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Haemodynamic Frailty as A Predictor of Acute Kidney Injury in Older Adults: A Systematic Literature Review

Dony Prasetya Nugraha[1*], Hery Emria[2]
Pertamina Hospital Tarakan, Indonesia[1]
Pertamina Central Hospital, Indonesia[2]
Email : donypn360@gmail.com[1*]

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ABSTRACT

Acute kidney injury (AKI) in older adults is closely associated with a diminished capacity of the cardiovascular system to maintain adequate renal perfusion during acute physiological stress. This study aimed to identify, critically evaluate, and synthesize evidence regarding the predictive value of hemodynamic frailty, characterized by hypotension, impaired perfusion, blood pressure variability, cardiac output, venous pressure, venous congestion, volume status, and fluid responsiveness, for AKI in older adults. A systematic literature review was conducted involving 36 articles published between 2021 and 2026. Methodological quality was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Tools, while bibliometric mapping was performed using VOSviewer. Of the included studies, 27 were classified as having high methodological quality, while nine were rated as moderate quality. The synthesis revealed that elevated central venous pressure (CVP) and venous congestion were the hemodynamic indicators most consistently associated with AKI. Reduced mean perfusion pressure, cardiac index, oxygen delivery index, and peripheral perfusion index were also associated with an increased risk of AKI. Hypotension remained a relevant predictor, although its predictive strength varied according to its severity, duration, and patients' baseline clinical conditions. Blood pressure variability provided additional predictive information, whereas the Venous Excess Ultrasound (VExUS) grading system, changes in inferior vena cava diameter, and fluid responsiveness demonstrated inconsistent predictive performance. These findings suggested that hemodynamic frailty may be more comprehensively assessed through the combined evaluation of arterial pressure, venous pressure, tissue perfusion, cardiac output, and volume status rather than reliance on any single hemodynamic parameter.

INTRODUCTION

Acute kidney injury (AKI) remains a major clinical concern because of its rapid onset, prolonged hospitalization, increased need for kidney replacement therapy, and associations with mortality and long-term deterioration in kidney function. Ostermann et al. (2025) reported that AKI affects approximately 10–15% of hospitalized patients and more than 50% of patients admitted to intensive care units (ICUs). This burden is expected to increase with population aging, as the United Nations (2024) projected that the global population aged 65 years and older would reach approximately 2.2 billion by the late 2070s. Older adults are particularly vulnerable because of reduced renal functional reserve, impaired blood pressure regulation, cardiovascular comorbidities, and diminished cardiovascular adaptability during acute illness (Damluji et al., 2020). Therefore, AKI prevention should not rely solely on changes in serum creatinine, which may become apparent after kidney injury has developed, but should also incorporate physiological risk indicators capable of identifying vulnerability before clinically detectable kidney dysfunction occurs.

The risk of AKI among older adults remains consistently elevated. Stille et al. (2022), in a meta-analysis of 30 studies, reported a pooled AKI incidence of 26.29% among older adults overall and 24.21% among those with acute heart failure, with AKI associated with more than threefold and fourfold increases in in-hospital mortality, respectively. Herget-Rosenthal et al.

(2025) identified AKI in 35.3% of 2,132 patients aged 80 years and older, with a 30-day mortality rate of 25.4%, compared with 7.6% among patients without AKI. Frailty was also identified as an independent risk factor (adjusted odds ratio [aOR] = 2.42; 95% confidence interval [CI]: 1.93–3.03). These findings suggest that chronological age alone does not adequately explain variations in AKI risk, highlighting the importance of physiological vulnerability and the capacity to maintain adequate organ perfusion.

One concept that may explain this vulnerability is hemodynamic frailty. Docherty et al. (2021) described this condition as an impairment in compensatory mechanisms responsible for maintaining circulating blood volume and adaptive hemodynamic responses, thereby increasing susceptibility to inadequate tissue perfusion during dehydration, fluid loss, blood pressure fluctuations, or acute physiological stress. Unlike general clinical frailty, which encompasses multidimensional declines in physiological function and resilience, hemodynamic frailty specifically concerns the cardiovascular system's capacity to maintain adequate blood flow and perfusion to vital organs. In the kidneys, uncompensated intravascular volume depletion may reduce renal blood flow, renal perfusion pressure, and glomerular filtration rate, thereby increasing the risk of AKI. This mechanism is conceptually related to acute kidney frailty, a premorbid condition characterized by diminished renal functional reserve (Sancho-Martínez & López-Hernández, 2023).

However, most studies examining the association between frailty and AKI have relied on general clinical frailty assessments rather than specific hemodynamic parameters. Beaubien-Souligny et al. (2021) investigated frailty as a determinant of mortality following severe AKI rather than as an early predictor of AKI onset. Similarly, Nowak et al. (2023) reported AKI in 57.3% of frail patients compared with 20.4% of nonfrail patients with acute coronary syndrome, using the Clinical Frailty Scale to assess frailty status. Although these findings establish frailty as an important indicator of physiological vulnerability, they do not determine whether this vulnerability can be identified through measurable hemodynamic parameters before AKI develops.

Studies directly evaluating hemodynamic parameters indicate that the relationship between circulatory dysfunction and AKI cannot be adequately explained by a single blood pressure threshold. Penev et al. (2024) identified an intraoperative mean arterial pressure (MAP) below 65 mmHg sustained for more than five minutes as the most frequently reported threshold associated with postoperative AKI, although the populations examined were not exclusively older adults. Kotani et al. (2021) found that relative hypotension following cardiac surgery was not associated with AKI progression, whereas elevated central venous pressure (CVP) and reduced mean perfusion pressure (MPP) were associated with AKI progression. Chen et al. (2022) demonstrated that both hypotension and venous congestion were associated with AKI, although only venous congestion remained associated with acute kidney disease (AKD). Furthermore, Sun et al. (2022) and Peng et al. (2022) provided additional evidence supporting the relevance of CVP and MPP variability in assessing AKI risk.

The research gap lies in the limited synthesis of evidence integrating multiple hemodynamic indicators to evaluate hemodynamic frailty as a potential predictor of AKI in older adults. Although Docherty et al. (2021) established a conceptual framework and emphasized the need for prospective investigations, Stille et al. (2022) did not specifically examine hemodynamic indicators, while Penev et al. (2024) did not exclusively investigate older adults or comprehensively evaluate CVP, MPP, cardiac output, venous congestion, and volume status.

Consequently, uncertainty remains regarding which hemodynamic parameters demonstrate the most consistent associations with AKI, which thresholds are clinically relevant, and whether combining multiple indicators provides greater predictive value than blood pressure measurements alone. Therefore, this systematic literature review aimed to identify, critically evaluate, and synthesize evidence regarding the predictive value of hemodynamic frailty, characterized by hypotension, impaired perfusion, blood pressure variability, cardiac output, venous pressure, venous congestion, volume status, and fluid responsiveness, for AKI in older adults.

METHOD

Study Design

This study employed a systematic literature review (SLR) to identify, critically appraise, and synthesize scientific evidence regarding the predictive value of hemodynamic frailty for acute kidney injury (AKI) in older adults. The review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). The search strategy was also reported following the PRISMA-S extension to ensure transparency and reproducibility in identifying and selecting relevant studies (Rethlefsen et al., 2021).

The research question was formulated using an adapted Population, Intervention, Comparison, and Outcome (PICO) framework for prognostic research. The intervention component was replaced with predictors or exposures because the review focused on evaluating the predictive value of hemodynamic vulnerability indicators for AKI occurrence rather than comparing treatment effectiveness.

Table 1. PICO Framework of the Study

Components	Operational Definition
P – Population	Older adults aged ≥60 years or populations studies with mean/median age ≥60 years that undergoing care acute, care intensive, measures surgery, cardiovascular intervention, or experienced acute illness
I – Index predictor/ Exposure	Haemodynamic frailty that represented by hypotension, mean arterial pressure (MAP), systolic/diastolic blood pressure, blood pressure variability, central venous pressure (CVP), mean perfusion pressure (MPP), cardiac output, cardiac index, venous congestion, VExUS, inferior venous cava, perfusion index, oxygen delivery, volume status, blood loss, vasopressor use, and fluid responsiveness
C – Comparison	patients with haemodynamic condition that more stable, exposure hypotension lower, perfusion pressure that more better, venous congestion lower, or group comparator consistent definition each studies
O – Outcome	AKI occurrence after measurement or exposure haemodynamic, particularly that was defined using criteria KDIGO or AKI definition that defined in a clear by researchers

Under this framework, the synthesis focused was directed in temporal relationship between haemodynamic changes and AKI occurrence. articles that only assessed condition after AKI occurred, such as mortality, renal recovery, or AKI progression that has been diagnosed, were not treated as primary predictive evidence.

Literature Search Strategy

The literature search covered for articles that published from 1 January 2021 to the final search date in August 2026. The information sources included Scopus, PubMed/MEDLINE, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, and Google

Scholar as an additional source to found articles not identified in primary search. Search was limited to articles primary research with full text that was available thereby process of assessment methodological and data extraction can be conducted for full text.

Keyword combinations constructed from three main concept groups, namely AKI, populations older adults, and indicator haemodynamic vulnerability. Boolean string main that was used is: ("acute kidney injury" OR AKI) AND ("older adult*" OR elderly OR geriatric OR aged) AND ("haemodynamic frailty" OR "hemodynamic frailty" OR haemodynamic* OR hypotension OR "mean arterial pressure" OR "blood pressure variability" OR "mean perfusion pressure" OR "renal perfusion pressure" OR "cardiac output" OR "cardiac index" OR "venous congestion" OR VExUS OR "inferior venous cava" OR "perfusion index" OR "oxygen delivery" OR "fluid responsiveness" OR "fluid balance" OR "blood loss" OR vasopressor*).

Syntax adjustments were conducted followed characteristics each database without changing concept main search.

Table 2. Article Inclusion and Exclusion Criteria

Appearance	Inclusion Criteria	Exclusion Criteria
Years	2021–2026	Published before 2021
Populations	age ≥60 years or mean/median age ≥60 years	Pediatric or populations age more younger without an older-adult subgroup analysis
Exposure /predictor	containing ≥1 indicator haemodynamic that is relevant with haemodynamic frailty	Only addressed biomarker, comorbidities, or frailty physical without haemodynamic components
Outcome	AKI as occurrence after exposure/measurement predictors	Only addressed mortality after AKI, renal recovery, or AKI progression that has occurred
Design	Prospective/retrospective cohort, case-control, observational analytical, or clinical trial studies that are relevant	Review, meta-analysis, editorials, letters, case reports, protocols, and conference abstracts
Access	Full text available	full text not was available

Study Selection and Data Extraction

All search results were compiled in one basis data reference and checked to remove duplicate articles. selection first was conducted through titles and abstracts with assessed population eligibility, haemodynamic variables, and AKI outcome. articles that passed initial screening then checked through full text. Reasons for exclusion in stage full-text assessment were recorded, particularly populations that are not consistent, absence of indicator haemodynamic, AKI not as outcome prediction, design publication that did not meet the criteria, or full text that was not available. after all stages selection completed, 36 articles met the criteria and was defined as articles final inclusion. identification process to inclusion these presented in the diagram in below this.

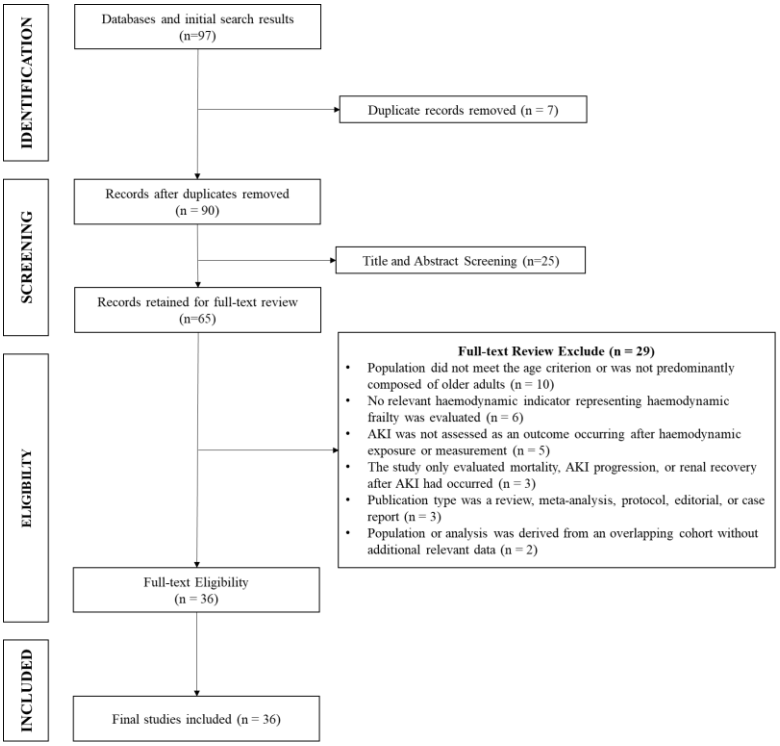


Figure 1. PRISMA 2020 Flow diagram of the Article Selection Process

Methodological quality each article assessed using JBI Critical Appraisal Tools that selected according to study design. JBI provides instrument that differs to studies cohort, case-control, cross-sectional, clinical trial, and design quantitative others thereby assessment can be directed in potential bias that relevant with design each article. assessment including clarity of participant selection, exposure measurement, ascertainment of AKI, control of confounding factors, appropriateness of the analysis, and completeness of follow-up where relevant. Appraisal Result was used to consider strength of evidence when synthesis was conducted, rather than as the sole basis for excluding articles. This approach is consistent with the function of the instruments JBI to assessed trustworthiness and limitations studies that included.

Extraction was performed using a structured form that containing Author, Year, country, Study Design, sample size, age participants, clinical condition, indicator haemodynamic, measurement method, AKI definition, observation period, measure of association, main findings, and conclusions regarding ability predictive.

Data Analysis and Synthesis

Data were analyzed through narrative synthesis and bibliometric analysis. narrative synthesis was conducted by grouping 36 articles according to the form of haemodynamic frailty, including hypotension and MAP, blood pressure variability, venous pressure and congestion, MPP, cardiac output/index, volume status and blood loss, perfusion and oxygenation network of, vasopressor use, and response for haemodynamic interventions. results then compared with according to direction of association, consistency prediction, magnitude of risk that reported, population characteristics, and clinical condition. findings that showing no significant association were also presented so that CONCLUSION not only formed by positive findings.

Bibliometric analysis was performed using VOSviewer version 1.6.21, version that available in June 2026. VOSviewer is designed to construct and visualize bibliometric networks and provides mapping through network visualization, overlay visualization, and density

visualization. Metadata from 36 articles prepared in format that can be interpreted VOSviewer, then analyzed through co-occurrence Keywords and terms in titles and abstracts. The minimum occurrence threshold was set at two so that terms that only emerged in a sporadically did not dominate the network.

Before mapping, thesaurus file was used to merge synonymous terms that with the same meaning, such as "AKI" was "acute kidney injury", "elderly" and "aged" was "older adults", "MAP" was "mean arterial pressure", "CVP" was "central venous pressure", and spelling variants "haemodynamic" and "hemodynamic". The results were presented as network map to examine thematic clustering, overlay visualization to demonstrated topic development by publication year, and density visualization to showed the most frequent terms and has strongest relationships. VOSviewer indeed developed to construct and display bibliometric mapping and association between elements literature in a visual (van Eck & Waltman, 2010). results bibliometric then integrated with narrative synthesis to assessed indicator haemodynamic frailty that most consistently was associated with AKI and part evidence that still requires further research.

RESULTS AND DISCUSSION

Descriptive Characteristics of the Articles

Characteristics descriptive was used to demonstrated pattern publication, design studies, and clinical condition that was setting observation association between haemodynamic frailty and acute kidney injury (AKI). Three characteristics these presented in one table so that overview general 36 articles can be interpreted in a more concise without separating information that were still at in level descriptive.

Table 4. Descriptive Characteristics of the Included Articles

Characteristics	Category	Number of Articles (n)	Percentage (%)
Publication year	2021	1	2,8
	2022	8	22,2
	2023	9	25,0
	2024	4	11,1
	2025	6	16,7
	2026	8	22,2
Study Design	Cohort/observational retrospective	28	77,8
	Prospective cohort/observational	5	13,9
	Randomized controlled trial	2	5,6
	Retrospective case-control	1	2,8
Main clinical condition	cardiac surgery/CABG/valve surgery	14	38,9
	Non-cardiac surgery/abdominal/urologic	8	22,2
	hip fracture/femoral and orthopedic trauma	5	13,9
	Sepsis/ICU/critical illness	6	16,7
	TAVI/TAVR	2	5,6
	Acute Heart Failure	1	2,8

Table 4 showed that publication most widely was found in 2023, namely nine articles (25.0%), followed by 2022 and 2026 that each consists of eight articles (22.2%). based on design studies, most articles using cohort or observational retrospective A total of 28 articles (77.8%), whereas prospective studies and trial randomized still relatively limited. from aspect clinical condition, cardiac surgery, CABG, or valve surgery was group largest with 14 articles (38.9%).

dominance populations these were associated with availability monitoring haemodynamic that was more intensive, including MAP, CVP, cardiac index, perfusion, and parameter during cardiopulmonary bypass. although therefore, evidence was also found in Non-cardiac surgery, fracture in older adults, sepsis, care intensive, TAVI/TAVR, and acute heart failure thereby association between haemodynamic vulnerability and AKI not only was found in patients cardiac surgery.

Methodological Quality Assessment Using JBI

After characteristics articles identified, methodological quality all studies assessed using JBI Critical Appraisal Checklist consistent design each articles. studies cohort and observational assessed using checklist cohort, studies case-control using checklist case-control, whereas trial randomized assessed using checklist randomized controlled trial. category quality was defined in an operational based on proportion answers "Yes", namely ≥80% as quality High, 60–79% as quality Moderate, and <60% as studies with methodological concerns.

Table 5. Methodological Quality Assessment of the Articles Using JBI

No.	Studies	Checklist Jbi	Appraisal Result	Category
1	Wang et al. (2023)	Cohort	8/11	Moderate
2	Li et al. (2026)	RCT	10/13	High
3	Zhang et al. (2025)	Cohort	10/11	High
4	Sun et al. (2022)	Cohort	10/11	High
5	Zhan et al. (2022)	Case-control	8/10	High
6	Peng et al. (2023)	Cohort	9/11	High
7	Andrei et al. (2023)	Cohort	10/11	High
8	Lisitano et al. (2023)	Cohort	8/11	Moderate
9	Kim et al. (2023)	Cohort	8/11	Moderate
10	Li et al. (2025)	Cohort	9/11	High
11	Qu et al. (2026)	Cohort	8/11	Moderate
12	Ge et al. (2022)	Cohort	8/11	Moderate
13	Ariyarathna et al. (2022)	Cohort	9/11	High
14	Wang et al. (2025)	Cohort	8/11	Moderate
15	Kutsal & Terzi (2024)	Cohort	7/11	Moderate
16	Chen et al. (2022)	Cohort	10/11	High
17	Haddad et al. (2023)	Cohort	8/11	Moderate
18	Li et al. (2022)	Cohort	10/11	High
19	Zhao et al. (2023)	Cohort	9/11	High
20	Demirjian et al. (2024)	Cohort	10/11	High
21	Li et al. (2026)	Cohort	9/11	High
22	Carrasco-Serrano et al. (2022)	Cohort	10/11	High
23	Nikravangolsefid et al. (2025)	Cohort	9/11	High
24	Pang et al. (2025)	RCT	10/13	High
25	Kang et al. (2023)	Cohort	9/11	High
26	Wang et al. (2023)	Cohort	8/11	Moderate
27	Lopez et al. (2021)	Cohort	10/11	High
28	Goeddel et al. (2025)	Cohort	10/11	High
29	McIlroy et al. (2026)	Cohort	9/11	High
30	Zeng et al. (2026)	Cohort	9/11	High
31	Liu et al. (2026)	Cohort	9/11	High
32	Li et al. (2024)	Cohort	10/11	High
33	Wang et al. (2024)	Cohort	9/11	High

34	Song et al. (2025)	Cohort	10/11	High
35	Xin et al. (2022)	Cohort	9/11	High
36	Liu et al. (2026)	Cohort	10/11	High

In a overall, 27 articles categorized high quality and nine articles moderated quality. Not there were articles that entered category concerns methodological severe. limitations that most frequently was found is use design retrospective, control of confounding factors that are not yet uniform, number AKI occurrence that small in some studies, and differences time measurement parameter haemodynamics. Appraisal Result was not used as baseline alone for excluding articles, but was consideration when assessed consistency findings across publications.

Characteristics and Findings of the Included Articles

All 36 articles subsequently presented to demonstrated populations, measures of sample, Haemodynamic Predictor, and main findings that was associated with AKI occurrence. Presentation all articles is required so that baseline formation synthesis can be traced from each source studies.

Table 6. Characteristics and Main Findings of the 36 Included Articles

No.	Author, Year	Sample	Population/ Condition	Haemodynamic Predictor	Conclusion
1	Wang et al. (2023)	644	Older adults, hip fracture	BNP, perioperative factors	AKI 12.1%; higher age and BNP increased risk
2	Li et al. (2026)	166	Older adults, hypertension, abdominal surgery	Individual SBP/MAP target, norepinephrine	Renal biomarkers improved; AKI not significantly different
3	Zhang et al. (2025)	163,131	≥65 years, non-cardiac surgery	Vasopressor, transfusion, perioperative factors	Predictive model: AUROC 0.77–0.80
4	Sun and al. (2022)	11,135	ICU with comorbidities	CVP	Each 1 mmHg CVP increase raised AKI odds by ~10%
5	Zhan et al. (2022)	308	>65 years, femoral neck fracture	Hypotension, blood loss	Intraoperative hypotension was an independent predictor
6	Peng et al. (2023)	2,155	Older adults, CABG	CPB, IABP, epinephrine/isoprenaline	Haemodynamic factors included in AKI prediction model
7	Andrei et al. (2023)	145	General ICU	VExUS	VExUS ≥2 not significantly associated with AKI
8	Lisitano et al. (2023)	206	Geriatric, CKD, orthopedic trauma	Blood loss	Blood loss was a major AKI predictor
9	Kim et al. (2023)	750	RALP, predominantly older adults	MAP variability/threshold	MAP did not predict AKI after adjustment
10	Li et al. (2025)	2,155	Older adults, CABG	IABP, perioperative factors	RF model showed highest AUC (0.737)
11	Qu et al. (2026)	368	Older adults, hypertension	MAP 65–75, 75–85, 85–95 mmHg	MAP 75–85 mmHg associated with better renal function
12	Ge et al. (2022)	92	Older adults, valve surgery	MAP during CPB	MAP 65–75 mmHg did not significantly reduce AKI
13	Ariyara Thna et al. (2022)	830	≥65 years, non-cardiac surgery	Hypotension, vasopressor	High vasopressor dose independently predicted AKI
14	Wang et al. (2025)	156	Older adults, hip fracture, ICU	Transfusion, perioperative factors	Intraoperative transfusion contributed to prediction model
15	Kutsal & Terzi (2024)	198	Older adults, TAVI	Right heart failure	No independent association with AKI
16	Chen et al. (2022)	5,127	Cardiac surgery	CVP, hypotension	Both associated with AKI;

					venous congestion more consistent with AKD
17	Haddad et al. (2023)	611	Hip fracture	Intraoperative factors	AKI 20.6%; haemodynamic exposure was not dominant
18	Li et al. (2022)	3,564	CABG	Postoperative CVP	CVP ≥10.9 mmHg increased AKI risk by ~50%
19	Zhao et al. (2023)	5,641	CABG	CVP during first 24 h	High/persistent CVP associated with more frequent AKI
20	Demirjian et al. (2024)	40,426	Cardiac surgery	CVP, MAP, cardiac index, HR	All four parameters strongly predicted AKI
21	Li et al. (2026)	340	TAVR	SBP/DBP variability	ARV-SBP associated with AKI; ARV-DBP was not
22	Carrasco-Serrano et al. (2022)	782	Valve surgery	Oxygen delivery index	Low DO_2i nearly doubled AKI risk
23	Nikrav Angolsefid et al. (2025)	3,128	Septic shock	CVP ≥8 mmHg	High CVP at 12 and 48 h associated with AKI
24	Düsseldorf t al. (2025)	179	≥60 years, abdominal surgery	Individualized BP targets	Hypotension decreased; 28% AKI reduction was not significant
25	Kang et al. (2023)	1,586	General surgery	Peripheral perfusion index	PPI <0.5 for >10% operative time doubled AKI odds
26	Wang et al. (2023)	781	Cardiac surgery, ≥60 years	Intraoperative/CPB Hb	Higher intraoperative Hb was protective
27	Lopez et al. (2021)	425	Cardiac surgery	Venous congestion/CVP	Intraoperative venous congestion independently increased AKI
28	Goeddel et al. (2025)	1,199	CABG	MAP and CVP	Low MAP with high CVP showed the highest AKI risk
29	McIlroy et al. (2026)	1,368	Cardiac surgery	Postoperative MAP	No MAP range independently predicted AKI
30	Zeng et al. (2026)	19,604	Acute heart failure	SBP	Nonlinear association; lowest risk around SBP 120 mmHg
31	Liu et al. (2026)	10,859	≥60 years, non-cardiac surgery	MAP	Nonlinear association; minimum risk around MAP 86 mmHg
32	Li et al. (2024)	5,867	Sepsis, ICU	MPP	MPP <63 mmHg increased AKI incidence
33	Wang et al. (2024)	2,048	Cardiac surgery with CPB	CVP during CPB	CVP ≥6.5 mmHg associated with higher AKI risk
34	Song et al. (2025)	108	Sepsis, ICU	VExUS	VExUS ≥2 not significantly associated with AKI
35	Xin et al. (2022)	849	Older adults with sepsis	MAP	MAP was an independent predictor of S-AKI
36	Liu et al. (2026)	266	CABG	ΔIVC and CVP	ΔIVC not significant; postoperative CVP independently associated with AKI

Notes: AKI = acute kidney injury; AKD = acute kidney disease; ARV = average real variability; AUC = area under the curve; AUROC = area under the receiver operating characteristic curve; BNP = B-type natriuretic peptide; CABG = coronary artery bypass grafting; CKD = chronic kidney disease; CPB = cardiopulmonary bypass; CVP = central venous pressure; DBP = diastolic blood pressure; DO_2i = oxygen delivery index; Hb = hemoglobin; HR = heart rate; IABP = intra-aortic balloon pump; ICU = intensive care unit; MAP = mean arterial pressure;

MPP = mean perfusion pressure; PPI = peripheral perfusion index; PSM = propensity score matching; RALP = robot-assisted laparoscopic prostatectomy; RF = random forest; S-AKI = sepsis-associated acute kidney injury; SBP = systolic blood pressure; TAVI = transcatheter aortic valve implantation; TAVR = transcatheter aortic valve replacement; VExUS = venous excess ultrasound; ΔIVC = changes inferior diameter venous cava.

Table 6 showed that predictive ability not distributed in an evenly in all haemodynamic indicators. CVP High and venous congestion emerged repeated as a predictor AKI in patients cardiac surgery, CABG, sepsis, and patients critically ill. conversely, association MAP with AKI more varied according to threshold pressure, duration exposure, clinical state, and characteristics baseline patients. MPP, oxygen delivery, and peripheral perfusion index also showed that assessment perfusion provided information that did not always was available through arterial pressure alone.

Synthesis of Haemodynamic Frailty as a Predictor of Acute Kidney Injury

Synthesis of 36 articles was directed in eight representations haemodynamic frailty that has been defined in aim studies, namely hypotension, reduced perfusion, blood pressure variability, cardiac output, venous pressure, venous congestion, volume status, and fluid responsiveness. Each criteria described was indicator that more specific consistent parameter that assessed in articles inclusion. separation each indicator was conducted so that direction findings, strength predictive, and limitations evidence can have been observed without combining parameters that have characteristics measurement different.

Table 7. Synthesis of Haemodynamic Frailty Indicators as Predictors of Acute Kidney Injury in Older Adults

Haemodynamic Frailty Criterion	Indicator	Key Finding	Sources
Hypotension	Minimum MAP	Lower minimum MAP was associated with higher AKI risk; the association was nonlinear.	Liu et al. (2026)
	Duration of intraoperative hypotension	Longer hypotension exposure was more strongly associated with AKI than transient hypotension.	Zhan et al. (2022); Ariyarathna et al. (2022)
	MAP threshold	A single MAP threshold did not consistently predict AKI across populations.	Kim et al. (2023)
	MAP Target 65–75 mmHg	Maintaining MAP 65–75 mmHg during CPB did not significantly reduce AKI.	Ge et al. (2022)
	MAP Target 75–85 mmHg	MAP 75–85 mmHg was associated with better kidney function in older adults with hypertension.	Qu et al. (2026)
	Individualized BP targets	Individualized BP reduced hypotension exposure, but did not significantly reduce AKI.	Pang et al. (2025); Li et al. (2026)
	SBP	Nonlinear association; lowest AKI risk was observed around SBP 120 mmHg.	Zeng et al. (2026)
	MAP in sepsis	MAP contributed to AKI prediction in older adults with sepsis.	Xin et al. (2022)
	Postoperative MAP	No postoperative MAP range consistently predicted AKI independently.	McIlroy et al. (2026)
Reduced infusion	MPP	MPP <63 mmHg was associated with higher AKI incidence in sepsis.	Li et al. (2024)
	MAP–CVP gradient	Low MAP combined with high CVP was associated with greater AKI risk.	Goeddel et al. (2025); Chen et al. (2022)
	Peripheral perfusion index	PPI <0.5 for >10% of surgery doubled AKI odds.	Kang et al. (2023)
	Oxygen delivery index	Low DO_2i during valve surgery increased AKI risk.	Carrasco-Serrano et al. (2022)
	Lactate	Higher lactate occurred with higher CVP; useful as	Zhao et al. (2023)

		a complementary perfusion marker.	
Blood pressure variability	ARV-SBP	Greater SBP variability after TAVR was associated with higher AKI occurrence.	Li et al. (2026)
	ARV-DBP	DBP variability showed weaker predictive association with AKI.	Li et al. (2026)
	Intraoperative MAP variation	MAP variation was not consistently an independent AKI predictor after adjustment.	Kim et al. (2023)
Cardiac output	Cardiac index	Low cardiac index was associated with higher AKI risk after cardiac surgery.	Demirjian et al. (2024)
	Cardiac output	Reduced cardiac output was associated with increased kidney injury risk.	Demirjian et al. (2024)
	IABP	IABP was an important component of AKI prediction models after CABG.	Peng et al. (2023); Li et al. (2025)
	BNP	Higher BNP was associated with AKI in older adults with hip fracture.	Wang et al. (2023)
	Machine-learning cardiovascular model	Random forest models combining cardiovascular and perioperative factors showed predictive value for AKI.	Li et al. (2025)
Venous pressure	CVP in critically ill patients	Higher CVP showed a graded association with AKI.	Sun et al. (2022)
	Post-CABG CVP	CVP ≥10.9 mmHg after CABG was associated with higher AKI risk.	Li et al. (2022)
	Persistent CVP	Persistently high CVP after CABG was associated with higher AKI occurrence.	Zhao et al. (2023)
	CVP during CPB	CVP ≥6.5 mmHg during CPB was associated with higher AKI risk.	Wang et al. (2024)
	CVP in septic shock	CVP ≥8 mmHg was associated with higher AKI occurrence.	Nikravangolsefid et al. (2025)
	Multi-period CVP	CVP combined with MAP and cardiac index improved AKI prediction.	Demirjian et al. (2024)
	Postoperative CVP with ΔIVC	Postoperative CVP remained associated with AKI, whereas ΔIVC was not an independent predictor.	Liu et al. (2026)
Venous congestion	Cumulative venous congestion	Longer exposure to venous congestion increased AKI risk.	Lopez et al. (2021)
	Intraoperative venous congestion	Venous congestion showed a stronger association with renal impairment than hypotension alone.	Chen et al. (2022)
	VExUS in general ICU	VExUS ≥2 was not significantly associated with AKI.	Andrei et al. (2023)
	VExUS in sepsis	VExUS did not show a consistent association with AKI in sepsis.	Song et al. (2025)
	ΔIVC	ΔIVC did not independently predict AKI after CABG.	Liu et al. (2026)
	Right heart failure	Right heart failure was not independently associated with AKI after TAVI.	Kutsal & Terzi (2024)
Status volume	Intraoperative blood loss	Greater blood loss was associated with higher AKI risk in geriatric orthopedic surgery.	Lisitano et al. (2023)
	Perioperative blood loss	Blood loss was associated with higher AKI risk after femoral neck fracture surgery.	Zhan et al. (2022)
	Intraoperative hemoglobin	Higher intraoperative Hb showed a protective tendency against AKI.	Wang et al. (2023)
	Intraoperative transfusion	Transfusion contributed to AKI prediction in older adults with hip fracture.	Wang et al. (2025)
	Perioperative transfusion	Transfusion was included as a predictor in AKI models after non-cardiac surgery.	Zhang et al. (2025)
	Intraoperative volume factors	Volume-related factors contributed to AKI risk, although not all remained independent predictors.	Haddad et al. (2023)
Vasopressor use	Vasopressor	Higher vasopressor dose independently predicted	Ariyarathna et al.

	Dosage	AKI after adjustment for hypotension.	(2022); Zhang et al. (2025)
Fluid responsiveness	Stroke volume variation	SVV was used to guide fluid optimization, but evidence for independent AKI prediction remains limited.	Pang et al. (2025)
	ΔIVC as dynamic volume indicator	ΔIVC did not consistently independently predict AKI after CABG.	Liu et al. (2026)
	Perioperative fluid optimization	Fluid management was relevant to haemodynamic management, but fluid responsiveness was not a consistent independent AKI predictor.	Haddad et al. (2023)
	Individualized haemodynamic strategy	Individualized strategies reduced haemodynamic instability, but did not consistently reduce AKI.	Pang et al. (2025); Li et al. (2026)
	Evidence limitation	Fluid responsiveness was more often used to guide therapy than as an independent AKI predictor.	Pang et al. (2025); Liu et al. (2026); Haddad et al. (2023)
Reduced infusion	Multiparameter haemodynamic factors in CABG	CPB, IABP, and vasoactive drugs jointly identified patients at higher AKI risk.	Peng et al. (2023)

Notes: AKI = acute kidney injury; [eos]ARV = average real variability; [eos]BNP = B-type natriuretic peptide; [eos]CABG = coronary artery bypass grafting; [eos]CPB = cardiopulmonary bypass; [eos]CVP = central venous pressure; [eos]DBP = diastolic blood pressure; [eos]DO_2i = oxygen delivery index; [eos]IABP = intra-aortic balloon pump; [eos]ICU = intensive care unit; [eos]IVC = inferior venous cava; [eos]MAP = mean arterial pressure; [eos]MPP = mean perfusion pressure; [eos]PPI = peripheral perfusion index; [eos]SBP = systolic blood pressure; [eos]SVV = stroke volume variation; [eos]TAVI = transcatheter aortic valve implantation; [eos]TAVR = transcatheter aortic valve replacement; [eos]VExUS = Venous Excess Ultrasound; ΔIVC = changes the lower diameter of the venous cava.

Table 7 demonstrated that ability haemodynamic frailty in predict AKI not same in all indicator. venous pressure, particularly CVP that increased or persistent, showed pattern association that most consistent, better in cardiac surgery, CABG, patients critically ill, as well as septic shock. reduced perfusion through MPP low, MAP-CVP gradient that not favorable, DO_2i low, and PPI low also showed association that sufficiently clear with AKI. in group hypotension, value MAP remained relevant, but results across studies showed that severity and duration decrease pressure more informative compared with application one MAP threshold in a uniform.

Blood pressure variability provided additional information, particularly through fluctuations SBP, whereas evidence regarding DBP still less consistent. Cardiac index and cardiac output demonstrated that adequacy flow is part important from ability renal maintain perfusion. Volume status also played a role through blood loss, changes hemoglobin, need transfusion, and dependence for support vasoactive. conversely, VExUS and ΔIVC has not demonstrated predictive ability that stable when was used as indicator alone.

Evidence regarding fluid responsiveness is part that most limited in between eight criteria. Stroke volume variation, ΔIVC, and response for strategy optimization fluid more frequently was used as guidance management haemodynamic than tested as independent predictor AKI. Findings this remained important because showed that not all components that in a theoretical represents haemodynamic frailty has has level evidence that same. In a overall, synthesis 36 articles more

supports use assessment multiparameter that includes arterial pressure, venous pressure, perfusion, flow cardiac, volume status, and dynamics response circulation to predict AKI risk in older adults.

Bibliometric Analysis Using VOSviewer

Analysis VOSviewer was used to examine interrelationships terms in 36 articles. after process of merging synonyms through thesaurus, network visualization produced six clusters. measures of node describes frequency occurrence terms, whereas line showed interrelationships between terms.

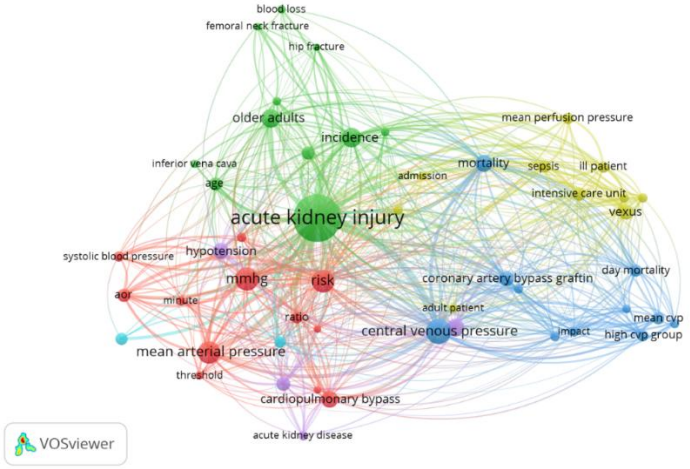


Figure 2. Network Visualization association between terms in studies Haemodynamic Frailty and Acute Kidney Injury

Network visualization demonstrated acute kidney injury as node largest and center linking six clusters. Cluster 1 centered in mean arterial pressure, systolic blood pressure, threshold, cardiopulmonary bypass, and risk, thereby describes studies that attempted to determine limit arterial pressure and duration hypotension that was associated with kidney injury. these associations have been observed in studies that assessed hypotension and vasopressor use in older adults (Ariyarathna et al., 2022), target MAP during CPB (Ge et al., 2022), and MAP as components prediction AKI in older adults with sepsis (Xin et al., 2022). Cluster 2 link acute kidney injury, older adults, incidence, blood loss, hip fracture, and inferior venous cava, that showed group studies based on older adults and perioperative factors; association blood loss and hypotension in fracture older adults has been observed in Zhan et al. (2022). Cluster 3 dominated central venous pressure, coronary artery bypass grafting, high CVP group, lactate level, and mortality. this pattern is consistent with evidence that increase CVP was associated with AKI after CABG (Li et al., 2022), that trajectory CVP has association with AKI and Lactate after CABG (Zhao et al., 2023), and that Intraoperative venous congestion was associated with AKI after cardiac surgery (Lopez et al., 2021). association CVP with AKI has also been observed in patients critically ill with comorbidities (Sun et al., 2022) and in analysis that compares effects venous congestion with hypotension (Chen et al., 2022). Cluster 4 including mean perfusion pressure, sepsis, intensive care unit, and VExUS, that demonstrated expansion assessment perfusion and congestion to patients critically ill. MPP that lower was associated with increase AKI in sepsis (Li et al., 2024), whereas VExUS initial has not demonstrated association significant in general ICU (Andrei et al., 2023). Cluster 5 merge hypotension, venous congestion, cardiac surgery, and acute kidney disease, indicates that arterial pressure and venous back pressure is two aspects that needs to be interpreted in a simultaneously; multiparameter analysis

Demirjian et al. (2024) showed interaction MAP, CVP, and cardiac index for AKI. Cluster 6 that was more small was associated with transcatheter aortic valve replacement and development, that showed emergence of haemodynamic studies in procedure valve transcatheter. overall network of also placed indicator perfusion peripheral as part from association haemodynamic–AKI, as PPI low associated with postoperative AKI by Kang et al. (2023).

After association between terms observed through network of, overlay visualization was used to determine changes focus studies according to mean Publication year.

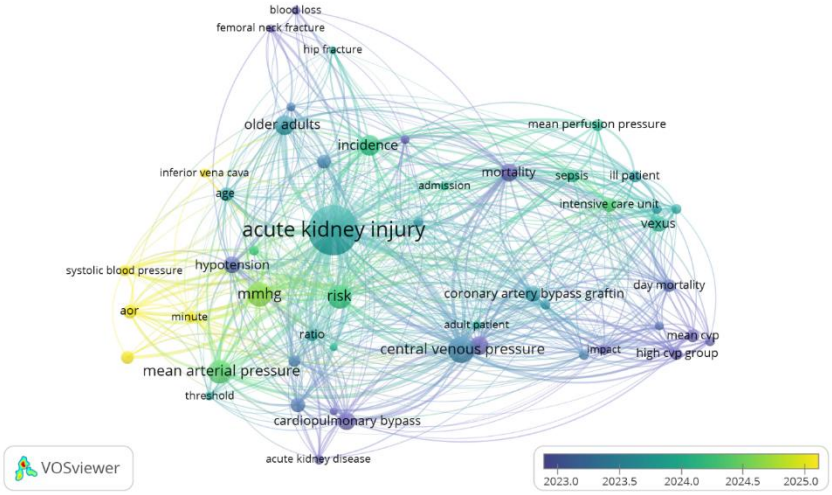


Figure 3. Overlay Visualization development themes studies Haemodynamic Frailty and Acute Kidney Injury

Overlay visualization demonstrated shift topics from studies that more initial regarding central venous pressure, CABG, cardiopulmonary bypass, and mortality toward terms that more new such as systolic blood pressure, mean perfusion pressure, VExUS, sepsis, and prediction model. color that increasingly progressing to green–yellow in terms these showed that recent studies not only assessed arterial pressure or venous separately, but began to consider variability pressure, perfusion pressure effective, ultrasonography congestion, and combination variables to predict AKI. This shift supports development concept haemodynamic frailty from assessment one parameter toward assessment response circulation that is more broad.

Density terms subsequently checked through density visualization to identify themes that most frequently emerged and has association most dense in between articles inclusion.

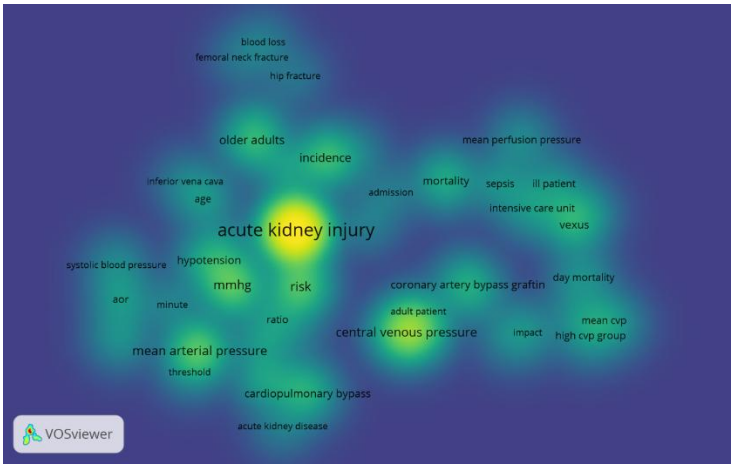


Figure 4. Density Visualization themes dominant studies Haemodynamic Frailty and Acute Kidney Injury

Density visualization showed highest density in acute kidney injury, followed by by central venous pressure, mean arterial pressure, older adults, incidence, and risk. Area with intensity that lower but remained has been observed there were in mean perfusion pressure, VExUS, inferior venous cava, blood loss, and cardiopulmonary bypass. pattern these demonstrated that literature not yet using terms haemodynamic frailty in a broad as label explicit, rather than operationalizing it through physiological components such as arterial pressure, venous pressure, perfusion, loss volume, and response circulation. With therefore, density network of supports framework studies that haemodynamic frailty in older adults is state that reflected from combination several indicators, not one measures of alone.

In an overall, synthesis of 36 articles showed that haemodynamic frailty has value as framework prediction AKI in older adults, but strength prediction different according to parameter that was used. CVP High and venous congestion provided association that most consistent, followed by by MPP low, impairment cardiac output/oxygenation, loss volume, and hypotension that sufficiently severe or prolonged. conversely, use one value MAP, VExUS, or ΔIVC separately not yet produced association that uniform. these findings support use This approach multiparameter that accounting for arterial pressure, venous pressure, flow, perfusion, volume status, and need support vasoactive when predicting AKI in patients older adults.

Haemodynamic Frailty as Reduced Reserve Circulation Renal in Older Adults

Synthesis of 36 articles showed that haemodynamic frailty more appropriately understood as reduced the ability of the circulatory system maintain renal perfusion when the body facing acute stress, not as one value blood pressure that is abnormal. pattern this important in older adults because process of aging accompanied by reduced physiological renal reserve, changes vascular responses, and increased possibility of chronic kidney disease and cardiovascular comorbidities. haemodynamic changes that can still be compensated by patients younger can produce renal consequences that differ in older adults. Merchant and Vathsala explained that aging renal was associated with reduced reserve function and increased vulnerability for impairment acute (Merchant & Vathsala, 2022). in a physiological, renal has mechanism autoregulation to maintain blood flow and filtration when pressure changes, but mechanism these were not always able to compensate for impairment circulation that severe, prolonged, or accompanied by inflammation and impairment microcirculation in acute illness (Juncos et al., 2022).

Results SLR this supports explanation these. Minimum MAP, duration hypotension, SBP, and blood pressure variability showed predictive value, but association with AKI do not form one threshold that is consistent in all populations. Ge et al. (2022) demonstrated that target MAP that higher during cardiopulmonary bypass does not automatically reduce AKI, whereas Pang et al. (2025) showed that individualization blood pressure able to reduced hypotension without produced reduction in AKI that clear. these patterns are consistent with understanding that AKI not only emerged due to arterial pressure low, but can be formed through perfusion impairment, inflammation, endothelial dysfunction, changes microcirculation, and renal baseline vulnerability (Kellum et al., 2021). With therefore, haemodynamic frailty obtain clinical meaning when blood pressure interpreted as part from ability adaptation physiological patients, not as rate that stands alone.

Venous Pressure and Gradient Perfusion Renal as Marker Risk That More Consistent

Findings that most consistent in synthesis is association increase venous pressure with AKI. CVP High or persistent repeated times was found in patients cardiac surgery, CABG, septic shock, and patients critically ill, whereas combination MAP low with CVP High provided an

overview risk that stronger compared with one one parameter separately. in a physiological, pattern these can be explained through decrease gradient pressure that driving renal perfusion. when venous pressure increased, pressure back in circulation renal also increased thereby pressure filtration effective decreased although MAP still appears adequate. congestion also increased pressure interstitial renal that can disrupt blood vessels small and tubules because renal were at in capsule that relatively not elastic (Lim & Kim, 2021).

Abe et al. placed renal congestion as an important mechanism AKI that needs to be distinguished from pure hypoperfusion, because fluid administration in patients who have already experienced congestion can increase venous pressure and worsen kidney function (Abe et al., 2023). explanation this is consistent with results Sun et al. (2022), Li et al. (2022), Zhao et al. (2023), Chen et al. (2022), and Goeddel et al. (2025), that generally placed CVP or congestion as marker risk that is more consistent than arterial pressure alone. De Backer et al. also emphasized that renal perfusion can remain impaired when blood pressure systemic as well as cardiac output appears adequate, thereby monitoring haemodynamic needs to move toward assessment organ-specific perfusion that is more specific (De Backer et al., 2024).

Recent evidence further strengthens direction these. in cardiovascular populations with age mean 74 years, venous congestion remained associated independently with AKI, whereas cardiac index low without congestion did not show independent association that same (Haurand et al., 2026). Findings These also aligned with network visualization This study that placed central venous pressure, venous congestion, mean perfusion pressure, and acute kidney injury in association thematic that closely related. By this reason, perfusion pressure effective that considers arterial aspect while also venous aspect appears more representative to interpret renal vulnerability in older adults.

Status Intravascular Volume and Response to Fluid Therapy Intravenous

Volume status was part important from haemodynamic frailty because deficiency as well as excess fluid can reduce renal perfusion quality. study findings showed that blood loss, decrease hemoglobin, need transfusion, and vasopressor use was associated with AKI in some populations older adults. however, evidence regarding fluid responsiveness as independent predictor still far more few compared with evidence regarding MAP or CVP. findings this important because patients that fluid responsive not yet necessarily obtain benefit from fluid administration additional without considering state venous. Fluid responsiveness only showed possibility increase stroke volume after preload increased, whereas decisions fluid administration remained needed to consider whether patients able to receive volume additional without experienced congestion.

Fahey et al. distinguished need resuscitation from risk accumulation fluid and emphasized need for evaluation repeated for perfusion, volume status, and sign congestion during AKI management (Fahey et al., 2024). consensus PeriOperative Quality Initiative also does not support fluid strategy that is too restrictive or too liberal to all patients; fluid therapy should be adjusted with type surgery, intravascular volume, disease concurrent, and physiological changes patients (Ostermann et al., 2024). This approach is consistent with perioperative review that placed goal-directed haemodynamic management as a strategy that combines fluid, vasopressor, and monitoring perfusion, not merely pursue target blood pressure (Douville et al., 2025).

Xing and Loh also emphasized that hypotension, management fluid, anemia, and support haemodynamic needs to be assessed together with in patients who are vulnerable for AKI (Xing & Loh, 2023). this helps explain why VExUS in articles inclusion not yet provided results

uniform. Andrei et al. (2023) and Song et al. (2025) did not find predictive ability that stable in populations that studied, whereas meta-analysis recently showed that VExUS ≥2 was associated with increase AKI in critically ill patients and these associations appear stronger in patients cardiac surgery (Melo et al., 2025). This difference showed that VExUS more consistently was used as complement assessment congestion than as replacement CVP, MPP, or evaluation volume status in an overall.

Implications Theoretical, Clinical, and Limitations Studies

In a theoretical, study findings this strengthens understanding that haemodynamic frailty not can be reduced was one value blood pressure or one indicator haemodynamic, but more appropriately understood as limitations reserve circulation in maintain organ-specific perfusion when the body facing acute stress. findings regarding association CVP, MPP, cardiac index, cardiac output, peripheral perfusion, volume status, and variation blood pressure for AKI showed that haemodynamic vulnerability formed through interaction between pressure entered, venous back pressure, adequacy flow, and ability maintain oxygenation network of. results VOSviewer also demonstrated shift attention studies from MAP and cardiopulmonary bypass toward MPP, VExUS, venous congestion, and prediction model, that showed development approach from This approach one parameter toward assessment haemodynamic that more integrated. findings these supports expansion concept haemodynamic frailty as construct physiological multiparameter that may explain why two patients with blood pressure similar can have AKI risk that different. position CVP is also insufficiently understood through one value threshold, because large increase, persistence, and its association with arterial pressure and perfusion appears more determinate for renal risk (Aligholizadeh et al., 2025).

In a clinical, study findings this showed that stratification AKI risk in older adults should not rested in one threshold haemodynamic. assessment initial remained can using arterial pressure and duration hypotension, but its interpretation needs to expand with CVP, MPP, cardiac index or cardiac output when available, peripheral perfusion indicator, Lactate, blood loss, volume status, and need vasopressor. monitoring serial more relevant compared with a single measurement because haemodynamic frailty reflects ability patients maintain stability circulation from time to time. pattern CVP that persistent High, decrease perfusion pressure, or worsening indicator flow can provide warning more initial before changes creatinine was clear. findings regarding volume status also showed that decisions fluid administration needs to consider two aspects while also, namely whether patients still require additional volume and whether circulation able to receive fluid additional without worsen congestion. by this reason, fluid responsiveness should not be interpreted separate from fluid tolerance. This approach multiparameter a form of this more consistent for patients older adults that frequently has reserve physiological more limited, cardiovascular disease concurrent, kidney function initial that varied, and response that different for vasopressor or fluid therapy. With therefore, application haemodynamic frailty in clinical practice more was directed in identifying early patients with room compensation circulation that increasingly narrow than in search one rate haemodynamic that applies for all patients.

Limitations this study particularly was associated with character available evidence. most articles inclusion used an observational retrospective, thereby association between indicator haemodynamic and AKI stronger to showed ability predictive compared with causal association. populations that studied also heterogeneous, began from cardiac surgery, Non-cardiac surgery, fracture in older adults, sepsis, care intensive, TAVI/TAVR, to acute heart failure, thereby clinical

significance one indicator did not always be applied same in each condition. definition, time measurement, and MAP threshold, CVP, MPP, VExUS, and indicator perfusion also not yet uniform. evidence regarding response to fluid therapy is part that most limited because fluid responsiveness, stroke volume variation, or haemodynamic changes after fluid administration more frequently was used to guide therapy than tested as a predictor AKI directly. in addition to this, terms haemodynamic frailty not yet was used in an explicit in most studies, thereby synthesis was conducted through indicator physiological that represents concept these. prospective studies subsequently need to use definition that more standardized, measure changes serial MAP, CVP, MPP, cardiac output, peripheral perfusion, volume status, and response to fluid therapy, then test combination indicators these in prediction model that validated in various group older adults. This approach these is required to determine whether haemodynamic frailty can be developed was tool stratification AKI risk that sufficiently stable to was used in collection clinical decisions.

CONCLUSION

The synthesis of 36 articles indicated that hemodynamic frailty has potential as a framework for predicting acute kidney injury (AKI) in older adults, although the predictive strength of individual indicators varied. Elevated central venous pressure (CVP) and venous congestion demonstrated the most consistent associations with AKI, followed by reduced mean perfusion pressure, cardiac index, oxygen delivery index, and peripheral perfusion index. Hypotension was also associated with AKI; however, its predictive value was influenced more by the severity and duration of blood pressure reduction than by a single, universally applied mean arterial pressure (MAP) threshold. Blood pressure variability, volume status, blood loss, and the need for vasoactive support provided additional information regarding diminished circulatory reserve. Conversely, the Venous Excess Ultrasound (VExUS) grading system, changes in inferior vena cava diameter, and hemodynamic responses to fluid administration did not demonstrate consistent predictive performance across the reviewed studies.

These findings suggested that clinical assessment of AKI risk in older adults should not rely solely on arterial blood pressure measurements. Monitoring CVP, perfusion pressure, cardiac output or cardiac index, tissue perfusion indicators, volume status, and serial changes in hemodynamic parameters may help identify patients experiencing impaired circulatory compensation before clinically detectable kidney dysfunction develops. This multiparametric approach is consistent with the concept of hemodynamic frailty, as renal perfusion depends on the interaction among arterial perfusion pressure, venous backpressure, cardiac output, oxygen delivery, and the patient's capacity to adapt to changes in circulating blood volume.

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CONFLICT OF INTEREST

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AUTHOR'S CONTRIBUTION

The author is responsible for all stages of the research, including the conceptualization of the research, the preparation of the methodology, the search and selection of the literature, the analysis of data, the interpretation of the results, the preparation of the manuscript, and the final revision of the article. The author has read and approved the final version of the manuscript for publication.

GENERATIVE ARTIFICIAL INTELLIGENCE USAGE STATEMENT

The author states that Generative Artificial Intelligence (AI) is not used to produce research data, conduct scientific analysis, or replace the author's intellectual contribution in the preparation of this manuscript. When used in the manuscript preparation process, AI is only used to a limited extent to help improve the language and writing structure. The author remains fully responsible for the accuracy, integrity, and final content of the manuscript.

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