Journal of Cardiothoracic and Vascular Anesthesia 37 (2023) 1579−1590

Contents lists available at ScienceDirect

Journal of Cardiothoracic and Vascular Anesthesia

journal homepage: www.jcvaonline.com

Special Article

Adult Cardiac Surgery-Associated Acute Kidney Injury: Joint Consensus Report

Jessica K. Brown, MD[*,1], Andrew D. Shaw, MB[†], Monty G. Mythen, MD[‡], Lou Guzzi, MD[§], V. Seenu Reddy, MD[||], Cheryl Crisafi, MSN, RN, CNL[**], Daniel T. Engelman, MD[**], on behalf of the PeriOperative Quality Initiative and the Enhanced Recovery After Surgery Cardiac Workgroup[††]

[*] *Department of Anesthesiology and Perioperative Medicine, the University of Texas, MD Anderson Cancer Center, Houston, TX*

[†] *Department of Intensive Care and Resuscitation, Cleveland Clinic, Cleveland, Ohio*

[‡] *University College London National Institute of Health Research Biomedical Research Center, London, United Kingdom*

[§] *Department of Critical Care Medicine, AdventHealth Medical Group, Orlando, Florida*

[||] *TriStar Centennial Medical Center, Nashville, TN*

[**] *Heart & Vascular Program, Baystate Health, University of Massachusetts Medical School−Baystate, Springfield, MA*

Objectives: Acute kidney injury (AKI) is increasingly recognized as a source of poor patient outcomes after cardiac surgery. The purpose of the present report is to provide perioperative teams with expert recommendations specific to cardiac surgery−associated AKI (CSA-AKI).

Methods: This report and consensus recommendations were developed during a joint, in-person, multidisciplinary conference with the Perioperative Quality Initiative and the Enhanced Recovery After Surgery Cardiac Society. Multinational practitioners with diverse expertise in all aspects of cardiac surgical perioperative care, including clinical backgrounds in anesthesiology, surgery and nursing, met from October 20 to 22, 2021, in Sacramento, California, and used a modified Delphi process and a comprehensive review of evidence to formulate recommendations. The quality of evidence and strength of each recommendation were established using the Grading of Recommendations Assessment, Development, and Evaluation methodology. A majority vote endorsed recommendations.

Results: Based on available evidence and group consensus, a total of 13 recommendations were formulated (4 for the preoperative phase, 4 for the intraoperative phase, and 5 for the postoperative phase), and are reported here.

All named authors contributed equally to this work.

[1] *Address correspondence to* Jessica K. Brown, MD, MD Anderson Cancer Center, 1515 Holcombe Boulevard, Unit 409, Houston, TX 77030.

E-mail address: jkbrown@mdanderson.org (J.K. Brown).

[††] Members of the Perioperative Quality Initiative (POQI) 8/Enhanced Recovery After Surgery (ERAS) Cardiac workgroup: Andrew D. Shaw, MB, Department of Intensive Care and Resuscitation, Cleveland Clinic, Cleveland, Ohio; Daniel T. Engelman, MD, Baystate Health, University of Massachusetts Medical School−Baystate, Springfield, Massachusetts; TJ Gan, MD, the University of Texas, MD Anderson Cancer Center, Houston Texas; Timothy Miller, MB, Duke University, Durham, North Carolina; Monty G. Mythen, MD, University College London, London, United Kingdom; Nicole R. Guinn, MD, Duke University, Durham, North Carolina; Solomon Aronson, MD, Duke University, Durham, North Carolina; Jonathon Schwartz, MD, Stony Brook University, Stony Brook, New York; Rakesh C. Arora, MD, PhD, Max Rady College of Medicine, University of Manitoba, Winnipeg, Manitoba, Canada; Vicki Morton-Bailey, DNP, AGNP-BC, Charlotte, North Carolina; C., Scott Brudney, MB, University of Manitoba, Winnipeg, Manitoba, Canada; Elliott Bennett-Guerrero, MD, Stony Brook University, Stony Brook, New York; V. Seenu Reddy, MD, Nashville, Tennessee; Lou Guzzi, MD, Department of Critical Care Medicine, Advent Health Medical Group, Orlando, Florida; Jessica Brown, MD, the University of Texas, MD Anderson Cancer Center, Houston, Texas; Cheryl Crisafi, MSN, RN, CNL, Baystate Medical Center, Springfield, Massachusetts; Jessica Brodt, MD, Stanford University School of Medicine, Stanford, California; Michael C. Grant, MD, Johns Hopkins University School of Medicine, Baltimore, Maryland; Michael Manning, MD, PhD, Duke University, Durham, North Carolina; Desiree Chappell, CRNA, Anesthesia Consultants Enterprises, Louisville, Kentucky.

https://doi.org/10.1053/j.jvca.2023.05.032

Conclusions: Because there are no reliable or effective treatment options for CSA-AKI, evidence-based practices that highlight prevention and early detection are paramount. Cardiac surgery−associated AKI incidence may be mitigated and postsurgical outcomes improved by focusing additional attention on presurgical kidney health status; implementing a specific cardiopulmonary bypass bundle; using strategies to maintain intravascular euvolemia; leveraging advanced tools such as the electronic medical record, point-of-care ultrasound, and biomarker testing; and using patient-specific, goal-directed therapy to prioritize oxygen delivery and end-organ perfusion over static physiologic metrics.

Key Words: expert consensus; perioperative care; acute kidney injury; cardiac surgery; goal-directed therapy

ACUTE KIDNEY INJURY (AKI) is among the most serious perioperative complications for patients undergoing cardiac surgery.[1-4] The complex nature of the cases, the hemodynamic perturbations encountered during cardiac surgery, and underlying patient comorbidities make these patients more susceptible to kidney injury than other surgical patients. Cardiac surgery−associated AKI (CSA-AKI) is thought to complicate as many as one third of procedures, leading to numerous undesirable clinical sequelae and doubling total hospitalization costs.[5,6] Its clinical consequences are multifold, and encompass increased in-hospital mortality, poor long-term survival, chronic kidney disease (CKD) development, and permanent loss of renal function requiring ongoing renal replacement therapy.[3,7-12]

Cardiac surgery−associated AKI is one of the strongest risk factors for death after cardiac surgery. Most CSA-AKI cases, approximately 90%, are considered mild; however, even mild AKI is associated with worse outcomes compared with patients who do not develop AKI, and is an independent predictor of 30-day postoperative mortality.[4,11] Mortality rates rise with increasing severity of AKI, and may be as high as 50% in the small portion (2%-5%) of cardiac surgery patients who develop severe CSA-AKI that requires renal replacement therapy.[13,14] Economically, CSA-AKI significantly burdens healthcare resources and expenditures.[1,3,12,15-19]

Treatment options are ineffective at circumventing kidney injury, and have made prevention and early identification of AKI the primary focus.[20] Furthermore, there is a growing body of clinical evidence that the application of bundled preoperative interventions and perioperative mitigation strategies can ameliorate the incidence of CSA-AKI.[21-23] In those patients who develop CSA-AKI, interventions promoting the early recovery of renal function have been associated with improved long-term survival.[24]

Methods

The PeriOperative Quality Initiative (POQI) and the Enhanced Recovery After Surgery (ERAS) Cardiac Society are both nonprofit organizations that assemble panels of international experts to collaborate on the development of consensus-based recommendations covering various aspects of perioperative medicine.[25,26] Details outlining the POQI consensus-building process have been previously published and are summarized in Supplementary Table S1.[26] The POQI methodology combines aspects of evidence appraisal with expert opinion, and is, therefore, different from a systematic review or Cochrane analysis; this combined approach helps clinicians make important decisions about patient care while waiting for the completion of large, prospective, randomized, controlled trials.[26] The review process is a nonsystematic, scoping review of the literature. The goals are several-fold: (1) to generate consensus statements that acknowledge the limitations of the literature; (2) to produce practical recommendations for patient care that are based on current evidence and are agreed on by the panel of experts attending the conference; and (3) to encourage future research in which data are lacking.

The eighth meeting of POQI convened with the ERAS Cardiac Society from October 20 to 22, 2021, in Sacramento, California, with an in-person assembly of multinational practitioners with diverse expertise in all aspects of cardiac surgical perioperative care, including clinical backgrounds in anesthesiology, surgery, and nursing, to address perioperative practices in cardiac surgery. This report is the result of a subgroup with expertise in AKI in the setting of cardiac surgery.

Before the conference, the POQI Board and conference directors assembled AKI workgroup members, led by 2 cochairs. The group performed individual electronic literature searches to stimulate discussion on the current knowledge gaps and areas of controversy or lack of consensus in the diagnosis, management, and treatment of AKI after cardiac surgery. An electronic literature search was conducted by searching Pubmed, Medline, Embase, and Cochrane CENTRAL with the terms “cardiac surgical procedures,” “cardiac surgery,” “acute kidney injury,” and “acute renal failure” and excluding case reports, editorials, and commentaries, as well as articles not published in the English language and those published before 2000. After an iterative review of titles and abstracts, the subgroup members identified manuscripts judged relevant for full-text review and agreed-upon reference applicability. Relevant articles were consolidated into a central repository. Topics chosen by the workgroup for focus included a concentrated investigation of biomarkers, goal-directed therapy (GDT)/volume status, point-of-care ultrasound, and machine learning and artificial intelligence (AI).[26]

During the conference, a 3-day interactive meeting agenda was divided into plenary sessions, during which questions, statements, and recommendations were presented, debated, and refined in a systematic progression of repeated rounds of voting, intertwined with smaller breakout sessions in which each workgroup addressed issues arising from the plenary sessions. Using this modified Delphi process, the group formulated a set of recommendations based on the current CSA-AKI diagnostic, management, and treatment evidence, then grouped them according to the perioperative phase of implementation. Content refinement continued until an agreement was achieved, resulting in a formal consensus document. The strength and level of evidence of each recommendation were established using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) framework,[27-29] an approach widely adopted by >100 organizations, including the World College of Physicians and the American College of Physicians. Recommendations evaluated using the GRADE system receive 2 scores: one that rates the *quality of evidence* (graded A through D) and one indicating the *strength of the recommendation* ("strong" or "weak"). When evidence is lacking, recommendations may be designated as ungraded and, therefore, identify areas for further research. The strength of the recommendation is not always reflective of the quality of evidence, but rather is determined by the balance between 2 interventions: one with desirable effects and the other with undesirable effects. "Strong" recommendations, therefore, represent interventions with desirable or undesirable effects that outweigh the other. However, when evidence suggests that these effects are more closely balanced, the recommendation becomes "weak." Therefore, in some instances, the level of evidence and the strength of the recommendation may be discordant.

Voting was conducted openly and included the review of each working group's statements by all conference members. Bias, influence, and partiality could not be excluded completely; however, dissenting opinions were encouraged, recognized, and accounted for. All final recommendations from the present meeting were endorsed by unanimous vote.

Results: Recommendations for the Prevention and Management of Aki After Cardiac Surgery

Preoperative Strategies (Table 1)

Recommendation I: Health systems are recommended to demonstrate a deliberate commitment to optimize kidney health and outcomes of patients at risk for, or who develop, CSA-AKI (evidence ungraded; weak recommendation)

The incidence of CSA-AKI is both alarming and a clear cause for action.[30,31] It has been shown in nonsurgical contexts that comprehensive programs such as those fostered by the Indian Health Service can decrease the incidence of end-stage renal disease in specific populations by as much as 40%.[32] Systems and individual hospitals are encouraged to adopt goals paralleling those of the Indian Health Service and the U.S. Department of Health and Human Services. These goals should be developed with the input of all stakeholders, including hospital system leadership, administrators, and individual providers, across the continuum of care. Goal setting should include provider education and awareness and the development of measurable targets for optimizing reactive response and treatment, surveillance, early detection, prevention, follow-up, and long-term outcomes.[13,33] An excellent framework for guiding such an initiative is provided in a 2021 review published by Kane-Gill.[34]

Recommendation II: Every patient is recommended to undergo a kidney health assessment before cardiac surgery, which should include an assessment of proteinuria and serum creatinine concentration (evidence ungraded; strong recommendation)

Any comprehensive, perioperative mitigation strategy requires preoperative recognition of risk factors that may contribute to the development of postoperative complications (Table 2).[20,35] Appropriate preventive renal-support strategies should be planned in advance of surgery, tailored to the patient's unique risk profile and instituted throughout the perioperative period.

The 3 most common preoperative risk scoring systems for renal complications after cardiac surgery, focusing primarily on renal replacement therapy, are those from Thakar et al. at the Cleveland Clinic,[37] the Mehta Score,[38] and the Toronto Simplified Renal Index.[39] Most cardiac surgery patients who develop AKI, however, develop mild-to-moderate disease, not requiring renal replacement therapy. Because even mild-to-moderate AKI contributes to an economic burden on the healthcare system and places emotional and financial strain on patients and their families, it is important to capture baseline risk factors in all patients by implementing a thorough preoperative assessment focusing on key questions and laboratory tests.

Table 1
Strategies for Preoperative Prevention of CSA-AKI

Consensus Statement		Strength of Recommendation	Evidence Grade
I	Health systems that demonstrate a deliberate commitment to optimize kidney health and outcomes of patients at risk for/or who develop CSA-AKI	Weak	U
II	Every patient should undergo a kidney health assessment before cardiac surgery, which should include assessment of proteinuria and serum creatinine concentration	Strong	U
III	Leveraging the electronic medical record to provide timely identification of patients who are at risk for CSA-AKI and prompt further evaluation	Weak	C
IV	Allowing the consumption of clear liquids up until 2 hours before general anesthesia to reduce the risk of dehydration	Strong	A

Abbreviations: A, strong; B, moderate; C, weak; CSA-AKI, cardiac surgery−associated acute kidney injury; U, ungraded.

Table 2
Risk Factors for Renal Hypoperfusion and CSA-AKI[20,35,36]

Phase		
Preoperative	Advanced age	Previous cardiac surgery
	Female sex	Emergency surgery
	Proteinuria	Diabetes mellitus
	Chronic kidney disease	Hypertension
	Chronic lung disease	Obesity
	Congestive heart failure	Anemia
Intraoperative	Duration of cardiopulmonary bypass	Hypothermia
		Intra-aortic balloon pump use Hemodilution
	Complex surgery	Blood transfusion
	Aortic cross-clamp time	
	Nephrotoxic products of hemolysis	
Postoperative	Low cardiac output	Hypovolemia
	Cardiogenic shock	Hypervolemia
	Atheroembolism	Hypotension
	Nephrotoxins	Sepsis
	Reoperation	

NOTE: Preoperative risk-scoring systems for renal complications after cardiac surgery adapted from Thakar CV, Arrigain S, Worley S, Yared JP, Paganini EP. A clinical score to predict acute renal failure after cardiac surgery. J Am Soc Nephrol 2005;16:162-8, Mehta RH, Grab JD, O'Brien SM, et al. Bedside tool for predicting the risk of postoperative dialysis in patients undergoing cardiac surgery. Circulation 2006;114:2208-16, and Wijeysundera DN, Karkouti K, Dupuis JY, et al. Derivation and validation of a simplified predictive index for renal replacement therapy after cardiac surgery. JAMA 2007;297:1801-9.
Abbreviations: CSA-AKI, cardiac surgery−associated acute kidney injury.

A formal kidney health assessment is recommended to be incorporated into the routine preoperative workup to help detect renal dysfunction and reduce the incidence of CSA-AKI. An algorithm for a risk-based kidney health assessment before and after noncardiac surgery has been described by the Acute Disease Quality Initiative in conjunction with POQI,[40] and following this framework is recommended while accounting for risk factors unique to cardiac surgery.

The extent of the required assessments will naturally vary between low-risk and high-risk patients, and may be limited to a simple history focusing on a previous history of AKI, cardiovascular health, and medications in conjunction with a physical examination.[40,41] A simple screening tool from the National Kidney Foundation consists of 8 simple questions that most patients can answer themselves.[42] This information can be combined with supplemental data from the patient's electronic medical record (EMR) to alert providers to elevated risk and the need for further investigation.

Preoperative proteinuria has been associated with CSA-AKI independent of the preoperative estimated glomerular filtration rate.[43,44] It is a powerful predictor of end-stage renal disease, stroke, and long-term all-cause mortality after cardiac surgery.[44,45] The inexpensive, simple, and useful dipstick assessment of proteinuria plus serum creatinine or, when a patient's risk is elevated, is recommended as a more detailed measure of current kidney function, stress, and subclinical or overt damage.[46] A positive dipstick protein score of 1+ (30 mg/dL protein), combined with increasing serum creatinine, could prompt providers to order a primary care evaluation or early nephrology consult for further workup, and to be on heightened alert for periprocedural hypotension, nephrotoxins, and perfusion deficits.[43-47]

Recommendation III: Leverage the electronic medical record to timely identify patients at risk for CSA-AKI to prompt further evaluation (grade C evidence; weak recommendation)

Despite the increased use of care bundles and checklists, risk assessment and early recognition of developing CSA-AKI remain challenging for many clinicians. This is clear from studies showing a 70%-to-80% discrepancy between the documentation or coding of AKI—a surrogate indicator of recognition—and evidence of AKI as confirmed by Kidney Disease: Improving Global Outcomes (KDIGO) criteria.[48,49]

The EMR, coupled with the use of clinical decision support tools,[50,51] other health information technology applications, and rapid progress in the field of machine learning technology and AI, has the potential to dramatically increase CSA-AKI awareness, reduce underrecognition, improve documentation, and, therefore, attenuate the severity and consequences of AKI through prevention and continuity of care.[52,53] Data within the EMR can and should be leveraged to improve recognition of CSA-AKI indicators as they develop, detect patterns and push alerts to providers to ensure timely assessment and appropriate intervention that may prevent or mitigate disease progression and improve outcomes.[54]

Clinicians need robust assessment tools that interface with the data captured within the EMR regarding medical history, clinical signs and symptoms, laboratory test results, and diagnostic biomarkers. AI can and should be further developed to note changes from baseline, predict risk, and offer protocols and checklists for addressing those indicators.[55,56]

Although it has been shown previously that formal documentation of AKI in the EMR is associated with reduced 30-day mortality, it also has been shown that electronic documentation of AKI may occur in <50% of patients.[57] Thus, the design of EMRs and AI tools must consider human-factors engineering to ensure optimal data sets and performance of various electronic tools for AKI alerts.[58]

Recommendation IV: Allow the consumption of clear liquids up to 2 hours before general anesthesia to reduce the risk of dehydration (grade A evidence; strong recommendation)

Both dehydration and fluid overload are undesirable states in patients undergoing major surgery, and are especially detrimental to kidney health. Furthermore, suboptimal fluid management resulting in dehydration during 1 phase of an episode of care can undermine the benefits of euvolemia in another phase. This is especially important in cardiac surgery, when fluid shifts are common during and after cardiopulmonary bypass (CPB). Therefore, perioperative fluid management should be individualized, goal-directed, and considered in the context of a continuum from the preoperative phase through the intraoperative and postoperative phases of care.[59]

Patients should be well-hydrated and euvolemic when they arrive in the operating room. Evidence supports the practice of allowing and even encouraging otherwise healthy patients to continue oral consumption of clear liquids until 2 hours before noncardiac surgery.[60-62] This practice has been adopted by ERAS cardiac programs with no reported evidence of increased risk of aspiration, although this topic warrants further formal study.[25,63,64] It is important to note, however, that in patients with underlying heart failure or delayed gastric emptying, preoperative fluid intake requires judicious attention.

Intraoperative Strategies (Table 3)

Recommendation V: Use of a cardiopulmonary bypass bundle in all patients to minimize CSA-AKI (grade C evidence; weak recommendation)

Consistently implementing a standardized bundle of evidence-based practices designed around a given procedure or intervention can help improve patient care and outcomes.[65,66] A cardiopulmonary bypass bundle was developed to minimize the incidence of CSA-AKI (Fig 1).

This bundle was built on the foundation of the 2017 KDIGO recommendations for noncardiac surgery patients,[23] modified to reflect subsequent evidence from the literature,[67] and the unique physiologic stresses encountered during CPB. It considers the need to actively manage factors at the cellular, hemodynamic, and systemic levels to decrease CSA-AKI and improve outcomes.

- Perform goal-directed perfusion by targeting global oxygen delivery (DO_2) >280 mL/min/m^2.[68] Additional detail is provided in recommendations VI and VIII.[68]
- Actively manage blood pressure during CPB to avoid periods of hypotension.[8,30,40]
- Avoid severe anemia, maintaining hematocrit above a prescribed threshold.[20] Consider the use of intraoperative blood salvage. If time permits, preoperative iron therapy or erythropoietin can be used.[69] Transfusion is also a potential risk factor for CSA-AKI and should be avoided if the DO_2 is not critically low.
- Optimize glycemic control by maintaining blood glucose <180 mg/dL.[8,40]
- Avoid hyperthermia.[70]
- Avoid excessive ultrafiltration. Additional detail is provided in recommendation VII.
- Individualize the continuation or discontinuation of angiotensin-converting enzyme inhibitors and angiotensin-receptor blockers in the immediate perioperative period based on the risk-benefit profile for each patient, taking into account renal and other postoperative outcomes.[71] At the current time, common practice is to withhold these medications for at least 24 hours before surgery to avoid perioperative hypotension, as the incidence of AKI is reduced when withholding these medications[30,72,73]; however, management strategies remain heavily debated.[71,74,75]
- Avoid the use of nephrotoxins (nonsteroidal antiinflammatory drugs, loop diuretics, and aminoglycoside antibiotics) whenever possible.[8,40]

Recommendation VI: Preservation of adequate intravascular volume in the setting of dynamic fluid shifts and cardiopulmonary compromise (grade B evidence; strong recommendation)

Dynamic fluid shifts are not uncommon during cardiac surgery, and are the result of inflammatory and physiologic changes and blood and fluid losses that precipitate the movement of fluid from the intravascular to the interstitial space.[76] Because renal perfusion is sensitive to changes in arterial blood flow and renal afterload, maintenance of adequate intravascular blood volume and hemodynamic stability is essential to protecting the kidneys from insult. To prevent CSA-AKI, intravascular blood volume, cardiac output, blood pressure, and oxygen flux (expressed as DO_2) must be carefully balanced to maintain complete oxygenation of organs and tissues.[77] Of these, the most difficult to measure and manage—consequent to the lack of a dependable indicator for euvolemia—is intravascular blood volume.[36]

Despite these challenges, clinicians can optimize intravascular blood volume using a multifaceted approach that considers the underlying cause of the fluid shift, the response to treatment, and the patient's clinical condition. Available intraoperative tools to assess volume status include transesophageal echocardiography, blood pressure, stroke-volume variation, and pulse-pressure variation. Preference varies across the United States[78]; according to the POQI 5 Consensus group, assessing fluid responsiveness, conceptually defined as the state of recruitable stroke volume in response to fluid

Table 3
Strategies for Intraoperative Prevention of CSA-AKI

Consensus Statement		Strength of Recommendation	Evidence Grade
V	Use of a cardiopulmonary bypass bundle in all patients to minimize CSA-AKI	Weak	C
VI	Preservation of adequate intravascular volume in the setting of dynamic fluid shifts and cardiopulmonary compromise	Strong	B
VII	No use of excessive ultrafiltration during cardiopulmonary bypass bundle	Strong	C
VIII	Use of individualized, perioperative goal-directed therapy to reduce the incidence of CSA-AKI	Strong	B

Abbreviations: A, strong; B, moderate; C, weak; CSA-AKI, cardiac surgery−associated acute kidney injury; U, ungraded.

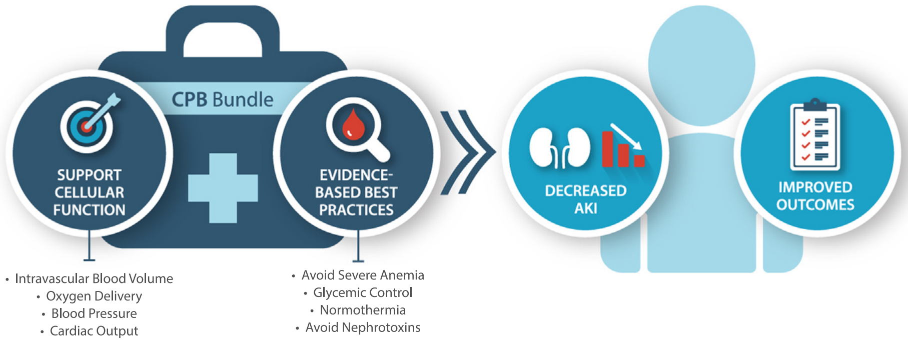

Fig 1. The cardiopulmonary bypass bundle should address multiple factors at the level of cellular function, circulation, and systemic physiology to decrease the risk of cardiac surgery-associated acute kidney injury. AKI, acute kidney injury.

administration, is one of the most effective methods to guide fluid therapy.[76]

Recommendation VII: No use of excessive ultrafiltration during cardiopulmonary bypass (grade C evidence; strong recommendation)

Because both anemia and red blood cell transfusion have been linked to AKI,[79] strategies, including conventional ultrafiltration, aimed at counteracting the effects of hemodilution during CPB, have been used. Conventional ultrafiltration minimizes CPB-related hemodilution effects with the goal of maintaining hemoglobin levels above a prescribed threshold by removing excess plasma water. However, excessive ultrafiltration during CPB leading to significant hemoconcentration at the conclusion of CPB may cause intravascular volume depletion, hypotension, and the need for vasopressors.[80,81] Paugh et al. found that increasing continuous ultrafiltration volumes was associated with an increased AKI risk in patients with glomerular filtration rate <99.6 mL/min, and, therefore, concluded that lower volumes of conventional ultrafiltration should be considered in these patients.[82] Manning et al. reached similar conclusions[83]; however, conflicting results by other studies finding no association between the volume of ultrafiltrate removed and AKI risk demonstrated the need for large randomized controlled trials to further guide recommendations.[84] As previously described, hypovolemia is deleterious to kidney function in the setting of cardiac surgery; therefore, these tools should be used only according to prespecified goals.[83,85]

Recommendation VIII: Use of individualized, perioperative goal-directed therapy to reduce the incidence of CSA-AKI (grade B evidence; strong recommendation)

Goal-directed therapy is a highly patient-specific approach to maintaining oxygen delivery and end-organ perfusion that uses specialized techniques to continuously monitor and balance physiologic variables that serve as surrogate measures of patient health at the cellular, microcirculatory, and macrocirculatory levels. These include cardiac output, stroke volume, mean arterial pressure, central venous and mixed venous oxygen saturation, and urine output.[40,59,60,77,86-88] Instead of targeting specific individual metrics for each parameter, in GDT, careful attention is paid to dynamic shifts in these parameters to help normalize and stabilize the patient's fluid balance, hemodynamic parameters, cardiac output, and oxygen delivery to the tissues.

While many clinicians use an informal approach, GDT uses standardized algorithms designed to align improvement in patient outcomes.[25] Evidence supports the use of GDT to reduce the risk of AKI after noncardiac surgery.[59,60,77,86-88] Its application is recommended in cardiac surgery as well, given the evidence to suggest the use of GDT is beneficial in cardiac surgical patients,[89,90] although it is acknowledged that this remains a matter of debate and may be most useful for patients with evidence of kidney stress or injury.[91]

Postoperative Strategies (Table 4)

Recommendation IX: Use of point-of-care ultrasound to augment the evaluation of postoperative intravascular volume status (grade C evidence; weak recommendation)

Hemodynamic assessment and management is an important strategy for CSA-AKI prevention, as low cardiac output has been linked to adverse outcomes after cardiac surgery.[92] Although ventricular performance should remain a target for optimization, venous congestion and volume overload after cardiac surgery must also be managed to mitigate their adverse effects on renal hemodynamics.[93] Furthermore, accurate assessment of fluid status is critical to the appropriate treatment of AKI.

Point-of-care ultrasound (POCUS) is a useful, simple, and validated adjunct for rapid assessment of the extent of venous congestion and adequacy of intravascular blood volume.[94,95] After cardiac surgery, a transhepatic view from the right chest is sufficient when chest tubes and dressings are in place in the subxiphoid location. The dynamic measures that may be derived from POCUS, including assessment of fluid responsiveness using arterial pulse-contour analysis and the cardiac output response to intravenous fluid bolus administration, have been shown to be a more accurate gauge of patient volume than central venous pressure, skin turgor, or fluid balance charts.[95] More recent POCUS-based assessments that also

Table 4
Strategies for Postoperative Prevention of CSA-AKI

Consensus Statement		Strength of Recommendation	Evidence Grade
IX	Use of point-of-care ultrasound to augment the evaluation of postoperative intravascular volume status	Weak	C
X	Use of a urinary biomarker-driven care bundle to enhance the evaluation of kidney health and to reduce CSA-AKI in the postoperative period	Weak	C
XI	No prophylactic or otherwise routine use of diuretic therapy.	Strong	A
XII	Development of new KDIGO stage 2 or 3 CSA-AKI, to prompt referral for long-term follow-up	Strong	A
XIII	Development of new, persistent, dialysis-dependent CSA-AKI should prompt a multidisciplinary review similar to other serious adverse hospital-acquired conditions	Strong	U

Abbreviations: A, strong; B, moderate; C, weak; CSA-AKI, cardiac surgery−associated acute kidney injury; KDIGO, Kidney Disease: Improving Global Outcomes; U, ungraded.

yield practical information about the intravascular blood volume status include dynamic measurement of the diameter of the inferior vena cava and calculation of its collapsibility and distensibility indices,[96,97] as well as indices of hepatic venous, portal venous, and intrarenal blood flow (the Venous Excess Ultrasound Score).[98,99]

Recommendation X: Use of a urinary biomarker-driven care bundle to enhance kidney health evaluation and reduce CSA-AKI in the postoperative period (grade C evidence; weak recommendation)

Once CSA-AKI has been recognized, protocols to prevent further progression must be initiated as quickly as possible. It has been shown that patients with CSA-AKI who recover renal function early are at improved odds of long-term survival.[24]

Traditional measures of kidney function, such as serum creatinine levels and urinary output, are insufficient for a timely diagnosis of CSA-AKI. Fluid administration and the effect of CPB may dilute serum creatinine, whereas decreased urine output may be a physiologic response to hypovolemia and, therefore, an unreliable indicator of CSA-AKI. To improve CSA-AKI risk prediction and early detection and to guide management decisions, the authors recommend including an evaluation of urinary biomarkers at appropriate intervals after cardiac surgical procedures.[100,101]

To date, insulin growth factor binding protein 7 (IGFBP7) and tissue inhibitor of metalloproteinases (TIMP-2), which are clinical indicators of tubular renal cell damage, renal stress, and risk for AKI, are the best studied.[21-23,100,102-104] In a single-center, randomized trial of cardiac surgery patients identified as moderate-to-high risk (urinary TIMP-2/IGFBP7 biomarker panel result of >0.3 ng/dL), implementation of a KDIGO bundle resulted in meaningful reductions in both the frequency and severity of AKI after cardiac surgery, compared to similar patients treated with standard of care.[22] A subsequent multicenter, multinational, randomized trial with a similar design showed that moderate and severe AKI occurrence was significantly lower in at-risk patients identified using the biomarker panel when a KDIGO-based intervention bundle was applied, compared with the control group.[23] A randomized trial in noncardiac surgery patients has shown similar results.[21]

A detailed example of a urinary TIMP-2/IGFBP7 biomarker-driven, staged algorithm for the prevention of postoperative CSA-AKI, which can be adapted for use in interested readers' clinical practices, can be found in Table 5. In an 847-patient evaluation of the algorithm, implementation resulted in an 89% relative reduction in the incidence of stage 2 or 3 AKI.[100]

Recommendation XI: No prophylactic or otherwise routine use of diuretic therapy (grade A evidence; strong recommendation)

Despite often being markedly fluid-positive immediately after cardiac surgery, patients may nevertheless be volume-depleted intravascularly. Diuretics should be administered selectively and with specific fluid-management goals in mind because the liberal, indiscriminate use of diuretic therapy in the early postoperative timeframe may exacerbate hypovolemia and, therefore, AKI.[8] In patients with preexisting renal dysfunction, an association exists between the use and dose of diuretics and the development of AKI. Diuretics should only be considered for managing fluid overload and not for preventing AKI.[40] The indiscriminate use of diuretics has not been consistently associated with improved renal function and cannot reverse the onset of oliguric renal failure unless it is caused by hypervolemic venous congestion.[8]

Recommendation XII: Development of new KDIGO stage 2 or 3 CSA-AKI should prompt referral for long-term follow-up (grade A evidence; strong recommendation)

It has been shown that patients who develop perioperative CSA-AKI—even if it is only transient KDIGO stage 1 or 2—have a significantly higher risk of death and are at increased risk of developing CKD and other complications.[106-109] In addition, recurrent AKI is not uncommon, affecting up to 25% of AKI survivors, and is related to the severity of the initial AKI insult and the presence of underlying comorbidities such as diabetes and CKD.[110] It is estimated that 80% of patients with moderate-to-severe AKI are unaware of their diagnosis.[111] Disease recurrence and progression can be mitigated through proper education, disease awareness, and care.[112] Evidence suggests that an AKI rehabilitation program can

Table 5
Urinary Biomarker–Driven, Staged Algorithm for Postoperative Prevention of CSA-AKI[100,105]

Nephrocheck test intended use	Intended to aid in assessing the risk of moderate-to-severe AKI in the following 12 h
Who to test	All cardiac surgery patients on postoperative day 1 at 05:30AM
Who not to test	Pre-op creatinine > 2, on dialysis, or received methylene blue
AKI Action Plan	
Urinary TIMP-2/IGFBP7 negative (<0.3) ng/dL Low risk for AKI Fast track	Remove Foley, arterial line, and central line Transfer to telemetry if all other criteria met (CI, heart rate, and respiratory function) Liberal diuretics May use ARBs/ACE-I Transfusion threshold Hgb <7.0 Check sCr daily
Urinary TIMP-2/IGFBP7 Low positive (0.3-0.7) ng/dL Mod-high risk for AKI Telemetry unit at 4 PM	Keep Foley and monitor hourly urine output until afternoon rounds Transfer to telemetry after 4 PM if all other transfer criteria are met (CI, heart rate, respiratory function) and no oliguria treatment was required Avoid nephrotoxins: NSAIDs, ARBs/ACE-I, vancomycin, gentamycin Transfusion threshold Hgb <7.0 unless oliguric If patient becomes oliguric (urine output <0.5 cc/kg/h for 3 h), activate AKRT/ nephrology consult Use lactated Ringer's boluses if CVP <8; PAD <14; hold Lasix unless CVP >20 or CHF Repeat Nephrocheck in 24 h
Urinary TIMP-2/IGFBP7 High positive (> 0.7) ng/dL AKRT	Keep Foley and monitor hourly urine output Maintain hemodynamic monitoring Avoid nephrotoxins: NSAIDs, ARBs/ACE-I, vancomycin, gentamycin Renal dosing of medications Goal-directed therapy (keep PAD >14 with LR, no diuretics unless PAD >20 or CHF) Reassess transfusion threshold CI >2.5; SBP > 130. Monitor SvO2; echo if <55% Nephrology consult Repeat Nephrocheck in 24 h

NOTE: Adapted from Engelman DT, Crisafi C, Germain M, et al. Using urinary biomarkers to reduce acute kidney injury following cardiac surgery. J Thorac Cardiovasc Surg 2020;160:1235-46.e2 and Engelman DT, Shaw AD. A turnkey order set for prevention of cardiac surgery-associated acute kidney injury. Ann Thorac Surg. 2023;115:11-15.
Abbreviations: ACE-I, ACE inhibitor; AKRT, Acute Kidney Response Team; ARB, angiotensin receptor blocker; CHF, congestive heart failure; CI, cardiac index; CSA-AKI, cardiac surgery–associated acute kidney injury; CVP, central venous pressure; Hgb, hemoglobin; IGFBP7, insulin growth factor binding protein 7; LR, Lactated Ringer's; NSAID, nonsteroidal antiinflammatory drug; PAD, pulmonary artery diastolic pressure; SBP, systolic blood pressure; sCr, serum creatinine; SvO2, venous oxygen saturation; TIMP-2, tissue inhibitor of metalloproteinases.

decrease the risk of rehospitalization or mortality at 30 days.[113]

Unfortunately, the current rate of follow-up care with a nephrologist is <50% in high-risk patients with severe AKI.[114] There are currently no standards to dictate who receives follow-up care[115]; patient risk factors and the degree of kidney injury and recovery should dictate the intensity of follow-up, although all patients, including those with KDIGO stage 1 AKI, warrant some level of outpatient assessment and monitoring.[114] Given that this represents almost one-third of cardiac surgical cases, the authors recommend prioritizing the allocation of limited specialty healthcare resources to patients with stage 2 and 3 AKI due to their higher risk and to prevent overburdening the healthcare system. Increasing duration and severity of in-hospital CSA-AKI should prompt a nephrology specialty care provider follow-up within a timeframe of weeks rather than months after hospital discharge.[116] Guidance on appropriate care should evolve as evidence-based guidelines emerge regarding which subsets of patients are most likely to benefit from follow-up care and at which intervals and duration.[116]

Recommendation XIII: Development of new, persistent, dialysis-dependent CSA-AKI should prompt a multidisciplinary review similar to other serious adverse hospital-acquired conditions (evidence ungraded; strong recommendation)

With appropriate care, attention, and adherence to evidence-based best practices, the progression of new-onset CSA-AKI to persistent, dialysis-dependent CSA-AKI can, in many cases, be mitigated and should be an extremely rare event.[33] Given that a hospital's rate of postoperative AKI requiring dialysis is a formal quality indicator within the Agency for Healthcare Research and Quality framework, as well as a component of the CMS Patient Safety and Adverse Events Composite that is included in the Agency for Healthcare Research and Quality's Hospital-Acquired Condition Reduction Program, the authors recommend that cardiac surgery teams and institutions embrace the designation of CSA-AKI as a hospital-acquired condition that is identifiable, addressable, and deserving of multidisciplinary review and continuous improvement efforts.

Discussion

There is a concerted effort to standardize evidence-based best practices to improve outcomes and prevent CSA-AKI development. This is reflected in recent publications such as the clinical practice guidelines for the prevention of CSA-AKI by the Society of Thoracic Surgeons (STS), Society of Cardiovascular Anesthesiologists (SCA), and the American Society of Extracorporeal Technology (AmSECT),[117] and the clinical practice update for the management of CSA-AKI by the SCA's Continuing Practice Improvement Acute Kidney Injury Working Group.[67]

These manuscripts offer useful information and are a welcome and valuable addition to current efforts to prevent and manage CSA-AKI. Although there is some overlap in the recommendations between these publications and the guidance offered in this manuscript, there are also some differences. For example, the STS/SCA/AmSECT guidelines focus on intraoperative strategies, whereas the present document broadens the recommendations to include other perioperative phases. The STS/SCA/AmSECT guidelines also suggest that fenoldopam may be reasonable for reducing CSA-AKI risk. Although the authors acknowledge heterogeneity in available studies, clinicians carefully should consider and weigh the risks and benefits of this off-label use.

Another recent publication, the SCA's Clinical Practice update for the management of CSA-AKI, is based on a survey of SCA members to select the 6 most renoprotective strategies.[67] The evidence-based review resulted in a limited number of high-quality, randomized trials that were insufficient to support making specific recommendations, but were in favor of only 3 strategies, including the application of a KDIGO bundle of care, use of vasopressin in vasoplegic shock, and goal-directed oxygen delivery during CPB.

It is encouraging to see a growing emphasis on the potential impact of interventions to prevent CSA-AKI and efforts being made to decrease its severity and improve patient outcomes. The value of the GRADE ranking system used here is that, in some instances when high-quality evidence is scarce, clinical consensus among experts can be valuable and useful in guiding decision-making and informing best practices. It is important, however, to continue to evaluate and update consensus recommendations as new evidence becomes available. The authors are pleased to contribute their recommendations highlighting a comprehensive approach from the beginning to end of the perioperative journey, including a preoperative kidney health assessment, intraoperative and postoperative bundles of care, and long-term follow-up.

Conclusions

Given the evidence that there are no reliable or effective treatment options to cure or reverse CSA-AKI, the authors would like to emphasize that prevention and early detection must be the primary focus. The risk of postoperative CSA-AKI may be reduced through evidence-based practices and guidance from experts in the field. It follows that hospitals, hospital systems, and the multidisciplinary teams providing perioperative care for cardiac surgery patients need to take action to reduce the incidence and impact of this life-threatening complication (Graphical Abstract).

The implementation of a thorough assessment of kidney health before undergoing cardiac surgery, the use of electronic alerts and novel tools for the early identification of kidney injury, bundles of care for best-practice management, and early and appropriate follow-up can affect outcomes positively and provide a clear argument for aggressive mitigation strategies.

Declaration of Competing Interest

None.

Acknowledgments

This study has been supported by the POQI and ERAS cardiac societies. The authors thank Jeanne McAdara, PhD, for the professional assistance with medical writing and manuscript preparation, which was funded by a generous unrestricted grant from the nonprofit ERAS cardiac society.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1053/j.jvca.2023.05.032.

References

1 Bastin AJ, Ostermann M, Slack AJ, et al. Acute kidney injury after cardiac surgery according to Risk/Injury/Failure/Loss/End-stage, Acute Kidney Injury Network, and Kidney Disease: Improving Global Outcomes classifications. J Crit Care 2013;28:389–96.
2 Englberger L, Suri RM, Li Z, et al. Clinical accuracy of RIFLE and Acute Kidney Injury Network (AKIN) criteria for acute kidney injury in patients undergoing cardiac surgery. Crit Care 2011;15:R16.
3 Hu J, Chen R, Liu S, et al. Global incidence and outcomes of adult patients with acute kidney injury after cardiac surgery: A systematic review and meta-analysis. J Cardiothorac Vasc Anesth 2016;30:82–9.
4 Machado MN, Nakazone MA, Maia LN. Prognostic value of acute kidney injury after cardiac surgery according to kidney disease: Improving global outcomes definition and staging (KDIGO) criteria. PLoS One 2014;9:e98028.
5 Kuitunen A, Vento A, Suojaranta-Ylinen R, et al. Acute renal failure after cardiac surgery: Evaluation of the RIFLE classification. Ann Thorac Surg 2006;81:542–6.
6 Vives M, Hernandez A, Parramon F, et al. Acute kidney injury after cardiac surgery: Prevalence, impact and management challenges. Int J Nephrol Renovasc Dis 2019;12:153–66.
7 Chawla LS, Bellomo R, Bihorac A, et al. Acute kidney disease and renal recovery: Consensus report of the Acute Disease Quality Initiative (ADQI) 16 Workgroup. Nat Rev Nephrol 2017;13:241–57.
8 Kellum JA, Lameire N, KDIGO, AKI Guideline Work Group. Diagnosis, evaluation, and management of acute kidney injury: A KDIGO summary (Part 1). Crit Care 2013;17:204.
9 Ostermann M. Diagnosis of acute kidney injury: Kidney Disease Improving Global Outcomes criteria and beyond. Curr Opin Crit Care 2014;20:581–7.
10 Ronco C, Kellum JA, Haase M. Subclinical AKI is still AKI. Crit Care 2012;16:313.
11 Schurle A, Koyner JL. CSA-AKI: Incidence, epidemiology, clinical outcomes, and economic impact. J Clin Med 2021;10:5746.
12 Thakar CV, Christianson A, Freyberg R, et al. Incidence and outcomes of acute kidney injury in intensive care units: A Veterans Administration study. Crit Care Med 2009;37:2552–8.
13 Fuhrman DY, Kellum JA. Epidemiology and pathophysiology of cardiac surgery-associated acute kidney injury. Curr Opin Anaesthesiol 2017;30:60–5.
14 Ishani A, Nelson D, Clothier B, et al. The magnitude of acute serum creatinine increase after cardiac surgery and the risk of chronic kidney disease, progression of kidney disease, and death. Arch Intern Med 2011;171:226–33.
15 Alshaikh HN, Katz NM, Gani F, et al. Financial impact of acute kidney injury after cardiac operations in the United States. Ann Thorac Surg 2018;105:469–75.
16 Coca SG, Yusuf B, Shlipak MG, et al. Long-term risk of mortality and other adverse outcomes after acute kidney injury: A systematic review and meta-analysis. Am J Kidney Dis 2009;53:961–73.
17 Dasta JF, Kane-Gill SL, Durtschi AJ, et al. Costs and outcomes of acute kidney injury (AKI) following cardiac surgery. Nephrol Dial Transplant 2008;23:1970–4.
18 Mangano CM, Diamondstone LS, Ramsay JG, et al. Renal dysfunction after myocardial revascularization: Risk factors, adverse outcomes, and

hospital resource utilization. The Multicenter Study of Perioperative Ischemia Research Group. Ann Intern Med 1998;128:194–203.
19 Sharfuddin AA, Molitoris BA. Pathophysiology of ischemic acute kidney injury. Nat Rev Nephrol 2011;7:189–200.
20 Nadim MK, Forni LG, Bihorac A, et al. Cardiac and vascular surgery-associated acute kidney injury: The 20th International Consensus Conference of the ADQI (Acute Disease Quality Initiative) Group. J Am Heart Assoc 2018;7:e008834.
21 Göcze I, Jauch D, Götz M, et al. Biomarker-guided intervention to prevent acute kidney injury after major surgery: The prospective randomized BigpAK study. Ann Surg 2018;267:1013–20.
22 Meersch M, Schmidt C, Hoffmeier A, et al. Prevention of cardiac surgery-associated AKI by implementing the KDIGO guidelines in high risk patients identified by biomarkers: The PrevAKI randomized controlled trial. Intensive Care Med 2017;43:1551–61.
23 Zarbock A, Küllmar M, Ostermann M, et al. Prevention of cardiac surgery-associated acute kidney injury by implementing the KDIGO guidelines in high-risk patients identified by biomarkers: The PrevAKI-multicenter randomized controlled trial. Anesth Analg 2021;133:292–302.
24 Swaminathan M, Hudson CC, Phillips-Bute BG, et al. Impact of early renal recovery on survival after cardiac surgery-associated acute kidney injury. Ann Thorac Surg 2010;89:1098–104.
25 Engelman DT, Ben Ali W, Williams JB, et al. Guidelines for perioperative care in cardiac surgery: Enhanced Recovery After Surgery Society recommendations. JAMA Surg 2019;154:755–66.
26 Miller TE, Shaw AD, Mythen MG, et al. Evidence-based perioperative medicine comes of age: The Perioperative Quality Initiative (POQI): The 1st consensus conference of the Perioperative Quality Initiative (POQI). Perioper Med (Lond) 2016;5:26.
27 Guyatt GH, Oxman AD, Kunz R, et al. Going from evidence to recommendations. BMJ 2008;336:1049–51.
28 Guyatt GH, Oxman AD, Vist GE, et al. GRADE: An emerging consensus on rating quality of evidence and strength of recommendations. BMJ 2008;336:924–6.
29 Guyatt GH, Oxman AD, Kunz R, et al. What is "quality of evidence" and why is it important to clinicians. BMJ 2008;336:995–8.
30 Ostermann M, Kunst G, Baker E, et al. Cardiac surgery associated AKI prevention strategies and medical treatment for CSA-AKI. J Clin Med 2021;10:5285.
31 Vervoort D, Meuris B, Meyns B, et al. Global cardiac surgery: Access to cardiac surgical care around the world. J Thorac Cardiovasc Surg 2020;159:987–96;e6.
32 U.S. Department of Health and Human Services. Advancing American kidney health. Updated July 10, 2019. Available at: https://aspe.hhs.gov/sites/default/files/private/pdf/262046/AdvancingAmericanKidneyHealth.pdf. Accessed April 15, 2022.
33 Li PK, Garcia-Garcia G, Lui SF, et al. Kidney health for everyone everywhere—from prevention to detection and equitable access to care. Am J Nephrol 2020;51:255–62.
34 Kane-Gill SL. Health system perspectives in acute kidney injury: Commitment to kidney health and planning implementation interventions. Curr Opin Crit Care 2021;27:593–603.
35 Chakravarthy M. Modifying risks to improve outcome in cardiac surgery: An anesthesiologist's perspective. Ann Card Anaesth 2017;20:226–33.
36 Navarro LH, Bloomstone JA, Auler JO, et al. Perioperative fluid therapy: A statement from the international Fluid Optimization Group. Perioper Med (Lond) 2015;4:3.
37 Thakar CV, Arrigain S, Worley S, et al. A clinical score to predict acute renal failure after cardiac surgery. J Am Soc Nephrol 2005;16:162–8.
38 Mehta RH, Grab JD, O'Brien SM, et al. Bedside tool for predicting the risk of postoperative dialysis in patients undergoing cardiac surgery. Circulation 2006;114:2208–16;quiz 2208.
39 Wijeysundera DN, Karkouti K, Dupuis JY, et al. Derivation and validation of a simplified predictive index for renal replacement therapy after cardiac surgery. JAMA 2007;297:1801–9.
40 Prowle JR, Forni LG, Bell M, et al. Postoperative acute kidney injury in adult non-cardiac surgery: Joint consensus report of the Acute Disease Quality Initiative and PeriOperative Quality Initiative. Nat Rev Nephrol 2021;17:605–18.
41 Kashani K, Rosner MH, Haase M, et al. Quality improvement goals for acute kidney injury. Clin J Am Soc Nephrol 2019;14:941–53.
42 National Kidney Foundation. Kidney pathways: Kidneys and your health. Available at: https://www.kidney.org/phi/form?version=health. Accessed February 17, 2023.
43 Li SY, Chuang CL, Yang WC, et al. Proteinuria predicts postcardiotomy acute kidney injury in patients with preserved glomerular filtration rate. J Thorac Cardiovasc Surg 2015;149:894–9.
44 Wu VC, Huang TM, Wu PC, et al. Preoperative proteinuria is associated with long-term progression to chronic dialysis and mortality after coronary artery bypass grafting surgery. PLoS One 2012;7:e27687.
45 Huang TM, Wu VC, Young GH, et al. Preoperative proteinuria predicts adverse renal outcomes after coronary artery bypass grafting. J Am Soc Nephrol 2011;22:156–63.
46 Wahl TS, Graham LA, Morris MS, et al. Association between preoperative proteinuria and postoperative acute kidney injury and readmission. JAMA Surg 2018;153:e182009.
47 Noble RA, Lucas BJ, Selby NM. Long-term outcomes in patients with acute kidney injury. Clin J Am Soc Nephrol 2020;15:423–9.
48 Khadzhynov D, Schmidt D, Hardt J, et al. The incidence of acute kidney injury and associated hospital mortality. Dtsch Arztebl Int 2019;116:397–404.
49 Schanz M, Schöffski O, Kimmel M, et al. Under-recognition of acute kidney injury after cardiac surgery in the ICU impedes early detection and prevention. Kidney Blood Press Res 2022;47:50–60.
50 Küllmar M, Zarbock A. Acute kidney injury and information technology. Contrib Nephrol 2018;193:81–8.
51 James MT, Hobson CE, Darmon M, et al. Applications for detection of acute kidney injury using electronic medical records and clinical information systems: Workgroup statements from the 15(th) ADQI Consensus Conference. Can J Kidney Health Dis 2016;3:9.
52 Liu KD, Goldstein SL, Vijayan A, et al. AKI!Now initiative: Recommendations for awareness, recognition, and management of AKI. Clin J Am Soc Nephrol 2020;15:1838–47.
53 Sautenet B, Caille A, Giraudeau B, et al. Deficits in information transfer between hospital-based and primary-care physicians, the case of kidney disease: A cross-sectional study. J Nephrol 2015;28:563–70.
54 Chandrasekar T, Sharma A, Tennent L, et al. A whole system approach to improving mortality associated with acute kidney injury. QJM 2017;110:657–66.
55 Tomašev N, Glorot X, Rae JW, et al. A clinically applicable approach to continuous prediction of future acute kidney injury. Nature 2019;572:116–9.
56 Mohamadlou H, Lynn-Palevsky A, Barton C, et al. Prediction of acute kidney injury with a machine learning algorithm using electronic health record data. Can J Kidney Health Dis 2018;5:2054358118776326.
57 Wilson FP, Bansal AD, Jasti SK, et al. The impact of documentation of severe acute kidney injury on mortality. Clin Nephrol 2013;80:417–25.
58 Hoste EA, Kashani K, Gibney N, et al. Impact of electronic-alerting of acute kidney injury: Workgroup statements from the 15(th) ADQI Consensus Conference. Can J Kidney Health Dis 2016;3:10.
59 Miller TE, Roche AM, Mythen M. Fluid management and goal-directed therapy as an adjunct to Enhanced Recovery After Surgery (ERAS). Can J Anaesth 2015;62:158–68.
60 Makaryus R, Miller TE, Gan TJ. Current concepts of fluid management in enhanced recovery pathways. Br J Anaesth 2018;120:376–83.
61 Zhu AC, Agarwala A, Bao X. Perioperative fluid management in the Enhanced Recovery after Surgery (ERAS) pathway. Clin Colon Rectal Surg 2019;32:114–20.
62 Joshi GP, Abdelmalak BB, Weigel WA, et al. 2023 American Society of Anesthesiologists practice guidelines for preoperative fasting: Carbohydrate-containing clear liquids with or without protein, chewing gum, and pediatric fasting duration-a modular update of the 2017 American Society of Anesthesiologists practice guidelines for preoperative fasting. Anesthesiology 2023;138:132–51.

63 Fleming IO, Garratt C, Guha R, et al. Aggregation of marginal gains in cardiac surgery: Feasibility of a perioperative care bundle for enhanced recovery in cardiac surgical patients. J Cardiothorac Vasc Anesth 2016;30:665–70.
64 Lu SY, Lai Y, Dalia AA. Implementing a cardiac enhanced recovery after surgery protocol: Nuts and bolts. J Cardiothorac Vasc Anesth 2020; 34:3104–12.
65 Kul S, Barbieri A, Milan E, et al. Effects of care pathways on the in-hospital treatment of heart failure: A systematic review. BMC Cardiovasc Disord 2012;12:81.
66 Hartjes T, Gilliam J, Thompson A, et al. Improving cardiac surgery outcomes by using an interdisciplinary clinical pathway. AORN J 2018;108:265–73.
67 Peng K, McIlroy DR, Bollen BA, et al. Society of Cardiovascular Anesthesiologists clinical practice update for management of acute kidney injury associated with cardiac surgery. Anesth Analg 2022;135:744–56.
68 Ranucci M, Johnson I, Willcox T, et al. Goal-directed perfusion to reduce acute kidney injury: A randomized trial. J Thorac Cardiovasc Surg 2018;156:1918–27;e2.
69 Guinn NR, Schwartz J, Arora RC, et al. Perioperative Quality Initiative and Enhanced Recovery After Surgery-Cardiac Society consensus statement on the management of preoperative anemia and iron deficiency in adult cardiac surgery patients. Anesth Analg 2022;135:532–44.
70 Newland RF, Tully PJ, Baker RA. Hyperthermic perfusion during cardiopulmonary bypass and postoperative temperature are independent predictors of acute kidney injury following cardiac surgery. Perfusion 2013; 28:223–31.
71 van Diepen S, Norris CM, Zheng Y, et al. Comparison of angiotensin-converting enzyme inhibitor and angiotensin receptor blocker management strategies before cardiac surgery: A pilot randomized controlled registry trial. J Am Heart Assoc 2018;7:e009917.
72 Yacoub R, Patel N, Lohr JW, et al. Acute kidney injury and death associated with renin angiotensin system blockade in cardiothoracic surgery: A meta-analysis of observational studies. Am J Kidney Dis 2013;62:1077–86.
73 Whiting P, Morden A, Tomlinson LA, et al. What are the risks and benefits of temporarily discontinuing medications to prevent acute kidney injury? A systematic review and meta-analysis. BMJ Open 2017;7: e012674.
74 Milne B, Gilbey T, Ostermann M, et al. Pro: We should stop ACE inhibitors early before cardiac surgery to prevent postoperative acute kidney injury. J Cardiothorac Vasc Anesth 2020;34:2832–5.
75 Tempe DK, Hasija S. Con: Does preoperative discontinuation of angiotensin-converting enzyme inhibitors/angiotensin II receptor blockers reduce postoperative acute kidney injury. J Cardiothorac Vasc Anesth 2020;34:2836–8.
76 Hirleman E, Larson DF. Cardiopulmonary bypass and edema: Physiology and pathophysiology. Perfusion 2008;23:311–22.
77 Martin GS, Kaufman DA, Marik PE, et al. Perioperative Quality Initiative (POQI) consensus statement on fundamental concepts in perioperative fluid management: Fluid responsiveness and venous capacitance. Perioper Med (Lond) 2020;9:12.
78 Aronson S, Nisbet P, Bunke M. Fluid resuscitation practices in cardiac surgery patients in the USA: A survey of health care providers. Perioper Med (Lond) 2017;6:15.
79 Karkouti K, Grocott HP, Hall R, et al. Interrelationship of preoperative anemia, intraoperative anemia, and red blood cell transfusion as potentially modifiable risk factors for acute kidney injury in cardiac surgery: A historical multicentre cohort study. Can J Anaesth 2015;62:377–84.
80 Searles B. Ultrafiltration techniques and CPB: What we know and what we think we know. J Extra Corpor Technol 2006;38:64–5.
81 Phoon PHY, Hwang NC. Conventional ultrafiltration-no more role in elective adult cardiac surgery? J Cardiothorac Vasc Anesth 2021; 35:1319–20.
82 Paugh TA, Dickinson TA, Martin JR, et al. Impact of ultrafiltration on kidney injury after cardiac surgery: The Michigan experience. Ann Thorac Surg 2015;100:1683–8.
83 Manning MW, Li YJ, Linder D, et al. Conventional ultrafiltration during elective cardiac surgery and postoperative acute kidney injury. J Cardiothorac Vasc Anesth 2021;35:1310–8.
84 Kandil OA, Motawea KR, Darling E, et al. Ultrafiltration and cardiopulmonary bypass associated acute kidney injury: A systematic review and meta-analysis. Clin Cardiol 2021;44:1700–8.
85 Goldstein S, Bagshaw S, Cecconi M, et al. Pharmacological management of fluid overload. Br J Anaesth 2014;113:756–63.
86 Grocott MP, Dushianthan A, Hamilton MA, et al. Perioperative increase in global blood flow to explicit defined goals and outcomes following surgery. Cochrane Database Syst Rev 2012;11:CD004082.
87 Giglio M, Dalfino L, Puntillo F, et al. Hemodynamic goal-directed therapy and postoperative kidney injury: An updated meta-analysis with trial sequential analysis. Critical Care 2019;23:1–13.
88 Hoste EA, Maitland K, Brudney CS, et al. Four phases of intravenous fluid therapy: A conceptual model. Br J Anaesth 2014; 113:740–7.
89 Johnston LE, Thiele RH, Hawkins RB, et al. Goal-directed resuscitation following cardiac surgery reduces acute kidney injury: A quality initiative pre-post analysis. J Thorac Cardiovasc Surg 2020;159: 1868–77;e1.
90 Magruder JT, Crawford TC, Harness HL, et al. A pilot goal-directed perfusion initiative is associated with less acute kidney injury after cardiac surgery. J Thorac Cardiovasc Surg 2017;153:118–25;e1.
91 Zarbock A, Engelman DT. Commentary: Should goal-directed fluid therapy be used in every cardiac surgery patient to prevent acute kidney injury. J Thorac Cardiovasc Surg 2020;159:1878–9.
92 Dupuis JY, Bondy R, Cattran C, et al. Amrinone and dobutamine as primary treatment of low cardiac output syndrome following coronary artery surgery: A comparison of their effects on hemodynamics and outcome. J Cardiothorac Vasc Anesth 1992;6:542–53.
93 Lopez MG, Shotwell MS, Morse J, et al. Intraoperative venous congestion and acute kidney injury in cardiac surgery: An observational cohort study. Br J Anaesth 2021;126:599–607.
94 Kaydu A, Gokcek E. Preoperative and postoperative assessment of ultrasonographic measurement of inferior vena cava: A prospective, observational study. J Clin Med 2018;7:1–11.
95 Stawicki SP, Braslow BM, Panebianco NL, et al. Intensivist use of hand-carried ultrasonography to measure IVC collapsibility in estimating intravascular volume status: Correlations with CVP. J Am Coll Surg 2009; 209:55–61.
96 Yildizdas D, Aslan N. Ultrasonographic inferior vena cava collapsibility and distensibility indices for detecting the volume status of critically ill pediatric patients. J Ultrason 2020;20:e205–9.
97 Thanakitcharu P, Charoenwut M, Siriwiwatanakul N. Inferior vena cava diameter and collapsibility index: A practical non-invasive evaluation of intravascular fluid volume in critically-ill patients. J Med Assoc Thai 2013;96(Suppl 3):S14–22.
98 Jury D, Shaw AD. Utility of bedside ultrasound derived hepatic and renal parenchymal flow patterns to guide management of acute kidney injury. Curr Opin Crit Care 2021;27:587–92.
99 Beaubien-Souligny W, Benkreira A, Robillard P, et al. Alterations in portal vein flow and intrarenal venous flow are associated with acute kidney injury after cardiac surgery: A prospective observational cohort study. J Am Heart Assoc 2018;7:e009961.
100 Engelman DT, Crisafi C, Germain M, et al. Using urinary biomarkers to reduce acute kidney injury following cardiac surgery. J Thorac Cardiovasc Surg 2020;160:1235–46;e2.
101 Ostermann M, Zarbock A, Goldstein S, et al. Recommendations on acute kidney injury biomarkers from the Acute Disease Quality Initiative Consensus Conference: A consensus statement. JAMA Netw Open 2020;3: e2019209.
102 Mayer T, Bolliger D, Scholz M, et al. Urine biomarkers of tubular renal cell damage for the prediction of acute kidney injury after cardiac surgery—a pilot study. J Cardiothorac Vasc Anesth 2017;31:2072–9.
103 Kashani K, Al-Khafaji A, Ardiles T, et al. Discovery and validation of cell cycle arrest biomarkers in human acute kidney injury. Crit Care 2013;17:R25.

104 Wen Y, Parikh CR. Current concepts and advances in biomarkers of acute kidney injury. Crit Rev Clin Lab Sci 2021;58:354–68.

105 Engelman DT, Shaw AD. A turnkey order set for prevention of cardiac surgery-associated acute kidney injury. Ann Thorac Surg 2023;115:11–5.

106 Linder A, Fjell C, Levin A, et al. Small acute increases in serum creatinine are associated with decreased long-term survival in the critically ill. Am J Respir Crit Care Med 2014;189:1075–81.

107 Lassnigg A, Schmidlin D, Mouhieddine M, et al. Minimal changes of serum creatinine predict prognosis in patients after cardiothoracic surgery A prospective cohort study. J Am Soc Nephrol 2004;15:1597–605.

108 Han SS, Shin N, Baek SH, et al. Effects of acute kidney injury and chronic kidney disease on long-term mortality after coronary artery bypass grafting. Am Heart J 2015;169:419–25.

109 O'Neal JB, Shaw AD, Billings FT. Acute kidney injury following cardiac surgery: Current understanding and future directions. Crit Care 2016;20:187.

110 Siew ED, Parr SK, Abdel-Kader K, et al. Predictors of recurrent AKI. J Am Soc Nephrol 2016;27:1190–200.

111 Greer RC, Liu Y, Crews DC, et al. Hospital discharge communications during care transitions for patients with acute kidney injury: A cross-sectional study. BMC Health Serv Res 2016;16:449.

112 Siew ED, Parr SK, Wild MG, et al. Kidney disease awareness and knowledge among survivors of acute kidney injury. Am J Nephrol 2019; 49:449–59.

113 Singh G, Hu Y, Jacobs S, et al. Post-discharge mortality and rehospitalization among participants in a comprehensive acute kidney injury rehabilitation program. Kidney360 2021;2:1424–33.

114 Silver SA, Siew ED. Follow-up care in acute kidney injury: Lost in transition. Adv Chronic Kidney Dis 2017;24:246–52.

115 Ostermann M, Bellomo R, Burdmann EA, et al. Controversies in acute kidney injury: Conclusions from a Kidney Disease: Improving Global Outcomes (KDIGO) Conference. Kidney Int 2020;98:294–309.

116 Liu KD, Forni LG, Heung M, et al. Quality of care for acute kidney disease: Current knowledge gaps and future directions. Kidney Int Rep 2020;5:1634–42.

117 Brown JR, Baker RA, Shore-Lesserson L, et al. The Society of Thoracic Surgeons/Society of Cardiovascular Anesthesiologists/American Society for Extracorporeal Technology clinical practice guidelines for the prevention of adult cardiac surgery-associated acute kidney injury. Anesth Analg 2023;136:176–84.