Chapter

Ultrasound of the Kidneys: Application of Doppler and Elastography

Moawia Gameraddin

Abstract

Doppler ultrasound of the kidneys is essential in the assessment and diagnosis of kidney diseases. There are several diseases involving the kidneys. Some are functional, diffuse and systematic. Using Doppler imaging provides an assessment of vascular changes which is easily evaluated. Doppler investigation is widely used for assessment of the perfusion of renal arteries. The Doppler indexes; resistive index, pulsatility index, peak systolic are utilized for evaluating the blood flow of the renal arteries. Doppler analysis provides useful diagnostic data that can predict early damage of the kidney tissue. In recent years, ultrasound elastography showed advanced development. It is a new promising technique that is used for assessing the renal tissue characterization. Elastography is an effective imaging for assessing kidney diseases. In the future, clinicians can use elastography instead of biopsy. In this chapter, we highlighted the applications of Doppler ultrasound and elastography in evaluation of various kidney diseases.

Keywords: Doppler, renal elastography, kidney disease, renal artery

1. Introduction

Doppler ultrasound is widely used in medical imaging. It is an application of diagnostic ultrasound utilized for assessing the blood flow speed and direction. These measurements depend on the Doppler effect is used to measure changes in the frequency of the echoes reflected from moving blood cells. In many cases, Doppler ultrasound replaces X-ray angiography. The most important advantage of Doppler ultrasound over other imaging methods that it provides a real-time assessment of blood flow.

The Doppler renal resistive index (RRI) is the most common Doppler parameter that is used to assess a variety of renal diseases such as assessment of rejection of transplanted kidney, detection of renal artery stenosis in hypertensive patients and evaluation of chronic kidney disease (CKD).

Ultrasound elastography is an advanced imaging method which is sensitive to tissue stiffness. In recent years, elastography has been further developed to enable quantitative assessments of tissue stiffness. Elastography is capable to assess changed elasticity of soft tissues resulting from specific pathological processes. It can differentiate between malignant and benign renal masses which may replace the need of biopsy. The combination of Doppler and elastography provide rich diagnostic data about the pathological processes with kidney tissue which is essential for management and treatment.

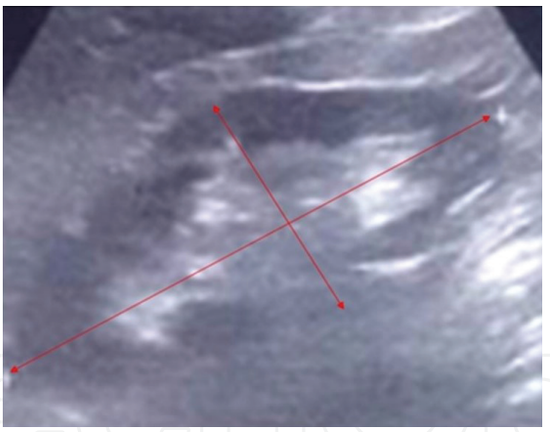

Figure 1.
The length and width of the kidney.

1.1 Ultrasound examination technique

The kidneys are examined with ultrasound in longitudinal and transverse scans planes using 3.5 and 5 MHz transducers. The organ is examined in supine position combined with the lateral decubitus. Then various planes are performed to demonstrate the entire kidney. Preferably, longitudinal and transverse planes are taken to determine the length and size of the kidney, as shown in **Figure 1**.

In the adult patient, a curved array transducer with of 2.5–3.5 MHz is used, while high-frequency 5–7 MHz is used in the pediatric patients.

Artifacts of the lowest ribs and gastric gases may obscure the upper poles of the kidneys. However, the whole kidney can be investigated during either normal respiration or breath hold, since the kidney will follow the diaphragm movement and change position accordingly [1].

2. The Doppler ultrasound: a general review

Doppler ultrasound has been extensively utilized in assessing reno-vascular diseases since it is a safe, non-invasive, available and cheap. These measurements depend on the Doppler effect is used to measure changes in the frequency of the echoes reflected from moving blood cells. In many cases, Doppler ultrasound replaces X-ray angiography. The most important advantage of Doppler ultrasound over other imaging methods that it provides a real-time assessment of blood flow.

2.1 Types of Doppler ultrasound imaging

All kinds of Doppler sonography are widely used in medical imaging. The advantages of these types are high accuracy in measurements, non-invasive nature, accessibility, and no harmful biological effects. Today, there are three types:

a. Color Doppler

b. Power Doppler

c. Pulse wave Doppler

The color Doppler (CD) converts Doppler shifts to an array of colors and form a picture of blood vessels to display the speed and direction of blood flow through

the vessels. The Doppler shift is the difference between the incident frequency and reflected frequency. Positive Doppler shift occurs when the reflector is moving away from the probe, and a negative shift occurs when the reflector moving toward the source of ultrasound. Thus, the Doppler shift is directly proportional to the velocity of the blood flow.

$$FD = \frac{2F0v\ cos\ 0}{C} \quad (1)$$

where F_0: is the transmitted ultrasound frequency; V: is the reflector velocity; C: is the speed of sound; Cos 0: is the cosine of the angle between the transmitted beam and the reflector path.

2.1.1 Factors influencing color flow image

1. Power: transmitted power into tissue*

2. Gain: affect sensitivity to flow signals

3. Frequency: affect sensitivity and resolution. High frequency provides better sensitivity to low flow while lower frequency has better penetration and lesser aliasing.

4. Pulse repetition frequency (PRF): called scale: low PRF concerns at low velocities and high PRF reduces aliasing.

5. Area of investigation: larger area reduces frame rate. Thus, reducing the color box of the flow area under examination will usually improve frame rate and may allow a higher color scan line density with improved spatial resolution

6. Focus: should be coincide to the region of interest [2].

2.1.2 Practical guidelines of color Doppler flow imaging

1. Choose the set-up key. This improve Doppler parameters for specific investigations.

2. Apply power within the study area and then adjust color gain. Ensure focus is set at the level of region of investigation. Adjust gain to improve color signal.

3. Position beam steering to get satisfactory beam angle for the selected artery or vein.

4. Adjust PRF to synchronize the flow status. Low PRF are very sensitive to low flows or velocities but may cause aliasing. High PRF decrease aliasing but are less sensitive to low flows/velocities [2].

5. Set the color flow area to suitable size. A small color flow 'box' or region may lead to a better frame rate and better resolution.

2.1.3 Spectral wave Doppler

Pulsed wave Doppler (PWD) ultrasound is used to generate a sonogram of a blood vessel (vein or artery) under study (**Figure 2**). PWD provides a measure of

the flow changing velocity throughout the cardiac cycle and display distribution of velocities in the sample volume (gate) as demonstrate in **Figure 3**. Velocities can be measured when an accurate angle correction is made.

2.1.4 Factors affecting the spectral Doppler image

1. Power: set the transmitted power to study area.

2. Gain: influence sensitivity to flow signals.

3. PRF: low PRF is used to detect low velocities while high PRF decrease aliasing.

4. Gate size: beam steering allows improved beam angle for accuracy of calculation of flow velocity.

2.1.5 Guidelines for practical spectral Doppler image

1. Set power to the selected study area.

2. Place the Doppler cursor on the artery/vein to be examined.

3. Gain should be adjusted so that the image is clearly visible and noiseless.

4. Apply the beam steering to get a satisfactory angle. Remember that angles approaching to 90° will give ambiguous image or unclear data. The beam angle must be 60° or less when velocity measurements are to be maintained.

5. Adjust the PRF/scale and baseline to suit flow conditions. The sonogram should be clear and not subjected to aliasing.

6. Adjust the sample volume (SV) to correct and suitable size coincided with area under investigation. Correct the angle to obtain accurate velocities. Use the B-mode and color flow image of the vessel to make the angle correction [2].

2.2 Doppler ultrasound of the kidneys

Doppler ultrasound is essential for evaluation of the kidneys. Doppler is considered more accurate than conventional sonography since it provides functional and

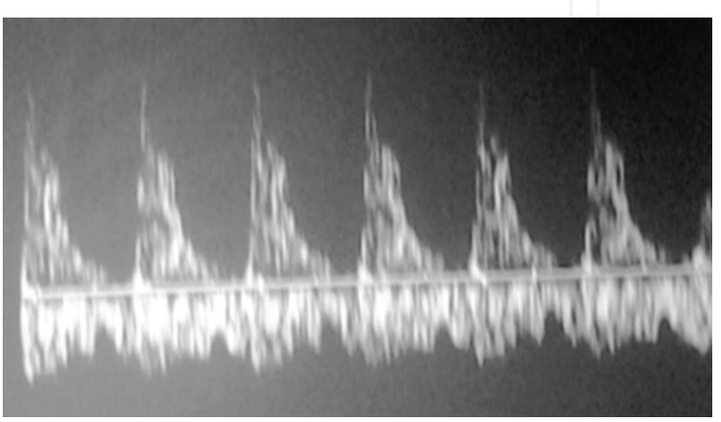

Figure 2.
Spectral wave Doppler. Renal arterial velocity waveform.

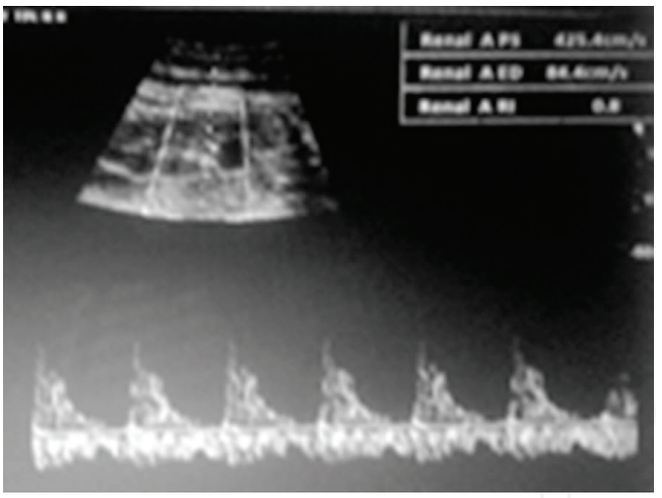

Figure 3.
Renal artery spectral Doppler demonstrates renal artery stenosis; PSV is 452.4 cm/s, RI= 0.80 in a 25-years male with hypertension and abnormal renal function (the sonogram taken by Dr. Moawia Gameraddin).

vascular information which are lacked in grayscale ultrasound. Doppler ultrasound assesses patterns of renal and extrarenal vascularization [3].

Doppler investigations must be performed properly to gain useful data. It allows information about the presence and direction of blood flow in renal vessels. Renal artery stenosis can be assessed by Doppler indices; resistive index (RI), pulsatility index (PI) and systolic to diastolic ratio (S/D). These indices provide hemodynamic and predictive information regarding the renal arteries. Analysis of the RI may provide helpful clinical information in various renal diseases [3].

2.2.1 Doppler procedure of the renal arteries

The investigation starts with the patient in the supine position using a low-frequency probe (2.5–5.0 MHz) to depict the abdominal aorta (AA) and renal arteries (RAs). The two main approaches for imaging the renal arteries are through the anterior abdominal wall. In most situations the anterior approach is used to assess the main RAs [4, 5].

The RAs arise from the lateral borders of the abdominal aorta (AA) at the level of the second lumbar vertebra, almost 1–2 cm inferior to the superior mesenteric artery (SMA) origin. The right RA arises from the anterolateral aspect of the abdominal aorta and it courses under the inferior vena cava (IVC) [8–10]. From this view, RA flow is in a direction that is parallel to the Doppler beam, optimizing signal reception. The patient usually needs to be placed in the opposite lateral decubitus position [4, 6].

A 3.5 MHz curvilinear array transducer with variable focal zone are used. The Doppler examination is usually performed in supine positions as stated by the renal ultrasound protocols. Each Kidney will be examined firstly with B-mode ultrasound in at least two planes to maintain the renal length for each kidney. The Doppler indices (RI and PI) are measured at interlobular or arcuate artery in the upper, middle, and lower portions of the kidney and the mean values were calculated for each kidney.

2.2.2 Normal vascularity of the renal artery

Doppler RI is efficient to detect intrarenal vascular pathological processes. Several studies have demonstrated that a normal mean renal RI is approximately 0.60. It was reported that a mean RI of 0.60 ± 0.01 for individuals without

pre-existing renal disease [7]. Other studies also reported normal mean RI values of 0.64 ± 0.05, 0.58 ± 0.05 [8], and 0.62 ± 0.04 [8, 9]. In addition, most sonographers have considered 0.70 to be the upper threshold of the normal RI in adults [10, 11].

2.2.3 The importance of Doppler resistive index

Doppler sonographic analysis of renal artery waveforms was empirically applied to disease characterization (**Figure 4**). Despite RI is a good predictor of several renal abnormalities, there are factors that affect the arterial waveform such as vascular resistance, vascular compliance, and heart rate. In a previous study, it was reported that renal RI was associated with "histological changes and poor renal outcome during chronic kidney disease". It was shown that RI ≥ 0.65 is associated with arteriosclerosis, severe interstitial fibrosis and renal function decline. Therefore, RI is essential Doppler parameter that contribute to diagnose patients at high risk of end-stage renal disease (ESRD) [12].

2.2.4 Application of Doppler in renal diseases

2.2.4.1 The role of Doppler in hypertension

Hypertension involves approximately 25–30% of the adult population and it was reported that the prevalence will increase. It is considered a main risk factor for the development of renal failure and cardiovascular disease. It was reported that 80% of patients with chronic kidney disease (CKD) are hypertensive. The relationship between hypertension and kidney disease is complex and it is attributed to the interrelated pathophysiology. Renal hypertension or renovascular hypertension means hypertension due to renal artery stenosis and kidney disease. Thus, patients who newly diagnosed hypertension must be screened for underlying kidney disease [13].

2.2.4.2 The role of Doppler RI in renal hypertension

The Doppler RI has been utilized for many years in a variety of clinical situations. Doppler ultrasonography detects renal abnormalities at macrovascular and microvascular levels. Assessment of renal RI at different regions of the renal parenchyma may suggest physiological or morphological changes within the kidneys. Therefore, it provides useful information for diagnosis and prognosis of the disease.

Recent studies revealed an increased renal resistive index (RRI) in patients with primary hypertension not only reflects vascular changes in intrarenal supply, but that it is also associated with atherosclerosis and systemic hemodynamics. Therefore, it provides useful prognostic information.

2.2.5 Doppler assessment of non-obstructive diseases

2.2.5.1 Acute and chronic kidney disease

Acute kidney injury: Acute kidney injury (AKI) was reported to associate with a high morbidity, long-term mortality and apparent economic impact [14].

Doppler ultrasound has been widely used in the assessment of renal diseases for diagnosis, prognosis and management. Doppler ultrasound is non-invasive, low cost and safe method for the evaluation of the renal blood flow. Recent studies reported different incidence of AKD among hospitalized patients classified as

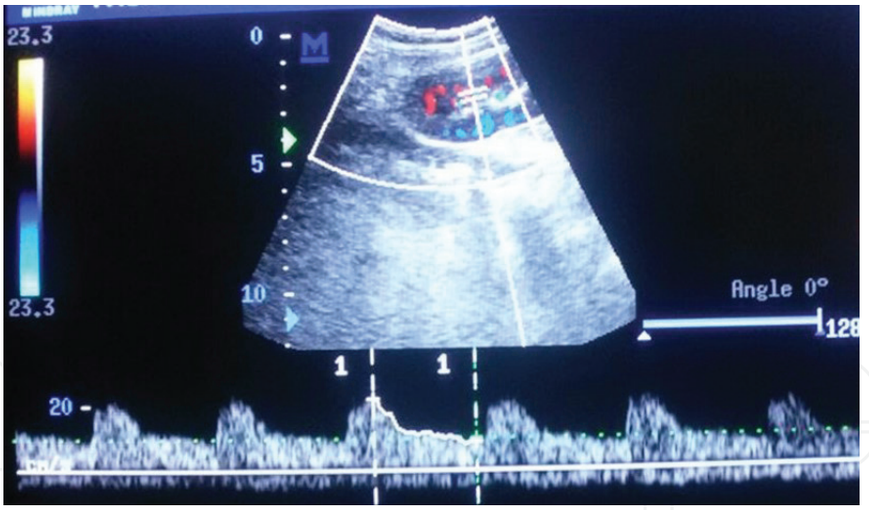

Figure 4.
Duplex Doppler reveals normal waveform of the renal artery (a sonogram taken from Awadia Gareeballah and Moawia Gameraddin researches).

"KDIGO classification (18.3 %), followed by AKIN (16.6 %) and RIFLE (16.1 %) and CK (7.0 %)."

2.2.5.2 Doppler evaluation of acute kidney injury

In gray scale ultrasound, AKD reveals increased renal parenchymal echogenicity which attributed to inflammatory states (acute glomerulonephritis, acute interstitial nephritis, acute tubular necrosis, HIV nephropathy) or infiltrative diseases (lymphoma, monoclonal, myeloma and gammopathies) decreased thickening of kidney cortex and echogenicity are also significant findings of AKI [15]. Color Doppler identifies the renal vessels localization to calculate RRI to monitor renal perfusion. In late stages of AKI, RRI usually exceed 0.7, and a threshold of 0.75 is reported as optimal in recognizing between renal and prerenal disease. However, RRI values lower than 0.7 are related to a good recovery after fluid rehydration, while RRI >0.7 suggest a developing ischemic acute tubular necrosis (ATN) and worse prognosis [16]. In conclusion, RRI play an effective role in different types of AKI.

2.2.6 Doppler assessment of chronic kidney disease

Chronic kidney disease (CKD) is considered as one of the public health problems worldwide [17]. According to the report of Global Burden of Disease in 2010 [2], CKD had been ranked the first cause of death worldwide at 27th to 18th over two decades. It was reported that "the surge of the CKD epidemic over these decades produced an 82% increase in years of life lost related to CKD, a disease toll of the same magnitude of that attributable to diabetes".

Ultrasonography of the kidneys is essential imaging modality among other renal imaging methods since it is available, low cost and safe. US can easily assess a CKD by measuring the length of the kidneys and evaluating the echogenicity of the kidney cortex. The reduction of size and increased echogenicity reflect pathological processes within the kidney.

The normal kidney length is about 11–12 cm (the left kidney is about 3 mm longer than the right kidney) in younger adults and a progressive atrophy with aging. Normal kidney is always as bright as normal liver or spleen tissue [18]. When the kidney cortex became brighter (echogenic) than hepatic tissue or splenic tissue,

this reflects inflammatory changes in the kidney tissues. CKD is often associated with increased echogenicity of the renal cortex since fibrous tissue such as glomerulosclerosis interstitial fibrosis, increases echogenicity.

However, those inflammatory conditions such as glomerulonephritis and acute interstitial nephritis (ATN) are associated with hyperechoic aspect of the renal parenchyma. In most cases, small and echogenic kidneys always suggest CKD instead of AKI.

Doppler ultrasound plays effective role in defining CKD and its progression to ESRD. Renal RI is reported to be correlated with arteriolosclerosis, glomerulosclerosis and tubulointerstitial lesions more than others morphologic parameters like kidney length and cortex area [19]. In general, higher values of renal RI (>0.7) ordinary reflects more severe arteriolosclerosis than normal values (<0.65) or high normal RRI ($0.65 \leq RI < 0.7$) [20]. However, patients with high-normal renal RI revealed good response to steroid therapy compared to a RRI > 0.7 [19]. Additionally, patients with advanced CKD stage showed significant higher RI than patients with earlier CKD stage.

2.2.7 Renal masses

Ultrasound plays a key role in screening renal cancer in asymptomatic patients. Most renal tumors remain are not accurately diagnosed on US and require CT for further characterization. However, US help to characterize cystic RCC that remain unclear on computerize tomography (CT). Recent technology in gray-scale imaging have improved the accuracy of US in the diagnosis and staging of kidney cancer. In addition, solid renal masses can grossly be categorized as completely solid, multifocal, or partially cystic tumors. The cystic appearance is mainly due to necrosis.

2.2.7.1 Ultrasound evaluation kidney cancer

Computed tomography (CT) is the gold standard for imaging the kidneys. It is accurate for detecting and characterizing renal neoplasms and staging renal cell carcinoma (RCC). On the other hand, ultrasound (US) has a less sensitivity in detecting small renal lesions, but it plays a key role in the early diagnosis of kidney cancer since it is routinely used in the evaluation of the abdomen. Renal masses were identified on US as a distortion of the normal tissue echotexture. Previous studies reported that RCC is detected incidentally in asymptomatic patients. Only 10% of patients with RCC present with the classic triad of hematuria, pain and a flank mass. Most of these patients often have advanced disease. More than 40% of the present with none of these three symptoms [21]. The RCC might be detected incidentally during abdominal sonography. The majority of RCC measure less than 3 cm or less on US. Early detection of RCC improves prognosis and survival rate.

The sonographic appearance of renal tumors vary between isoechoic-, hypoechoic, and hyperechoic compared with the normal renal parenchyma [22]. Doppler US assesses the blood flow patterns of vascularity in renal tumor tissue. It reveals vessels with high velocities. In RCC, the hypervascularity is attributed to neovascularization. The Doppler RI on spectral Doppler US was reported to be useful in detecting RCC in patients with ESRD [23].

2.2.8 The Doppler assessment of transplanted kidney

US is the most imaging modality for assessment of the transplanted kidneys (TK) (**Figure 5**). The TR is located in the right or left iliac fossa. The superficial location of the graft make the US examination accurate and ideal. The renal graft

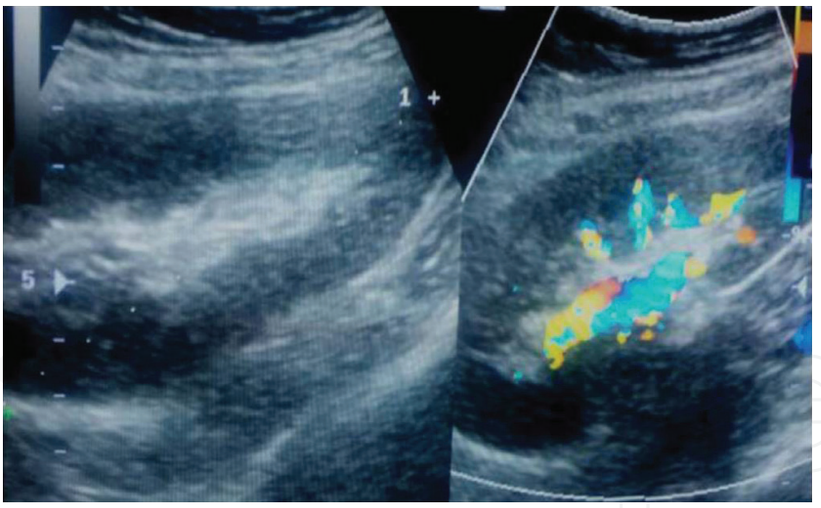

Figure 5.
A sonogram of a transplanted kidney shows normal size and normal color flow.

is vulnerable to several pathologic changes which might occur immediately or later. The sonographic appearance for evaluation of immediate post-plant pathologies may not be specific such as acute tubular necrosis (ATN), acute rejection, and toxicity associated with immunosuppressive calcineurin inhibitors [24].

The Doppler renal RI has a significant correlation with renal allograft size. It was reported that RI of 0.8 or higher was considered a strong predictor of graft failure and morphological changes [25]. The increase of RI was reported to correlate with presence of acute rejection and ATN [26]. On the other hand, elevated serum creatinine levels in renal transplant patient reveals high RI values. Therefore, the renal RI was a good predictor of graft function.

3. Renal elastography

Ultrasound elastography (USE) was first described in the 1990s. It is an imaging technology which is sensitive to tissue stiffness. In recent years, elastography has been further developed to enable quantitative assessments of tissue stiffness. Elastography is capable to assess changed elasticity of soft tissues resulting from specific pathological or physiological processes [27]. For example, tissue of solid tumors tends to differ mechanically from surrounding healthy tissues. Furthermore, fibrosis makes diseased tissue to be stiffer than normal ones. The role of elastography is to differentiate diseased tissue from normal one for diagnostic applications.

Ultrasound elastography (USE) of the kidneys is a potential application is an advanced imaging tool that may become a clinical biomarker for disease. However, elastography of renal transplant cortex and the corticomedullary strain ratio have been studied and they were found to correlate with renal cortical fibrosis [28, 29]. Shear-wave elastography (SWE) of the kidney utilizing acoustic radiation force impulse (ARFI) is a potential clinical application which was reported to demonstrate successful clinical applications in human organs [29]. In the kidney, SWE has shown promise in the evaluation of CKD, renal transplant function, and renal vein thrombosis (RVT).

3.1 Renal fibrosis

USE is clinically useful to detect and assess fibrosis in CKD and transplanted kidneys. USE with both strain imaging and SWI methods are noninvasively to

Criteria	Doppler ultrasound	Elastography
Main principle	Evaluates vascularity	Assesses elasticity
Renal transplantation	Renal blood resistivity index (renal RI) above 0.8 indicates renal graft dysfunction.	Assesses cortical fibrosis in early stage. Additionally, elastography assesses the grades of fibrosis; distinguish mild from moderate fibrosis.
Obstructive and non-obstructive hydronephrosis	Doppler US distinguishes between obstructive and non-obstructive hydronephrosis. Obstructive hydronephrosis reveals higher RI values than non-obstructive hydronephrosis.	Measurements did not enable distinguishing of obstructive hydronephrosis from non-obstructive hydronephrosis in children
Differentiation between malignant and benign tumors	Doppler US is useful in characterization of renal pseudotumors. Doppler allows differentiation of normal vascularity from tumor neovascularity. On the other hand, benign renal masses characterized by less or peripheral vascularity, homogeneous echotextures and well-defined margins.	Malignant tumors are stiffer than benign masses.

Table 1.
Comparison between Doppler ultrasound and elastography in evaluation of abnormalities of the kidney.

detect, stage and monitor kidney fibrosis, thus, reducing the need for renal biopsy [30]. SWI is preferable to strain imaging in evaluating kidney fibrosis in both renal graft and native kidneys since it is independent of external compression [30]. A previous study reported that SWE renal stiffness was higher in patients affected with CKD than in healthy controls [31]. Therefore, tissue stiffness measured by USE was significantly correlated with histopathologic renal fibrosis. This finding concluded that, USE is a non-invasive tool for predicting kidney fibrosis.

3.2 Characterization of focal renal lesions using elastography

USE is useful for characterizing focal renal masses since US features are not specific for malignancy. Assessment of renal masses with USE have shown controversial results. Some results found SW velocity values could differentiate between benign and malignant masses. Another study compared between malignant and benign renal masses concluded that malignant tumors are 2.8 times stiffer than benign masses [32]. A previous study reported that USE can differentiate between renal cell carcinoma (RCC) and transitional cell carcinoma (TCC) [33]. In general, quantification of kidney tissue using USE is more complex than other organs since the high heterogeneity of the renal tissue. However, the combination of doppler ultrasound and elastography will provide better assessment of kidney abnormalities as compared in **Table 1**.

4. Conclusion

In summary, Doppler ultrasound and USE are very effective imaging method to the kidneys. Doppler assesses vascularity of the kidneys while elastography evaluates tissue elasticity. USE is a new developing method and various studies have been made using elastography in kidneys. It is very effective on the transplanted and CKD kidneys to evaluate the corticomedullary fibrosis to prevent invasive biopsy.

Conflict of interest

The author declares there was no conflict of interest regarding this chapter.

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