality urogram or angiogram is better than with CT.

Ultrasonography and Doppler

Ultrasonography uses sound waves as the basis of its imaging, and because sound waves are nonionizing, it can be used in children and pregnant patients without concern about a radiation dose. Combined with the relatively low cost of the equipment, its availability, and its capability for Doppler, ultrasonography has become a routine method for evaluating the kidneys, especially for a first evaluation. However, there are limitations to ultrasonography. Ultrasonic sound waves have trouble transmitting through some substances, such as bone and gas. Ultrasonography is also an operator-dependent technique, and although there is a low barrier to performing a study, mastery of the technique and avoiding misleading artifacts takes practice.

Ultrasonography has a very powerful ability to characterize the relative speeds of the sound waves returning to the transducer and can create a Doppler profile of these returning sound waves. This Doppler signal can then be coded into color and superimposed on a grayscale image of the area in question. Doppler signal allows for very sensitive and dynamic evaluation of blood flow in arteries and veins and is useful for evaluating the renal arteries in native and transplant kidneys, as well as surveying the renal parenchyma vasculature. An example of both a grayscale and Doppler evaluation of the kidney can be seen in Figure 2. Spectral Doppler renders the Doppler information received by the transducer more explicitly, and in addition to directional information, it also reveals the speed of blood flow and relative flow during systole and diastole, which is very useful for characterizing a stenosis or detecting end-organ vascular resistance. Power Doppler increases the ultrasound machine's sensitivity to very slow flow, but at the cost of directional information.

Ultrasound contrast in the form of microbubbles was only recently approved by the US Food and Drug Administration for use in the United States. The technique is similar to contrast administration in other imaging modalities; the microbubbles are administered intravenously, some time passes as the contrast moves into the arterial circulation, and the kidney is imaged when the contrast reaches the renal vasculature (Fig 3). The microbubbles, which are an inert gas surrounded by a phospholipid shell, are smaller than a red blood cell and travel through the renal vasculature "enhancing" the image of

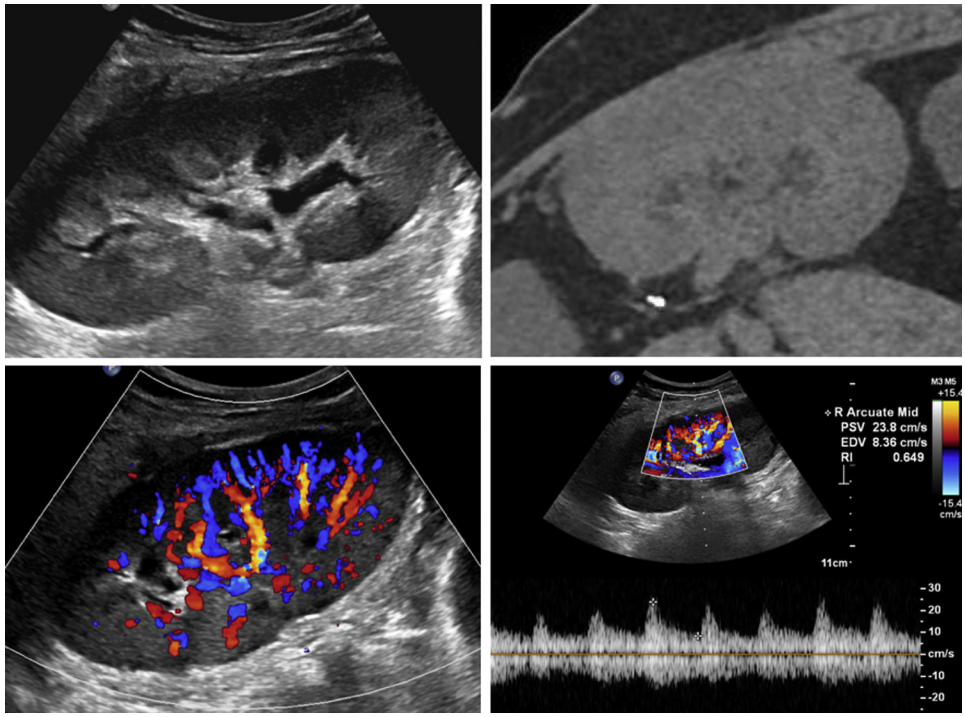

Figure 2. Imaging of a patient who presented for evaluation of pain over a kidney transplant. (Top left) Static grayscale ultrasound image of his transplant, which has a normal appearance. (Top right) The spatial resolution of ultrasound can be compared to a noncontrast computed tomographic image of the patient's transplant kidney. (Bottom left) The transplant is being evaluated with color Doppler and shows a normal appearance without areas of high velocity, turbulence, or decreased perfusion. (Bottom right) Spectral Doppler evaluation of one of the arcuate arteries at the interpolar region. There is a normal arterial waveform without indication of abnormal renal vascular resistance.

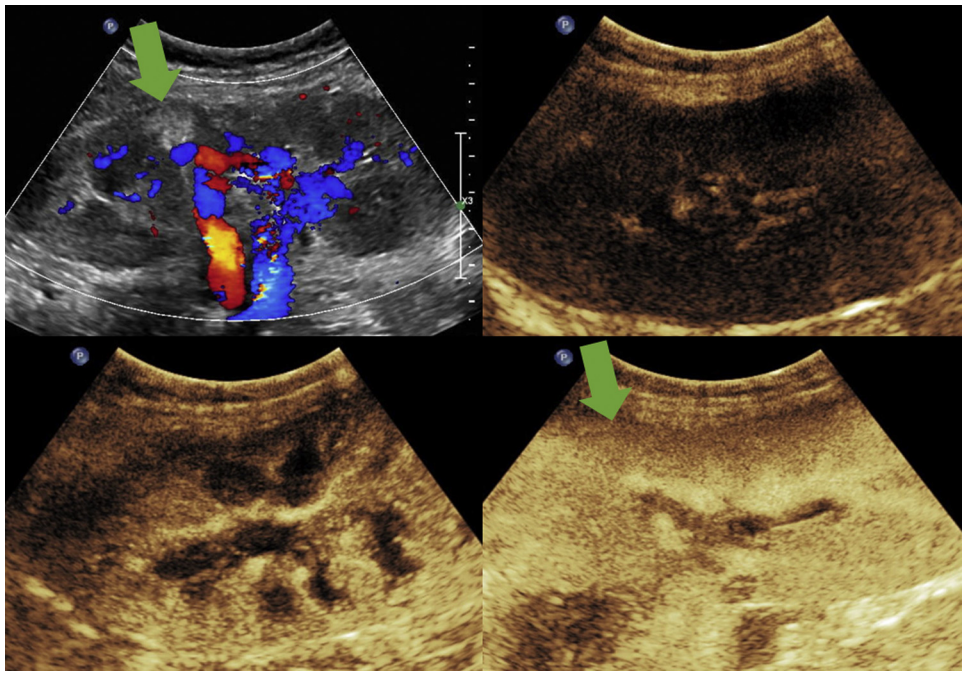

Figure 3. Ultrasonographic examination of a patient who received a kidney transplant a year before the examination. (Top left) On a color Doppler evaluation, the green arrow points to the area of concern for a focal area of abnormal perfusion in the upper pole of the transplant. Three contrast-enhanced ultrasound images follow, as ultrasound contrast is washing into the transplant kidney. (Top right) No contrast has reached the kidney and it has a dark (unenhanced) appearance. (Bottom left) Contrast is beginning to wash into the kidney with prominent enhancement of the main and interlobar arteries, as well as enhancement of some of the cortex, but no enhancement yet of the medulla. The appearance is analogous to the corticomedullary phase on computed tomography (see Fig 4). (Bottom right) Contrast is in both the cortex and medulla and the dark central portions are calyces and infundibula of the collecting system. The green arrow points to the area of concern and there is no decreased perfusion, indicating a false-positive on the color Doppler examination.

the kidney when they interact with the ultrasound wave. Currently, microbubbles are most often used in the kidney for characterization of renal masses.

One of the benefits of ultrasound contrast is that the gas is exhaled, and unlike iodine-contrast agents, it is neither filtered nor secreted, which makes it a useful imaging technique in patients with poor kidney function who may not qualify for contrast otherwise. Ultrasound contrast also has a good safety profile with few contraindications to its use.

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CT/CT Urography/CTA

CT relies on x-rays for imaging, just like plain radiography and IV urography, but the x-rays are obtained at numerous angles around the patient and the resulting data set is deconvoluted by computer to create a cross-sectional image. The technology has evolved rapidly since it was first introduced in 1973 and has been revolutionary for patient care in multiple specialties. Each new CT generation produces images faster, with improved tissue and spatial contrast. With the introduction of helical and then multidetector CT in the 1990s and 2000s, thin-section isotropic data sets can be produced within seconds.

The principles of CT evaluation of the kidneys are similar to those of other imaging technologies. A CT study without IV iodinated contrast can characterize some aspects of the kidneys, such as stones and hydronephrosis, but other aspects are more difficult to evaluate, such as renal masses. Administration of contrast "enhances" the image of the kidneys, allowing much better characterization of their structure (and sometimes function).

Varying the time elapsed between contrast administration and image acquisition will result in different

appearances of the kidney as the contrast washes in and as some of it is filtered into the collecting system. This forms the basis of "multiphase" imaging in which the kidneys are imaged at fixed time points after administration of a single intravenous bolus of contrast. The information gathered from each "phase" is useful for full characterization (Fig 4). These multiphase protocols have different names at different institutions but are often considered "renal mass" protocols.

CT urography (CTU) also relies on the multiphase principle to focus on an "excretory" phase after the contrast has filtered into the collecting system and bladder, essentially creating an IV urogram with vastly improved tissue contrast. Different institutions have different protocols for their CTU studies, varying in the number of phases obtained, the contrast bolus profile, and whether 3-dimensional images of the kidneys and bladder are generated.

CTA of the abdomen times the IV contrast bolus for maximum enhancement of the renal arteries. This results in an angiogram and can be useful to evaluate for renal artery stenosis or renal vascular malformations, for example. The benefit over traditional angiography is that it does not require an arterial catheter and one can manipulate the CT data set to view the renal vessels from any angle and can do this with a single acquisition and single contrast bolus.

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MRI/MR Urography/MRA

MRI takes advantage of differences in the molecular microenvironment to generate images from the spins of hydrogen atoms (mostly hydrogen atoms in water molecules in different microenvironments). Radiowave frequencies are sent into the patient and then received from the patient while altering the magnetic field strength to determine the spatial orientation and contrast of images. The radiowave energy is nonionizing like ultrasonography, and MRI can be used in children and pregnant patients without concern for a radiation dose.

The real strength of MRI lies in the ability to create different "sequences" of magnetic field changes and radiowave pulses to bring out different types of contrast in the image. Customizing sequences to accentuate different types of pathology is the basis of different MRI protocols (a set of sequences). Many sequences fall into T1-weighted or T2-weighted categories, which describe what spin will be used for the basis for generating the image. T2-weighted sequences are typically "fluid sensitive," and free fluid (eg, urine in the collecting system) is bright on the image. See Figure 5 for a comparison of noncontrast MRI and noncontrast CT imaging. See Figure 6 for a comparison of T1-weighted imaging, T2-weighted imaging, CTU, and retrograde urography.

Despite its remarkable capacity for tissue contrast, MRI has some drawbacks. First, it is the most expensive imaging technology and requires constant technical

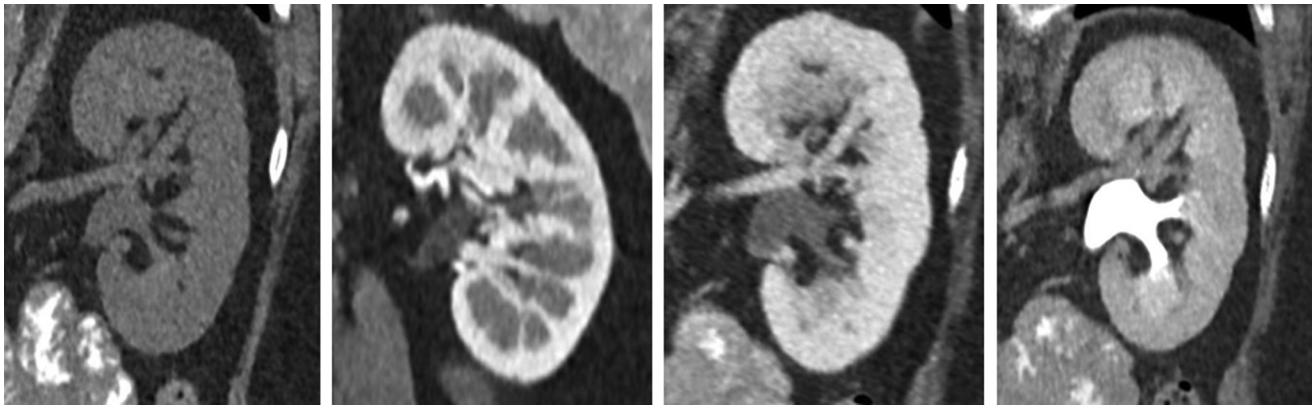

Figure 4. Four coronal computed tomographic images of a kidney at different contrast phases. (First image) Noncontrast image: no contrast has been administered yet and the kidney has a uniform attenuation. (Second image) The corticomedullary phase: obtained approximately 30 to 45 seconds after the administration of intravenous (IV) contrast. There is distinction between the cortex and medulla at this time point, and it can occasionally be difficult to detect small heterogeneously enhancing masses during this phase. (Third image) Nephrographic phase: approximately 90 to 120 seconds after IV contrast administration. This is generally considered the most useful phase for evaluation of renal masses and inflammatory processes in the kidney. (Fourth image) Excretory phase: this usually occurs at about 3 minutes in someone with normal kidney function. The highly attenuating contrast has entered into the collecting system and the renal parenchymal enhancement is beginning to fade.

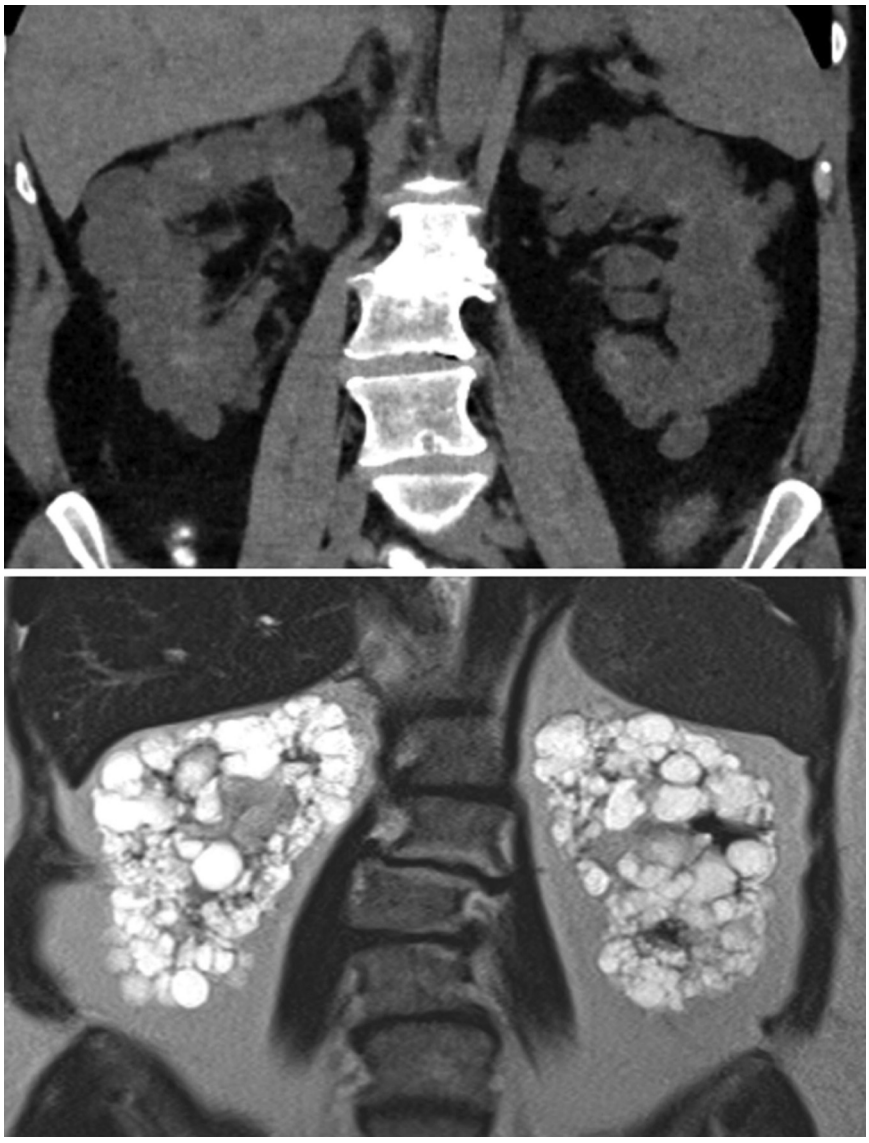

Figure 5. Imaging of a patient with autosomal dominant polycystic kidney disease. A (top) coronal computed tomographic (CT) image is compared with a (bottom) coronal magnetic resonance (MR) image. On CT, the numerous cysts are a low attenuation around the level of water, compatible with their cystic content. There are patchy areas of increased attenuation in the cysts, which represents a small amount of proteinaceous debris layering in some cysts. On the noncontrast MR image, the same cysts are bright because this is a fluid-sensitive T2-weighted sequence; darker shades correspond with proteinaceous or hemorrhagic debris. Notice the improved tissue contrast of the cysts on MR imaging relative to CT. The boundaries of the cysts are much better visualized.

monitoring to keep the magnet and machine in top form. Second, acquisition times are relatively long compared with other modalities. Whereas CT can acquire all the data it needs for a sophisticated multiplanar reformat in seconds, a full MRI protocol is on the order of a few minutes per sequence, so it is not unusual for an MRI protocol to take 15 to 30 minutes. This length of time is a problem in two ways: (1) patient motion degrades MRI images so a patient has to be able to remain motionless for minutes at a time, and (2) the MRI gantry is narrow and patients may find it difficult to stay still in a tight space for the full length of the study. Finally, because MRI relies on strong magnetic fields, metallic objects in or on the patient can markedly degrade the image, or worse, depending on the metal, the object could heat up or pull violently toward the magnetic field.

The strength of the magnet is roughly correlated with the quality of the spatial resolution of the image. The first clinical MRI magnets were on the order of 0.1 to 0.3 Tesla (T). Many closed-bore MRI machines are currently 1.5 T, but 3-T magnets are also common. Magnets stronger than this (eg, 7 T) are not currently in clinical use due to technical challenges. Weaker magnets in the range of 0.3 to 0.7 T can be found in "open" MRI machines that are designed to accommodate patients with claustrophobia, but the weaker field strength limits the quality of the image.

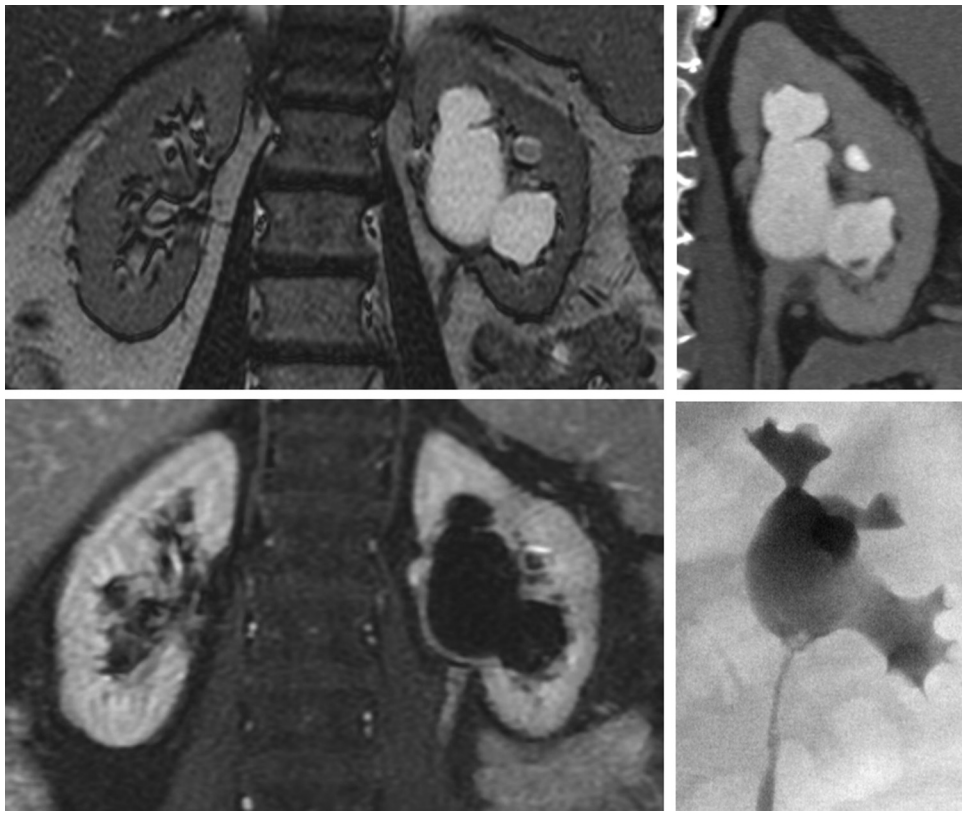

Figure 6. Imaging of a patient who presented with left-sided abdominal pain and was found to have hydronephrosis of the left kidney. (Left images) Coronal images from a magnetic resonance imaging study. (Top left) The dilated left upper collecting system is bright because the urine is bright in this fluid-sensitive sequence. Compare with the normal nondilated right kidney. (Bottom left) Also compare with an image that shows the same dilated left renal pelvis to be dark. This is a T1-weighted image and fluid is not bright, although the renal parenchyma is bright because it is enhancing postcontrast. (Top right) Image from the patient's computed tomography urogram. The iodinated intravenous contrast entering the collecting system is bright, but there is no bright contrast in the proximal ureter, suggesting that there is an obstruction at this level. (Bottom right) Image from the patient's retrograde pyelogram. Contrast extends from the ureter into the dilated renal pelvis, so a complete obstruction can be excluded.

MRI sequences can be enhanced in a similar manner to ultrasonography and CT. An IV agent, most often an organic gadolinium complex, is most often used. These agents have very strong signal on T1-weighted sequences, resulting in vascular enhancement similar to that seen on CT. For more about gadolinium contrast and NSF, see the section later in this article.

An MRI protocol with multiple specialized T2-weighted sequences can be constructed to simulate a CTU. This MR urography is not in wide use in adults because the spatial resolution of MR tends to be less than that of CT and adequate spatial resolution is important for evaluation of the urinary tract, especially for resolution of small structures such as renal papilla and the ureter. MR urography is more often used in pediatric patients, for whom the loss of spatial resolution is considered acceptable in return for a nonionizing study. Also similar to CT, an MRI protocol can be designed to accentuate the arteries, resulting in an MR angiogram.

Thus, the answer to question 1 is (d). MRI transmits and receives energy in the radiowave frequency spectrum for imaging and it is nonionizing, without a radiation dose. Ultrasonography is also nonionizing but uses sound waves for imaging. CT uses x-rays for imaging and the radiation is ionizing.

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Nuclear Medicine/PET

The imaging modalities described so far have some capacity for functional evaluation of the kidney, but their

fundamental approach is anatomic. Nuclear medicine, however, has a different approach. It is mostly concerned with functional imaging and only secondarily concerned with anatomic imaging.

Nuclear medicine also involves another fundamentally different approach to imaging. In the techniques we have been discussing, radiation is introduced into the body and either passes through it in a characteristic way (radiography and CT) or the body echoes back the signals in a characteristic way (ultrasonography and MRI). With nuclear medicine and PET, a radioactive substance (a radiopharmaceutical) is introduced into a patient and the radiation travels from within the patient outward to detectors around the patient. This is called emission imaging.

Radiopharmaceuticals generally comprise a radioactive isotope (such as technetium 99 [^{99m}Tc]) joined to a ligand that permits targeted physiologic imaging. The radiopharmaceuticals in renal imaging are generally classed as glomerular filtration agents, tubular secretion agents, or "renal cortical" agents that bind to the tubules for longer than the other two agents. The choice of which class to use depends on the clinical question being asked (Box 1).

One of the most valuable aspects of imaging in nuclear medicine is that function can be quantitatively evaluated; counting the relative number of scintilliations per kidney gives an accurate evaluation of split function. As an example, see Figure 7. The dynamic aspect of nuclear medicine imaging can also differentiate between complete versus partial renal obstruction, something that can be difficult to determine on other imaging modalities.

PET is a type of nuclear medicine imaging. It can use a number of radiopharmaceuticals, but most commonly uses fluorine-18 fluorodeoxyglucose (F-FDG) in routine clinical practice. Glucose transporters bring F-FDG into cells, like glucose, but because it cannot be metabolized, it becomes trapped in the cell. This means that the tracer distribution on imaging is essentially an indication of glucose metabolism and the imaging technique has found clinical utility in evaluation of inflammation and neoplasms. Unfortunately, because F-FDG is renally excreted, there is normally a large amount of signal in the kidneys at baseline, which obscures lesions in the kidneys. Although there are some experimental and niche uses of PET in kidney disease, such as evaluation of potential cyst infection in autosomal dominant polycystic kidney disease, PET is uncommonly used in routine practice for evaluation of renal parenchymal disease or renal masses.

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Box 1. Classes of Radiopharmaceuticals for Renal Imaging

Technetium-99m diethylenetriamine pentaacetic acid (DTPA)

Clearance:
- Glomerular filtration (~100%)
- Analogous to inulin

Utility:
- Estimation of glomerular filtration rate

Indications:
- Imaging of kidney perfusion
- Imaging of kidney function

Technetium-99m-labeled agent mercaptoacetyltriglycine (mertiatide or MAG3)

Clearance:
- Proximal tubular secretion (95%)
- Glomerular filtration (5%)
- Analogous to para-aminohippurate (PAH)

Utility:
- Estimation of effective renal plasma flow
- Higher extraction fraction that DTPA, better for imaging obstructed or reduced-function kidneys

Indications:
- Imaging of kidney perfusion
- Imaging of kidney function
- Renogram curves
- Evaluation for urinoma

^{99m}Tc-dimercaptosuccinic acid (DMSA)

Clearance:
- Cortical agent (binds to proximal convoluted tubule)

Utility:
- Imaging the renal cortex; suboptimal for evaluation of excretion

Indications:
- Problem-solving when evaluating the renal cortex, such as for evaluating regions of cortical scarring or pseudotumors

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Part 2: Select Clinical Scenarios

Evaluation of Acute Kidney Injury/Chronic Kidney Disease

Ultrasonography is the first-choice modality for evaluation of acute or chronic kidney failure. It is well suited for evaluating whether kidney injury is postrenal (hydronephrosis) and it can also rule out structural abnormalities such as renal developmental anomalies or polycystic kidney disease. Ultrasonography is especially useful in a patient with an elevated creatinine level when it is unclear whether it is an acute or chronic condition. Reduced kidney size and decreased cortical thickness is the hallmark of parenchymal loss seen in chronic kidney failure. Increased echogenicity of the renal parenchyma is associated with medical kidney

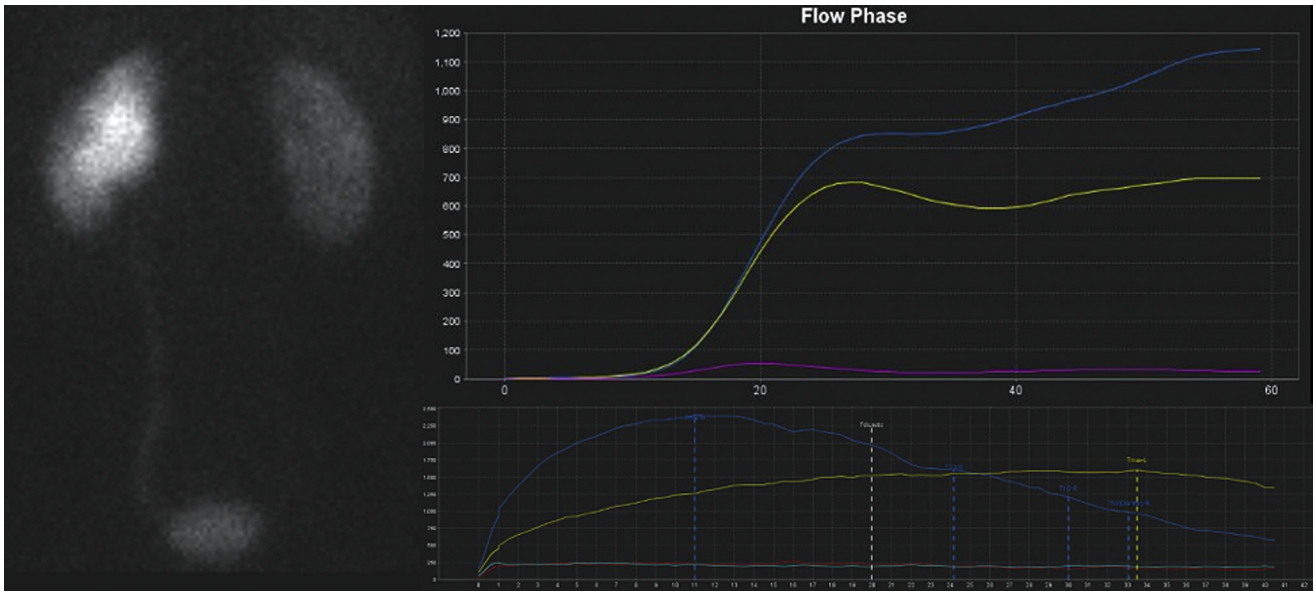

Figure 7. Renogram for the patient with the left pelvic obstruction in Figure 6. (Left) Scintigraphic image. These studies are obtained with the patient in a prone position so the dilated left kidney in on the left of the image. The brightness of the left kidney indicates radiotracer trapped in the renal pelvis. (Right) Renogram, tracing the scintillations in the renal pelvis over time. The left kidney is the yellow tracing. (Upper graph) Shows the split function of the kidneys: 68% on the right and 32% on the left. (Lower graph) Shows sluggish clearance of tracer before furosemide administration, but after furosemide, there is mostly stasis of the tracer in the left renal pelvis. This indicates functional obstruction. Compare this with the right kidney (blue tracing), which accumulates tracer and then the tracer activity declines with time as it is then excreted and passed out of the renal pelvis.

disease and can be seen in reversible kidney injury and chronic kidney failure.

Color Doppler ultrasonography can be used to survey perfusion to the kidneys and the patency of the renal vasculature to distinguish possible reduced kidney perfusion. This technique is also useful for showing ureteral jets when imaging the bladder to confirm urinary flow into the bladder from the ureters.

If an obstruction is incompletely defined on ultrasonography, additional imaging techniques including MRI and CT can be considered, but functional assessment of obstruction is best accomplished using nuclear medicine techniques (accompanied by diuretics). This is particularly useful in differentiating between a normal system, partial obstruction, and complete obstruction (Fig 7).

An old kidney injury is commonly incidentally inferred on imaging examinations performed for other reasons. Anatomic abnormalities (eg, atrophy and renal cortical scarring) and perfusion abnormalities on cross-sectional imaging following the administration of contrast suggest chronic changes from vascular disease, infection, or vesicoureteral reflux.

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Evaluation of Renal Infection/Inflammation

Imaging is rarely indicated for an initial evaluation of a patient with high clinical suspicion of uncomplicated acute pyelonephritis. Several clinical risk factors may prompt imaging evaluation for complications of pyelonephritis, including patients with diabetes, immunocompromised patients, those with a history of nephrolithiasis, prior renal or urinary tract surgery, and those who do not respond to appropriate antimicrobial therapy. In these clinical scenarios, imaging can prove useful in defining a nidus causing recurrent infection or a serious complication more likely in these patient populations.

Contrast-enhanced CT is most typically used to look for complications of pyelonephritis. In addition to evaluating renal parenchymal abnormalities, it can also characterize obstructive uropathy and is particularly sensitive for the detection of urolithiasis. Perinephric abscess is a complication that is well evaluated with CT. CT is also useful for detection of renal parenchymal gas in emphysematous pyelonephritis, a particularly morbid entity that classically affects diabetic and immunocompromised patients (Fig 8). With a technically skilled sonographer and experienced radiologist, both emphysematous pyelonephritis and perinephric abscess can be detected on ultrasound as well, but often the extent of disease is difficult to determine on ultrasound and these patients are almost always further evaluated using CT.

Although ultrasonography and CT are the workhorse modalities for evaluation of kidney infection, MRI can be a useful tool in certain patient populations, namely patients for whom

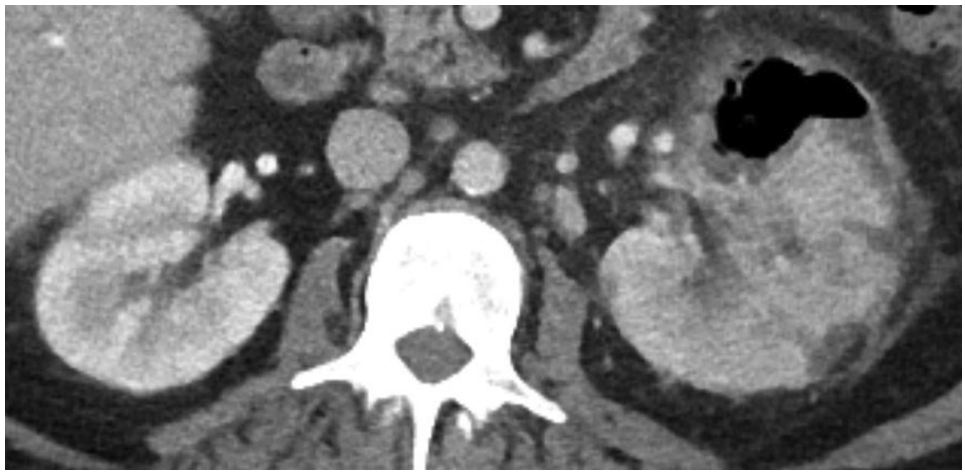

Figure 8. Imaging of a patient with a history of long-standing diabetes mellitus who presented to the emergency department with fever, nausea, and severe left flank pain. Computed tomography of the abdomen and pelvis was the first study ordered and it revealed an enlarged hypoenhancing left kidney with gas within the parenchyma (the kidney on the right of the image, patient's left side). Compare with the normal right kidney (on the left side of the image). Given the gas, the appearance is compatible with emphysematous pyelonephritis, which requires emergent treatment. Because the patient was a suboptimal candidate for surgery, the perinephric abscess was percutaneously drained.

an ultrasound is indeterminate and ionizing radiation should be avoided (eg, pregnancy). In cases in which IV contrast cannot be used, MRI with diffusion-weighted sequences may be helpful for evaluation of abscess.

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Evaluation of Renovascular Hypertension/Renal Artery Stenosis

Case, cont: *You are considering CTA to evaluate for possible renal artery stenosis in the patient.*

Question 2: Which of these indicates that Doppler ultrasonography would be a better test?

a) The patient has a body mass index > 40 kg/m^2
b) The patient has an estimated glomerular filtration rate (eGFR) < 30 mL/min/1.73 m^2
c) The patient has a cardiac pacemaker
d) The patient has a spinal injury and limited mobility

For the answer to the question, see the following text.

Imaging evaluation of renal arterial flow has been found to be useful in a workup for possible renovascular hypertension. There are multiple imaging modalities that can evaluate arterial flow to the kidney, each with its strengths and weaknesses, but with each modality there is usually some kind of trade-off between anatomic imaging and quantitating flow.

Often, the first modality that clinicians turn to is Doppler ultrasonographic evaluation of the renal arteries. It poses no radiation risk and can evaluate the renal parenchyma with grayscale ultrasonography in the same study. A good Doppler examination can accurately evaluate asymmetric flow to the kidneys, whether a proximal stenosis has a downstream effect on renal parenchymal arterial flow, and whether there is any venous abnormality (Fig 9).

However, there are limitations to a Doppler evaluation for renal artery stenosis. It is one of the most technically demanding studies for a radiologist or sonographer to perform. Bowel gas or a patient's body habitus often limits evaluation of the small and central proximal renal arteries, which is a critical part of the examination. If these are not well seen, evaluation relies on secondary findings to suggest a flow-limiting stenosis. Despite this drawback, it is still considered a first-line modality for evaluation in a patient with decreased kidney function and who may not qualify for IV contrast.

Contrast-enhanced cross-sectional imaging in the form of MRA and CTA may also be useful in the workup of renovascular diseases and they are often used first line for a patient who can receive contrast. These modalities are particularly helpful in anatomically characterizing proximal renal artery stenosis, which depending on the patient, may be near impossible to evaluate on ultrasonography.

Although far less commonly used than other techniques, renal scintigraphy with the administration of captopril can also be used for the characterization of kidney perfusion/function and its physiologic response to angiotensin-converting enzyme inhibitors. This method is less useful in cases of bilateral renal artery stenosis, decreased kidney

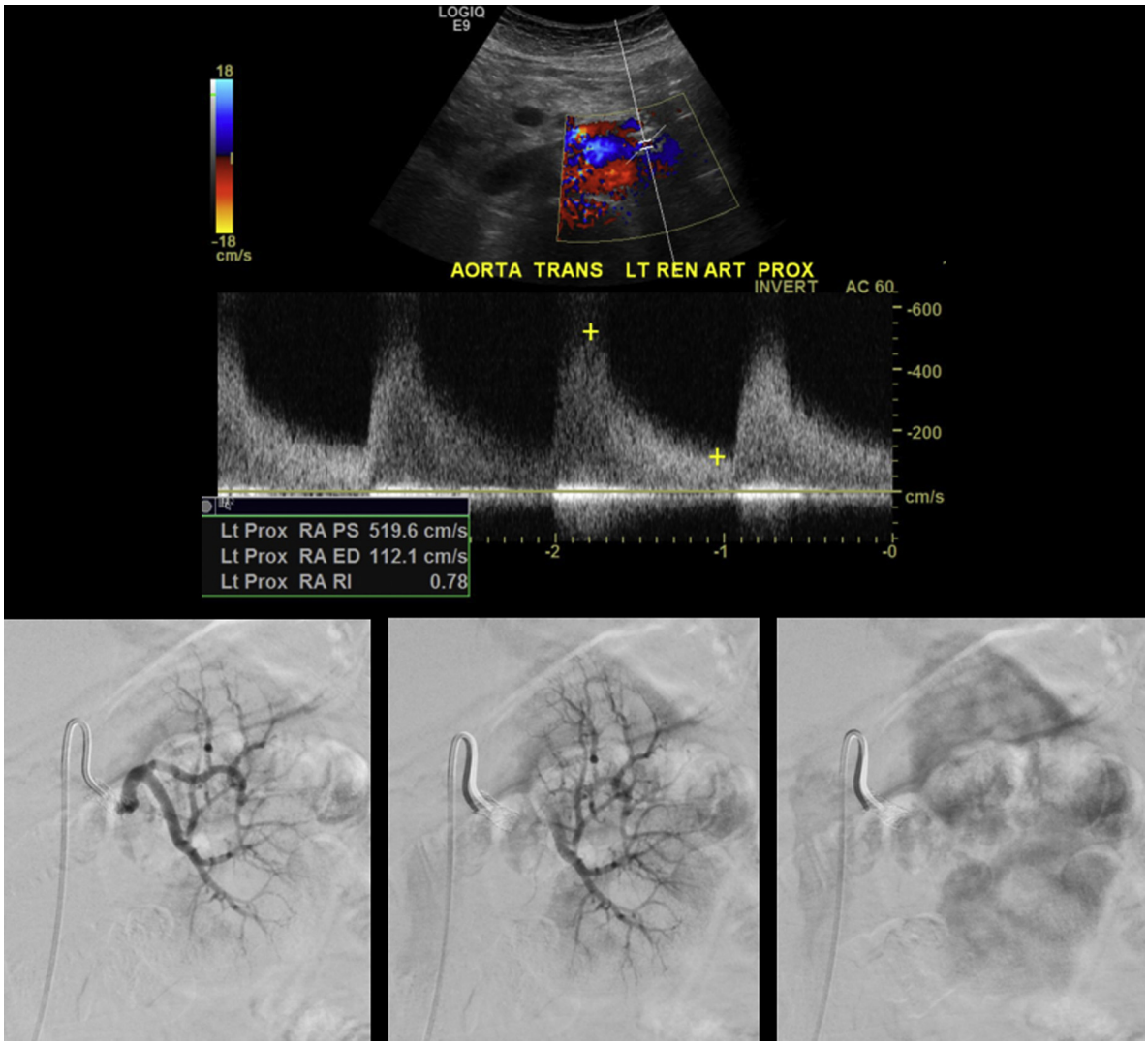

Figure 9. Imaging of a patient who had a renal stent placed for renovascular hypertension. Difficult-to-control hypertension recurred, and (top image) a Doppler ultrasound evaluation of the kidney was ordered. This showed very high velocities in the proximal left renal artery in the region of the stent (peak systolic velocity, 519.6 cm/s; normal range, 100-200 cm/s). The high velocity and turbulent spectral Doppler waveform were suspicious for re-stenosis, so an angiogram was obtained (bottom 3 images). The three images from left to right show a run of contrast administered from the arterial catheter through the stent and subsequent passage of contrast from the larger hilar and parenchymal arteries into a vague reniform "blush" as the contrast enters smaller vessels below the resolution of the fluoroscope. The stenosis was subsequently balloon dilated (not shown).

function, and urinary obstruction due to decreased specificity of imaging findings in these clinical scenarios.

As the reference standard, conventional angiography can be used to confirm renal artery stenosis and is used for renal artery stent evaluation, as can be seen in Figure 9.

Thus, the answer to question 2 is (b). Ultrasonography is considered a better first-line test for renal artery stenosis when eGFR is <30 mL/min/1.73 m^2. MRA without contrast could also be considered for this patient. However, a cardiac pacemaker could potentially be a contraindication to MRI and the spinal hardware could potentially create artifacts that severely interfere with the MR image. Limited mobility is a relative contraindication for Doppler ultrasonography, which requires patients to roll into different positions to optimize imaging. A high body mass index interferes with all imaging modalities but would likely be most compromising to ultrasonography.

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Kidney Transplant Imaging

Grayscale and color Doppler ultrasonography is the mainstay of kidney transplant evaluation in both the immediate and remote postoperative periods. Ultrasonography provides an efficient means of evaluating both anatomic and vascular complications. Grayscale ultrasonography is used to evaluate for peritransplant collections and kidney transplant hydronephrosis. With color Doppler ultrasonography, iatrogenic vascular complications such as arteriovenous fistulas and pseudoaneurysms can be diagnosed. Spectral Doppler evaluation can also reveal renal vein thrombosis and transplant renal artery stenosis. It should be noted that kidney transplant ultrasonography requires an experienced operator, and in some cases, imaging findings can be misinterpreted without a detailed surgical history (eg, the presence of two donor renal arteries).

CT and MRI can be helpful adjuncts in defining the extent of anatomic complications when suboptimally evaluated using ultrasonography (eg, when the transplant is shadowed by bowel gas). Similarly, cross-sectional angiographic techniques, with or without IV contrast, such as MRA can be used for evaluation of vascular patency when ultrasonography proves technically unfeasible.

Renal scintigraphy is uniquely positioned to offer functional analysis of the kidney transplant. Perfusion, excretory function, and obstruction can be evaluated using this technique. Improvements in kidney function can be detected using renal scintigraphy before the rebound of kidney function laboratory abnormalities, offering important prognostic information in some cases.

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Management of the Incidental Renal Cyst or Renal Mass

Case, cont: *During the patient's ultrasonographic evaluation for renal artery stenosis, the radiologist notices a 3-cm cystic lesion in the left kidney.*

Question 3: Does this finding require follow-up?

a) Yes
b) Yes, but with contrast ultrasonography
c) No
d) It depends on the quality of the image

For the answer to the question, see the following text.

Simple benign renal cysts are common in the general population and often can be readily distinguished from more suspicious lesions on both unenhanced and enhanced CT and MRI, as well as with ultrasonography. Mildly complex proteinaceous/hemorrhagic cysts are also common, and many of these lesions are comfortably categorized as benign using ultrasonography, CT, and MRI without the use of contrast. There are technical challenges to the interpretation of small renal lesions on contrast-enhanced CT to consider, such as the phenomenon of pseudo-enhancement, which results in artificially increased attenuation in small cysts and may make them appear as enhancing solid neoplasms. These technical caveats aside, indeterminate lesions on CT requiring further investigation are typically higher attenuation lesions with variable enhancement on contrast-enhanced techniques. If a cystic lesion is considered likely benign, but too complex to be definitively categorized as benign with absolute certainty, follow-up imaging to document stability and/or follow-up with a different imaging study may be recommended by the interpreting radiologist.

Incidental cystic lesions are generally evaluated on the basis of "complexity" of the cyst and whether there are features that are suspicious for a cystic neoplasm (such as thickened walls, calcifications, mural nodules, or enhancing components). These features are captured in the Bosniak criteria, which stratify the risk of cystic lesions for malignancy into 5 different categories (I, II, IIF, III, and IV). Although these criteria were formulated more than 30 years ago, this categorization has held up well and is still frequently used as a first approximation for follow-up, although follow-up has become less aggressive over time.

Incidental solid renal lesions also may be either benign or malignant. Some benign solid lesions will demonstrate features that allow for relatively definitive characterization at initial imaging, such as a solid renal lesion demonstrating macroscopic fat on CT, typical of a benign angiomyolipoma. However, even this example illustrates the diagnostic challenge involved in characterization of solid renal lesions; a subset of benign angiomyolipomas are lipid poor and will appear as small hyperattenuating and homogenously enhancing masses. Evaluation of the kinetics of enhancement of a lesion on multiphase imaging, such as with triple-phase CT ("renal mass" protocol which involves imaging in three phases of contrast enhancement: noncontrast, corticomedullary, and nephrographic phases) can be helpful in showing an enhancement pattern suspicious for malignancy. Unfortunately, there are still cases in which this approach does not offer definitive diagnosis.

MRI, particularly with the use of IV contrast, is often used as a problem-solving tool for possibly malignant incidental renal lesions that cannot be definitively characterized on ultrasonography or CT or for patients for whom these other imaging modalities are undesirable or

unfeasible. For patients who cannot undergo MRI and/or CT or who cannot receive IV iodinated or gadolinium contrast, contrast-enhanced ultrasonography is becoming a more common alternative.

For the interested reader, Herts et al contains suggested diagnostic workup pathways for incidental solid and cystic renal masses.

Thus, the answer to question 3 is (d). The need for follow-up depends on the quality of the imaging and one's confidence for how simple the cyst is. In a patient with a very large body habitus, acoustic attenuation may make it difficult to see the criteria for a simple cyst: anechoic contents, no color Doppler flow, smoothly marginated with a thin wall, and a perceptible back wall. Solid masses may masquerade as cystic lesions and if the image quality is suboptimal, follow-up with a different imaging modality may be a good option. If the lesion can clearly be defined on ultrasound (or other imaging) as a simple cyst, it does not require follow-up.

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Part 3: Renal Imaging—Contrast and Radiation

Postcontrast Acute Kidney Injury (PC-AKI) and Contrast-Induced Nephropathy

Case, cont.: *The patient had his renal artery stented and both his blood pressure and kidney function improved. Seven months later, he became nauseated with intense abdominal pain that radiated into his back. CTA ordered in the emergency department showed a leaking abdominal aortic aneurysm. The patient was hospitalized and underwent open repair of the aneurysm. On the second day of his inpatient stay, serum creatinine concentration increased to twice its baseline level.*

Question 4: What term best defines the change in the patient's kidney function?

a) Contrast-induced nephropathy (CIN)
b) Postcontrast acute kidney injury (PC-AKI)

For the answer to the question, see the following text.

Iodinated contrast media is primarily excreted by glomerular filtration, and one of the classic risks associated with its use is CIN. This decrease in kidney function from iodinated contrast has received assiduous attention over decades, and a short synopsis does not do the subject justice. The interested reader can investigate some of the additional readings as a small entry into the larger discussion.

The American College of Radiology (ACR) *Manual on Contrast Media* distinguishes CIN (when there is a direct link between contrast administration and decreased kidney function) from PC-AKI, a correlative diagnosis that refers to decreased kidney function within 48 hours after IV administration of iodinated contrast). Thus, the ACR considers CIN much less common and a subgroup of PC-AKI.

Risk factors for the development of CIN are thought to be age older than 60 years, pre-existing history of kidney disease, single kidney or history of kidney transplantation, kidney cancer, prior kidney surgery, a history of hypertension requiring medical therapy, and diabetes mellitus. The strength of these risk factors is unclear. There are risk calculators for CIN that are used in clinical practice, but one should note that many of these assess risk after percutaneous coronary intervention, which has a different route of contrast, bolus profile, and patient population compared with IV administration of low-osmolarity contrast agents used in renal diagnostic studies. Various renal protective maneuvers have been tried before contrast administration, but the utility of any of these agents is uncertain.

Thus, the answer to question 4 is (b). Without a direct causal relationship of IV contrast to kidney injury, the association between contrast administration and decreased kidney function has been termed PC-AKI rather than CIN.

NSF

In the early 2000s it became clear that some patients who had undergone MRI were developing NSF, a progressive irreversible skin thickening with pruritus. Organs besides the skin could be affected, and NSF occasionally resulted in death.

The offending agent was found to be the gadolinium-based contrast agents used in MRI. An association was made between administration of gadolinium-based contrast agents, end-stage kidney disease, and the development of NSF. The most widely accepted hypothesis was that the gadolinium ion in the contrast dissociates from its chelate, and the naked gadolinium is responsible for triggering the fibrosis of NSF.

However, there are some nuances to this association. Some gadolinium contrast agents appeared more likely (sometimes much more likely) to cause NSF than others. It is thought that gadolinium is less tightly bound to a linear agent and riskier than gadolinium bound to a macrocyclic agent. NSF is also thought to be much more likely in patients with AKI or those with chronic kidney disease stage 4 or 5; NSF developing in a patient with an eGFR > 30 mL/min/1.73 m^2 is exceedingly rare.

Currently, gadolinium-based contrast agents can be divided into three groups based on their risk for developing NSF. Group I includes agents associated with a greater number of NSF cases. These are mostly older agents and are essentially contraindicated in patients at risk for NSF (AKI, eGFR < 30 mL/min/1.73 m^2, and treated by dialysis). Group II agents have a negligible risk for NSF regardless of kidney function or dialysis status. Group III agents do not

have enough evidence to classify into group I or II and are effectively treated as group I. For patients with eGFRs ≥ 30 mL/min/1.73 m^2 (and who do not have AKI), an agent from any group may be used. For more on gadolinium contrast selection, see the essential readings that follow.

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Radiation and Imaging Studies

Of the imaging modalities covered in this review, conventional radiographic imaging and angiography, CT, and nuclear medicine all expose the patient to ionizing radiation. Ultrasonography and MRI are considered to have no risk in this regard.

So how does a clinician weigh the risk of radiation when ordering a study? First, not all these studies involve the same amount of radiation. CT uses a much larger radiation dose than radiographic studies, but CT studies also vary quite a bit in how much radiation they require. Low-dose stone protocol CT aims for a dose ≤ 3 mGy. Multiphase CTU may be 12 to 20 mGy or higher, depending on factors such as obesity.

Radiologists follow the ALARA (as low as reasonably achievable) principle with radiation dose. All things being equal, they aim for the least amount of radiation to answer a clinical question. However, although radiation dose is minimized, it is important to keep in mind the overall risk of radiation exposure when thinking about imaging. Calculating the stochastic risk for malignancy from a procedure with ionizing radiation is elusive and controversial. Risks are population-level risks and difficult to individualize. Comparing radiation exposure from an imaging study with more familiar sources of radiation is often helpful to get a sense of scale. For instance, a dose of 20 mSv to the abdomen and pelvis, which could occur from CTU in an obese patient, is considered the equivalent of 7 years of natural background radiation. The radiation dose from a diagnostic imaging study should never be high enough to cause effects such as erythema or desquamation.

The rationale for using ionizing radiation for imaging is that the benefit is greater than the stochastic risk for developing radiation-induced cancer. This is obviously a clinical judgment and involves multiple factors. One should remember that some populations are more vulnerable to the effects of radiation over a lifetime, including pediatric and pregnant patients. Nonionizing imaging modalities are almost always used first line for these patients. Conversely, for some groups of patients (such as those with a metastatic malignancy), the risk for a radiation-induced cancer decades into the future is of much less concern. Consulting the radiologist about a radiation-prudent imaging strategy can often be helpful.

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The Future of Renal Imaging

If the past 50 years are any guide, medical imaging in nephrology will likely evolve in leaps and bounds. An emphasis in radiology research on precision imaging will likely have a great impact: molecular imaging, targeted ultrasound contrast, and functional imaging involving MRI, as well as advanced nuclear medicine techniques, all have the potential to advance the field. New CT technologies such as spectral and photon-counting CT will likely continue to lower radiation dose while maintaining image quality. More robust imaging informatics systems, radiomics, and machine learning will also likely come into play. The future is radiant for improving patient care with new and evolving imaging techniques.

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