# How to Determine Fluid Management Goals during Continuous Kidney Replacement Therapy in Patients with AKI: Focus on POCUS

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## Abstract

**The utilization of kidney replacement therapies (KRT) for fluid management of patients who are critically ill has significantly increased over the last years. Clinical studies have suggested that both fluid accumulation and high fluid removal rates are associated with adverse outcomes in the critically ill population receiving KRT. Importantly, the ideal indications and/or fluid management strategies that could favorably affect these patients are unknown; however, differentiating clinical scenarios in which effective fluid removal may provide benefit to the patient by avoiding congestive organ injury, compared with other settings in which this intervention may result in harm, is direly needed in the critical care nephrology field. In this review, we describe observational data related to fluid management with KRT, and examine the role of point-of-care ultrasonography as a potential tool that could provide physiologic insights to better individualize decisions related to fluid management through KRT.**

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## Introduction

AKI is a frequent complication of critical illness, affecting up to 50% of intensive care unit (ICU) populations, with 5%–15% of patients requiring kidney replacement therapy (KRT) (1,2). Importantly, AKI-KRT is associated with a higher risk of mortality and significant burden of morbidity in survivors (1–4). KRT is commonly needed in the ICU for managing patients with AKI and concomitant electrolyte or acid-base derangements and fluid overload (FO). Continuous kidney replacement therapy (CKRT) modalities are commonly used to support patients who are hemodynamically unstable because these modalities provide better hemodynamic stability and the ability to manage FO more effectively (5–7). Nonetheless, significant practice heterogeneity has been demonstrated in relation to fluid management with KRT through different survey studies (8,9). Further, the coronavirus disease 2019 pandemic has reinforced the importance of KRT in the comprehensive management of patients who are critically ill with multiorgan failure and FO (10).

Multiple observational studies have shown a dose-response relationship between FO, mortality, and multiorgan dysfunction during AKI and critical illness (11,12). Therefore, fluid management during KRT (through net ultrafiltration rate [$UF_{NET}$]) is an important goal of extracorporeal support. Despite the observation that higher FO at the time of CKRT initiation is associated with a higher risk of 90-day major adverse kidney events, including mortality and decreased kidney recovery, there is a paucity of interventional data to guide optimal rates of fluid removal during KRT (13). Recent observational studies highlighted a potential U-shape relationship between $UF_{NET}$ and mortality, which highlights the concept of patient tolerance to fluid removal (14–16). It is also important to recognize that fluid balance targets are not always achieved, not only due to patients' inability to tolerate fluid removal but also due to logistical factors specific to KRT delivery, such as treatment interruptions or inadequate prescription.

In this review, we describe observational data related to net ultrafiltration during CKRT, and examine the role of point-of-care ultrasonography (POCUS) as a potential tool that could assist the evaluation and fluid management of critically ill patients with AKI requiring KRT.

## Effect of $UF_{NET}$ on Mortality

$UF_{NET}$ refers to the net fluid removal rate from the patient or the hourly difference between patient and CKRT machine fluid balances. It should be differentiated from the machine-set fluid removal rate. $UF_{NET}$ is a critical CKRT parameter because it refers to the actual volume of extracellular fluid being removed from the patient by the CKRT machine. Importantly,

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one should note that $UF_{NET}$ is closely linked to the overall fluid balance target of the patient, and that the same $UF_{NET}$ may have a different effect on a different patient according to the clinical context.

Murugan and colleagues (14) were among the first to comprehensively examine the relationship of $UF_{NET}$ with mortality in critically ill patients with AKI on KRT. In an observational cohort study of 1075 patients with FO of ≥5% before KRT initiation, they found that $UF_{NET}$ intensity >25 versus ≤20 ml/kg per day was associated with lower 1-year risk-adjusted mortality. In this study, the authors determined $UF_{NET}$ as the net volume of fluid ultrafiltered per day from initiation of KRT until the end of ICU stay, adjusted for patient hospital admission body weight (14). A subsequent study by the same group of investigators used data from 1434 patients enrolled in the Randomized Evaluation of Normal vs Augmented Level of Replacement Therapy (RENAL) trial (15). $UF_{NET}$ was defined as the volume of fluid removed per hour adjusted for patient body weight. They found that, when not restricting the cohort to patients with a pre-defined level of FO as the prior study, $UF_{NET}$ rates >1.75 ml/kg per hour (highest tertile) versus <1.01 ml/kg per h (lowest tertile) were associated with a lower rate of 90-day survival. One important observation in this study was that patients in the highest tertile of $UF_{NET}$ had more hypophosphatemia and cardiac arrhythmias when compared with the lower tertiles (15). A subsequent analysis evaluated these $UF_{NET}$ thresholds according to time on treatment (*i.e.*, early $UF_{NET}$ within the first 48 hours) and showed concordant results (17). One additional study addressed the indication bias inherent to $UF_{NET}$ observational data by mediation analysis to further examine the association of $UF_{NET}$ with mortality and its interaction with possible mediators, such as fluid balance, hemodynamic status, and/or electrolyte abnormalities. The investigators concluded that $UF_{NET}$ >1.75 ml/kg per hour was independently associated with increased hospital mortality, and this effect was not mediated by fluid balance, low BP, vasopressor use, hypokalemia, or hypophosphatemia (18). In another study, the investigators evaluated the heterogeneity of effect of $UF_{NET}$ in critically ill patients receiving CKRT and found that both high and low $UF_{NET}$ rates may be harmful, especially in those with edema, sepsis, and greater acuity of illness severity (19). When evaluating kidney recovery, one study found that $UF_{NET}$ >1.75 ml/kg per hour was independently associated with lower kidney recovery rates (20). Table 1 provides a summary highlighting the aforementioned studies.

One should note that, thus far, there is a dire need for interventional studies testing different $UF_{NET}$ approaches and/or comprehensive strategies for fluid management (*i.e.*, deresuscitation) in critically ill patients with AKI on CKRT. Further, standardization of terminology, implementation of logistics for dynamic monitoring of CKRT fluid management parameters, and the feasibility of these clinical trials first need to be achieved and/or determined.

## Role of POCUS

Despite the epidemiologic association between cumulative fluid balance and outcomes in the setting of AKI, it is evident that this parameter alone is insufficient to guide decisions related to mechanical fluid removal through KRT. Indeed, cumulative fluid balance can be unrepresentative of fluid status in many clinical situations in which FO was already present before ICU admission, such as congestive heart failure, or when fluid input or output cannot be reliably quantified. Therefore, clinicians must rely on the integration of multiple clinical parameters to orient fluid management, including physical examination at the bedside. Beyond careful evaluation of peripheral edema and measured hemodynamic parameters, POCUS has emerged as a potential adjunct to refine the evaluation and decision-making process of clinicians with regards to the prescription of fluid removal.

### Lung Ultrasound

Air impedes the transmission of ultrasound and renders the aerated lung impossible to image using two-dimensional ultrasound. Nevertheless, lung ultrasonography has been used to assess the presence of lung pathologies because it enables the detection of pleural and parenchymal anomalies (21). The presence of increased density from water-thickened interlobular septa in the first millimeters of lung parenchyma produces a vertical line artifact, commonly referred to as the "B-line," which arises from the pleura (as shown in Figure 1) (22). The presence of diffuse pulmonary B-lines indicates interstitial-alveolar syndrome, which may indicate the presence of cardiogenic pulmonary edema. This was previously well documented in patients with ESKD. In this population, lung congestion, as detected by the presence of B-lines, is associated with adverse outcomes (23). B-lines disappear in real time with ultrafiltration in this population, enabling this bedside technique to monitor lung decongestion (24). Lung ultrasound has been shown to perform better than auscultation (25) or chest x-ray (26) for the early detection of lung congestion. Lung ultrasound can be easily learned and rapidly performed at the bedside in a matter of minutes (27,28).

Identifying lung congestion at the bedside of critically ill patients on KRT could identify patients for which fluid removal is most likely to lead to an improvement in respiratory status. B-line artifacts decrease rapidly in the context of fluid removal during hemodialysis (24,29). Therefore, repeated assessments could be useful to determine when net fluid removal could be tapered down or stopped to avoid complications.

However, in the setting of critical illness, many other etiologies can produce an interstitial-alveolar syndrome resulting in the diffuse bilateral presence of B-line artifacts. Such etiologies include acute respiratory distress syndrome (ARDS) (30), viral pneumonia (31), and other interstitial lung diseases. Some features may enable the ultrasonographer to differentiate pulmonary edema from ARDS. Common findings in ARDS or pneumonia that are rare in cardiogenic edema include reduced pleural motion, the presence of subpleural consolidations, a patchy pattern with spared areas, and pleural line abnormalities (32,33). The identification of these features may be challenging for a novice ultrasonographer. Furthermore, ultrasonographers' systematic ability to differentiate cardiogenic pulmonary edema and ARDS is not well reported. Consequently,

**Table 1. Featured observational studies evaluating the association of $UF_{NET}$ with clinical outcomes**

| Study | Sample | Independent Variable | Outcomes | Results | Comments |
|---|---|---|---|---|---|
| Murugan *et al.*, 2018 (14) | 1075 adult patients with FO ≥5% before KRT initiation | $UF_{NET}$ | 1-year mortality | $UF_{NET}$ intensity >25 versus ≤20 ml/kg per day was associated with lower 1-year risk-adjusted mortality | $UF_{NET}$ was calculated as the net volume of fluid ultrafiltered per day from initiation of KRT until the end of ICU stay, adjusted for patient hospital admission body weight |
| Murugan *et al.*, 2019 (15) | 1434 adult patients from RENAL trial | $UF_{NET}$ | 90-day mortality | $UF_{NET}$ rates >1.75 ml/kg per (highest tertile) versus <1.01 ml/kg per hour (lowest tertile) were associated with lower survival | $UF_{NET}$ was defined as the volume of fluid removed per hour, adjusted for patient body weight |
| Naorungroj *et al.*, 2020 (17) | 347 adult patients | Early $UF_{NET}$ (first 48 h of KRT) | 28-day mortality | Early $UF_{NET}$ rates >1.75 versus <1.01ml/kg per hour were associated with increased mortality | Early $UF_{NET}$ was defined as the volume of fluid removed per hour, adjusted for patient body weight in the first 48 h |
| Naorungroj *et al.*, 2020 (18) | 347 adult patients | $UF_{NET}$ | Hospital mortality | $UF_{NET}$ >1.75 ml/kg per hour was independently associated with increased hospital mortality, and this effect was not mediated by fluid balance, low BP, vasopressor use, hypokalemia, or hypophosphatemia | Interaction evaluation of $UF_{NET}$ with possible mediators (fluid balance, hemodynamic status, key electrolytes) through mediation analysis |
| Serpa Neto *et al.*, 2020 (19) | 1434 adult patients from RENAL trial | $UF_{NET}$ evaluated in clusters of patients according to baseline characteristics | 90-day mortality | Both high and low $UF_{NET}$ rates may be harmful, especially in those with edema, sepsis, and greater acuity of illness | Two clusters of patients were identified; cardiovascular SOFA scores modulate the association of $UF_{NET}$ with mortality |
| Murugan *et al.*, 2021 (20) | 1433 adult patients from RENAL trial | $UF_{NET}$ | Kidney recovery (alive and independent of KRT) | $UF_{NET}$ rates >1.75 ml/kg per hour compared with rates 1.01–1.75 and <1.01 ml/kg per hour were associated with a longer duration of dependence on KRT | Competing risk multivariable regression models were used |

$UF_{NET}$, net ultrafiltration rate; FO, fluid overload; KRT, kidney replacement therapy; ICU, intensive care unit; RENAL, Randomized Evaluation of Normal vs Augmented Level of Replacement Therapy; SOFA, Sequential Organ Failure Assessment.

although lung ultrasound is a sensitive modality to identify interstitial-alveolar syndrome, additional information related to the clinical context of the patient is important to determine the main physiopathologic drivers and whether hydrostatic pressure is the main culprit. Nevertheless, the presence of ARDS may also be an indication to treat and prevent fluid accumulation. Although not focused on fluid removal on KRT, the Fluids and Catheters Treatment Trial (FACTT) trial showed that a conservative fluid management strategy resulting in a near-neutral cumulative fluid balance in patients with ARDS was associated with an increased number of ventilator-free days, as compared with a liberal strategy in which fluid accumulation occurred in most patients (34). Finally, preexisting interstitial lung pathologies or pleural disease may also generate artifacts akin to B-lines that may be mistaken for increased extravascular lung water.

### Inferior Vena Cava

The inferior vena cava (IVC) is readily accessible through the liver using POCUS. Its assessment has been proposed to help differentiate phenotypes of shock and predict fluid responsiveness and fluid tolerance. The IVC is a highly compliant structure that is affected by variations in intrathoracic and intra-abdominal pressure. In spontaneous breathing, inspiration decreases intrathoracic pressure, which leads to increased venous return and a transient decrease in IVC diameter. However, an elevation of right atrial pressure (RAP) leads to a plethoric IVC with an absence of respiratory variations (Figure 2). During positive pressure ventilation, this relationship is reversed because the positive pressure during ventilation tends to increase venous pressure, resulting in distention and, therefore, an increase in diameter, instead of a collapse. Assessments performed before and after intubation or changes in positive end expiratory pressure may reveal the effect of mechanical ventilation on the appearance of the IVC.

RAP can be roughly estimated by measuring the maximal and minimal diameters of the IVC in the longitudinal view, as proposed by the American Society of Echocardiography guidelines (presented in Table 2) (35). This classification

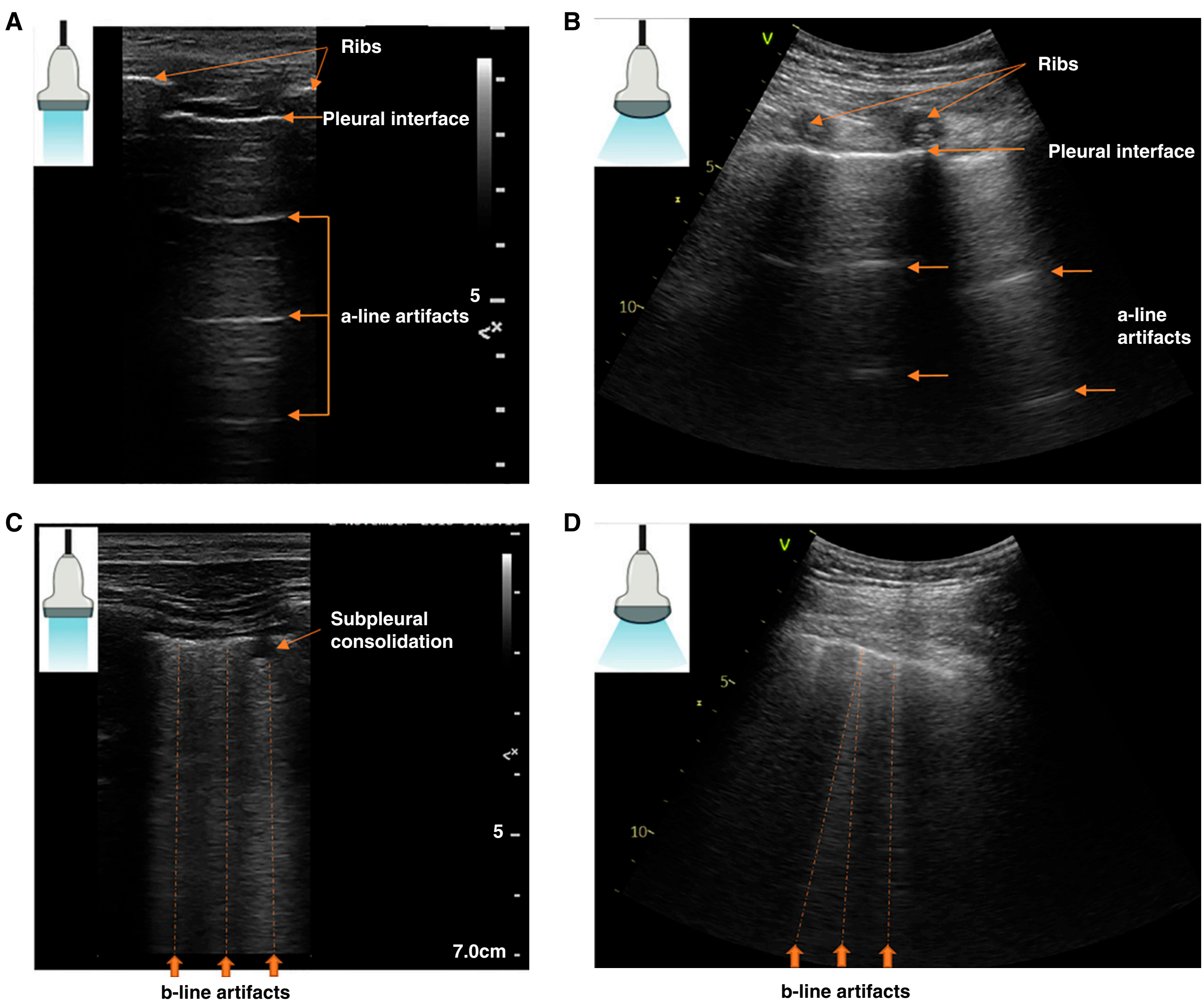


**Figure 1. | Lung ultrasound using a (A) linear and (B) curvilinear probe.** The normal appearance included the rib shadow, the pleural interface with the pleural sliding motion, and horizontal A-line artifacts. (C and D) The presence of interstitial-alveolar syndrome is associated with the appearance of vertical B-line artifacts that arise from the pleura and move with respiration.

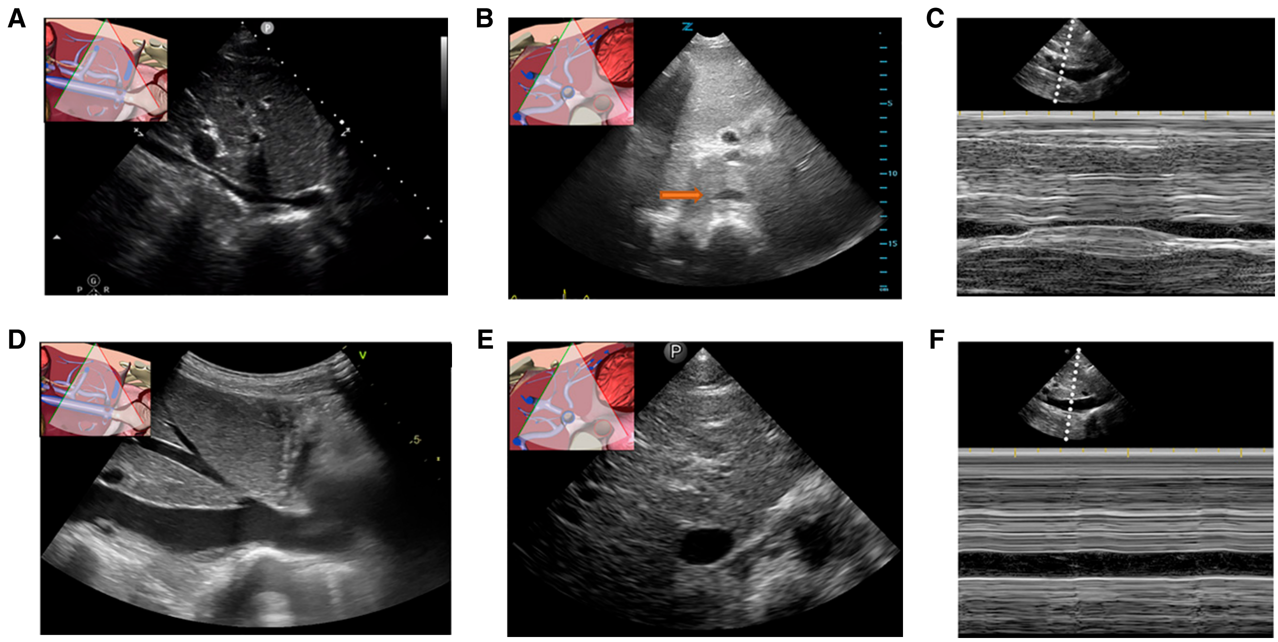


**Figure 2. | (A, B, and C) Inferior vena cava (IVC) assessment in the context of a normal/low (0–5 mm Hg) right atrial pressure (RAP) compared with a high RAP (>10 mm Hg).** In the context of a normal/low RAP, the IVC will typically have (A) a maximal diameter inferior to 2.1 cm, (B) an oval appearance in transverse view, and (C) respiratory variations >50%. In the setting of a high RAP, (D) the IVC will be distended, (E) with a round appearance, and (F) an absence of respiratory variations. Anatomic representations obtained using the Vimedix simulator (CAE Healthcare).

offers a coarse estimation with a broad range of RAP values for each category in patients who are nonmechanically ventilated. An IVC assessment suggesting a normal/low RAP may still be present despite increased total body water content if a redistribution phenomenon is present, such as third spacing, vasoplegia, and vascular leak syndrome. Consequently, fluid removal may still be warranted. However, an IVC assessment suggesting a normal/low RAP might be useful to identify patients unlikely to have venous hypertension who may benefit from a slower rate of fluid removal to avoid the occurrence of intradialytic hypotension (36).

Rather than estimating a static RAP, a collapsibility index (CI) has been proposed to predict fluid responsiveness (Table 2). This is measured 2–4 cm from the cavoatrial junction and is calculated as: CI=(IVC maximum–IVC minimum)/IVC maximum, with maximum and minimum values measured through the respiratory cycle. Studies have various thresholds for predicting fluid responsiveness and range from a CI of 12% to 42% (37). Overall, the CI has moderate predictive utility of fluid responsiveness in patients who are mechanically ventilated, but only fair predictive utility (poor sensitivity) in patients with spontaneous breathing, in part due to irregular or large swings in intrathoracic pressure (38).

There are several limitations to consider when using this technique. Although a plethoric IVC is suggestive of a high RAP, it is unlikely that this parameter alone will be sufficient to differentiate between moderate or severe elevation of venous pressures. Whereas moderate elevations of RAP are ubiquitous in patients who are critically ill due to the use of positive pressure ventilation, severe elevations of RAP may mediate congestive organ injury and might, therefore, represent an urgent indication for decongestive treatment with diuretics and/or KRT. This level of nuance is likely necessary to identify patients who are most likely to benefit from directed fluid removal.

Although IVC ultrasound is generally presented as an easy technique, there are several technical factors to consider. First, the IVC is an oval-shaped cylinder, and measuring it off axis can easily under- or overestimate its diameter. Experienced ultrasonographers often suggest also obtaining a transverse view to assess the shape of the IVC to avoid these issues. Second, the movement of the diaphragm can extend into the line of measurement or provide a false impression of collapse near the junction with the right atrium. Hence, respiratory variations should be

**Table 2. Estimation of right atrial pressure using echocardiography**

| Diameter of the Inferior Vena Cava, cm | Percent Collapsibility, % collapse | Estimated RAP, mm Hg (range) |
|---|---|---|
| ≤2.1 | >50 | 3 (0–5) |
| ≤2.1 | <50 | 8 (5–10) |
| >2.1 | >50 | |
| >2.1 | <50 | 15 (10–20) |

Estimation of RAP using echocardiography as suggested by the American Society of Echocardiography (35). RAP, right arterial pressure.

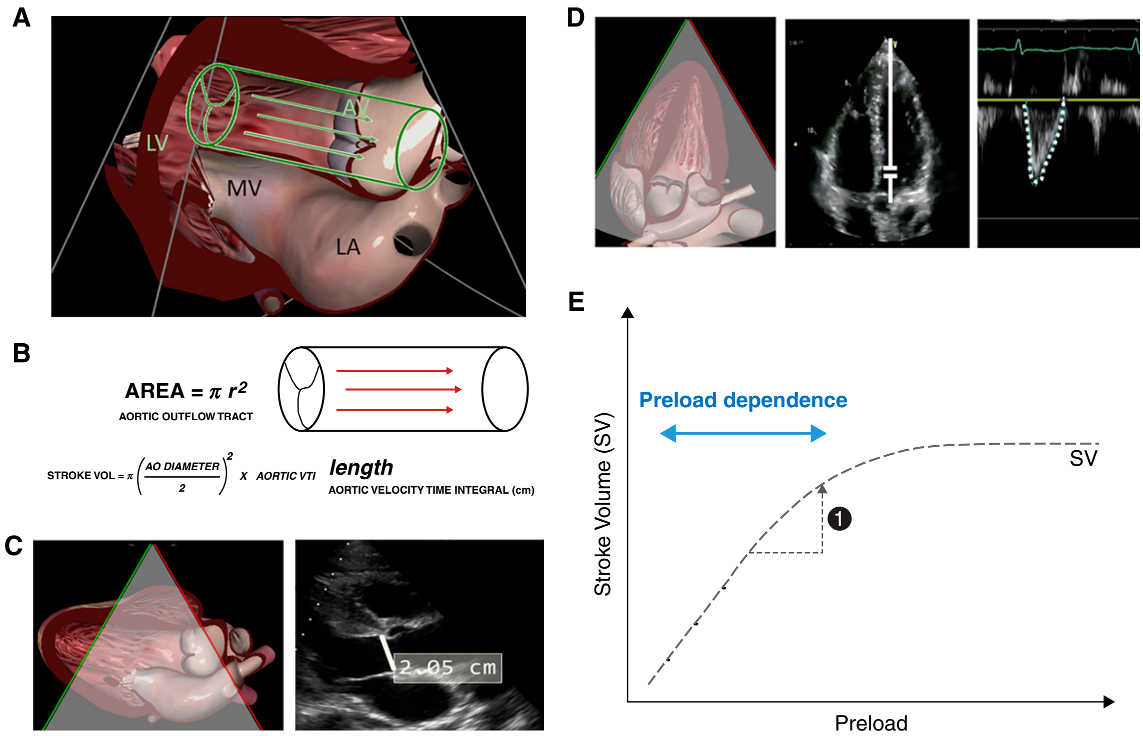


**Figure 3. | Stroke volume assessment using left ventricular outflow tract (LVOT) Doppler ultrasound.** (A) Three-dimensional representation of the left ventricular outflow tract. (B) Schematic representation of the measurements to estimate the stroke volume (SV) as a column of blood as it exits the left ventricle (LV) through the aortic valve (AV). (C) Measurement of the LVOT diameter at the level of the AV through a parasternal long-axis view. (D) Pulse-wave Doppler of the LVOT obtained using an apical five-chamber view, resulting in the measurement of a velocity-time integral (VTI). (E) Change over repeated assessments after a preload modifying maneuver can inform whether preload dependence is present. AO, aorta; LA, left atrium; MV, mitral valve; vol, volume. Anatomic representations obtained using the Vimedix simulator (CAE Healthcare).

assessed in the intrahepatic portion of the IVC. Furthermore, multiple physiologic factors can affect IVC diameter and lead to misinterpretation. Patient positioning, respiratory status, and effort can modify the degree of collapsibility. Special consideration should be given to any factors affecting intra-abdominal or intrathoracic pressure. These factors could modify IVC dimensions and may mislead interpretations if used as a single tool for the purpose of informing KRT fluid removal decisions. Similarly, patients with severe congestive heart failure or pulmonary hypertension may remain with a distended noncollapsible IVC because they may depend on elevated cardiac filling pressure to generate a viable cardiac output. Therefore, some patients exhibiting a plethoric IVC may still experience episodes of hypotension in response to fluid removal (39).

### Echocardiographic Assessment of Preload Dependence

An additional way to anticipate tolerance to fluid removal is by assessing preload dependence before the initiation of fluid removal (40,41). By applying a preload modifying maneuver, we can infer the position on the Frank–Starling relationship by measuring changes in left ventricular stroke volume. Multiple types of technology have been developed for this purpose; however, they are costly or invasive. Stroke volume can also be assessed noninvasively by using the aortic velocity-time integral (VTI) in conjunction with the diameter of the aortic outflow tract (as shown in Figure 3) (42). The VTI value can be compared before and after an intervention, such as the passive leg raising test, fluid bolus, or inotropic support (43). In this context, an absolute increase of 12%–15% or more is considered to indicate preload dependence. Additionally, a >12% respirophasic variation of the VTI with breathing is also considered a sign of preload responsiveness in patients who are mechanically ventilated (44). Even by experienced operators, adequate cardiac views may not be possible in up to 15% of patients who are critically ill. Alternatively, changes in stroke volume could be measured indirectly with Doppler examination of the common carotid artery (45,46).

Assessing preload dependence may be useful to predict reduced tolerance to fluid removal in critically ill patients with AKI on KRT (44,47). In an exploratory study in 39 critically ill patients on intermittent KRT, Monnet *et al.* (48) showed that the change in cardiac output induced by passive leg raise and measured by invasive pulse contour analysis predicted KRT-related hypotension. However, larger studies are needed to validate these findings.

Similar to when echocardiography is used to assess fluid responsiveness, these methods may produce misleading results in some particular contexts. The risk of intolerance to fluid removal may be underestimated in patients with right ventricular failure, increased intra-abdominal pressure, and cardiac arrhythmias, whereas the technique may overestimate the risk in the setting of reduced lung compliance, increased respiratory rate, or open chest (49).

### Venous Doppler Ultrasound

By assessing blood velocity during the cardiac cycle in the systemic venous circulation, Doppler ultrasound enables the operator to appreciate the pattern of venous return during the cardiac cycle and determine whether RAP variations are transmitted backward through a noncompliant venous circulation.

In the individual with normal RAP, venous return predominates in systole, when the right atrium dilates and the tricuspid annulus moves downward during right ventricular contraction. When RAP is high, the already dilated right atrium cannot accommodate as well for venous return and this may be aggravated by systolic right ventricular dysfunction, which limits tricuspid valve systolic excursion. In these circumstances, venous return occurs predominantly in diastole, when the tricuspid valve opens. With very high RAP, and particularly when significant tricuspid regurgitation is present, venous return during systole is absent and retrograde flow (away from the heart) is observed.

To assess this using POCUS, the hepatic veins represent a window of this physiologic principle. The identification of a dominant diastolic component can reliably identify elevated RAP (50–52), whereas a retrograde systolic component is suggestive of, but not synonymous with, hemodynamically significant tricuspid regurgitation (53,54). Although the reproducibility of the assessment has been reported to be excellent (55), the use of concurrent electrocardiogram tracing to ensure the proper identification of the systolic and diastolic phases remains critical for accurate interpretation.

In the normal individual, the pattern observed in the hepatic veins is attenuated, or blunted, progressively in the venous circulation as we move upstream away from the heart. This is due to the high compliance of the venous system, which impairs the transmission of rapid pressure variations observed in the right atrium during the cardiac cycle. Venous flow in the splanchnic circulation and within distal organs, such as the kidney, is, therefore, usually devoid of important cardiophasic velocity variations (pulsatility), resulting in a continuous waveform on pulse-wave Doppler. The distension of the venous circulation in pathologic states of high venous pressure renders it noncompliant, resulting in the distal transmission of cardiophasic pressure variations. This results in a pulsatile pattern that can be observed at multiple sites, including in the main portal vein of the liver and interlobar veins of the kidney, using pulse-wave Doppler.

Doppler assessment of the portal vein in a normal individual will reveal minimal variations of velocities during the cardiac cycle. In the patient with venous systemic hypertension, the portal vein Doppler pattern becomes pulsatile,

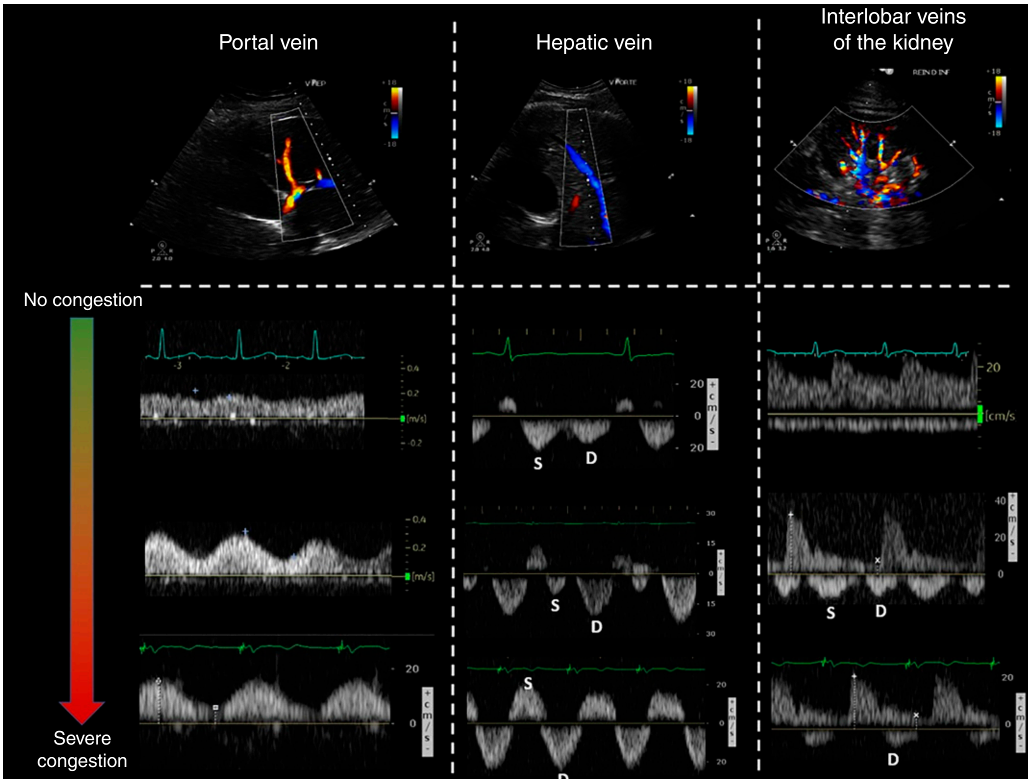


**Figure 4.** | **Venous Doppler patterns with worsening venous congestion.** Portal vein Doppler exhibits increased pulsatility as venous pressure increases. In the hepatic vein, the systolic (S) component of venous return decrease and disappear or become retrograde with severe elevation in right atrial pressure. In the interlobar veins of the kidney, interruptions in the venous Doppler signal become prolonged as the venous systolic component disappear. D, diastolic.

with minimal velocity in systole and maximal velocity in late diastole. A pulsatility index ([maximum velocity–minimum velocity]/maximum velocity) of >0.5 is considered abnormal (56,57). Portal vein pulsatility has been described in the setting of heart failure, where it correlates with disease severity (57–60) and outcomes (61), and in the settings of cardiac surgery (62,63) and critical illness (64), where it was also associated with adverse outcomes, including AKI. Most interestingly, some reports indicated that the portal pulsatility index correlates better with perfusion pressure (mean arterial pressure–central venous pressure) than with central venous pressure itself (63). As such, it may be a better marker of the overall hemodynamic effect of venous hypertension.

The Doppler assessment of interlobar veins of the kidney may further inform about the pattern of venous return and the presence of abnormal venous compliance. Contrary to the normal individual, for which intrarenal venous velocities are continuous or with a brief interruption during atrial contraction only, the Doppler pattern becomes interrupted with systolic and diastolic phases in individuals with reduced systemic venous compliance. This pattern progresses to severe alteration, characterized by prolonged interruption, with the venous signal typically present only during diastole, which testifies to the altered pattern of systemic venous return as previously described for the hepatic veins. As the alteration of intrarenal venous Doppler progresses, a detectable venous signal is seen for a shorter period of time in relation to the duration of the cardiac cycle. The intrarenal Doppler pattern has been shown to be highly predictive of death or rehospitalization in patients with congestive heart failure (65), and is also associated with AKI after cardiac surgery (63). Nonetheless, its utility has not been evaluated in critically ill patients on KRT.

The typical continuum of venous Doppler waveforms is presented in Figure 4. Confounding factors related to the site of assessment might be present when performing venous Doppler (66–69). For this reason, assessing venous Doppler at multiple sites may be beneficial because verifying that the information is consistent across multiple sites may mitigate the effect of potential confounders. The Venous Excess UltraSound grading system is an attempt at proposing the integration of venous Doppler ultrasound assessment at multiple sites (70). Using data from a previously performed cohort study in patients who underwent cardiac surgery, it was observed that the presence of at least two or three severe Doppler anomalies on the hepatic, portal, and intrarenal Doppler assessment in conjunction with a dilated (≥2 cm) IVC at ICU admission is very specific (96%) for the subsequent development of AKI presumed to be of congestive etiology.

## Integrating POCUS to Support Decisions on Mechanical Fluid Removal

The clinician prescribing mechanical fluid removal through KRT must balance the potential risk of congestive organ injury from persistent fluid accumulation with the probability of hemodynamic instability due to a high $UF_{NET}$. Due to the complexity and dynamic nature of critical illness, it is unlikely that either a "one-size-fits-all" fluid

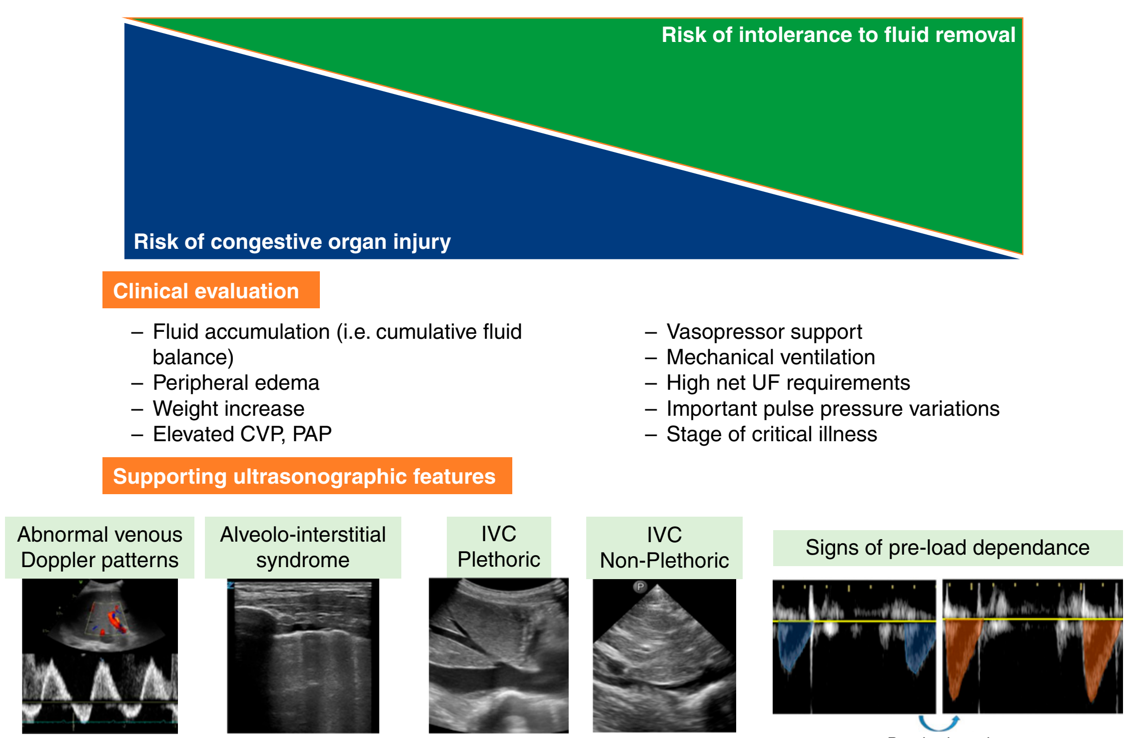


**Figure 5. | Evaluating the risk and benefit of fluid removal involves a multimodal assessment combining multiple sources of clinical information that can be supported by the identification of point-of-care ultrasound features suggestive of organ congestion or preload dependence.** CVP, central venous pressure; PAP, pulmonary artery pressure; UF, ultrafiltration.

management strategy or that an approach involving only a single clinical parameter will be optimal.

We propose that a multimodal evaluation integrating ultrasound features to support clinical decision making may represent one of the components of an optimal fluid management strategy on KRT (Figure 5). Two frequent clinical dilemma could be improved by the use of POCUS.

First, ultrasound features of congestion on lung ultrasound and venous Doppler may identify a subgroup of patients for which prompt decongestion should be prioritized. This may be particularly helpful when other sources of clinical information, such as cumulative fluid balance, are likely erroneous. This can occur in the presence of preexisting fluid accumulation before ICU admission (*i.e.*, known heart failure), or when nonquantified fluid gains or losses limit the value of fluid balance estimation. A systematic documentation of features compatible with organ congestion may lead to the identification of patients for which fluid removal should be initiated or increased to prevent congestive organ injury. Repeated assessments may also yield valuable information that could be used to titrate fluid removal.

Second, tolerance to fluid removal is known to be highly variable and dynamic among patients who are critically ill. Intradialytic hypotension might, in part, mediate adverse outcomes seen with high $UF_{NET}$ in observational studies, but it is unlikely that a single maximal high $UF_{NET}$ threshold could be generalized to all patients with critical illness. Tolerance to fluid removal might be better predicted using dynamic markers rather than static parameters. A significant drawback is the need for cardiac output monitoring, but left ventricular outflow tract VTI assessment might provide a useful adjunct in this setting to predict tolerance to fluid removal during KRT, without requiring intensification of patient monitoring or additional costs.

The value of POCUS as a tool to support decision making related to fluid removal prescription in the context of KRT is largely unexplored at the present time. Although the available and evolving technology makes this avenue promising, it is still unknown in what proportion of patients the addition of POCUS to other sources of clinical information will meaningfully change fluid management. With the recent increase in the adoption of POCUS training in critical care medicine and nephrology, we expect that future efforts will gradually fill the knowledge gaps in this field.

## Summary Statement

On an epidemiologic basis, both fluid accumulation and high $UF_{NET}$ are associated with adverse outcomes in critically ill patients with AKI receiving KRT. The ideal fluid management strategy may involve distinguishing clinical situations in which effective fluid removal may benefit the patient by avoiding congestive organ injury, compared with other settings in which this intervention will result in harm. POCUS may provide physiologic insights to better individualize decisions related to fluid removal through KRT.

### Disclosures

W. Beaubien-Souligny reports receiving honoraria from Baxter, and being employed by Centre Hospitalier de l'Université de Montréal (CHUM). J.A. Neyra reports serving as guest editor and on the editorial board of *Advances in Chronic Kidney Disease*, as section editor of *Clinical Nephrology*, as guest editor of *Critical Care Nephrology*, and on the editorial board of *Kidney360*; having consultancy agreements with Baxter Healthcare Inc., Biomedical Insights, and Leadiant Biosciences; and being employed by the University of Alabama at Birmingham. The remaining author has nothing to disclose.

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### Author Contributions

W. Beaubien-Souligny and J.A. Neyra reviewed and edited the manuscript; W. Beaubien-Souligny, J.A. Neyra, and T. Trott wrote the original draft and were responsible for data curation; and J.A. Neyra conceptualized the study and provided supervision.

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