AUIQ Complementary Biological System
ISSN: 3007-973X
Journal homepage:
https://acbs.alayen.edu.iq

Manuscript 1061

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AUIQ COMPLEMENTARY BIOLOGICAL SYSTEM 3 (2026) 107–116

REVIEW

Perioperative Fluid Management in Cardiac Surgery: Contemporary Evidence and Clinical Controversies

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ABSTRACT

Perioperative fluid therapy is a cornerstone of anesthetic management in cardiac surgery, where both hypovolemia and hypervolemia are associated with increased morbidity, forming a "U-shaped" relationship with outcomes. This narrative review synthesizes evidence from peer-reviewed literature (2000–2024) identified via PubMed, Scopus, and the Cochrane Database, focusing on randomized trials, meta-analyses, and guidelines for adult cardiac surgery.

A central debate persists regarding fluid choice. Current evidence supports the preferential use of balanced crystalloids over normal saline, as large-volume saline is linked to hyperchloremic acidosis and reduced renal perfusion. Colloids like albumin and hydroxyethyl starch (HES) offer efficient volume expansion but require caution: contemporary data favor albumin over synthetic colloids in high-risk patients due to coagulation and renal concerns with HES. The review also addresses the impact of cardiopulmonary bypass on hemodilution, inflammation, and electrolyte balance.

Key findings indicate that goal-directed or restrictive fluid strategies, guided by advanced monitoring, reduce postoperative complications compared to liberal regimens. However, significant uncertainty remains regarding optimal volumes in specific subgroups (e.g., ventricular dysfunction, complex procedures) and the comparative effectiveness of different balanced crystalloids. Ultimately, fluid management in cardiac surgery must be tailored, evidence-informed, and guided by real-time physiological data.

Keywords: Cardiac surgery, Intravenous fluids, Fluid therapy, Crystalloid, Colloid

1. Introduction

Perioperative fluid therapy remains a cornerstone of anesthetic management in cardiac surgery, with direct implications for patient outcomes. The relationship between administered fluid volume and postoperative complications follows a well-recognized U-shaped pattern: both hypovolemia and hypervolemia are independently associated with increased morbidity and mortality [1–3]. Hypovolemia may compromise tissue perfusion and cardiac output, leading to organ dysfunction, whereas fluid overload can precipitate pulmonary edema, impair myocardial recovery, and prolong mechanical ventilation [4, 5]. Achieving optimal fluid balance is particularly challenging in cardiac surgical patients due to the unique physiological perturbations imposed by cardiopulmonary bypass (CPB), including hemodilution, systemic inflammatory response syndrome (SIRS), and increased capillary permeability [6–8].

Received 31 January 2026; revised 25 February 2026; accepted 2 March 2026.
Available online 11 March 2026

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https://doi.org/10.70176/3007-973X.1061

Recent evidence has refined our understanding of perioperative fluid management. The international Perioperative Quality Initiative (POQI) consensus recommendations emphasize that fluid therapy should be individualized, taking into account surgical complexity, patient comorbidities, and real-time hemodynamic data [9, 10]. In cardiac surgery specifically, a 2024 network meta-analysis of twenty randomized controlled trials demonstrated that fluid choice significantly influences postoperative outcomes, with balanced crystalloids associated with reduced complications compared to saline-based regimens [11]. Similarly, a contemporary meta-analysis by Chen et al. comparing colloids and crystalloids in cardiac surgery patients found no differences in mortality, acute kidney injury, or transfusion requirements, although crystalloid use was associated with reduced postoperative chest tube output [12].

The crystalloid-colloid debate continues to evolve. Albumin, a natural colloid with favorable effects on endothelial glycocalyx integrity, has been the subject of renewed investigation. A 2024 systematic review and meta-analysis by Skubas et al. confirmed that albumin administration in cardiac surgery is safe and may confer benefits in specific subgroups, particularly patients with hypoalbuminemia or those undergoing complex procedures [13]. Conversely, the safety profile of hydroxyethyl starch (HES) remains concerning; following the retraction of numerous studies by Boldt and subsequent regulatory actions by the European Medicines Agency, contemporary guidelines advise against routine HES use in cardiac surgery due to associated risks of acute kidney injury and bleeding [9, 12, 14].

Among crystalloids, the choice between balanced solutions (e.g., Ringer's lactate, Plasmalyte) and normal saline has important physiological implications. Large-volume saline infusion is associated with hyperchloremic metabolic acidosis, reduced renal cortical perfusion, and increased vasopressor requirements [15–17]. Accordingly, current evidence favors balanced crystalloids for both maintenance and resuscitation in cardiac surgical patients [9, 12]. However, significant knowledge gaps persist regarding optimal fluid volumes in high-risk subgroups, the comparative effectiveness of different balanced crystalloid formulations, and the role of goal-directed therapy guided by advanced hemodynamic monitoring [18, 19].

This narrative review aims to summarize current evidence on fluid selection and perioperative fluid strategies in adult cardiac surgery, with emphasis on contemporary findings from recent meta-analyses, clinical guidelines, and randomized controlled trials.

2. Methods

Given the broad and evolving nature of the evidence on perioperative fluid therapy in cardiac surgery, a narrative review methodology was selected to provide a comprehensive overview of current concepts, controversies, and clinical recommendations. This approach allows for the synthesis of diverse study types—including randomized controlled trials, meta-analyses, observational studies, and clinical guidelines—to present a balanced and clinically applicable perspective.

2.1. Search Strategy

A systematic literature search was conducted using the following electronic databases: PubMed/MEDLINE, Scopus, Web of Science, and the Cochrane Database of Systematic Reviews. The search covered the period from January 2000 to December 2024 to capture both foundational studies and contemporary evidence.

2.2. Search terms

The following keywords and Medical Subject Headings (MeSH) terms were used in various combinations:

- "cardiac surgery" OR "cardiovascular surgery" OR "cardiopulmonary bypass" OR "coronary artery bypass"
- "fluid therapy" OR "intravenous fluids" OR "crystalloid" OR "colloid" OR "albumin" OR "hydroxyethyl starch" OR "balanced solutions" OR "normal saline"
- "perioperative care" OR "goal-directed therapy" OR "hemodynamic monitoring"
- "fluid overload" OR "hypovolemia" OR "complications"

2.3. Inclusion criteria

Studies were considered for inclusion if they:

(1) involved adult patients (≥18 years) undergoing cardiac surgery;
(2) evaluated perioperative fluid management strategies, fluid types, or associated outcomes;
(3) were published in peer-reviewed journals;
(4) were written in English. Priority was given to large randomized controlled trials, meta-analyses, systematic reviews, and evidence-based clinical guidelines published within the last decade. Landmark studies published before 2010 were retained

if they provided foundational context or historically significant data.

2.4. Exclusion criteria

Studies were excluded if they:

(1) focused primarily on pediatric cardiac surgery;
(2) addressed fluid therapy in non-cardiac surgical settings without relevant extrapolation to cardiac surgery;
(3) were case reports, editorials, or conference abstracts without full-text availability.

2.5. Study selection and data synthesis

Titles and abstracts were screened for relevance by two reviewers (H.A.H. and H.A.). Full-text articles were assessed independently, with disagreements resolved through consensus. Due to the narrative design, formal quality assessment or meta-analytic pooling was not performed. Instead, key findings were synthesized thematically, with emphasis on areas of consensus, ongoing controversy, and implications for clinical practice.

2.6. Rationale for narrative approach

A systematic review with meta-analysis was not feasible due to the clinical heterogeneity among studies (varying patient populations, surgical procedures, fluid protocols, and outcome definitions). The narrative format enables integration of evidence from multiple study designs, providing clinicians with a practical overview of fluid management principles while highlighting areas requiring further investigation.

3. Results and discussion

3.1. Colloids or Crystalloids? A critical appraisal of the evidence

Beyond the ongoing debate regarding liberal versus restrictive fluid regimens, a long-standing controversy surrounds the choice between crystalloids and colloids, as well as comparisons among different colloid formulations [6, 18, 19]. Early observational data suggested an association between large-volume crystalloid administration and increased mortality, leading some investigators to recommend colloids for intravascular volume restoration in cardiac surgical patients [3, 6, 7]. However, these findings must be interpreted cautiously given the observational design and potential confounding by indication. Contemporary evidence, including multiple large randomized trials and meta-analyses, has substantially refined our understanding of this complex issue and highlights the importance of critical appraisal.

3.2. Crystalloids: Balanced solutions versus normal saline

Crystalloid solutions differ fundamentally in their electrolyte composition, which may influence not only the risk of edema and fluid overload but also acid-base balance and renal perfusion [1]. Historically, normal saline (0.9% NaCl) has been the most commonly administered crystalloid worldwide, largely due to its availability, low cost, and historical precedent. However, this practice warrants re-examination in light of accumulating evidence.

3.2.1. Critical appraisal of evidence

The association between large-volume saline administration and adverse effects is supported by both physiological studies and clinical outcomes research. A landmark randomized crossover study by Chowdhury et al. demonstrated that healthy volunteers receiving 2-liter saline infusions exhibited significant reductions in renal blood flow velocity and renal cortical perfusion compared to those receiving balanced solutions [15]. This physiological finding is clinically relevant, as renal hypoperfusion may contribute to acute kidney injury—a common complication after cardiac surgery. However, it is important to note that this study was conducted in healthy volunteers, not cardiac surgical patients, and the observed effect sizes, while statistically significant, may not directly translate to clinical outcomes.

Subsequent observational studies have corroborated these findings. A large propensity-matched analysis by Shaw et al. involving over 30,000 surgical patients found that saline administration was associated with higher rates of major adverse kidney events compared to balanced crystalloids [20]. Nevertheless, observational data are subject to residual confounding, and the absence of large randomized trials comparing saline to balanced solutions specifically in cardiac surgery represents a significant evidence gap.

A 2024 network meta-analysis by the Perioperative Medicine Group, pooling data from twenty randomized controlled trials across surgical populations, demonstrated that balanced crystalloid use was associated with reduced postoperative complications compared to saline-based regimens [11]. However, this analysis included heterogeneous surgical populations, and subgroup analysis restricted to cardiac surgery patients showed a similar but non-

significant trend, likely due to insufficient statistical power. Thus, while current evidence favors balanced crystalloids, the strength of this recommendation in cardiac surgery specifically is moderate rather than definitive.

3.2.2. Clinical implications

Balanced solutions (Ringer's lactate, Hartmann's solution, Plasmalyte) more closely mimic plasma electrolyte composition and help maintain acid-base stability—particularly relevant during and after cardiopulmonary bypass when large fluid volumes are administered [16, 21]. Based on the available evidence, most contemporary guidelines, including the 2024 POQI consensus recommendations, advise preferential use of balanced crystalloids over saline in cardiac surgery [9]. Notably, some investigators have suggested incorporating mannitol into CPB priming solutions to mitigate hypervolemia risk, though robust evidence supporting this practice remains limited and derives largely from small, single-center studies [18].

3.3. Albumin: The natural colloid

Albumin, a human-derived colloid, remains a frequently administered option in cardiac surgery due to its favorable safety profile and physiological properties [22]. Unlike synthetic colloids, albumin supports endothelial glycocalyx integrity and exhibits antioxidant and anti-inflammatory effects—properties that may be particularly beneficial in the context of CPB-induced systemic inflammation [23, 24].

3.3.1. Critical appraisal of evidence

Approximately 90% of infused albumin remains intravascular, providing sustained volume expansion—a distinct advantage in patients with compromised cardiac output [6, 25, 26]. However, the clinical significance of this pharmacokinetic property requires careful examination. A study by Ernest et al. demonstrated that 5% albumin produced superior plasma volume expansion compared to crystalloids in postoperative cardiac surgical patients [25]. While this finding supports albumin's physiological efficacy, the study was small (n = 16) and did not assess patient-centered outcomes such as mortality, complications, or length of stay.

Jacob and colleagues further showed that albumin administration was associated with minimal tissue edema compared to both crystalloids and synthetic colloids, attributed to preservation of vascular barrier function [23]. This experimental study using isolated heart models provides mechanistic insight but requires confirmation in clinical settings.

A meta-analysis by Wilkes et al. reported reduced postoperative bleeding and transfusion requirements with albumin compared to hydroxyethyl starch [27]. This finding has clinical relevance, as bleeding and transfusion are independently associated with morbidity after cardiac surgery. However, the included studies were conducted before modern HES formulations were available, limiting generalizability to current practice.

The most robust contemporary evidence comes from a 2024 systematic review and meta-analysis by Skubas et al., encompassing 42 randomized controlled trials and over 19,000 patients [13]. This analysis confirmed the safety of albumin in cardiac surgery and suggested potential benefits in high-risk subgroups, particularly patients with preoperative hypoalbuminemia or those undergoing complex valvular or aortic procedures. Importantly, no mortality benefit was observed across the overall population, and the quality of evidence for subgroup effects was moderate due to heterogeneity and risk of bias in included studies.

3.3.2. Limitations and unanswered questions

Despite these findings, significant knowledge gaps persist. The efficacy of albumin as a CPB priming solution has not been conclusively demonstrated; a meta-analysis by Russell et al. found no consistent benefit over crystalloids for this indication [28]. Additionally, albumin's high cost and limited availability restrict widespread use, and adverse effects have been reported in specific populations, including patients with traumatic brain injury, where the SAFE study demonstrated increased mortality with albumin resuscitation [24, 29]. Whether these findings extrapolate to cardiac surgical patients without brain injury remains uncertain.

3.4. Hydroxyethyl starch: Evolving safety concerns

Hydroxyethyl starch (HES) solutions have been widely used for hypovolemia correction due to their potent and sustained volume-expanding effects [9]. However, their safety profile has been the subject of intense scrutiny and controversy, representing one of the most significant evolutions in fluid resuscitation practice over the past decade.

3.4.1. Critical appraisal of evidence

Early retrospective studies, including a chart review by Knutson et al., reported increased postoperative bleeding and transfusion requirements in cardiac surgical patients receiving HES [28]. While this finding has been consistently replicated, retrospective designs cannot establish causality, and the possibility of

confounding by indication (sicker patients receiving HES) cannot be excluded.

Subsequent investigations have raised concerns regarding HES-associated coagulopathy and acute kidney injury. A prospective randomized study by Van der Linden et al. comparing newer-generation HES (130/0.4) with gelatin found no difference in bleeding outcomes, suggesting improved safety with modern formulations [27, 30]. However, this study was underpowered for clinically important outcomes, and the confidence intervals were wide, precluding definitive conclusions.

The most influential evidence comes from large randomized trials in critically ill patients. The CHEST trial (n = 7,000) found no benefit of HES over saline and suggested increased renal replacement therapy requirements [31]. The 6S trial (n = 800) demonstrated increased mortality and renal injury with HES compared to Ringer's acetate in septic patients [32]. While these trials were not conducted exclusively in cardiac surgery, their findings have substantially influenced practice guidelines and regulatory actions.

A 2024 meta-analysis by Chen et al. specifically examining cardiac surgery populations found no difference in mortality or acute kidney injury between HES and crystalloids but confirmed increased transfusion requirements and chest tube output with HES compared to albumin or crystalloids [12]. Notably, this analysis included studies with significant heterogeneity in HES formulations, doses, and patient populations, limiting the strength of conclusions.

3.4.2. Regulatory and guideline context

The controversy surrounding HES was profoundly influenced by the retraction of numerous studies conducted by Boldt following investigations into research misconduct [33]. Subsequent regulatory actions—including a black-box warning from the US Food and Drug Administration and restrictions by the European Medicines Agency—have substantially curtailed HES use in critically ill and surgical patients [14]. Contemporary consensus guidelines, including those from the POQI and the European Society of Anaesthesiology, recommend against routine HES use in cardiac surgery [9, 34].

3.5. Gelatins and other colloids

Gelatins, modified fluid colloids derived from bovine collagen, offer an alternative synthetic option with a distinct safety profile. Their advantages include a short intravascular half-life (approximately 2–3 hours) and minimal impact on coagulation and renal function in most studies [6, 30]. However, the evidence base for gelatins is less robust than for albumin or crystalloids, with few large randomized trials in cardiac surgery.

3.5.1. Critical appraisal

A randomized study by Van der Linden et al. comparing gelatin to HES 130/0.4 found comparable efficacy and safety, though the study was underpowered for bleeding outcomes [27]. Concerns regarding potential allergic reactions and, historically, theoretical risks of prion transmission have reduced their popularity in some regions [4]. The absence of contemporary large-scale safety data represents a significant evidence gap.

3.6. Hypertonic saline

Hypertonic saline (HS) (7.2% and 7.5%) has been investigated in cardiac surgery for its hemodynamic and immunomodulatory effects. By mobilizing endogenous fluid into the intravascular space, HS achieves rapid volume expansion with reduced total fluid volume. Potential benefits include improved cardiac index, reduced systemic vascular resistance, and attenuated inflammatory responses [4].

3.6.1. Critical appraisal

Evidence supporting routine HS use remains limited to small physiologic studies and pilot trials. A meta-analysis by Cochrane Group found insufficient evidence to recommend HS for perioperative fluid management [31]. Concerns regarding hypernatremia, osmotic demyelination, and lack of long-term outcome data restrict its application to select cases and research settings.

Table 1 provides a comparative summary of the intravenous fluids discussed in this review, synthesizing their advantages, disadvantages, clinical considerations, and the strength of contemporary evidence supporting their use. As illustrated, the evidence base varies considerably across fluid types. Balanced crystalloids and albumin are supported by the most robust recent data, including 2024 meta-analyses and consensus guidelines [9, 11–13]. In contrast, HES carries regulatory warnings based on high-quality evidence of harm from large randomized trials [31, 32], while gelatins and hypertonic saline lack adequate outcome studies, representing significant evidence gaps [35]. This heterogeneity in evidence quality should inform both clinical decision-making and future research priorities. Clinicians must weigh not only the physiological properties of each fluid but also the strength and limitations of the supporting evidence when selecting perioperative fluid strategies for individual patients.

Table 1. Comparison of Common Intravenous Fluids Used in Cardiac Surgery.

Fluid Type	Advantages	Disadvantages	Clinical Considerations	Key Evidence (2024)
Balanced Crystalloids (Ringer's lactate, Hartmann's solution, Plasmalyte)	•Physiologic electrolyte composition •Maintains acid-base stability •Low cost •Widely available	•Risk of edema with large volumes •Less sustained intravascular expansion •Shorter duration of effect	•Preferred first-line for maintenance and replacement •Recommended over saline by current guidelines •Particularly beneficial when large volumes required	**Network meta-analysis (2024)** [11]: Reduced postoperative complications vs. saline across surgical populations; similar trend in cardiac subgroup (moderate evidence strength)
Normal Saline (0.9% NaCl)	•Widely available •Inexpensive •No potassium •Long historical use	•Hyperchloremic metabolic acidosis •Reduced renal cortical perfusion •Increased vasopressor requirements •Possible acute kidney injury risk	•Avoid volumes exceeding 2 L •Not recommended as first-line •Consider alternatives in patients with renal impairment	**Chowdhury et al. (2012)** [15]: Reduced renal blood flow in volunteers (high-quality physiologic evidence) **POQI 2024 guidelines** [9]: Advise against routine use (strong recommendation, moderate evidence)
Albumin (4-5%, 20–25%)	•90% intravascular retention •Supports endothelial glycocalyx •Anti-inflammatory effects •Antioxidant properties •Reduced transfusion vs. HES	•High cost •Limited availability •Adverse effects in brain injury •No mortality benefit in unselected patients	•Useful in hypoalbuminemia •Consider for low cardiac output states •Beneficial in complex procedures (valvular, aortic) •Subgroup benefits likely, but overall population benefit uncertain	**Skubas et al. (2024)** [13]: Meta-analysis (42 RCTs, >19,000 patients); confirmed safety; subgroup benefits in high-risk patients (moderate evidence) **Wilkes et al. (2001)** [25]: Reduced bleeding vs. HES (limited by era)
Hydroxyethyl Starch (HES)	•Potent volume expansion •Sustained effect •Single dose effective	•Coagulopathy •Acute kidney injury risk •Increased bleeding •Increased transfusion requirements •Regulatory warnings	•Avoid routine use •Contraindicated in sepsis, renal impairment, bleeding disorders •Not recommended by current guidelines •Historical context important (Boldt retractions)	**Chen et al. (2024)** [12]: No mortality difference but increased transfusions (moderate evidence) **CHEST/6S trials** [31, 32]: Increased renal injury in critically ill (high-quality evidence) **FDA/EMA warnings** [14]: Black-box warning; restricted use
Gelatins	•Short half-life (2–3 hours) •Minimal coagulation effect •Renal profile favorable vs. HES	•Transient effect only •Allergic potential •Regional availability limited •Limited contemporary safety data	•Temporary volume support only •Not suitable for sustained resuscitation •Declining use in many centers •Evidence gap for long-term outcomes	**Van der Linden et al. (2005)** [27]: Comparable to HES 130/0.4 for efficacy; underpowered for safety (low-quality evidence) **No large contemporary RCTs**—significant evidence gap
Hypertonic Saline (7.2–7.5%)	•Rapid volume expansion •Reduced total fluid volume •Improved cardiac index •Decreased vascular resistance •Immunomodulatory effects	•Hypernatremia risk •Osmotic demyelination concern •Limited outcome data •Not routinely available	•Investigational only •Select cases in experienced centers •Not standard of care •Requires close electrolyte monitoring	**McAlister (2021)** [35]: Insufficient evidence for routine use (low-quality evidence) **Small physiologic studies only**—major evidence gap

4. Limitations

This narrative review has several limitations that should be acknowledged when interpreting its findings.

4.1. Methodological limitations

As a narrative review rather than a systematic review or meta-analysis, the study selection process was not formally protocol-driven or registered. While we conducted comprehensive searches of multiple databases (PubMed/MEDLINE, Scopus, Web of Science, Cochrane Database) using predefined keywords, the absence of a duplicate, independent screening process with conflict resolution—beyond the two-reviewer consensus described in the Methods—introduces the potential for selection bias. Furthermore, no formal quality assessment tools (e.g., GRADE, Cochrane Risk of Bias) were applied to included studies, limiting the ability to quantitatively weight evidence strength. The narrative synthesis approach, while appropriate for integrating diverse study types, does not provide pooled effect estimates and is inherently more subjective than meta-analytic methods.

4.2. Search and scope limitations

Although the search period spanned January 2000 to December 2024, it is possible that relevant studies published in non-indexed journals, non-English languages, or before 2000 were inadvertently omitted. The exclusion of non-English publications may introduce language bias, potentially overlooking regional practices or evidence from non-Western populations. Additionally, the broad scope of this review—encompassing multiple fluid types, clinical outcomes, and surgical procedures—necessarily limits its depth in any single area. Readers seeking detailed analyses of specific subtopics (e.g., fluid management in minimally invasive cardiac surgery, pediatric populations, or specific coagulation outcomes) should consult more focused systematic reviews.

4.3. Evidence heterogeneity

The included studies exhibit substantial clinical and methodological heterogeneity, including variations in:

- Patient populations (elective vs. emergency surgery; isolated CABG vs. complex combined procedures)
- Fluid protocols (dosing, timing, co-interventions)
- Outcome definitions (acute kidney injury criteria, bleeding definitions, transfusion triggers)
- Era effects (changes in surgical techniques, CPB technology, and perioperative care over the 24-year review period)

This heterogeneity complicates direct comparisons and limits the generalizability of findings across all cardiac surgical settings.

4.4. Publication and reporting bias

As with any literature review, the findings are susceptible to publication bias, as studies with positive or statistically significant results are more likely to be published than those with null findings. The

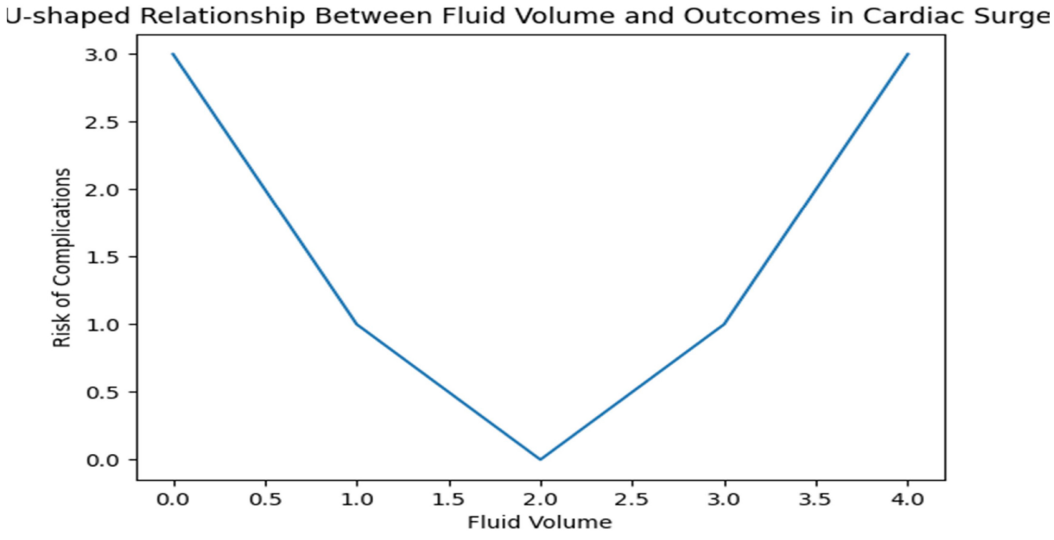

Fig. 1. Conceptual U-shaped relationship between perioperative fluid volume and postoperative complications in cardiac surgery.

retraction of numerous studies by Boldt and colleagues [33]—some of which were included in earlier meta-analyses—highlights the importance of considering research integrity when synthesizing evidence. While we have incorporated the retraction context into our critical appraisal, the full impact of these retractions on the historical evidence base remains difficult to quantify.

4.5. Rapidly evolving evidence base

Perioperative fluid management is a dynamic field, with new trials and meta-analyses published frequently. Despite including evidence through December 2024, it is possible that studies published after this review's search cutoff or in press at the time of writing may alter the conclusions presented herein. Readers are encouraged to consult ongoing trial registries (e.g., ClinicalTrials.gov) for emerging evidence.

4.6. Scope and generalizability

This review focused specifically on adult cardiac surgery involving cardiopulmonary bypass. The findings may not be directly applicable to:

- Pediatric cardiac surgery populations
- Off-pump coronary artery bypass (OPCAB) procedures
- Non-cardiac thoracic surgery
- Intensive care unit settings after cardiac surgery, where different fluid dynamics may apply

5. Conclusion

Perioperative fluid management in cardiac surgery has evolved substantially over the past decade, moving from rigid, volume-based formulas toward individualized, physiology-driven strategies. This review synthesizes current evidence to provide clinicians with practical guidance for daily practice.

5.1. What clinicians should do differently

5.1.1. First, prioritize balanced crystalloids over normal saline

The evidence is now clear: large-volume normal saline infusion causes hyperchloremic metabolic acidosis and reduces renal perfusion [15, 36]. For routine maintenance and replacement, balanced solutions (Ringer's lactate, Plasmalyte, Hartmann's) should be the default choice. Restrict saline to situations where balanced solutions are contraindicated (e.g., severe hyperkalemia) or unavailable.

5.1.2. Second, use albumin selectively, not routinely

Albumin is safe and physiologically advantageous, but its high cost and absence of mortality benefit in unselected patients argue against universal use [13]. Reserve albumin for high-risk subgroups where evidence suggests benefit: patients with preoperative hypoalbuminemia, those undergoing complex valvular or aortic procedures, and individuals with low cardiac output states requiring sustained volume expansion.

5.1.3. Third, avoid hydroxyethyl starch entirely

The evidence of harm—coagulopathy, acute kidney injury, increased transfusion requirements—is consistent and compelling [12, 31, 32]. Regulatory warnings from the FDA and EMA, combined with contemporary guideline recommendations, leave no role for HES in modern cardiac surgery practice [9, 14].

5.1.4. Fourth, adopt goal-directed therapy guided by dynamic monitoring

Fixed-volume regimens are obsolete. Use advanced hemodynamic tools (transesophageal echocardiography, pulse contour analysis, dynamic indices) to assess fluid responsiveness in real time. This approach minimizes both hypovolemia and fluid overload—the twin hazards represented by the U-shaped outcome curve (Fig. 1).

5.1.5. Fifth, recognize evidence gaps and avoid over-reliance on weak data

Gelatins and hypertonic saline lack robust outcome studies and cannot be recommended as standard care [33]. When evidence is insufficient, default to options with proven safety profiles—balanced crystalloids and, in selected cases, albumin.

5.2. The take-home message

In cardiac surgery, fluid therapy should be:

- **Balanced** (prefer balanced crystalloids over saline)
- **Restrictive in starch** (avoid HES entirely)
- **Selective with albumin** (reserve for high-risk patients)
- **Goal-directed** (guide by dynamic monitoring)
- **Individualized** (tailor to patient and procedure)

The era of "one-size-fits-all" fluid regimens has ended. By integrating contemporary evidence with real-time physiological data, clinicians can optimize outcomes, reduce complications, and move closer to the goal of precision perioperative care. Ongoing research will continue to refine these recommendations, particularly regarding optimal volumes in

specific subgroups and the comparative effectiveness of different balanced crystalloid formulations.

Acknowledgment

We thank Al-Ayen Iraqi University for helping to complete this work.

Conflict of interest

The authors declare no conflict of interest.

Ethical approval

Not applicable.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Funding

This research received no external funding.

Author contributions

Hussein Ali Hussein Al-Hchaimi, Hussein Alkhfaji and Majid Fakhir Al-Hamaidah contributed to conceptualization, methodology, and data collection. Mohammad Ali Hassan Jassim, Ammar Hoom Mahdi, Fatima Al-sharwood and Sunder Etta performed data analysis and interpretation, also contributed to writing original draft preparation and critical review. All authors reviewed and approved the final manuscript.

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