

Acute kidney injury in patients with COVID-19 receiving mechanical ventilation

Lesión renal aguda en pacientes con COVID-19 bajo ventilación mecánica

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Abstract

Acute kidney injury (AKI) has emerged as one of the most frequent and prognostically relevant complications in hospitalized patients with COVID-19, particularly among those with acute respiratory distress syndrome (ARDS) requiring invasive mechanical ventilation. During the pandemic, the National Institute of Respiratory Diseases (INER) in Mexico City was designated as a national referral center for critically ill patients, facing an unprecedented burden of severe respiratory failure and COVID-19-associated AKI. This narrative review integrates international and national evidence on the epidemiology, pathophysiology, diagnosis, and management of COVID-19 and associated AKI, explicitly incorporating the clinical and scientific experience generated at INER. We discuss the high incidence of AKI observed in Mexican cohorts, the distinction between community-acquired and hospital-acquired AKI, and the central role of lung-kidney crosstalk in patients with ARDS. Particular emphasis is placed on the impact of mechanical ventilation strategies, especially driving pressure and reduced lung compliance, as key determinants of adverse kidney outcomes. We also review the role of urinary biomarkers for early detection of kidney injury and a stage-based management approach that includes conventional kidney replacement therapies and adjunctive extracorporeal support strategies. The INER experience highlights the importance of early nephrology involvement in the care of critically ill patients and the generation of local evidence to improve kidney-related outcomes in COVID-19.

Keywords: Acute kidney injury. COVID-19. Acute respiratory distress syndrome. Mechanical ventilation. Kidney replacement therapy.

Resumen

La lesión renal aguda (LRA) se ha consolidado como una de las complicaciones más frecuentes y de peor pronóstico en pacientes hospitalizados con COVID-19, particularmente en aquellos con síndrome de dificultad respiratoria aguda (SDRA) que requieren ventilación mecánica invasiva. Durante la pandemia, el Instituto Nacional de Enfermedades Respiratorias (INER) de la Ciudad de México fue designado como centro de referencia nacional para la atención de pacientes críticos, enfrentando una elevada carga de enfermedad respiratoria grave y una incidencia sin precedentes de LRA. Esta revisión integra la evidencia internacional y nacional sobre la epidemiología, fisiopatología, diagnóstico y manejo de la LRA asociada a COVID-19, de manera explícita incorpora la experiencia clínica y científica generada en el INER. Se discute la alta incidencia de LRA observada en cohortes mexicanas, la diferenciación entre LRA adquirida en la comunidad e intrahospitalaria y el papel central de la interacción pulmón-riñón en pacientes con SDRA. Se analiza el impacto de la ventilación mecánica, en particular de

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la driving pressure y la baja distensibilidad pulmonar, como determinantes de eventos renales adversos. Asimismo, se revisa el uso de biomarcadores urinarios para la detección temprana de daño renal y un enfoque de manejo escalonado basado en estadios de LRA, que incluye terapias de reemplazo renal convencionales y estrategias extracorpóreas adyuvantes. La experiencia del INER resalta la importancia de la integración temprana de la nefrología en el cuidado del paciente crítico y de la generación de evidencia local para optimizar los desenlaces renales en COVID-19.

Palabras clave: Lesión renal aguda. COVID-19. Síndrome de dificultad respiratoria agudo. Ventilación mecánica. Terapia de reemplazo renal.

Introduction

In December 2019, a novel coronavirus was identified, subsequently designated as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), whose capacity to produce severe respiratory illness and acute respiratory distress syndrome (ARDS) abruptly transformed clinical practice worldwide.^{1,2} Within months, the rapid spread of the virus and the high proportion of patients requiring hospitalization and ventilatory support placed unprecedented pressure on healthcare systems, particularly in middle-income countries.

In Mexico, the Instituto Nacional de Enfermedades Respiratorias Ismael Cosío Villegas (INER) was designated early on as one of the principal national centers for the care of critically ill patients with COVID-19.³ This reconversion entailed not only a massive expansion of intensive care beds but also the adaptation of multiple hospital areas for the management of patients with severe respiratory failure.⁴ Even for an institution with extensive experience in high-complexity respiratory disease, the magnitude, duration, and clinical complexity of the pandemic represented an unprecedented challenge.

INER has historically served as a referral center for the management of ARDS secondary to viral infections, such as influenza A(H1N1), a context in which the high frequency of acute kidney injury (AKI) and its adverse prognostic impact were already well recognized.⁵ This prior experience enabled anticipation that renal involvement would be a central component of COVID-19 disease, particularly in a population with a high prevalence of type 2 diabetes mellitus (T2DM), obesity (OB), and hypertension (HTN) – conditions associated with reduced renal reserve and greater susceptibility to acute kidney damage.⁶

As clinical experience accumulated during the early months of the pandemic, it became evident that AKI was a frequent complication in patients with severe COVID-19, particularly in those who developed ARDS and required invasive mechanical ventilation (IMV). AKI episodes tended to cluster in the early phases of IMV

and were associated with greater respiratory severity, greater hemodynamic complexity, and worse clinical outcomes.⁷

During pandemic peaks, INER simultaneously managed more than 150 patients under IMV, distributed across multiple reconverted areas of the hospital.⁴ This concentration of patients with severe ARDS translated into a high incidence of AKI and the need to rapidly expand kidney replacement therapies (KRT) and other extracorporeal therapies to non-conventional settings, including temporary areas adapted to provide continuous renal support. In this context, institutional nephrology rapidly consolidated its role as a strategic component of critical patient management. Early integration of the nephrologist into multidisciplinary teams not only optimized clinical care but also enabled the generation of relevant scientific evidence regarding the epidemiology, pathophysiology, and clinical course of COVID-19-associated AKI.

The present review article aims to integrate international and national evidence on the epidemiology, pathophysiology, diagnosis, and treatment of COVID-19-associated AKI, explicitly incorporating the clinical and scientific experience generated at INER, with particular emphasis on lung-kidney crosstalk in patients with ARDS undergoing IMV.

Epidemiology of COVID-19-associated acute kidney injury

The incidence of AKI in hospitalized patients with COVID-19 showed wide variability in initial reports. In the earliest series from China and Italy, the incidence ranged from 0.5% to 29%, reflecting differences in the severity of included patients, the diagnostic criteria used, and the availability of longitudinal follow-up. However, as larger cohorts with a greater proportion of critically ill patients were published – particularly from the United States – the reported incidence of AKI increased substantially, reaching figures approaching 35-40%.⁸

AKI occurred predominantly in patients with severe respiratory failure requiring IMV and developed early, frequently within the first 24-72 hours following hospital admission.⁹ This temporal pattern coincided with the development of ARDS and with the systemic hyperinflammatory phase, suggesting a close relationship between severe pulmonary injury and acute renal dysfunction.¹⁰

In Latin America, the first structured data and the largest national series came from INER in Mexico City. INER cohorts demonstrated a notably elevated incidence of AKI, approaching 70-75% of hospitalized patients, with early onset and greater frequency in patients with OB, HTN, and T2DM.¹¹ This pattern contrasted with reports from other regions and was accompanied by a substantial increase in demand for specialized nephrology care and KRT.

A particularly relevant epidemiological finding in these cohorts was the distinction between community-acquired AKI and hospital-acquired AKI. Approximately two-thirds of cases corresponded to AKI present at admission, while one-third developed during hospitalization. Both scenarios were associated with high mortality, suggesting that metabolic, nutritional, and critical illness factors contribute early to renal injury, even before the initiation of intensive therapies.^{12,13}

Pathophysiology of lung-kidney crosstalk in patients with COVID-19-related ARDS

The high incidence of AKI in patients with COVID-19-associated ARDS reflects a complex interplay between severe pulmonary injury, the systemic inflammatory response, and the hemodynamic and biological effects of IMV.² In this context, the lung-kidney axis assumes a central role in the genesis and perpetuation of renal injury (Fig. 1).¹⁴ ARDS is associated with profound hypoxemia and hypercapnia, which induce renal vasoconstriction, alterations in blood flow autoregulation, and tubular dysfunction.¹⁴ Concomitantly, the injured lung acts as a proinflammatory organ, releasing cytokines such as IL-6, PAI-1, and other endothelial mediators that increase capillary permeability, promote microvascular dysfunction, and amplify remote renal injury.^{14,15}

IMV represents a critical point in this interaction. Increased intrathoracic pressure reduces venous return and cardiac output, while elevated positive end-expiratory pressure (PEEP) levels can increase renal venous pressure and promote venous congestion, thereby reducing the glomerular filtration gradient.¹⁴⁻¹⁷

These hemodynamic effects are particularly deleterious in stiff, poorly recruitable lungs, as occurs in severe forms of SARS-CoV-2-related ARDS.

Beyond PEEP or tidal volume considered in isolation, driving pressure (ΔP) emerges as a key determinant of pulmonary stress. Studies conducted at INER demonstrated that elevated ΔP (> 14 cmH₂O) in association with reduced lung compliance is independently associated with major adverse kidney events and persistent AKI. This ventilatory pattern reflects a sustained mechanical load that promotes ventilator-induced lung injury (VILI) and greater systemic cytokine release, evidenced by urinary elevations of IL-6 and neutrophil gelatinase-associated lipocalin (NGAL).¹⁸ These findings support the notion that in patients with COVID-19-related ARDS, AKI is not only a consequence of hypoperfusion or systemic inflammation but also of the cumulative impact of ventilatory mechanics.

Diagnosis and recognition of COVID-19-associated acute kidney injury

The clinical history is fundamental for establishing the temporal trajectory of COVID-19-associated AKI. In most cohorts, AKI develops during hospitalization; however, a relevant proportion of patients present with AKI at admission, particularly those with comorbidities and reduced renal reserve.^{9,12} The diagnostic workup must be systematic and aimed at identifying a multifactorial etiology. It includes serum studies, urinalysis with urinary sediment, strict monitoring of urine output, and imaging studies. Urinalysis is particularly relevant, with frequent reports of proteinuria and hematuria, especially in hospital-acquired AKI.¹⁹ Given that serum creatinine (Cr) is a late marker, the use of urinary biomarkers has emerged as a key tool. At INER, elevated values of (TIMP-2) $\times$ (IGFBP7) and urinary NGAL were associated with the development of AKI, persistent AKI, and major adverse kidney events, even in the absence of initial functional criteria.²⁰

Treatment of COVID-19-associated acute kidney injury

Conservative treatment and initial medical management

In the early stages of AKI, management focuses on hemodynamic optimization, precise fluid balance management, individualized pharmacologic therapy, and appropriate nutritional support. In the critically ill patient,

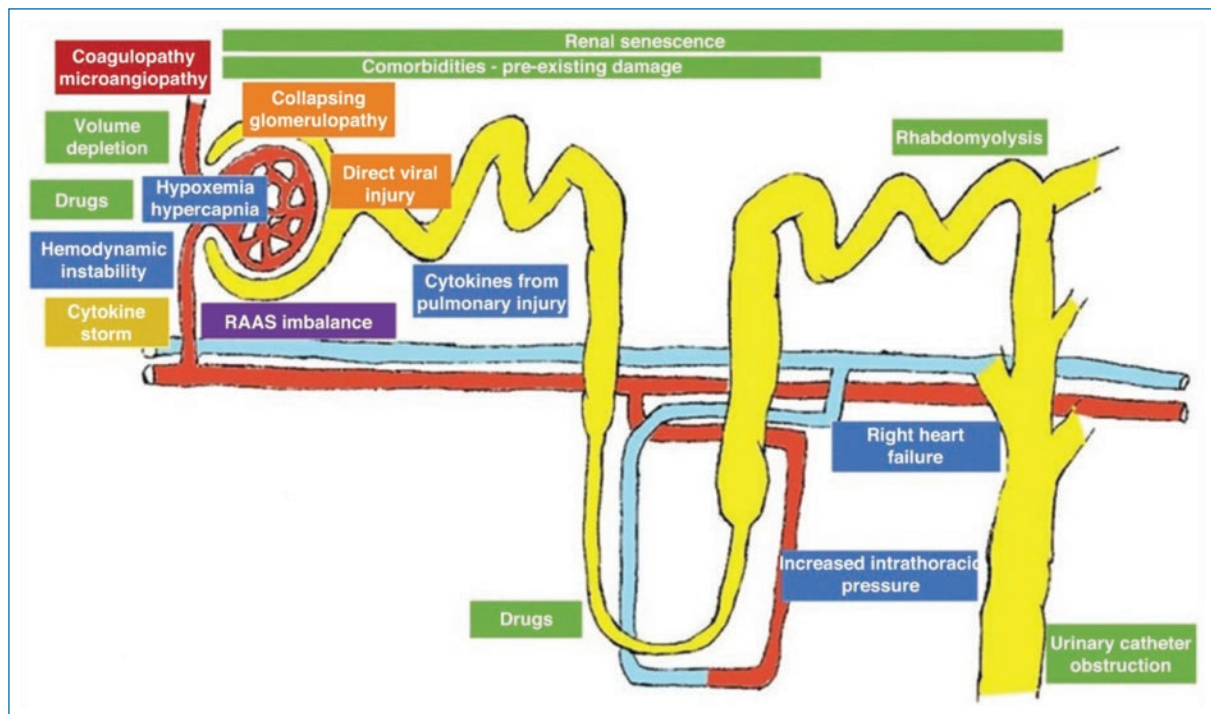


Figure 1. Pathophysiology of acute kidney injury associated with SARS-CoV-2 infection. Pathophysiological mechanisms are illustrated according to their involvement and site of injury. SARS-CoV-2: severe acute respiratory syndrome coronavirus 2.

these interventions cannot be considered in isolation, as their interaction with IMV is decisive.²¹ In this context, ΔP control must be integrated as a fundamental component of the nephroprotective strategy, given its influence on both renal perfusion and the systemic inflammatory response.¹⁸

The proposed medical management follows a progressive algorithm that begins with the systematic identification of patients with suspected AKI (Fig. 2). From the earliest phases, the algorithm emphasizes detection of classical, non-modifiable risk factors – such as T2DM, SAH, OB, and chronic kidney disease (CKD), particularly in patients already on KRT such as hemodialysis (HD) or peritoneal dialysis (PD) – as well as active malignancy and use of immunosuppressive agents. Specifically, in the context of COVID-19 or other seasonal viral infections (e.g., influenza), lack of vaccination is incorporated as a relevant risk factor.²¹

A central component of the early approach is estimation of renal functional reserve (RFR), defined as the capacity of the kidneys to increase the glomerular filtration rate (GFR) in response to a physiological demand or stress stimulus.⁶ Although formal RFR measurement requires an amino acid loading test, its

reduction may be inferred in various clinical conditions characterized by prior renal injury or by chronic utilization of this reserve, such as pregnancy, aging, renal transplantation, and states of physiological hyperfiltration (DM, SAH, OB, CKD, and nephrotic syndrome, among others). The clinical relevance of this concept lies in the fact that, even when serum Cr and GFR return to baseline values following an AKI episode, a significant loss of RFR may have occurred, thereby increasing the patient's susceptibility to future renal events.⁶

It is likewise essential to distinguish whether AKI has been acquired in the community (CA-AKI) or whether it constitutes a hospital-acquired AKI (HA-AKI), since – although therapeutic approaches may appear similar – their efficacy and timing differ substantially. In particular, CA-AKI requires early, coordinated intervention by a multidisciplinary team to modify its clinical trajectory.²²

Subsequently, classification of the AKI stage constitutes a critical step in decision-making. In the absence of new evidence to supersede them, the criteria proposed by KDIGO 2012 (Kidney Disease: Improving Global Outcomes) remain in effect.²³ According to the degree of renal deterioration, interventions must be

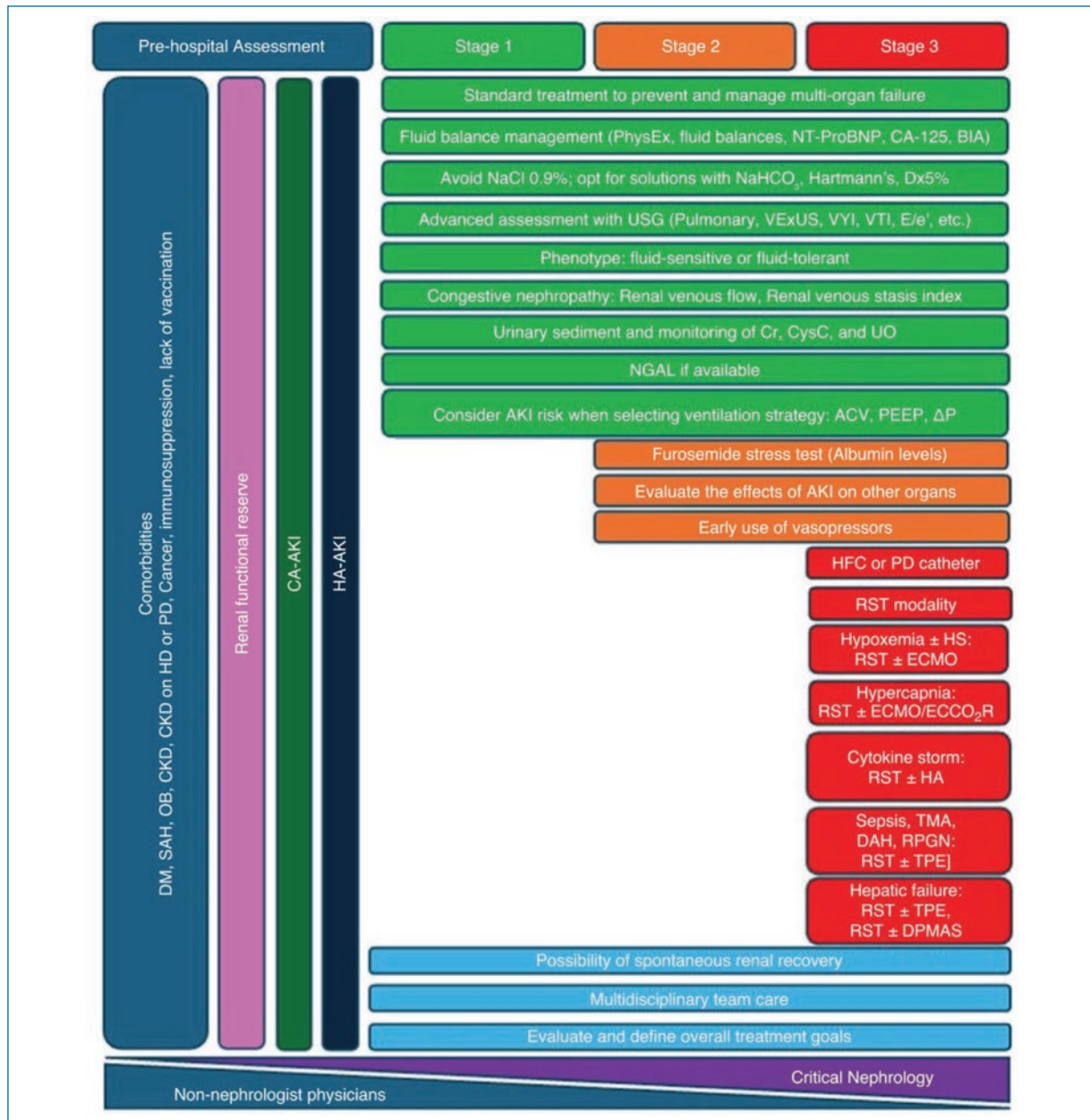


Figure 2. Stepwise strategy for the evaluation and treatment of acute kidney injury (AKI) in critically ill patients with COVID-19, organized by severity stage. The approach integrates initial assessment, comorbidities, and renal functional reserve with progressive management including conservative measures, hemodynamic optimization, and pharmacological adjustment. In advanced stages, initiation of renal support therapies (peritoneal dialysis, intermittent hemodialysis, hybrid modalities, or continuous KRT) is considered according to hemodynamic stability. Adjunctive extracorporeal therapies and advanced respiratory support are incorporated, highlighting the lung-kidney interaction and the critical nephrology approach. BIA: bioelectrical impedance analysis; HFC: high-flow catheter; Cr: creatinine mg/dL; CysC: cystatin C; DM: diabetes mellitus; PD: peritoneal dialysis; ΔP: driving pressure, calculated as plateau pressure minus PEEP; DPMAS: double plasma molecular adsorption system; Dx5%: dextrose 5%; CKD: chronic kidney disease; PhysEx: physical examination; ECCO₂R: extracorporeal CO₂ removal; ECMO: extracorporeal membrane oxygenation; RPGN: rapidly progressive glomerulonephritis; UO: urine output; HA: hemoabsorption; DAH: diffuse alveolar hemorrhage; SAH: systemic arterial hypertension; HD: hemodialysis; VTI: velocity-time integral; CA-AKI: community-acquired acute kidney injury; HA-AKI: hospital-acquired acute kidney injury; OB: obesity; PEEP: positive end-expiratory pressure; HD support: hemodynamic support; HS: hemodynamic support; TMA: thrombotic microangiopathy; NaCl 0.9%: 0.9% sodium chloride; NGAL: neutrophil gelatinase-associated lipocalin; NaHCO₃: sodium bicarbonate (INER: 133 mEq NaHCO₃ + 42 g glucose); TPE: therapeutic plasma exchange; RST: renal support therapy; USG: ultrasound/sonography; ACV: assist-control ventilation; VExUS: venous excess ultrasound score.

escalated proportionally and kept active in the event of progression, avoiding delays in the implementation of supportive measures.

Multidisciplinary approach and fluid balance management

The first phase of the algorithm requires the coordinated participation of a multidisciplinary team comprising critical care medicine, pulmonology, clinical nutrition, pharmacovigilance, specialized nursing, critical nephrology, and other subspecialties according to patient needs. This approach enables truly holistic management, adapted to the complexity of the critically ill patient.

Fluid balance management begins with a detailed physical examination and careful review of nursing records. It is important to recognize that accumulated errors in fluid balance records can range between $-3,606$ and $+2,020$ ml,²⁴ which may significantly impact therapeutic decisions. In this context, the use of biomarkers such as B-type natriuretic peptide (BNP), its aminoterminal fraction (NT-proBNP), and carbohydrate antigen 125 (CA-125)²⁵ may be useful for estimating the degree of congestion at the time of initial assessment. Another potential tool is bioelectrical impedance analysis (BIA); however, the VENUS clinical trial (VolumE maNagement Under Body Composition Monitoring in Critically Ill patientS on CRRT) did not demonstrate a higher rate of euvolemia at seven days of follow-up, and thus its application in the critically ill patient should be interpreted with caution.²⁶ Collectively, these tools should be regarded as complementary to – and not substitutes for – clinical judgment, as each has inherent limitations and lacks universal standardization in this setting. Therefore, decision-making regarding fluid management must be grounded in the dynamic integration of clinical examination, hemodynamic data, biomarkers, and available imaging tools, avoiding the isolated interpretation of any one of these elements and favoring an individualized, pathophysiologically oriented approach.

The intravenous solutions should be selected carefully and based on the clinical context. It is well documented that the use of 0.9% NaCl solutions may be associated with hyponatremia, increased mortality, and hyperchloremia – which initially impairs glomerular filtration through afferent arteriolar vasoconstriction and subsequently promotes the development of hyperchloremic metabolic acidosis.²⁷⁻²⁹ In this regard, the BICAR-ICU-1 study demonstrated that, in the subgroup of

patients with moderate-to-severe AKI, sodium bicarbonate administration was associated with lower 28-day mortality and reduced need for KRT. More recently, the BICAR-ICU-2 study did not demonstrate a reduction in all-cause mortality at 90 days, although it did report fewer days of dialysis requirement, with greater benefit in patients with $\text{pH} < 7.1$ and a lower incidence of cardiac arrest.³⁰

Advanced hemodynamic assessment and renal monitoring

Integration of advanced hemodynamic assessment is mandatory, relying on ultrasound-based tools to determine congestion status – such as lung ultrasound and the VExUS score, among others. This approach enables patients to be phenotyped as a fluid responder, defined by increased cardiac output and improved tissue perfusion following preload expansion, or as fluid tolerant, meaning a patient who can receive fluids without developing congestion or organ dysfunction. Identification of these phenotypes and their implications for renal function is key to avoiding both hypovolemia and fluid overload.³¹⁻³⁴

Renal function monitoring should be supported by classical biochemical parameters, such as serum Cr, complemented by emerging markers, such as cystatin C and NGAL, with the aim of improving diagnostic accuracy, stratifying risk, and more precisely evaluating the evolution of renal injury.²²

Lung-kidney crosstalk and ventilatory strategies

The pathophysiological interaction between the lungs and kidneys in the critically ill patient constitutes a central axis in the understanding of multiorgan injury associated with IMV. In this context, VILI has emerged as a key systemic determinant that extends beyond the pulmonary parenchyma, triggering hemodynamic, inflammatory, and neurohormonal alterations capable of compromising renal function.⁷ From this interaction emerges the concept of ventilator-induced kidney injury (VIKI), understood as the set of renal alterations derived directly or indirectly from non-protective ventilatory strategies and the biomechanical stress imposed on the cardiorespiratory system.⁷

From a biological perspective, VILI generates bio-trauma, with release of inflammatory mediators that reach the systemic circulation. In parallel, the mechanical perturbations associated with increased intrathoracic

Table 1. Advanced renal and extracorporeal support therapies

Modality	Filter type	Evidence	Limitations
HD	High-flux dialyzers (polysulfone, polyethersulfone); in some hospitals medium cut-off membranes or hemodiafiltration	Helps control volume, solutes, K ⁺ , and acidosis, which may reduce pulmonary congestion and facilitate ventilation	Higher risk of hemodynamic instability and abrupt osmotic shifts. Intermittent sessions hinder fine volume control in patients with high PEEP or vasoplegic shock
PD	No extracorporeal filter. The peritoneum serves as the membrane. Requires glucose- or icodextrin-based solutions	In COVID-19, has been used as an alternative when vascular access or CRRT resources are unavailable. Allows relatively continuous depuration and ultrafiltration with hemodynamic stability, but without clear evidence of direct benefit on oxygenation or survival in ARDS	Increases intraabdominal pressure and may reduce functional residual capacity and lung compliance, especially with large fill volumes or during prone ventilation. Less capacity to remove mid-sized molecules and to rapidly adjust fluid balance compared with CRRT
CRRT	High-flux hemofilters (AN69/AN69-ST, polysulfone, polyethersulfone, polymethylmethacrylate); some with adsorptive properties and high permeability	In ARDS, CRRT is associated with improved oxygenation, reduced fluid overload and better fluid balance, with possible favorable impact on survival	Requires continuous anticoagulation with heparin or citrate. Requires trained personnel and close monitoring
HA	Resin adsorption cartridges/columns: CytoSorb (polystyrene-divinylbenzene), Jafron HA330/380, hybrid filters such as oXiris (hemodiafiltration membrane + adsorption). Integrable into CRRT, HD, or ECMO-VV circuits	In sepsis, ARDS, and COVID-19: reduction of IL-6 and other mediators, decreased norepinephrine requirements and improved PaO ₂ /FiO ₂ . No consistent effect on mortality	Heterogeneous evidence, many observational studies and small series. Possible unintended removal of antibiotics, sedatives, and vasopressors. Its role is adjunctive and not yet standardized. High cost
TPE	Plasma separator + replacement with fresh frozen plasma or albumin	In COVID-19 and other hyperinflammatory ARDS settings, has been used for elimination of cytokines and prothrombotic mediators. Possible mortality reduction	Invasive and resource-intensive technique (blood products, albumin, personnel, and time). Risk of hypotension, hypofibrinogenemia, hypocalcemia, and plasma reactions. Respiratory benefit is indirect (inflammatory/coagulopathy modulation)
DPMAS	Non-cellular hepatic support system: 1) plasma separation filter, 2) specific adsorption columns (resins for bilirubin, bile acids, cytokines), and 3) may be combined with CRRT	Solid evidence in acute/acute-on-chronic liver failure: improves bilirubin levels and coagulopathy	Requires specific infrastructure and expertise. Evidence virtually nonexistent in ARDS without significant hepatic failure
ECMO (primarily VV-ECMO)	Membrane oxygenator (polymethylpentene) with biocompatible coatings; often combined with CRRT filters and/or HA cartridges in the same circuit	In very severe ARDS with refractory hypoxemia. In severe COVID-19: survival rates of 50-60%, requires appropriate patient selection and protective ventilation strategies	Complex, costly technique dependent on experienced centers. Risks: hemorrhage, circuit clotting, neurological complications, infections, ECMO-associated AKI. Combination with CRRT/HA further increases complexity. Indication restricted to refractory ARDS in patients with recovery potential
ECCO ₂ R	Low-flow circuits (200-400 ml/min) with low-surface membrane oxygenators (polymethylpentene) integrated into venovenous catheters, coupled to CRRT (Prismalung)	Allows "ultra-protective" ventilation (very low VT and driving pressure) in moderate-to-severe ARDS with hypercapnia, improving PaCO ₂ and pH	Risk of complications similar to ECMO (bleeding, thrombosis, hemolysis). Indication primarily for refractory hypercapnia. Benefit-risk ratio not yet clearly defined. Does not correct hypoxemia

PD: peritoneal dialysis; DPMAS: double plasma molecular adsorption system; ECCO₂R: extracorporeal CO₂ removal; VV-ECMO: venovenous extracorporeal membrane oxygenation; HA: hemoadsorption; HD: intermittent hemodialysis; IL-6: interleukin-6; AKI: acute kidney injury; PaCO₂: partial pressure of carbon dioxide in arterial blood; PaO₂/FiO₂: partial pressure of oxygen in arterial blood/inspired fraction of oxygen; PEEP: positive end-expiratory pressure; ARDS: acute respiratory distress syndrome; TPE: therapeutic plasma exchange; CRRT: continuous kidney replacement therapy.

pressure modify preload and cardiac output, directly influencing renal autoregulation.⁷ In this scenario, the roles of PEEP and ΔP take on central relevance. Although PEEP is indispensable for maintaining alveolar stability and improving oxygenation, excessive levels significantly increase intrathoracic pressure, reduce venous return, decrease cardiac output, and result in a secondary fall in renal blood flow – effects that are amplified in preload-dependent patients or in shock states. ΔP and PEEP are considered among the most reliable markers of alveolar stress and strain; elevated values have been associated with both higher mortality in ARDS and a more intense systemic inflammatory profile. Amplification of biotrauma associated with elevated ΔP can extend injury to the renal microcirculation, promoting inflammation, tubular apoptosis, and alterations in medullary perfusion. Recognition of these mechanisms reinforces the need for clearly protective ventilatory strategies aimed at minimizing ΔP , individualizing PEEP, optimizing oxygenation, and avoiding severe hypercapnia – with the ultimate goal of reducing the incidence and severity of IMV-associated AKI.³⁴

Advanced strategies and renal support therapies

In a second phase of the algorithm, implementation of the furosemide stress test – at doses of 1 or 1.5 mg/kg in patients with prior diuretic use – allows assessment of renal blood flow, tubular integrity, and diuretic responsiveness, complemented by monitoring of natriuresis.³⁵⁻³⁷

Early use of vasopressors has been shown to allow a net negative fluid accumulation of approximately –1,500 ml and to reduce mortality by up to 69%. In this context, vasopressin emerges as a promising alternative to norepinephrine, due to its effects on the efferent arteriole and its potential benefit in preserving glomerular filtration.^{37,38}

In the final phase, the algorithm establishes the indications for initiating renal support therapies (RST), which include intermittent HD, PD, hybrid modalities such as PIRRT (prolonged intermittent renal replacement therapy), continuous KRT, hemoadsorption, double plasma molecular adsorption systems (DPMAS, double plasma molecular adsorption system), and therapeutic plasma exchange. Likewise, articulation of these therapies with advanced extracorporeal modalities – such as extracorporeal membrane oxygenation (ECMO) or ECCO₂R (extracorporeal CO₂ removal) – is considered when the clinical context warrants it³⁹ (Table 1).

Collectively, this algorithm synthesizes a structured, multidisciplinary, and adaptable approach for the critically ill patient, facilitating decision-making and promoting timely, precise, and pathophysiologically grounded renal care.

Conclusions

INER's response to the COVID-19 pandemic demonstrated that the timely integration of critical nephrology – grounded in the systematic generation of clinical and pathophysiological knowledge – not only enabled management of an unprecedented public health emergency but also consolidated INER as an institution capable of producing relevant scientific evidence comparable to that of international referral centers for the benefit of the understanding and comprehensive management of the lung-kidney axis in critically ill patients.

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Conflicts of interest

The authors declare no conflicts of interest.

Ethical considerations

Protection of human and animal subjects. The authors declare that no experiments involving human subjects or animals were performed for this research.

Confidentiality, informed consent, and ethical approval. The study does not involve personal patient data and does not require ethical approval. The SAGER guidelines are not applicable.

Statement on the use of artificial intelligence. The authors declare that no generative artificial intelligence was used in the writing of this manuscript.

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