Review Article

Doppler Ultrasound Changes in Renal Artery Hemodynamics During Acute Kidney Injury: Correlation With Glomerular Function

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Abstract

Acute kidney injury is a frequent and severe clinical condition associated with high morbidity, mortality, and risk of progression to chronic kidney disease. Its pathophysiology is strongly linked to disturbances in renal hemodynamics, including impaired autoregulation, reduced renal perfusion, microvascular dysfunction, and interstitial edema. These alterations affect both renal blood flow and glomerular filtration rate and may precede detectable changes in conventional biomarkers such as serum creatinine and urine output. In this context, renal Doppler ultrasound has emerged as a valuable, non-invasive tool for the assessment of renal hemodynamics in acute kidney injury. Renal Doppler ultrasound allows real-time evaluation of both macrovascular and microvascular renal circulation through parameters such as the renal resistive index, pulsatility index, power Doppler perfusion, and venous flow patterns. Elevated renal resistive index values consistently reflect increased intrarenal vascular resistance and have been associated with the development, severity, and persistence of acute kidney injury, as well as with declines in glomerular filtration rate and adverse long-term renal outcomes. Power Doppler ultrasound and venous Doppler patterns further contribute to the assessment of renal perfusion and congestion, enhancing diagnostic and prognostic accuracy. When integrated with clinical evaluation and laboratory data, renal Doppler ultrasound facilitates early diagnosis, risk stratification, and longitudinal monitoring of renal function, particularly in critically ill and perioperative patients. However, its interpretation is influenced by systemic hemodynamic factors, inflammation, operator experience, and technical variability, highlighting the need for standardized protocols and adequate training. Emerging approaches, including contrast-enhanced ultrasound and artificial intelligence–based analysis, offer promising avenues to refine renal perfusion assessment. Overall, renal Doppler ultrasound represents a complementary and physiologically informative modality that enhances understanding, diagnosis, and management of acute kidney injury.

Key words

Acute kidney injury, Renal Doppler ultrasound, Renal hemodynamics, Resistive index, Glomerular filtration rate, Microcirculation.

Introduction

Acute kidney injury is defined as a rapid deterioration in renal function, most commonly identified by an increase in serum creatinine levels or a reduction in urine output, and it is consistently associated with high morbidity and mortality among hospitalized patients [1]. This condition represents a frequent and clinically significant complication across a wide range of settings, including sepsis, cardiac surgery, and states of acute circulatory failure, where its presence is closely linked to adverse clinical outcomes and a substantial increase in healthcare utilization and costs [2, 3].

Despite their central role in current diagnostic criteria, conventional biomarkers of renal function such as serum creatinine and urine output present important limitations. Serum creatinine is an indirect marker of glomerular filtration that often rises only after a significant decline in renal function has already occurred, resulting in a delayed diagnosis of kidney injury. In addition, its interpretation is influenced by nonrenal factors including muscle mass, age, hydration status, and hemodilution, which may obscure early changes in renal function [1]. Similarly, urine output is affected by multiple physiological and therapeutic variables and lacks specificity for intrinsic renal injury. As a consequence, reliance on these markers frequently leads to under recognition of early or subclinical acute kidney injury, postponing the initiation of targeted interventions and potentially contributing to worse clinical outcomes [2].

In this context, Doppler ultrasound has emerged as a valuable adjunctive tool for the assessment of renal function in acute kidney injury by enabling a noninvasive, bedside, and real-time evaluation of renal blood flow and perfusion. Unlike conventional biomarkers, Doppler ultrasound directly reflects renal hemodynamic changes that occur early during kidney injury, thereby offering the potential for earlier detection [4]. Increasing evidence indicates that Doppler-derived parameters, particularly the renal resistive index and power Doppler ultrasound scores, can predict the development of acute kidney injury in critically ill patients with greater sensitivity and specificity than serum creatinine or urine output alone [2]. Importantly, Doppler ultrasound allows for the simultaneous assessment of both renal microcirculation and microcirculation, providing a more comprehensive characterization of renal hemodynamics. In septic acute kidney injury, for example, studies have demonstrated reductions in renal blood flow accompanied by prolonged microcirculatory transit times, highlighting the contribution of microvascular dysfunction to renal impairment [5].

The integration of Doppler ultrasound into critical care practice further enables dynamic monitoring of renal perfusion over time and supports the individualization of therapeutic strategies. By tracking changes in renal blood flow parameters, clinicians can better guide fluid resuscitation, vasoactive therapy, and overall hemodynamic management, with the goal of optimizing renal perfusion while avoiding deleterious effects of over- or under-resuscitation [4, 6].

The objective of this article is to analyze changes in renal artery Doppler parameters in the setting of acute kidney injury and to evaluate their correlation with glomerular function, with the aim of clarifying the pathophysiological significance of renal hemodynamic alterations and assessing the clinical utility of Doppler ultrasound as a complementary tool for the early detection, monitoring, and prognostic evaluation of acute kidney injury.

Methodology

For the development of this review on Doppler ultrasound–derived changes in renal artery parameters in acute kidney injury, a comprehensive analysis of the available literature was conducted with the aim of examining the pathophysiological basis, diagnostic relevance, and clinical implications of renal hemodynamic alterations and their correlation with glomerular function. Particular emphasis was placed on Doppler-derived indices, including the renal resistive index and other velocity-based parameters, their relationship with markers of renal function, and their potential role in early diagnosis, monitoring, and prognostic assessment in acute care settings.

The review was based on a structured search of established scientific databases, including PubMed, Scopus, and Web of Science, selected for their relevance to nephrology, critical care, emergency medicine, and medical imaging. Clearly defined inclusion and exclusion criteria were applied to ensure methodological rigor and clinical relevance. Articles published between 2020 and 2025 in English or Spanish were included if they addressed key aspects such as the definition and pathophysiology of acute kidney injury, principles of renal Doppler ultrasound, changes in renal artery Doppler parameters during acute kidney injury, and correlations with glomerular filtration rate, serum creatinine, or urine output. Studies without peer review, those with incomplete or nonreproducible data, and publications with overlapping or duplicated content were excluded. The search strategy incorporated the following keywords and their combinations: Acute kidney injury, renal Doppler ultrasound, renal hemodynamics, resistive index, glomerular filtration rate, microcirculation.

The initial search yielded a total of 29 relevant sources, including original research articles, observational and prospective studies, systematic reviews, and clinical practice guidelines from recognized nephrology and critical care societies. These sources were critically appraised to extract data on renal hemodynamic mechanisms, Doppler measurement techniques, reported threshold values, temporal changes during injury and recovery, and their association with clinical outcomes and renal function parameters.

Artificial intelligence tools were used as complementary support during the synthesis process, facilitating thematic organization of the literature, identification of conceptual links between renal hemodynamics and glomerular dysfunction, and optimization of textual coherence. These tools contributed to a more efficient integration of heterogeneous data while preserving the scientific integrity of the review.

The analysis followed a qualitative and comparative approach. Findings were organized thematically to describe patterns of Doppler parameter alterations across different etiologies of acute kidney injury, to compare their diagnostic and prognostic performance with conventional biomarkers, and to identify limitations, confounding factors, and areas of uncertainty. This methodological approach allowed for a structured and evidence-based overview of current knowledge, highlighting the potential clinical value of renal Doppler ultrasound as a complementary tool for the assessment of acute kidney injury and underscoring the need for standardized protocols and further prospective research.

Pathophysiology of Renal Hemodynamics in Acute Kidney Injury

Renal autoregulation is a fundamental physiological mechanism that maintains relatively stable renal blood flow and glomerular filtration rate across a wide range of renal perfusion pressures through dynamic adjustments in intrarenal vascular resistance. Under normal conditions, this adaptive response allows the kidneys to preserve filtration despite fluctuations in systemic blood pressure. However, in the context of critical illness, autoregulatory capacity may become impaired or overwhelmed, resulting in tissue hypoperfusion and a substantially increased risk of acute kidney injury [7].

Within this framework, the renal microcirculation plays a central role in sustaining oxygen and nutrient delivery to renal tissues. The peritubular capillary network is particularly important for tubular function and recovery from injury. Nevertheless, its unique anatomical and functional characteristics render it especially vulnerable to ischemic damage. This susceptibility is most evident in the renal medulla, which physiologically receives significantly less blood flow than the cortex and therefore operates at lower oxygen tension. As a result, even modest reductions in perfusion can precipitate medullary hypoxia and contribute to the development of acute kidney injury [8].

Hemodynamic alterations vary according to the underlying etiology of acute kidney injury, although they ultimately converge on impaired renal perfusion and filtration. In prerenal acute kidney injury, reduced renal perfusion secondary to systemic hypotension or volume depletion leads to a decline in renal blood flow and glomerular filtration rate. In response, the kidney attempts to preserve filtration through compensatory increases in vascular resistance and activation of autoregulatory mechanisms. When hypoperfusion is prolonged or severe, these compensatory responses become insufficient, predisposing the kidney to intrinsic structural damage [7]. In contrast, intrinsic acute kidney injury is primarily associated with direct injury to renal parenchymal structures. Ischemia–reperfusion injury represents a prototypical example, characterized by profound microvascular dysfunction and endothelial damage. These alterations disrupt normal capillary perfusion, promote peritubular capillary rarefaction, and create conditions that favor progression toward chronic kidney disease [8, 9]. Postrenal acute kidney injury, on the other hand, arises from obstruction to urinary outflow, which increases intratubular pressure and directly reduces glomerular filtration rate. The resulting hemodynamic response involves complex changes in renal vascular resistance and perfusion pressure that further compromise renal function [10].

Across these etiologies, microvascular dysfunction and interstitial edema emerge as unifying mechanisms that exacerbate renal injury. Microvascular dysfunction, defined by impaired capillary blood flow and endothelial injury, plays a critical role in limiting oxygen delivery to renal tissues and increasing susceptibility to ischemic damage [11, 12]. Concurrently, interstitial edema develops as a consequence of increased vascular permeability and fluid extravasation, leading to elevated interstitial pressure. This process further impairs capillary perfusion, aggravates tissue hypoxia, and perpetuates renal dysfunction. Together, microvascular dysfunction and interstitial edema contribute to a self-reinforcing cycle of worsening renal injury that not only hinders recovery from acute kidney injury but also increases the risk of long-term progression to chronic kidney disease [8, 10].

Principles of Renal Doppler Ultrasound

A rigorous and standardized examination protocol is essential to ensure the reliability and reproducibility of renal Doppler ultrasound measurements. Standardization involves the use of consistent machine settings adapted to patient-specific characteristics, such as body habitus and hemodynamic status, as well as the application of uniform measurement techniques across examinations. Adequate operator training is a central component of this process, as it minimizes technical variability and reduces the risk of measurement bias, thereby improving the overall quality and interpretability of Doppler-derived parameters [13].

From a technical standpoint, advances in imaging techniques have expanded the diagnostic capabilities of renal ultrasound. In particular, contrast-enhanced ultrasound has demonstrated significant value in improving the detection and characterization of renal artery stenosis. This modality enhances visualization of renal perfusion and vascular anatomy and has shown high sensitivity and specificity when compared with digital subtraction angiography, which remains the reference standard for vascular assessment [14].

Operator training plays a decisive role in the accuracy of renal Doppler ultrasound examinations. The quality of Doppler signal acquisition, angle correction, and waveform interpretation is strongly influenced by operator experience. Consequently, professional training programs focused on renal vascular ultrasound are necessary to ensure consistent and accurate diagnoses, particularly in complex clinical settings such as acute kidney injury and critical illness [14].

Renal Doppler ultrasound allows for the evaluation of both the main renal arteries and the intrarenal arterial circulation, each providing distinct but complementary information. Assessment of the main renal arteries is particularly relevant for the detection of renal artery stenosis, a condition with important implications for the management of hypertension and preservation of renal function [15]. In contrast, intrarenal Doppler evaluation focuses on smaller vessels, most commonly the interlobar arteries, to assess renal perfusion and intrarenal hemodynamics. This approach is especially useful in predicting the reversibility of renal dysfunction and in monitoring dynamic changes in renal blood flow. Parameters such as the resistive index and pulsatility index are routinely measured at this level to reflect downstream vascular resistance and compliance [6].

Among Doppler-derived parameters, the resistive index is one of the most widely used indicators of intrarenal hemodynamics. It provides indirect information about vascular resistance and has been shown to predict outcomes in a range of conditions, including diabetic nephropathy and acute kidney injury. Beyond renal disease, elevated resistive index values have also been associated with an increased risk of cardiovascular events in patients with hypertension, highlighting its broader prognostic significance. The pulsatility index complements the resistive index by offering additional insight into intrarenal vasoconstriction and arterial compliance, and it has been shown to be relevant in assessing disease progression in diabetic nephropathy [16, 17]. Peak systolic velocity and end-diastolic velocity constitute the fundamental components used to calculate these indices and provide direct information on arterial flow dynamics. In specific clinical contexts, such as kidney transplantation, low end-diastolic velocity has been associated with an increased risk of mortality, underscoring its clinical relevance as a prognostic marker [18].

Despite the robustness of these parameters, sources of variability must be carefully considered. Inter-observer and inter-scanner variability represent potential limitations; however, available evidence indicates good to excellent agreement for resistive and pulsatility index measurements when standardized protocols are applied and operators are adequately trained [13]. Nevertheless, operator dependence remains an inherent characteristic of Doppler ultrasound. The accuracy and clinical utility of renal Doppler assessments are closely linked to operator expertise, reinforcing the importance of structured training programs and protocol adherence to ensure reliable integration of this technique into routine clinical practice [14].

Doppler Parameter Changes in Acute Kidney Injury

Acute kidney injury is associated with characteristic Doppler ultrasound patterns that reflect underlying alterations in renal hemodynamics and vascular resistance. Among these, the renal resistive index has emerged as a key parameter, with elevated values indicating increased intrarenal vascular resistance. Higher renal resistive index values are frequently observed in patients with acute kidney injury and have been consistently associated with an increased risk of developing this condition, supporting their role as an early hemodynamic marker of renal impairment. Complementary to this finding, power Doppler ultrasound provides a semiquantitative assessment of renal perfusion. Reduced power Doppler ultrasound scores, which reflect diminished parenchymal blood flow, are commonly detected in acute kidney injury and correlate with the severity of renal hypoperfusion observed in these patients [2, 19].

Beyond arterial indices, alterations in renal venous hemodynamics have also been described in acute kidney injury. Abnormal renal venous flow patterns, particularly increased venous pulsatility, are indicative of impaired venous outflow and elevated renal interstitial pressure. These changes have been linked to more severe forms of acute kidney injury and are thought to reflect the combined effects of venous congestion, interstitial edema, and reduced renal compliance [3].

Doppler ultrasound findings may also help differentiate between transient and persistent renal dysfunction. The combined evaluation of renal resistive index and power Doppler ultrasound has led to the development of composite measures, such as the renal resistive index to power Doppler ultrasound ratio. Higher values of this ratio have been shown to strongly predict the development of acute kidney injury and are particularly suggestive of persistent renal dysfunction, reflecting sustained increases in vascular resistance alongside reduced parenchymal perfusion [2]. In contrast, lower renal resistive index values are more commonly associated with transient renal dysfunction, indicating potentially reversible hemodynamic alterations. Persistently elevated renal resistive index values over time, however, are indicative of ongoing renal impairment and a reduced likelihood of functional recovery [6].

The interpretation of Doppler patterns in acute kidney injury must also account for the influence of systemic factors that can modify renal perfusion and Doppler measurements. Systemic blood pressure and heart rate directly affect renal perfusion pressure and flow dynamics, potentially altering Doppler-derived indices and influencing the accuracy of acute kidney injury prediction models [20]. In addition, elevated intra-abdominal pressure represents an important confounding factor, as it can increase renal vascular resistance, reduce renal blood flow, and lead to artificially elevated renal resistive index values. This phenomenon complicates the assessment of renal function, particularly in critically ill patients, and highlights the need to interpret Doppler findings within the broader clinical and hemodynamic context [6].

Correlation Between Doppler Findings and Glomerular Function

The relationship between renal Doppler parameters and glomerular function has been extensively explored, with the renal resistive index emerging as a key marker of intrarenal hemodynamic alterations. An increase in the renal resistive index has been consistently associated with a decline in estimated glomerular filtration rate in patients with chronic kidney disease. In this context, elevated renal resistive index values, particularly when accompanied by proteinuria, act as independent predictors of disease progression. A significant inverse correlation has been demonstrated between continuous renal resistive index measurements and changes in estimated glomerular filtration rate, supporting the concept that higher intrarenal vascular resistance is closely linked to progressive loss of renal function [21]. Even in the absence of proteinuria, an intrarenal resistive index equal to or greater than 0.80 has been shown to predict a more rapid decline in renal function and increased long-term mortality, although its discriminatory performance as a standalone marker remains limited [22].

Beyond its association with estimated glomerular filtration rate, Doppler ultrasound parameters have also been correlated with traditional biochemical markers of renal function. The resistive index demonstrates a meaningful relationship with serum creatinine levels, indicating its potential utility for longitudinal monitoring of renal function. In non-proteinuric chronic kidney disease, elevated resistive index values are associated with a faster rise in serum creatinine, further reinforcing its role as a marker of hemodynamic stress and declining renal function [22]. In addition, other Doppler-derived variables provide complementary information. End-diastolic velocity and renal cortical perfusion intensity have been independently associated with estimated glomerular filtration rate, suggesting that reductions in diastolic flow and parenchymal perfusion directly reflect functional impairment of the kidney [23].

The temporal evolution of Doppler parameters offers further insight into the dynamic nature of renal injury and recovery. Both the resistive index and power Doppler ultrasound have demonstrated comparable performance in predicting acute kidney injury, highlighting their potential role in tracking the progression of renal dysfunction over time as well as in monitoring recovery phases [19]. Longitudinal changes in Doppler parameters, particularly in the resistive index, have been shown to mirror the progression or stabilization of renal disease in studies evaluating chronic kidney disease over extended follow-up periods, underscoring their value as dynamic rather than static biomarkers of renal health [21, 22].

From a prognostic perspective, elevated renal resistive index values carry important implications for renal outcomes and patient survival. Increased resistive index has been identified as a significant predictor of renal disease progression and overall mortality in patients with chronic kidney disease, emphasizing its relevance beyond short-term functional assessment [22]. The prognostic value of Doppler ultrasound is further strengthened when resistive index measurements are considered alongside proteinuria, as the combination of these two parameters markedly increases the likelihood of reaching adverse renal endpoints. This interaction highlights the importance of integrating hemodynamic and structural markers in comprehensive prognostic assessments of renal disease [21].

Clinical Applications

Renal Doppler ultrasound plays an increasingly important role in the early diagnosis of acute kidney injury by enabling rapid, bedside assessment of renal blood flow and perfusion. Unlike conventional biomarkers, which often reflect renal injury only after a significant functional decline has occurred, Doppler ultrasound can detect hemodynamic alterations at an earlier stage. Changes in renal perfusion and vascular resistance may be identified before measurable increases in serum creatinine, thereby creating an opportunity for earlier recognition of acute kidney injury and more timely therapeutic intervention [2, 4].

Within this context, the renal resistive index has emerged as one of the most clinically useful Doppler-derived parameters for early risk identification. Elevated renal resistive index values have been consistently associated with an increased likelihood of developing acute kidney injury, supporting its role as a reliable early diagnostic marker. By reflecting increased intrarenal vascular resistance, the renal resistive index provides pathophysiologically relevant information that complements traditional laboratory data and enhances early risk assessment in vulnerable patient populations [2, 6].

Beyond early diagnosis, renal Doppler ultrasound is also instrumental in risk stratification and longitudinal monitoring of disease progression. Doppler-derived measures of renal blood flow and time-averaged velocity decrease as acute kidney injury severity increases, allowing differentiation between milder and more severe forms of renal dysfunction. This stratification capability has important clinical implications, as it supports prognostic assessment and informs the intensity of monitoring and therapeutic strategies. Moreover, Doppler ultrasound provides insight into both macrocirculatory and microcirculatory alterations within the kidney. Prolonged microcirculatory time parameters, for example, have been shown to correlate with severe acute kidney injury, highlighting the contribution of microvascular dysfunction to disease severity [5]. In perioperative settings, particularly following cardiac surgery, Doppler measurements have demonstrated predictive value for postoperative acute kidney injury, enabling the implementation of preventive measures in high-risk patients [3].

The clinical utility of renal Doppler ultrasound is further enhanced when its findings are integrated with laboratory results and comprehensive clinical evaluation. By adding direct hemodynamic information to biochemical markers and clinical parameters, Doppler ultrasound contributes to a more individualized and physiologically informed approach to patient management. This integrated assessment can guide decisions regarding fluid therapy, hemodynamic optimization, and renal-protective strategies in acute care settings [24]. The combined use of Doppler ultrasound with other diagnostic modalities increases the overall accuracy of acute kidney injury diagnosis and management, particularly in critically ill patients who often present with complex and rapidly evolving clinical conditions [4, 25]. Furthermore, the incorporation of advanced imaging techniques such as contrast-enhanced ultrasound can further refine the evaluation of renal perfusion and function, offer a more comprehensive and nuanced assessment of renal hemodynamics and support more precise clinical decision-making [26].

Limitations and Pitfalls

The interpretation of renal Doppler ultrasound findings in acute kidney injury is influenced by several confounding factors that must be carefully considered to avoid misinterpretation. Patient-specific variables represent an important source of variability, as differences in body habitus, such as obesity, and the presence of anatomical anomalies can degrade image quality and Doppler signal acquisition. These factors may limit adequate visualization of renal vessels and introduce inaccuracies in Doppler-derived measurements, thereby affecting their diagnostic reliability [5, 19].

Hemodynamic instability is another critical confounder in the assessment of renal Doppler findings. Fluctuations in systemic blood pressure and cardiac output directly influence renal perfusion and can alter Doppler waveforms independently of intrinsic renal pathology. In critically ill patients, rapid changes in circulatory status may therefore obscure the distinction between functional, hemodynamically mediated alterations and structural renal injury, complicating the clinical interpretation of Doppler measurements [25].

Sepsis and systemic inflammation further add complexity to Doppler ultrasound assessment. In septic acute kidney injury, profound alterations occur at both the macrocirculatory and microcirculatory levels, including endothelial dysfunction, capillary leakage, and heterogeneous perfusion. These changes can significantly modify Doppler ultrasound parameters and confound the evaluation of renal perfusion, as abnormal findings may reflect systemic inflammatory effects rather than isolated renal pathology. As a result, Doppler findings in sepsis must be interpreted within the broader context of systemic hemodynamic and inflammatory status [5].

Beyond patient- and disease-related factors, interobserver variability and technical constraints represent inherent limitations of renal Doppler ultrasound. The accuracy and consistency of Doppler measurements are highly dependent on operator skill and experience, as proper vessel identification, angle correction, and waveform interpretation require technical expertise. Variations in operator proficiency can therefore lead to inconsistent results and reduced reproducibility across examinations [3]. Equipment-related factors also contribute to measurement variability. Differences in ultrasound systems, transducer quality, and machine settings can affect signal resolution and Doppler sensitivity, limiting comparability of results across different clinical environments [27]. Finally, the absence of universally standardized protocols for renal Doppler ultrasound in acute kidney injury remains a significant challenge. Variability in acquisition techniques and parameter definitions can lead to discrepancies in data interpretation and clinical decision-making, underscoring the need for standardized methodologies to improve the reliability and clinical applicability of Doppler ultrasound in this setting [19].

Future Perspectives

Advanced ultrasound approaches are increasingly expanding the clinical potential of renal hemodynamic assessment in acute kidney injury by improving the evaluation of perfusion at both macrovascular and microvascular levels. Intrarenal Doppler has gained particular relevance as it enables a more detailed characterization of renal perfusion through simultaneous assessment of arterial and venous flow patterns. Within this framework, parameters such as the renal resistive index and intrarenal venous flow patterns have been highlighted as clinically meaningful markers, not only for predicting the development of acute kidney injury but also for supporting hemodynamic decision-making and guiding individualized circulatory support strategies in acute care settings [6].

In parallel, contrast-enhanced ultrasound has emerged as a valuable technique for the non-invasive evaluation of renal microcirculation. By enhancing visualization of parenchymal perfusion, contrast-enhanced ultrasound can identify microvascular perfusion abnormalities at early stages, including changes that may occur before serum creatinine rises. This characteristic makes it particularly relevant for early diagnosis of acute kidney injury, as it provides functional insight into perfusion impairment that precedes conventional biochemical manifestations of renal dysfunction [28].

The potential role of artificial intelligence further strengthens these emerging perspectives by offering tools capable of processing complex clinical and imaging datasets. Machine learning approaches have shown high potential for predicting acute kidney injury, particularly through the integration of multiple variables that may not be readily interpretable through conventional clinical reasoning alone. In this setting, artificial intelligence can support the interpretation of Doppler ultrasound by improving pattern recognition, enhancing diagnostic accuracy, and facilitating earlier risk identification, thereby promoting timely intervention. However, to translate these advantages into routine practice, future research must focus on refining artificial intelligence models to ensure consistent performance across different patient populations and healthcare systems, including environments with limited resources, where variability in data availability and imaging quality may be substantial [29].

Despite these promising developments, important research gaps remain. Model refinement is required to improve the inclusiveness and generalizability of artificial intelligence tools by incorporating diverse patient characteristics and clinical contexts, thereby minimizing bias and strengthening external validity [29]. In addition, broader validation of advanced Doppler techniques and contrast-enhanced ultrasound is needed to confirm their effectiveness and reproducibility across various clinical scenarios, particularly among critically ill patients in whom hemodynamic instability and systemic inflammation frequently confound renal perfusion assessment [2, 3].

Conclusion

Acute kidney injury is fundamentally driven by complex disturbances in renal hemodynamics that involve both impaired autoregulation and profound microcirculatory dysfunction. The vulnerability of the renal microvasculature, particularly within the medulla, together with the development of interstitial edema and endothelial injury, creates a pathophysiological cascade that links systemic hemodynamic instability to sustained reductions in renal perfusion and glomerular filtration. Although the initial hemodynamic alterations differ among prerenal, intrinsic, and postrenal etiologies, they ultimately converge on shared mechanisms that not only worsen acute renal dysfunction but also increase the risk of incomplete recovery and progression to chronic kidney disease.

Renal Doppler ultrasound provides a physiologically meaningful and clinically applicable window into these hemodynamic alterations. Doppler-derived parameters, especially the renal resistive index, pulsatility index, power Doppler perfusion scores, and venous flow patterns, reliably reflect changes in intrarenal vascular resistance, perfusion, and compliance. Their correlation with glomerular filtration rate, serum creatinine, and long-term renal outcomes supports their value as dynamic biomarkers that complement conventional laboratory measures. When performed using standardized protocols and adequate operator training, renal Doppler ultrasound enables early detection of acute kidney injury, differentiation between transient and persistent dysfunction, and improved risk stratification across diverse clinical settings.

Despite its demonstrated clinical potential, the broader implementation of renal Doppler ultrasound requires careful consideration of its limitations and future development. Hemodynamic instability, systemic inflammation, and technical and operator-dependent variability can confound interpretation, underscoring the need for contextualized analysis and standardized methodologies. Emerging techniques such as contrast-enhanced ultrasound, intrarenal venous Doppler assessment, and artificial intelligence–based analytical models hold promise for refining perfusion assessment and improving diagnostic and prognostic accuracy. Further validation studies and the development of robust, generalizable protocols are essential to consolidate renal Doppler ultrasound as an integral component of acute kidney injury evaluation and management.

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