Renal Artery Duplex Ultrasonography

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Abstract

Renal artery duplex ultrasonography (RADUS) is a non-invasive, safe, inexpensive and accurate method for assessing the renal arteries. Common uses for RADUS include diagnosis of renal artery stenosis (RAS) in patients with clinical clues suggestive of the disease; surveillance of patients with known native or transplant artery RAS; following renal artery stent revascularization; and for corroboration after suspicious findings are found by other imaging modalities. The RADUS examination includes spectral Doppler velocities obtained from the abdominal aorta at the level of the renal arteries, throughout the entire renal artery, and in the renal parenchyma. It is noteworthy that as the kidneys are located in the retroperitoneum, imaging of native renal arteries with RADUS requires a high degree of technical skill and extensive training. Due to this and several other inherent limitations, use of other imaging modalities should be considered to corroborate RADUS findings prior to intervention.

Keywords

Renal artery stenosis • Renal artery duplex ultrasonography • Renal to aortic ratio • Renal resistive index • Renal artery stent revascularization

Introduction

Renal artery stenosis (RAS) is common and most often caused by aortic atherosclerosis which extends into the artery ostium. It is most prevalent in at-risk populations, such as patients with poorly controlled hypertension (HTN) [1] or among patients with coronary [2] and/or peripheral artery disease (PAD), where it has been found in up to 59 % of patients [3]. Potential clinical consequences of RAS include difficult to control hypertension, progressive renal

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dysfunction and cardiac disturbance syndromes (recurrent congestive heart failure, refractory angina and "flash" pulmonary edema) [4, 5].

Multiple diagnostic tools are at a clinician's disposal when RAS is suspected. However, none surpasses an initial high index of suspicion based on a series of clinical "clues." A clinical algorithm has resulted in sensitivity and specificity of 65 % and 87 %, respectively when compared to nuclear renal scintigraphy before and after an angiotensin converting enzyme inhibitor was administered [6]. However, radionucleotide studies often are difficult to interpret in patients with chronic kidney disease, and the technique cannot be used to identify RAS reliably if the patient has bilateral disease or if only one kidney is present. Furthermore, accuracy has not been consistent among studies [7]. Plasma renin activity in it of itself, even with captopril stimulation, has poor accuracy due to overlap in patients with primary HTN [8].

Modern non-invasive methods include renal artery duplex ultrasonography (RADUS), computed tomography angiography (CTA) and magnetic resonance angiography (MRA), while invasive methods consist of contrast angiography (CA), intravascular ultrasound and translesional pressure measurements [9]. This chapter will concentrate on the role of RADUS.

Common uses for RADUS include screening for RAS, surveillance of patients with native artery RAS or after renal artery stent revascularization, and for corroboration after suspicious findings are found by other imaging modalities [10]. Recently published "appropriate use criteria" suggest that RADUS is reasonable to consider when evaluating patients with HTN that is resistant, malignant, difficult to control or present in patients younger than 35 years; unexplained increase in creatinine or renal failure in conjunction with aortic dissection and in patients with either HTN or elevated creatinine and unexplained size difference >1.5 cm between kidneys or an epigastric bruit [11]. Interestingly, these same criteria suggest that RADUS was inappropriate to use as a screening tool in asymptomatic patients with atherosclerosis in other vascular beds. Choosing RADUS over other modalities should include consideration of its various advantages and disadvantages as outlined in Table 12.1.

Table 12.1 Advantages and disadvantages of renal artery duplex ultrasound for detecting renal artery stenosis

Characteristic	Comments
Advantages	
Accurate when compared to other modalities	-see text-
Reproducible	
No radiation or contrast	
Suitable for patients with claustrophobia	
Inexpensive	
Disadvantages	
Requires high technical skill	Data cannot be obtained in as many as 20 % of patients [12]
Time consuming	Routinely, a complete bilateral exam may take as much as 1.5 h, especially in inexperienced hands
Divides RAS into broad categories	Currently RADUS criteria do not offer a finer differentiation than normal, 1–59 %, 60–99 % stenosis or renal artery occlusion
Inferior imaging of the distal renal artery	
Difficult to visualize accessory renal arteries	
Cannot image multiple vascular beds at once	A disadvantage particularly when trying to ascertain the etiology of RAS [13]
Focused on the kidneys and may miss extra-renal ancillary findings	
Limited in assessing renal artery pathology, other than atherosclerotic disease	Examples include dissection, segmental arterial mediolysis, vasculitis. Beading characteristic of medial fibroplasias type of the fibromuscular dysplasia can sometimes be seen
Difficult to use in obese patients	
Limited by overlying bowel gas	
Limited in patients who are tachypneic	Excessive movement of the renal arteries

RAS renal artery stenosis, *RADUS* renal artery duplex ultrasonography

Renal Artery Duplex Ultrasonography as an Epidemiological Tool

Although some small studies attempted to define the natural history of atherosclerotic RAS (ARAS) with a combination of CA and clinical surveillance, results have been heterogeneous [14]. Subsequently, similar attempts have been made with RADUS. Interpreting these studies should take into account the specific subjects studied as well as the exact manner by which events were defined. In an unselected sample of 750 Japanese patients with coronary, cerebrovascular or peripheral artery disease, ARAS was found in 40 by RADUS criteria and later confirmed by CA in 35 people [15]. Noting small numbers, subgroup analysis revealed ARAS to be most prevalent in patients with carotid and peripheral artery disease (20 %). Renal artery stenosis epidemiology has been studied further in the Cardiovascular Health Study, a longitudinal, population based cohort study of elderly outpatients [14, 16]. In 834 people in whom RAS ≥ 60 % was defined by peak systolic velocity (PSV) ≥ 180 cm/s, the prevalence was 6.8 % [16]. Prevalence of coronary artery disease was greater in patients with evidence of ARAS [17]. Follow up in 119 subjects 8 years later revealed that none of the patients previously diagnosed with ARAS progressed to renal artery occlusion and that new RAS was found in 9 of the 235 analyzed renal arteries [14]. Disease progression, defined as an increase in PSV greater than 2 standard deviations in the cohort (≥45 cm/s), occurred in 29 renal arteries. In another study that examined ARAS in 170 hypertensive patients, RAS progression was defined as an increase in PSV > 100 cm/s and occurred in 31 % over 5 years [18]. In another study 76 patients were prospectively followed over 3 years and anatomic progression was found in 20 % [19]. However, in this study RAS ≥ 60 % was defined by a combination of PSV ≥ 180 cm/s and RAR > 3.5. Thus, patients who had PSV ≥ 180 cm/s at the beginning of the study, but did not meet the RAR criterion, were not defined as having significant RAS. It is noteworthy that this study also reported 7 % of subjects progressed to occlusion.

Technique for Performance of Renal Artery Duplex Ultrasonography

As the kidneys are located in the retroperitoneum, imaging of native renal arteries with RADUS requires a high degree of technical skill and extensive training. In our vascular diagnostic laboratory, we have the following requirements for a technologist to perform RADUS independently:

- Hold the Registered Vascular Technologist (RVT) certification
- Observe 50 RADUS examinations by a trained and experienced colleague
- Attend an off-site 2-week hands-on training course specific to RADUS
- Perform 50 sequential RADUS exams under direct observation by a trained and experienced colleague
- Maintain documented ongoing proficiency in our regular quality assurance program

The RADUS examination includes spectral Doppler velocities obtained from the abdominal aorta at the level of the renal arteries, throughout the entire renal artery, and in the renal parenchyma [20]. The vascular testing division of the Intersocietal Accreditation Commission (ICAVL) has specified the minimum requirements for a complete RADUS examination (Table 12.2). Ideally, RADUS should be performed in the early morning hours after the patient has completed an overnight fast in order to minimize bowel gas overlying the renal arteries. Imaging is achieved from two approaches. First the aorta and renal arteries are interrogated from the supine, midline approach with the patient in the reverse Trendelenburg position. Subsequently, the patient is turned into the lateral decubitus position with the arm raised over the head in order to increase the imaging zone in the intercostal or subcostal space (Fig. 12.1a, b). In our vascular laboratory, we require that the entire renal artery from the ostium through the hilum of the kidney to be imaged and sampled in order to qualify as

Table 12.2 The vascular testing arm of the Intersocietal Accreditation Commission Guidelines for native renal artery duplex ultrasonography

Gray scale and/or color Doppler images must be documented as required by the protocol and must include at a minimum[a]:
Adjacent aorta at the level of the renal arteries
Renal arteries
Renal veins
Gray scale pole to pole renal length measurements
Spectral Doppler waveforms and velocity measurements must be documented as required by the protocol and must include at a minimum[a]:
Adjacent aorta at the level of the renal arteries
Proximal, mid and distal main renal artery
Parenchymal/hilar arteries (when appropriate)
Accessory renal artery (when present)
Renal veins, when appropriate (does not require velocity measurements)

Data from American College of Cardiology Foundation et al. [11]
[a]Measurements should be bilateral (when two kidneys are present)

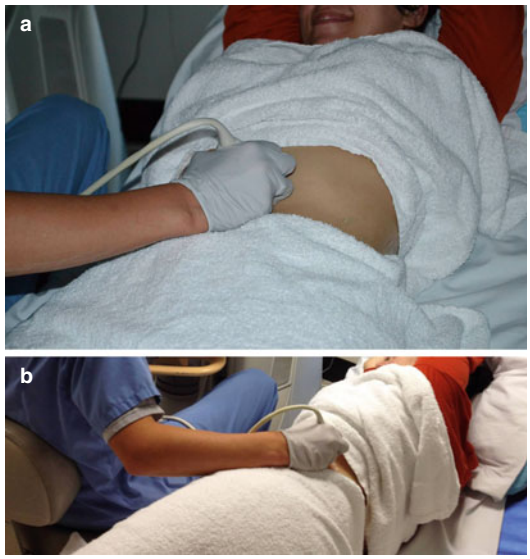

Fig. 12.1 (**a**, **b**) Renal artery duplex ultrasound patient and technologist positioning. (**a**) Midline approach. (**b**) Left flank approach. This is also replicated from the right

a complete examination. Interrogation of a transplanted renal artery and its related anastomosis to the inflow iliac artery is easier as it is typically more superficial.

A RADUS requires imaging equipment that includes low frequency (typically 2.25- to 4.0-MHz) curved linear- or phased array transducers. A vascular software package is also needed [20]. The examination begins with identification of the aorta in the sagittal plane throughout its length, assessing for an aneurysm or atherosclerosis while the patient is in the supine position. At the level of the renal arteries, the PSV is measured. The normal abdominal aortic PSV ranges from 40 to 100 cm/s. Next, the probe is rotated 90°, and each renal artery origin is located in the transverse plane (Fig. 12.2). The angle of insonation is maintained at 60° or less while imaging parallel to the direction of renal artery blood flow. Doppler spectral waveforms are obtained. The PSV is obtained in both renal arteries from the aortic origin to renal hilum. The presence of post-stenotic turbulence identified as the presence of as a chaotic Doppler spectral waveform with blunting of the peak of the waveform, should also be noted [21] (Fig. 12.3). This process is repeated from the flank approach (Fig. 12.4). A complete RADUS includes imaging of the kidney including maximal pole-to-pole renal length, demonstration of cortical, medullary and hilar blood flow and identification of associated findings such as cysts or masses (Figs. 12.5 and 12.6). Intrarenal sampling is performed at a 0° Doppler angle in the superior and inferior pole of the kidney, within the cortex and medulla.

Table 12.3 outlines common technical and interpretation errors in RADUS.

Native Renal Artery Duplex Ultrasonography

In a normal kidney, arterial flow is low resistance, demonstrating continuous flow during systole and diastole [22]. The two most common measures for assessing RAS are PSV and the ratio of the PSV as measured in the renal artery origin and the PSV in the aorta at the level of the renal artery, referred to as the renal aortic ratio (RAR). The RAR cannot be used when significant aortic disease is present (PSV > 100 cm/s) or

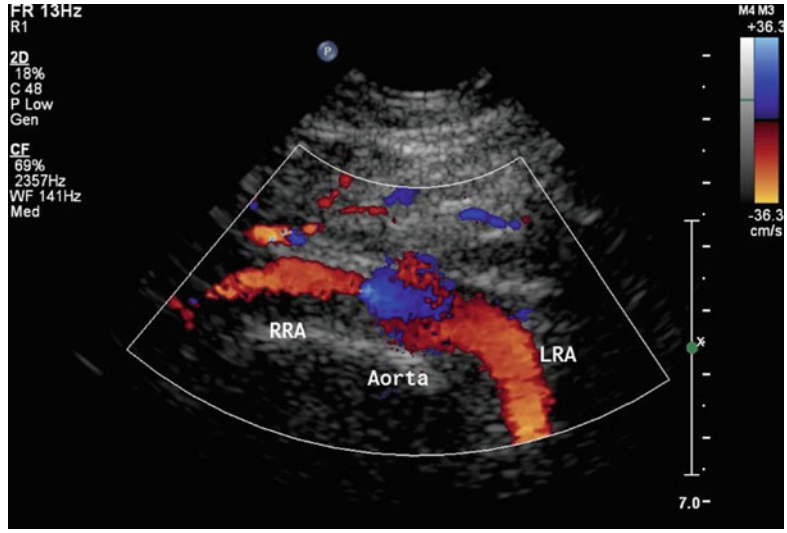

Fig. 12.2 Color flow renal artery duplex ultrasound from the midline approach demonstrating the aorta in transverse plane and the two renal arteries. *RRA* Right renal artery, *LRA* left renal artery

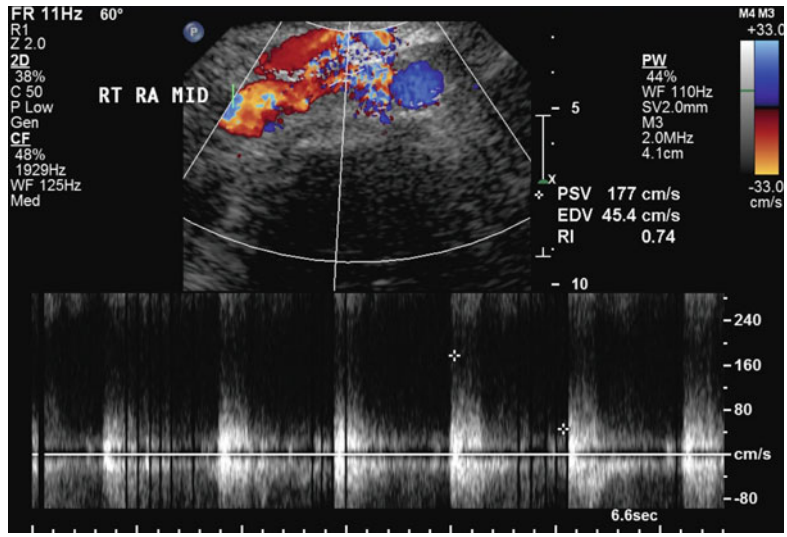

Fig. 12.3 Pulse wave Doppler and color flow renal artery duplex ultrasound demonstrating turbulent flow in the mid-distal renal artery. This suggests more proximal stenosis

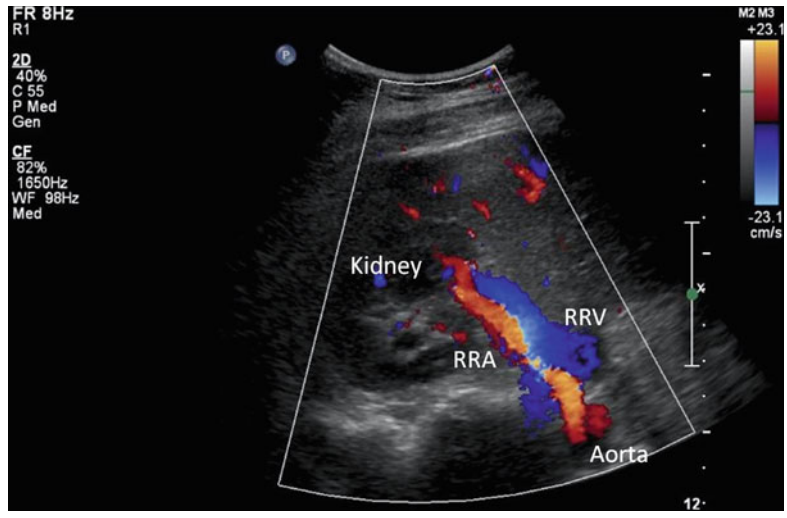

Fig. 12.4 Color flow renal artery duplex ultrasound from the right flank approach demonstrating the right renal artery (*RRA*) course from the renal hilum to the aorta. Notice the right renal vein (*RRV*)

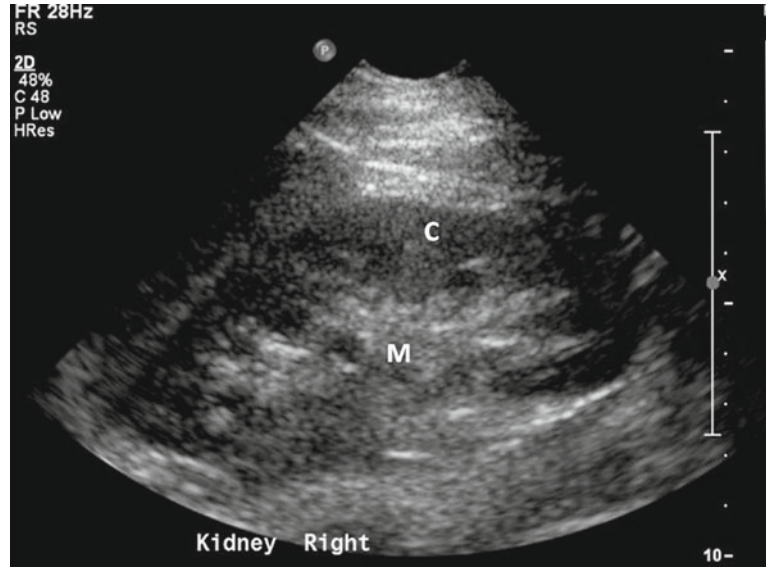

Fig. 12.5 A B-mode image of the right kidney from the flank approach demonstrating maximal pole-to-pole length and cortical thickness. Note the cortex (*C*) and medulla (*M*)

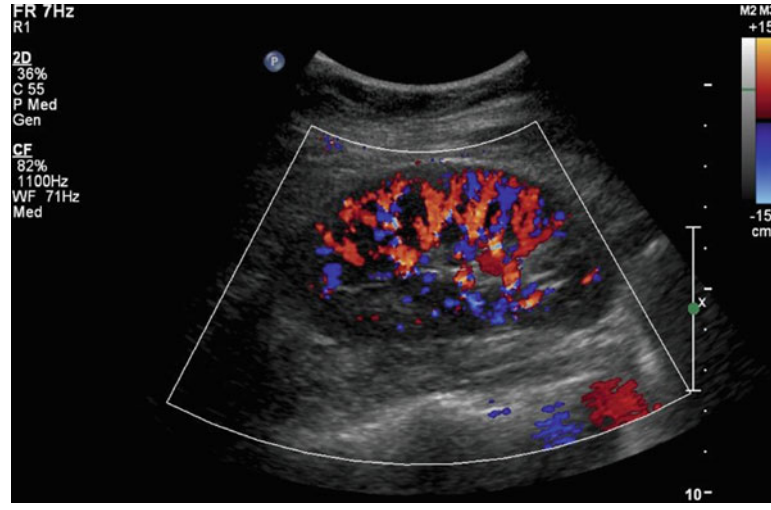

Fig. 12.6 Color flow image of cortical and medullary blood flow in the right kidney from the flank approach

Table 12.3 Common errors in renal artery duplex ultrasonography performance and interpretation

Mistake	Effect of the mistake	Ways to avoid the mistake
Measuring velocities with an incorrect Doppler angle	Erroneous velocity and therefore erroneous conclusions about the degree of stenosis	The Doppler angle should ideally be $\leq 60^{\circ}$ and parallel to the artery walls. A long enough segment of the artery should be available for interrogation
Interrogation of a different artery and mistakenly referring to this as the renal artery (lumbar, mesenteric)	Incorrect conclusions of the patency of the renal artery	It is best to identify each artery and to follow it to the kidney before starting to register flow velocities; look for the normal renal artery Doppler spectral image

Table 12.3 (continued)

Mistake	Effect of the mistake	Ways to avoid the mistake
Missing accessory renal arteries	The main renal artery may be patent, but a smaller accessory renal artery may be stenotic and result in renin-mediated hypertension	An excellent renal artery duplex ultrasound should include identification of the renal arteries but also of adjacent vessels. An attempt should be made to follow such arteries from the aorta to the kidney; in addition, imaging of the superior and inferior poles of the kidney may demonstrate differences in the RRI or spectral Doppler waveform, suggestive of an accessory renal artery
Missing the ostium of the renal artery by "spot checking" the artery	The measurement may not reflect the actual renal artery ostial velocity and significant renal artery stenosis may be missed	The probe should be "walked" from the aorta into the renal artery and then back into the aorta. The ostium is the location where atherosclerotic RAS occurs
Reporting an abnormal RAR	Misclassification of renal artery stenosis	A RAR can only be used if the flow velocity in the aorta at the level of the renal artery ranges 40–100 cm/s
Using criteria for native renal arteries on stented renal arteries	Misclassification of renal artery stenosis	The criteria for stented renal arteries are different than those for native arteries
Mistaking calcifications for a stent	Misclassification of renal artery stenosis and confusion regarding patient treatment and surveillance	Calcifications may be symmetrical and linear and may be mistaken for a stent. Patient history should be reviewed prior to performing the RADUS
Missing findings outside of the renal artery	Cysts and tumors may be overlooked. The appearance of the kidney and especially the cortex may suggest kidney viability	Kidney visualization should be part of an excellent renal artery duplex ultrasound. Abnormal findings should be documented
Reporting an incorrect renal resistive index	Reassurance of the status of the ipsilateral kidney	Perform Doppler angle independent assessment in the medullary branches of the kidney in the superior and inferior pole

PW pulse wave, *RAR* renal aortic ratio

in within an abdominal aortic aneurysm (PSV < 40 cm/s) [23].

Multiple studies have validated RADUS criteria for RAS, most often by comparison to CA as the "gold standard" (Table 12.4). Most have shown RADUS to have excellent sensitivity and specificity, most commonly reported to be above 80 %. An early retrospective analysis of 122 kidneys with single main renal arteries in 74 patients showed RADUS to have 93 % sensitivity, 98 % specificity, 98 % positive predictive value, 94 % negative predictive value, and an overall accuracy of 96 % as compared to CA [21]. The criteria that are most commonly used in clinical practice have been derived from a prospective, blinded study, in which 102 patients who were clinically suspected of having RAS underwent both RADUS and CA within 30 days of each other [44]. Using a PSV of ≥200 cm/s or a RAR of ≥3.5 resulted in sensitivity of 98 %; specificity 99 %; positive predictive value 99 %; and negative predictive value 97 %. Another retrospective comparison utilized the more accurate quantitative vessel analysis (QVA) method in 67 renal arteries, 34 of which demonstrated RAS ≥ 60 % [12]. Both PSV and RAR correlated with RAS; however, RAR was found to be more accurate by ROC curve analysis. More recently, several comparisons of RADUS derived criteria and estimated RAS as assessed by invasive translesional pressure gradients were performed. This method is considered to be more accurate in detecting hemodynamically significant RAS than visual estimation of degree of stenosis [53]. A first such study was performed in 75 renal arteries in 60 patients [25]. Renal artery DUS derived PSV demonstrated a sensitivity, specificity and accuracy of 89 %, higher than values derived for

Table 12.4 Summary of studies defining and validating duplex ultrasound criteria for native renal artery stenosis

Source	Year	Number of patients	Examined parameters				Criteria for RAS ≥ 60 %	Test performance		Comments
			PSV	RAR	AT	Ac		Sensitivity (%)	Specificity (%)	
AbuRahma et al. [24]	2012	313	X	X			PSV ≥ 285 cm/s; RAR ≥ 3.7	PSV – 67 RAR – 72	PSV – 90 RAR – 81	Analyzed for multiple cutoffs. RAR was just as good as PSV
Drieghe et al. [12]	2008	47	X	X			PSV > 200; RAR > 3.5	PSV – 100 RAR – 80	PSV – 31 RAR – 78	% Stenosis was assessed with pressure measurements
Kawarada et al. [25]	2006	60	X				PSV > 219 cm/s	89	89	Comparison to translesional pressure gradient >20 mmHg which corresponded with >50 % stenosis
Conkbayir et al. [26]	2003	50	X	X			Combination of PSV > 180–200 cm/s and RAR > 3.0	92	88	Both PSV values were found to be equally accurate when combined with RAR > 3.0
Nchimi et al. [27]	2003	91	X	X			PSV > 180 cm/s or RAR > 3.5	91	97	
de Haan et al. [28]	2002	78	X	X			Combination of PSV >180 cm/s and RAR >3.5	50	91.3	These authors could not show good test characteristics for RADUS compared with CA
Ripolles et al. [29]	2001	65			X	X	AT > 80 ms and Ac ≤ 1 m/s^2	89	99	Assessed for RAS > 75 %
Voiculescu et al. [30]	2001	36	X				PSV > 200 cm/s	96	89	Side-to-side RI difference was also studied
Claudon et al. [31]	2000	122	X	X			Combination of PSV cutoff of 140–200 cm/s and RAR cutoff of 3–3.5	80	80.8	An average of several centers was reported
Hua et al. [32]	2000	58	X	X	X	X	PSV ≥ 200 cm/s; RAR ≥ 3.5	PSV-91 RAR-72	PSV-75 RAR-92	Acceleration time >100 ms was less accurate
Motew et al. [33]	2000	41	X				PSV ≥ 200 cm/s	91	96	Hillar measurements did not add to the accuracy
Radermacher et al. [34]	2000	226	X		X		Combination of PSV > 180 cm/s or AT > 70 ms	96.7	98	Also utilized post-stenotic turbulence; Assessed for RAS >50 %

Souza de Oliveira et al. [35]	2000	50	X	X			PSV > 150 cm/s; RAR > 3.5	83.3	89.5	Results are for PSV, that trumped RAR
House et al. [36]	1999	63	X	X	X		PSV > 180 cm/s; RAR > 3; AT > 70 ms	85	76	A combination of PSV and RAR provided the best results as presented
Kaplan-Pavlovcic and Nadja [37]	1998	28	X	X			Combination of PSV > 180 cm/s and RAR > 3.5	83	81	
Mollo et al. [38]	1997	53	X		X		PSV > 150 cm/s; AT > 50 ms	75	100	PSV criteria detected RAS >50 %; AT was not sufficient for the diagnosis
Baxter et al. [39]	1996	73			X		AT > 120 ms	70	90	Detected RAS >70 %; RI did not differ between stenotic and non-stenotic kidneys
Burdick et al. [40]	1996	73			X	X	AT > 60 ms; Ac < 7.4 m/s^2	N/A	N/A	Compared with RAS >50 %
Miralles et al. [41]	1996	78	X	X			PSV > 198 cm/s; RAR > 3.3	PSV – 87.3 RAR – 76.4	PSV – 91.5 RAR – 92.4	RAR did not add to PSV
Miralles et al. [41]	1996	78	X	X			PSV > 198 cm/s; RAR > 3.3	PSV – 87.3	PSV – 91.5	RAR did not add to the diagnostic utility of RADUS
Missouris [42]	1996	21				X	Ac < 3.5 m/s^2	85	79	Values were improved by using contrast enhanced DUS
Helenon et al. [43].	1995	94	X				PSV ≥ 150 cm/s	89	99	PSV was combined with waveform analysis. The proximal renal artery could not be detected in 25 % of cases
Olin et al. [44]	1995	102	X	X			PSV ≥ 200 cm/s; RAR ≥ 3.5	98	99	EDV ≥ 150 cm/s was also claimed to be diagnostic for significant RAS, but disputed [45]
Kliewer et al. [46]	1993	57	X		X	X	PSV > 100 cm/s; AT > 70 ms; Ac ≤ 3 m/s^2			Only AT and Ac could differentiate between stenotic and non-stenotic renal arteries ($p<0.05$)

(continued)

Table 12.4 (continued)

Source	Year	Number of patients	Examined parameters				Criteria for RAS ≥ 60 %	Test performance		Comments
			PSV	RAR	AT	Ac		Sensitivity (%)	Specificity (%)	
Stavros et al. [47]	1992	56			X	X	AT > 70 ms; Ac < 3 m/s^2	N/A	N/A	
Antonica et al. [48]	1991	111	X		X	X	PSV > 130 cm/s or AT > 100 ms or Ac < 2.5 m/s^2	95	97	Limited discussion of the analysis that resulted in these parameters
Hoffmann et al. [49]	1991	41	X	X			PSV > 180 cm/s; RAR > 3.5	PSV – 95 RAR – 92	PSV – 90	Specificity was only 62 % for RAR
Hansen et al. [21]	1990	74		X			RAR ≥ 3.5	93	98	Prospective validation of criteria; RAR was combined with distal renal artery turbulence
Hawkins et al. [50]	1989	80		X			RAR ≥ 3.5	87		It is unclear what the degree of RAS was
Taylor et al. [51]	1988	29		X			RAR > 3.5	84	97	Prospective
Avasthi et al. [52]	1984	26	X				PSV > 100 cm/s	89	73	Presence of turbulent flow complemented the diagnosis

Table 12.5 Suggested renal artery duplex ultrasound criteria for renal artery stenosis

PSV[a]	RAR	Other findings	Interpretation
Native renal artery			
<200 cm/s	<3.5		Normal
<200 cm/s	<3.5	Post-stenotic turbulent flow, visible plaque	1–59 %
>200 cm/s	>3.5	Post-stenotic turbulence, visible plaque	60–99 %
No flow detected		Patent ipsilateral renal vein	Occluded
Stented renal artery[b]			
<240 cm/s			1–59 %
240–300 cm/s		Indirect findings must be used, including color evidence of in stent restenosis, color mosaic appearance within the stent, post-stenotic turbulence distal to the stent, and (if available), progression from a prior exam	Indeterminate
>300 cm/s			60–99 %
No flow detected			Occluded

PSV peak systolic velocity, *RAR* renal aortic ratio
[a]When there is discrepancy, absolute peak systolic velocity with post-stenotic turbulence is more important than RAR
[b]Different laboratories should standardize their criteria for stented renal arteries according to other imaging modalities locally

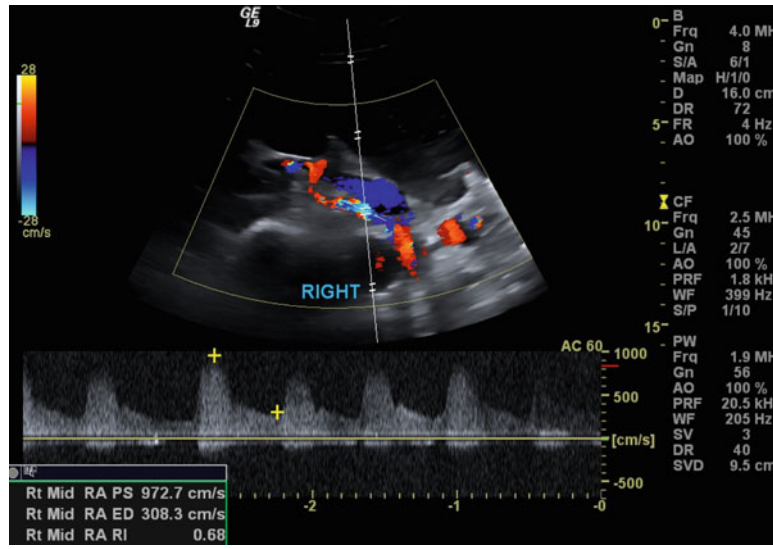

Fig. 12.7 Pulse wave Doppler measurements of flow velocity within the renal artery demonstrating marked increase in flow velocity denoting renal artery stenosis

the RAR. A second comparison was performed in 56 renal arteries in 47 patients [12]. Analysis by receiver operator characteristic (ROC) curves showed that PSV > 318 cm/s, end-diastolic velocity >73 cm/s and RAR > 3.74 best corresponded to CA proven RAS > 50 %, while commonly accepted criteria (Table 12.5) resulted in false positive results, especially when compared to pressures gradients. A RADUS demonstrating RAS can be seen in Fig. 12.7. Renal artery occlusion, on the other hand, is diagnosed by lack of arterial flow coupled by flow detected in the ipsilateral renal vein.

The renal resistive index (RRI) is another measure obtained during a complete RADUS examination. This is an ultrasound-derived technique designed to evaluate the status of parenchymal renal arterial perfusion. Peak systolic velocity and end-diastolic velocity (EDV) obtained in branches of the renal artery at the level of the medulla are used to calculate the RRI [20]. It is an angle independent measurement obtained in both the

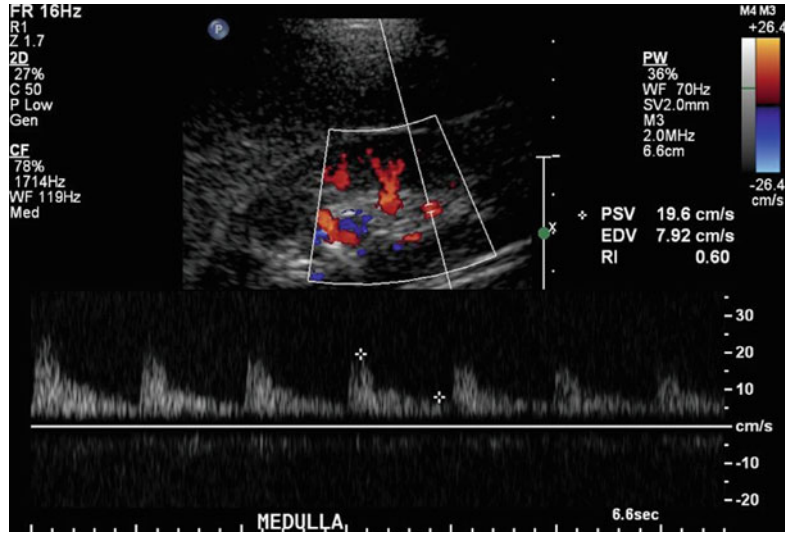

Fig. 12.8 Pulse wave Doppler measurements of flow velocity within the renal medulla and resistive index (*RI*) measurement

superior and inferior poles of the kidney. The resistive index is calculated by the following equation:

$$\left[1-\left(\frac{EDV}{PSV}\right)\right]\times 100$$

Thus, a lower RRI will theoretically suggest a "healthier" kidney (Fig. 12.8). Furthermore, according to one study, a RRI < 0.8 may suggest better clinical outcomes following renal revascularization [54], although this has been challenged by more recent publications [55]. Surprisingly, in two studies collectively examining 286 patients, the RRI was significantly lower in kidneys with RAS than in normal renal arteries [56, 57]. However, the RRI has questionable reliability. First, small measurement errors can result in significant changes in the calculated RRI. Also, conditions other than renal artery disease may affect the RRI. Examples include obstructive uropathy, hypotension, bradycardia and a peri-nephric fluid collection [22]. The RRI may have more utility in surveillance of transplanted kidneys [58].

Another approach is to calculate the difference in RRI between the two kidneys (ΔRRI). In a comparison of 40 CA proven normal renal arteries with 29 renal arteries with varying degrees of RAS, a ΔRRI > 0.05 was found to correlate with RAS > 50 % [57]. Another study comparing ΔRRI between 59 patients with RAS > 70 % and 155 patients with normal renal arteries also reported the ΔRRI to be significantly higher in patients with RAS [56]. All patients were hypertensive. A ΔRRI of 0.08 produced sensitivity of 92.5 % and specificity 97.5 % in a ROC curve analysis.

Other alternatives to PSV and RAR have been suggested. One such alternative is the acceleration time (AT), obtained from spectral analysis of Doppler waveforms from renal hilar vessels by means of a flank approach. The AT is a measure of waveform dampening. Theoretically, a longer AT points to a dampened waveform resulting from a more proximal stenosis. There are data to suggest that significant changes in renal artery waveform contour only occur with very severe stenosis [46]. Most studies have found AT to be useful in the detection of RAS (Table 12.4). Conversely, in a retrospective analysis of 76 kidneys in 41 patients, 51 of which had CA proven RAS > 60 %, hilar flow analysis has been reported to have lower sensitivity and accuracy as compared to conventional RADUS criteria [33].

Contrast enhanced DUS is another method that has been attempted with the purpose of simplifying the RADUS exam. Several seconds after injection of a contrast agent, it ultrasonographically enhances the arterial circulation for several minutes. Theoretically this should result in easier localization of the renal arteries and quicker acquisition of measurements. In a prospective comparison of conventional RADUS, contrast

enhanced RADUS and CA in 21 hypertensive patients, examination time was shorter and sensitivity and specificity were improved for Acceleration <3.75 m/s^2 when contrast was used [42]. In this context, acceleration referred to the slope of the line between the start of systole to the early systolic peak.

Other duplex derived methods for the diagnosis of RAS including the pulsatility index [59] and waveform analysis from the main renal artery [47, 60] have not proven to be useful clinically. Indirect imaging of the distal main renal artery or parenchymal branches, demonstrating a parvus et tardus waveform, is used by some as a criterion for a proximal stenosis. However, the accuracy of this method as a single data point is inferior to direct imaging of the main renal artery [39].

Recently several novel ultrasound-derived criteria have been reported. Power Doppler generates a color map that reflects the cumulative density of red blood cells within an examined volume of arterial blood. In a small study of nine patients power Doppler was found to be more sensitive and specific for RAS than conventional Doppler [61]. B-flow imaging (BFI) is a non-Doppler ultrasound technology that utilizes high frequency digital encoded sound waves to generate a real-time picture of blood flow in a display that resembles an angiogram [62]. In a comparison of BFI and RADUS in 51 patients with angiographically proven RAS > 50 %, the two techniques performed similarly. Sensitivity and specificity for BFI and PSV were 88 and 94 % and 100 and 71 %, respectively. Seven renal arteries were excluded because of excessive abdominal gas. Velocimetric waveform analysis is another technique that allows calculation of maximal acceleration (ACC_{max}) within early systole and the maximal acceleration index ($AI_{max} = ACC_{max}/PSV$). Saeed et al. retrospectively examined the utility of these measures in 169 patients who underwent both angiography and duplex ultrasonography and found sensitivity and specificity for ACC_{max} to be 85 and 75 %, respectively and for AI_{max} 83 and 79 %, respectively [63]. No direct comparison was made with PSV or RAR. Until larger prospective validation studies have been completed, we routinely use renal artery PSV and RAR as our main criteria for detecting RAS.

It should be noted that despite widespread clinical use of RADUS criteria that rely on these studies, they all suffer from the well-recognized limitation of verification bias. These studies have performed the comparison study (i.e., CA) based on the result of RADUS. When the reference standard procedure depends on the investigated test, a reliable estimate of diagnostic accuracy is precluded. Theoretically, to obtain valid accuracy estimates of RADUS criteria, all subjects should undergo both RADUS and CA regardless of preliminary RADUS results [64].

Another important note is the considerable variability between studies for similar measures (Table 12.4). This could theoretically be explained by variations in operator experience between studies; however, there are no data to support this hypothesis. Notwithstanding, in a meta-analysis the PSV was the most accurate parameter with sensitivity and specificity of 85 and 92 %, respectively [7].

Finally, RADUS has also demonstrated accuracy in the diagnosis and surveillance of renal artery fibromuscular dysplasia (FMD), albeit in a small series. It may identify the typical beaded appearance of the medial fibroplasia variant and suggest mid or distal artery involvement by PSV measurements [65, 66].

Ultrasound Surveillance Criteria Following Renal Artery Stent Revascularization

When discussing stented (as opposed to native) renal artery DUS, two issues should be mentioned. The first is the timing of surveillance after the procedure. While there are no prospective comparative studies, patients are usually followed within a month from the procedure, after 6 months and after 12 months and annually thereafter. It is noteworthy that the aforementioned appropriateness criteria denoted surveillance during the first year post-procedure as having uncertain value and found surveillance to be appropriate only after this interval [11]. The second issue is the choice of DUS criteria for in-stent restenosis

(ISR). Theoretically, the DUS criteria for ISR may differ from those of native RAS because of altered arterial compliance and thus altered blood flow patterns [64]. Similar to native renal arteries, DUS criteria for renal ISR have been derived from comparisons of RADUS with CA and similarly different reports resulted in somewhat different values for both PSV and RAR in the diagnosis of ISR. Thus, in some publications both PSV and RAR are reported to be higher in ISR than in native RAS, while in others these values were actually lower. A retrospective analysis examined the value of PSV and RAR as compared to CA for detecting ISR > 50 % in 33 renal stents and found a PSV > 226 cm/s and a RAR > 2.7 to offer optimal ROC curves (sensitivity and specificity of 100 and 90 % and sensitivity and specificity of 100 and 94 % for PSV and RAR, respectively) [67]. In the RENAISSANCE trial, a prospective, single-arm, renal artery stenting study, an 86.6 % concordance was found between RADUS and CA in 30 lesions [68]. The RADUS criteria for ISR used to correlate with CA ISR ≥ 50 % were a RAR ≥ 3.5 or an absolute PSV ≥ 225 cm/s in association with post-stent turbulence. In another study, a retrospective analysis of 47stented renal arteries in 30 patients by using ROC curves, a PSV of 250 cm/s was associated with a sensitivity of 59 %, specificity of 95 %, an accuracy of 83 %, and a positive predictive value of 87 % [64]. Another retrospective comparison of PSV and RAR between 31 patients with angiographically proven ISR and 30 patients with angiographically proven native RAS suggested that a PSV of 395 cm/s and an RAR of 5.1 most valuable for detecting ISR ≥ 70 % (sensitivity of 83 %, specificity of 88 %, and accuracy of 87 % and sensitivity of 94 %, specificity of 86 % and accuracy of 88 %, for PSV and RAR, respectively) [69]. As there are no uniform criteria for renal ISR, before re-intervention is attempted clinicians should consider the clinical indications first (i.e., worsening blood pressure control or declining renal function) in conjunction with the abnormal DUS result and not act on just the abnormal DUS result alone [69].

Some controversy exists regarding RADUS criteria for covered renal stents (as opposed to bare-metal stents). To date, one retrospective analysis of prospectively collected data of addressed this matter by reporting DUS criteria for covered and uncovered renal artery stents placed in conjunction to endovascular repair of abdominal aortic aneurysms [70]. Six of 231 covered stents developed ISR and the authors reported that a PSV > 280 cm/s and a RAR > 4.5 resulted in optimal detection of these events, by comparing RADUS, CTA and CA findings.

Transplant Renal Artery Duplex Ultrasonography

Transplant RADUS is performed in order to identify pathology in the transplant kidney, artery, vein and collecting system. It is usually first performed soon after surgery and later routinely or based on patient clinical and biochemical characteristics. The discussion hereafter will focus on the transplant renal artery. As the renal transplant graft is usually placed extraperitoneally and superficially, most commonly in the right lower abdominal quadrant, use of a high frequency probe should be considered to achieve optimal visualization of structures [71]. The transplanted kidney arterial inflow anastomosis type depends on donor and recipient anatomy and may be end to end (EE) to the internal iliac artery or end to side (ES) with either the internal or, more commonly, the external iliac artery [72]. The IAC-vascular division guidelines for transplant RADUS are similar to those for native arteries (Table 12.2), with variations that include the need to examine the peri-transplant region with gray scale images, the arterial anastomosis with spectral Doppler waveforms and velocity measurements as well as the venous anastomosis with spectral Doppler waveforms [11]. It should be noted that as external iliac artery stenosis can result in impaired blood flow to the transplanted kidney, this artery should also be interrogated as part of a complete examination [73]. Furthermore, transplant renal arteries have two characteristics that may cause elevated PSV without stenosis. First, an ES anastomosis may result in local tortuosity and second, a transplant kidney tends to undergo hypertrophy and may be supplied by a higher than normal blood volume.

Also, there is significant normal variability of PSV in transplant renal arteries [74]. Published PSV that have been shown to identify transplant RAS range between 150 and 300 cm/s [75–77]. These have relied on relatively small series. Other measures have therefore been added to supplement the PSV such as the AT and the renal artery: external iliac artery ratio (RIR), though considerable variability has been noted with these criteria as well [74]. A retrospective analysis of 38 transplant renal arteries with severe RAS, 19 representing each kind of anastomosis, was undertaken and revealed the AT to be similar between EE and ES types, while PSV was much higher in the EE type of anastomosis [72]. This analysis did not, however, have a control group and therefore could not assess for a cutoff for the diagnosis of RAS. A recent comparison of RADUS, MRA and CA was performed in 10 transplant renal arteries found to have CA proven RAS > 50 % and 12 arteries in patients in whom stenosis was not suspected clinically [73]. The best accuracy for RAS detection was achieved with PSV > 250 cm/s, AT > 0.1 s and RIR > 2. As a single measure, AT offered the best results, while RI did not differ between the groups. A PSV > 200 cm/s resulted in better sensitivity (90 % vs. 70 %). To further overcome the aforementioned physiologic changes in transplant renal artery blood flow a study of RADUS characteristics in 14 transplant renal arteries with CA proven stenosis ≥80 % used a ratio of the renal artery PSV to the PSV in the interlobar renal arteries >13 as a discriminator [78]. Finally, the intraparenchymal AT was significantly longer when RAS was present in a comparison between 15 transplant renal arteries without stenosis and 4 arteries with RAS > 50 % [79].

Other Findings on RADUS

As stated, a complete RADUS should include bilateral visualization of the entire length of the renal artery and also of the kidney parenchyma. In a prospective surveillance of 101 kidneys for an average of 14.4 months, 26 % of 49 kidneys with RAS > 60 % demonstrated >1 cm length reduction, while atrophy was absent in all other patients [80]. In another prospective surveillance of 204 kidneys over a mean of 33 months renal atrophy, defined as 1 cm length reduction, occurred in 20.8 % of patients with RAS ≥ 60 %, more than in patients with normal or less severe stenosis (5.5 % and 11.7 %, respectively, $P = 0.009$) [81]. Cortical thickness should also be evaluated. A study comparing cortical thickness between contralateral kidneys in 26 patients with unilateral RAS found significant differences in both cortical thickness and kidney length as assessed by CTA [82]. Furthermore, the technician and interpreting physician must be vigilant for the presence of unusual findings such as FMD, benign cysts or tumor. Fibromuscular dysplasia is suspected when peak systolic velocity is elevated in the mid or distal renal artery. In addition, a typical beaded appearance will suggest the medial fibroplasia variant of FMD. If present, the location, size and number of benign cysts should be documented [83]. Lack of flow within a cyst should be documented as opposed to tumor masses that may present with neovascularization or with echogenic material within the mass [84]. Any suspicion for tumor should prompt recommendation of a more sophisticated examination.

Conclusion

RADUS is an inexpensive, convenient and accurate method for assessing native, stented and transplant renal arteries for stenosis. While it has inherent limitations, it is the most commonly used tool for screening and surveillance of patients with RAS. Use of other imaging modalities and correlation with local outcomes should be utilized to corroborate RADUS findings prior to intervention.

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