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A systemic review and meta-analysis of renal injury outcomes following Piggyback versus Caval Replacement techniques in liver transplantation

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Points to Note:

1- The difference in AKI incidence after the Piggyback technique vs the Conventional Caval Replacement technique is not yet established.

2- In this meta-analysis, we found the Piggyback technique to have a 43% lower risk of postoperative AKI compared to the Conventional Caval Replacement.

3- Overall mortality was lower with PB: OR 0.60 (95% CI 0.40–0.89)

4- Future RCTs are needed to confirm this finding.

Abstract

Acute kidney injury (AKI) after liver transplantation is associated with graft loss, and mortality. Whether the piggyback (PB) technique reduces AKI compared with conventional caval replacement (CCR) remains uncertain. This meta-analysis compared PB with CCR. The protocol was registered on Prospero [1448889]. No funding was sought. We searched PubMed, Scopus, Wiley, and Cochrane through July 12th, 2026, including comparative studies of adults

undergoing whole-graft liver transplantation. Case reports, case series, reviews, letters, protocols, and non-peer-reviewed abstracts were excluded. The intervention was the PB technique versus CCR, with AKI incidence as the primary outcome. A random-effects model was applied in Python. Risk of bias was assessed using Cochrane's Risk of Bias 2 for randomized controlled trials (RCTs) and Risk of Bias in Non-randomized Studies of Interventions for observational ones, and certainty of evidence was graded with GRADE. Fifteen studies comprising 4,480 patients were included, and eleven of them (2,648 patients; 1,669 PB, 979 CCR) were pooled for AKI. The PB technique was associated with 43% lower odds of AKI compared with CCR (odds ratio 0.565, 95% confidence interval 0.408–0.783, z = –3.43, p = 0.0006, I^2 = 52.0%). Five of the 13 observational studies assessed were at serious risk of bias, and the association was not significant in the three studies using validated AKI definitions (OR 0.65, 95% CI 0.37–1.15). Certainty of evidence was very low. Overall mortality was lower with PB: OR 0.60 (95% CI 0.40–0.89). PB was associated with lower AKI in low-certainty, predominantly observational evidence, but this was not confirmed in studies using validated AKI definitions, and technique allocation was confounded by indication. Adequately powered randomized trials are needed.

Introduction

The overall incidence of acute kidney injury after liver transplant is between 25% and 60% and is associated with renal replacement therapy, graft loss and mortality[1]. The piggyback (PB) technique for liver transplant was introduced in 1989 to preserve the recipient inferior vena cava, maintain hemodynamic stability, avoid venovenous bypass (VVB) and reduce blood loss; renal protection was suggested only by later studies It has since been widely adopted in many centers [2], and there has been an ongoing debate on whether it is better than the conventional caval replacement (CCR) technique for liver transplant, primarily for renal injury outcomes.

However, there is a paucity of high-quality, well-designed randomized controlled studies on the subject, and only two previous meta-analyses exist [3, 4], with both finding no significant difference in renal injury outcomes between the two techniques. The earlier network meta-analysis pooled three techniques (CCR, standard PB and modified PB) and included many older studies[3]. We therefore compared PB directly with CCR. The primary outcome was AKI incidence; secondary outcomes were operative time, blood loss, ICU stay, renal replacement therapy, biliary complications, and survival.

Methods

The study protocol was registered on Prospero before study search began [1448889].

Institutional review board approval was not needed.

Search strategy

PubMed, Scopus, Wiley Library, and Cochrane were searched using these search strings. The last search was conducted on 12th of July, 2026.

PubMed

("liver transplantation"[MeSH] OR "liver transplant*"[tiab] OR "orthotopic liver transplant*"[tiab]) AND ("piggyback"[tiab] OR "piggy-back"[tiab] OR "cavocavostomy"[tiab] OR "modified piggyback"[tiab] OR "standard piggyback"[tiab]) AND ("caval replacement"[tiab] OR "conventional technique"[tiab] OR "venovenous bypass"[tiab] OR "veno-venous bypass"[tiab]) AND ("acute kidney injury"[tiab] OR "AKI"[tiab] OR "renal failure"[tiab] OR

"renal dysfunction"[tiab] OR "renal function"[tiab] OR "creatinine"[tiab] OR "RIFLE"[tiab] OR "KDIGO"[tiab] OR "dialysis"[tiab])

Scopus

("liver transplant*" OR "orthotopic liver transplant*") AND ("piggyback" OR "cavocavostomy" OR "modified piggyback" OR "standard piggyback") AND ("caval replacement" OR "conventional technique" OR "venovenous bypass" OR "veno-venous bypass") AND ("acute kidney injury" OR "AKI" OR "renal failure" OR "renal dysfunction" OR "renal function" OR "creatinine" OR "RIFLE" OR "KDIGO" OR "dialysis")

Wiley

"Title: ("piggyback" OR "cavocavostomy") AND Abstract: ("caval replacement" OR "conventional technique" OR "venovenous bypass") AND Abstract: ("acute kidney injury" OR "renal dysfunction" OR "renal failure")"

Cochrane

("liver transplantation" OR "liver transplant" OR "orthotopic liver transplantation") AND (piggyback OR "modified piggyback") AND ("caval replacement" OR "conventional technique" OR "venovenous bypass") AND ("acute kidney injury" OR "renal dysfunction" OR "renal failure")

Randomized and non-randomized comparative studies were eligible. Case reports, case series, reviews, letters, study protocols, and abstracts without peer review were excluded.

Population, Intervention, Comparator, Outcome (PICO)

The population was adults 18 years or older who received whole-graft liver transplants (auxiliary and split-graft transplants were excluded because caval replacement cannot be applied to them). The primary intervention was the PB (standard or modified) technique, compared with the CCR technique (with or without veno venous bypass (VVB)). The main outcome was the incidence of acute kidney injury (AKI), with the secondary ones being operative time, blood loss, ICU stay, graft/patient survival, and biliary complications.

Data Screening

Two independent reviewers independently screened abstracts, and then full texts against our eligibility criteria, using Rayyan (Rayyan Systems Inc.) software on blind mode. Disagreements were resolved by discussion and consensus between the two reviewers.

Data extraction

Two independent reviewers then extracted data into a standardized Microsoft Excel 2016 spreadsheet (Microsoft Corporation, Redmond, WA, USA), covering baseline characteristics: study ID, Country, single/multicenter, study design, total sample size per arm, follow-up duration in months for each arm, age, male patients' percent, etiology of liver disease, model for end-stage liver disease (MELD) score, body mass index (BMI), PB or CCR subtype, whether VVB was used, graft type, cold ischemia time, warm ischemia time, donor type for each arm, renal replacement therapy (RRT) usage, whether the randomization method was described, allocation concealment, blinding of outcome assessors, and blinding type; and outcomes: AKI events per arm, AKI criteria, AKI stage, biliary complications, intensive care unit (ICU) stay

(days), blood loss (ml), operative time (minutes), 1 year patient survival, and overall mortality. Extraction discrepancies were resolved by discussion and consensus between the two reviewers.

Statistical Analysis

Dichotomous outcomes were pooled on the log odds ratio (OR) scale, using inverse-variance weighting under the DerSimonian–Laird (DL) random-effects estimator. A significance level of $P < 0.05$ was considered significant. Continuous outcomes were pooled as mean differences, with the same DL random-effects estimator and z-test. Random-effects model DL was run in Python (Python Software Foundation, Wilmington, DE, USA) software (NumPy, SciPy). Four subgroup analyses, prespecified in the PROSPERO protocol, were run according to study design (RCT vs observational), AKI definition (KDIGO, RIFLE/AKIN, other), use of VVB in the CCR arm (studies whose CCR arm used VVB vs studies whose CCR arm did not), and PB subtype (standard vs modified). Between-subgroup differences were tested with Cochran's Q. Heterogeneity was assessed using Cochrane's Q, I^2, and τ^2. Forest plots were made for each outcome.

Risk of bias assessment

Cochrane's Risk of Bias 2 tool (RoB 2) tool was used for risk of bias assessment for randomized controlled trials (RCTs), and Risk of Bias in Non-randomized Studies of Interventions (ROBINS-I tool) was used for observational ones. Two independent reviewers ran each assessment, and disagreements were resolved by discussion and consensus between them.

Sensitivity Analysis

Sensitivity analyses included leave-one-out analysis, RCTs only analysis, studies with more than 30 n per arm only analysis, and lower-risk-of-bias studies only reanalysis, defined as (1) ROBINS-I overall ≤ Moderate OR RoB2 ≤ Some concerns; (2) AKI defined using KDIGO or RIFLE criteria for AKI outcome; (3) Both arms with complete N data). Publication bias was assessed with a funnel plot and Egger's linear regression test for the primary AKI outcome. A further sensitivity analysis added the direct PB-versus-CCR studies from the two previous meta-analyses that were not included in this review.

Certainty of evidence

Certainty of evidence was assessed by GRADE approach, applied to the primary outcome, rated by two independent reviewers, with disagreements resolved by discussion and consensus.

Results

The search and review were conducted in accordance with PRISMA 2020 guidelines (Figure 1). The search identified 71 records. After removal of 35 duplicates, 36 records were screened by title and abstract and 21 were excluded; all 15 full-text reports assessed were included. Eleven of these 15 studies provided dichotomous AKI event counts in both arms (table 1)[6–16], four studies reported renal outcomes only as continuous trajectories or narratively, and were, therefore, excluded from the primary pooled analysis [17–20]. A total of 4,480 patients were included, with 2,890 in the PB arm and 1,590 in the CCR arm.

The analysis revealed 43% lower odds of AKI with the PB technique than with the CCR technique. Pooled OR = 0.565, 95% confidence interval (CI) = 0.408–0.783, z = –3.43, p =

0.0006. Heterogeneity was moderate to substantial ($Q = 20.85$, $df = 10$, $p = 0.022$, $\tau^2 = 0.125$, $I^2 = 52.0\%$) (figure 2).

All the individual studies were consistent with favoring piggyback, except Sutherasan et al. 2022 (OR = 2.33, CI = 0.28–19.45) (figure 2).

Subgroup Analyses

The direction and magnitude of benefit favoring piggyback was consistent across all four subgroups, and none of the between-subgroup differences reached statistical significance (all Q-between $p > 0.10$) (table 2) (figure 3). This suggests the moderate heterogeneity ($I^2 = 52\%$) was not explained by any of the subgroups. Moreover, the RCT subgroup ($k = 2$) was too small, and the CI too wide ($p= 0.27$, CI= 0.07–1.00 $I^2=0\%$, Q-between $p= 0.261$), to draw firm conclusions.

Risk-of-Bias Assessments

RoB 2 risk-of-bias assessment

Both RCTs were rated as having some concerns (table 3): Jovine et al. because allocation concealment and sequence generation were not reported, and Brescia et al. because the trial registry did not fully pre-specify endpoints.

ROBINS-I risk of bias assessment

Of the 13 observational studies assessed (table 4), 5 were at serious overall risk of bias (Hannon et al., Laroche et al., Nishida et al., Cabezuelo et al., Sutherasan et al.) and 8 were at moderate risk. The main sources of bias were indication-driven technique allocation, historical controls, imbalance in VVB use, and non-validated AKI definitions. Only three studies (Brescia et al.,

Sakai et al., Widmer et al.) used validated AKI criteria (RIFLE or KDIGO) and were at moderate risk of bias or better.

Grade approach for all study outcomes

Certainty of evidence for the primary AKI outcome was very low, downgraded for risk of bias, inconsistency, imprecision, and suspected publication bias (table 5). For the three studies using validated AKI criteria, certainty was low. Certainty was low or very low for all other outcomes.

Sensitivity Analyses

Leave-one-out

The results were not swayed by any single study, with pooled OR ranging from 0.52 to 0.62 across all 11 leave-one-out iterations, with every confidence interval excluding 1, even when excluding the study with the aberrant findings, Sutherasan et al. 2022, OR 0.55 (0.40–0.76), I^2= 53.3% (table 6).

Studies with ≥30 patients/arm only

k = 6: OR = 0.60 (0.44–0.83), p = 0.002, I^2 = 58%. Consistent with the primary result.

High-Quality Studies Only

Studies excluded: Hannon et al., 2020, Laroche et al., 2021, Nishida et al., 2006, Cabezuelo et al., 2003, Sutherasan et al., 2022 (Serious ROB); Khan et al., 2006, Hesse et al., 2000, Nikeghbalian et al., 2014, Jovine et al., 1997 (non-validated AKI criteria); Reddy et al. 2000, Vieira de Melo et al. 2011 (AKI not reported).

Restricting AKI outcomes analysis to high-quality studies gave a pooled OR of 0.65 (95% CI 0.37–1.15; k = 3; I^2 = 48%) compared with 0.565 in the full set. The point estimate was similar, but the confidence interval widened and included no effect, so the association was not statistically significant in this subset. With only three studies this analysis is imprecise, and the benefit seen in the full set may partly reflect confounding and non-standardized outcome ascertainment in lower-quality studies. GRADE certainty for this high-quality subset was LOW (observational evidence base; imprecision due to limited events) (table 5).

Publication Bias

Funnel plot revealed mild asymmetry by visual inspection, but with only 11 studies (several very small, e.g., Jovine k=37, Laroche k=46,) this was difficult to interpret reliably.
Egger's regression test intercept was –0.78 and the standard error (SE) was 0.80, the test statistic (t) = –0.98, p = 0.354, revealing no statistically significant evidence of publication bias (Figure 4).

Secondary outcomes analyses:

Operative Time

The piggyback technique significantly reduced operative time across 6 pooled studies MD: −51.1 min (95% CI = −75.3 - −27.0), z = −4.15, p < 0.0001, Q = 13.39, df = 5, p = 0.020; I^2 = 62.7%; τ^2 = 530.3 (figure 5).

Operative Time Leave-one-out sensitivity analysis

The trend was unchanged in every leave-one-out iteration (range −42.7 to −59.2 min). However, heterogeneity was substantial, I^2 = 63%.

ICU Stay (days)

Pooled analysis: −1.22 days (95% CI = −2.63 - +0.20), k = 4, z = −1.69, p = 0.091, Q = 0.20, df = 3, p = 0.977; I^2 = 0%; τ^2 = 0 (figure 6).

ICU Stay (days) Leave-one-out sensitivity analysis

Piggyback was associated with a numerically shorter ICU stay across 4 pooled studies with no heterogeneity (I^2 = 0%), but the difference was not statistically significant (p = 0.091), and this finding was stable on leave-one-out analysis.

Biliary Complications

Pooled OR: 1.98 (95% CI = 0.87 - 4.49), k = 4, **z** = 1.64, p = 0.102, Q = 6.32, df = 3, p = 0.097; I^2 = 52.5%; τ^2 = 0.319 (figure 7).

Biliary Complications Leave-one-out sensitivity analysis

The pooled estimate was neither significant (OR 1.98, p = 0.102) nor stable. Omitting Sutherasan et al. 2022 (the smallest and most imprecise contributor) shifted the pooled OR from 1.98 to 2.67 and made the result significant (95% CI = 1.51–4.72). Removing Widmer et al. 2018 pulled the other direction (OR 1.14). With only 4 studies and borderline heterogeneity, this outcome should be interpreted conservatively. No conclusion can be drawn on biliary complications.

1-Year Patient Survival

Pooled OR 1.60 [0.90–2.86], k = 8, z = 1.66, p = 0.108, Q = 13.12, , df = 7, p = 0.069; I^2 = 46.7%; τ^2 = 0.269 (figure 8).

1-Year Patient Survival Leave-one-out sensitivity analysis

The pooled OR favored piggyback but did not reach significance. Moreover, omitting Sakai et al., 2010 (the largest positive contributor) pulled it to 1.28 (0.85, 1.93), while omitting Nikeghbalian et al. 2014 (the one study favoring conventional) pushed it to a significant 1.83 (1.01, 3.33). This outcome was borderline, with two individual studies doing most of the work in opposite directions.

Mortality (Overall / Study-Period)

Pooled OR: OR 0.60 (95% CI 0.40–0.89), p = 0.012; Q = 13.00, df = 8, p = 0.112; I^2 = 38.4%; τ^2 = 0.127 (Figure 9).

Mortality (Overall / Study-Period) Leave-one-out sensitivity analysis

Mortality was the only secondary outcome reaching statistical significance, and the most robust in sensitivity testing. Heterogeneity was moderate (I^2 = 38.4%), but Q was not significant (p = 0.114), so this was a comparatively stable finding within this dataset.

Blood Loss (mL)

Four studies reported blood loss means between PB versus (vs) CCR (Hannon et al. 2020: 2000 vs 2500 mL; Jovine et al. 1997: 2100 vs 2500 mL; Nikeghbalian et al. 2014: 1529 vs 2319 mL; Sutherasan et al. 2022: 3500 vs 3100 mL), but only Jovine et al. 1997 reported a usable SD for both arms., so this outcome could not be quantitatively pooled.

Three studies numerically favor piggyback (Hannon et al., Jovine et al., Nikeghbalian et al.); Sutherasan et al. 2022 favored conventional. This evidence was not strong enough to draw a directional conclusion

Cross-Outcome Summary

Piggyback was associated with shorter operative time and lower overall mortality, both stable on leave-one-out analysis, although both are likely confounded by indication. ICU stay, 1-year survival and renal replacement therapy showed no significant difference, and the 1-year survival and biliary complication estimates were unstable on leave-one-out analysis.

Discussion

These results show an association between the PB technique and a lower risk of AKI compared with the CCR technique. However, the certainty of evidence was very low, the association was not statistically significant in the three studies using validated AKI definitions (OR 0.65, 95% CI 0.37–1.15), and renal replacement therapy did not differ significantly. The findings are in sharp contrast with [3] Khajeh et al 2023 and Gurusamy et al. 2011[4], who found no significant differences in AKI incidence. This discrepancy could be explained by that, in contrast to this study, they included any study comparing 2 of the 3 surgical techniques, which led to the inclusion of 25 more studies, many of them older [20, 21]. This analysis included only studies that compared the intervention and comparator, but this restriction may also reflect study selection and the use of non-validated AKI definitions, so our findings should not be read as overturning earlier conclusions. The analysis also included a new 2022 study [13].

It has long been theorized that the PB technique, which avoids total clamping of the inferior vena cava (IVC), would not reduce vena cava flow as much as CCR technique [20]. Our findings are consistent with this theory but cannot confirm it.

Renal perfusion pressure, the critical determinant of renal blood supply[22], is affected by both arterial supply and venous outflow. During liver transplantation, decreases in preload are related to hemorrhage and inferior vena cava clamping (IVCC), resulting in a decreased cardiac output[23]and hypovolemia [24], thereby reducing renal arterial blood supply. Moreover, IVCC increases renal venous pressure, causing venous congestion. Critically, venous congestion impairs renal perfusion pressure more than an equivalent arterial pressure drop[25], highlighting

that minimizing IVC clamping time is paramount to minimizing the risk of AKI development[26].

Additionally, renal perfusion pressure was found to correlate mechanistically with either liver transplant technique: where complete IVCC in caval replacement is associated with substantial renal ischemia, partial clamping in piggyback dampens this effect, with one study finding renal perfusion pressure differing significantly between the two techniques (median 18 mmHg IQR 8–25 with PB vs 24 mmHg IQR 19.5–27 with CCR)[27]. Even more, renal pressure gradient was directly associated with the probability of AKI (OR 1.06 per 1 mmHg; 95% CI =1.01–1.13)[27].

As has been suggested by earlier studies[11], VVB use in the CCR technique was not associated with a clear renal benefit in our subgroup analysis (CCR with VVB, OR 0.52; CCR without VVB, OR 0.59; between-subgroup p = 0.697). VVB decompresses the portal vein and iliac/femoral vein, returning blood to the systemic circulation via the axillary vein, thereby maintaining cardiac preload and MAP. On the other hand, it does not decompress the renal veins directly. During full IVCC in CR, the IVC is ligated above the renal veins. Renal venous outflow is, therefore, obstructed regardless of whether VVB is running, so the renal vein pressure remains elevated[27].

Furthermore, in all the included studies, VVB was selectively used in patients with worse hemodynamic tolerance, higher MELD scores, or pre-existing renal impairment, introducing systemic bias. Naturally, any comparison of CR with VVB vs PB (no VVB) will favor the PB arm. This confounding variable was captured in Schmitz et al. 2014 [20], where within the CR arm, the VVB subgroup had significantly higher MELD scores (p=0.008).

This finding should not be over-interpreted. A large retrospective study of non-piggyback transplants found that VVB was associated with a lower incidence of postoperative AKI in recipients with compromised pretransplant renal function (creatinine ≥1.2 mg/dL; 37.2% vs 50.8%), but not in those with normal pretransplant renal function[28]. Because VVB was used selectively in our included studies, comparisons of CCR with VVB are biased against that arm, and our subgroup analysis cannot determine whether VVB offsets the renal effect of caval clamping. The choice of caval technique therefore cannot be considered separately from the use of VVB.

Besides, many centers used a trial clamping approach, whereby they clamped the IVC briefly, instituting VVB only if hemodynamics deteriorated. Patients who tolerated clamping, and therefore did not receive VVB, were inherently hemodynamically more robust, creating two biases simultaneously: Patients who received VVB in the CR arm had an inflated AKI rate, while those who did not receive it had a deflated AKI rate.

The secondary outcomes analyses echoed previous studies. The PB technique seemed to reduce operative time[17,28], owing to omitting one anastomosis. Piggyback technique was also associated with a numerically, but not significantly, shorter ICU stay [16, 30], possibly due to shorter operation duration, with less time under anesthesia, or due to less anatomic disruption and tissue trauma compared to vena cava replacement. It could also be explained by reduced hemodynamic compromise intraoperatively. Furthermore, in contrast to previous meta-analyses[3], piggyback showed a trend toward improved 1-year survival (OR 1.60 , p = 0.108),

and was associated with lower overall mortality (OR 0.60, p = 0.012), although allocation by clinical indication makes this finding susceptible to confounding.

Biliary complications showed a non-significant and unstable trend toward being more frequent with PB. If real, this could be explained by the relative paucity of experience with this technique, being much more novel than the long-established CCR technique. In one study[15], each successive year after adoption of the PB technique correlated with a higher rate of success.

Most of the included studies found that piggyback technique required less blood products[5, 10, 15], with the cause probably being less tissue trauma, due to avoiding retro-hepatic IVC dissection, and less intraoperative hemodynamic compromise. These findings echo earlier analyses[15].

An outcome that was not analyzed is hepatic venous outflow obstruction (HVOO). Tzakis et al. 1989[20] originally described the piggyback technique as anastomosing the recipient's middle and left hepatic veins (MHV and LHV, respectively) with the donor's IVC. This led to frequent stenosis or kinking of the graft venous outflow path[31–33]. It was theorized that this was due to caliber mismatch between the anastomosed hepatic veins and the much wider vena cava[34] Cescon et al. 2005 [34] found that anastomoses between LHV and MHV without cavoplasty carried a 10.8% risk of HVOO. On the other hand, only 1.8% of cases developed this complication when the venous cuff included a portion of the caval wall longer than 1 cm, consolidating that wider caliber anastomoses reduce the risk of HVOO. Eventually, surgeons began modifying the technique to address this issue, at first attempting to include all three veins in their anastomosis. Robles et al.[32] found HVOOs significantly more common with two-vein anastomosis [8%] compared to three-vein anastomosis (1.2%). By the same token, Parrilla et al.

[31]. found that the incidence of acute Budd-Chiari syndrome was 1.6% when using two veins, but only 0.28% when using all three veins. Finally, authors attempted to forgo the hepatic veins altogether, and instead anastomosed the recipient vena cava to that of the donor. Calne et al described the end to side cavocavostomy technique in 1968 [35]. Afterwards, Belghiti et al modified the technique into the now popular side to side cavocavostomy in 1992[36].

A major limitation in this study is the observational nature of most included studies, with only two RCTs pooled. Moreover, in all but one study[12], technique allocation was by surgeon's preference. Patients chosen to undergo CCR were more likely to have difficult anatomy due to cirrhosis, or hepatocellular carcinoma near the IVC, or Budd Chiari syndrome, or even a large caudate lobe[10, 12, 16]. More crucially, patients who were predicted to not tolerate IVC clamping were allocated into the piggyback group[17]. Combined, these two sources of bias confounded the results, particularly the AKI risk, operative time, ICU stay time, and mortality. Also, Jovine 1997[6] and Sutherasan et al. 2022[14] required continuity correction (due to zero cells), with Sutherasan et al.'s conventional arm having only 11 patients, making effect outcomes imprecise. Furthermore, 4/15 extracted studies could not contribute to the primary dichotomous outcome, reducing power and introducing selective-outcome-reporting bias. Only 3 of the 11 studies used validated AKI criteria, so outcome misclassification is likely, and VVB use varied and was applied selectively. Finally, the GRADE assessments ranged between low to very low, owing to small study number and sample sizes, and significant heterogeneity (table 5).

In low-certainty, predominantly observational evidence, the piggyback technique was associated with lower AKI, shorter operative time, and lower overall mortality than caval replacement, with no significant difference in renal replacement therapy, ICU stay or 1-year survival. The AKI association was not significant in studies using validated definitions, and confounding by indication and selective VVB use limit interpretation. Choice of technique should remain based on anatomy, disease, and center experience. Adequately powered randomized trials using standardized KDIGO-defined outcomes, with technique and VVB use analyzed together, are needed.

Table 1. Characteristics and AKI Incidence in Included Studies

Study	Design	AKI definition	PB events/N	Conv events/N	OR [95% CI]
Jovine 1997 et. al.	RCT	Other	0/18	4/19	0.09 [0.00–1.87]*
Cabezuelo 2003 et. al.	Retrospective	Other	14/80	43/104	0.30 [0.15–0.60]
Hesse 2000 et. al.	Prospective	Other	15/73	6/25	0.82 [0.28–2.41]
Khan 2006 et. al.	Prospective	Other	62/246	43/138	0.74 [0.47–1.18]
Sakai 2010 et. al.	Retrospective	RIFLE	26/169	33/95	0.34 [0.19–0.62]
Nikeghbalian 20 et. al. 14	Retrospective	Other	49/172	18/55	0.82 [0.43–1.57]
Brescia 2015 et. al.	RCT	RIFLE	7/17	10/15	0.35 [0.08–1.48]
Widmer 2018 et. al.	Retrospective	KDIGO	26/177	30/201	0.98 [0.56–1.73]
Laroche 2021 et. al.	Retrospective	KDIGO	2/29	8/17	0.08 [0.01–0.47]
Sutherasan 2022 et. al.	Retrospective	RIFLE	17/90	1/11	2.33 [0.28–19.45] *
Hannon 2020 et. al.	Retrospective	Other	241/598	155/299	0.63 [0.47–0.83]

Summary of study designs, AKI definitions, and event counts for the 11 studies included in the primary AKI meta-analysis: Jovine et al. 1997 [6], Cabezuelo et al. 2003 [7], Hesse et al. 2000 [8], Khan et al. 2006 [9], Sakai et al. 2010 [10], Nikeghbalian et al. 2014 [11], Brescia et al. 2015 [12], Widmer et al. 2018 [13], Laroche et al. 2021 [15], Sutherasan et al. 2022 [14], and Hannon et al. 2020 [16]. *0.5 continuity correction applied (zero cell present). Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of

Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

Table 2. Subgroup Analysis for AKI Risk

Subgroup	k	Pooled OR [95% CI]	I^2	Q-between p
Design — RCT	2	0.27 [0.07–1.00]	0%	0.261
Design — Observational	9	0.59 [0.42–0.83]	57%	
AKI definition — KDIGO	2	0.33 [0.03–3.63]	86%	0.693
AKI definition — RIFLE/AKIN	3	0.44 [0.19–1.03]	32%	
AKI definition — Other	6	0.61 [0.46–0.83]	31%	
Conventional-arm VVB — With	5	0.52 [0.31–0.85]	37%	0.697
Conventional-arm VVB — Without	6	0.59 [0.37–0.96]	64%	
Piggyback subtype — Standard	5	0.48 [0.31–0.74]	55%	0.329
Piggyback subtype — Modified	6	0.68 [0.40–1.16]	46%	

Detailed subgroup results for AKI risk comparing Piggyback vs. Conventional techniques, categorized by study design, diagnostic criteria, and surgical modifications. Data are pooled from the 11 primary studies [6–16]. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

Table 3. Risk of bias assessment of included randomized controlled trials using the Cochrane Risk of Bias 2 (RoB2) tool.

Study	Country	Design	D1: Randomization Process	D2: Deviations from Intended Interventions	D3: Missing Outcome Data	D4: Outcome Measurement	D5: Selection of Reported Results	Overall RoB
Jovine et al., 1997 [6]	Italy	RCT	Some concerns Allocation concealment not reported; sequence generation method unclears	Low No VVB in PB arm by design; co-intervention imbalance unlikely to bias primary outcome; care providers aware of allocation (open-label surgery)	Low Only 1/39 patients lost (2.6%); no differential attrition between arms	Low Objective surgical/clinical outcomes; assessors not blinded but AKI events hard outcomes	Some concerns Protocol not pre-registered; outcomes selected post-hoc; limited reporting of all pre-specified endpoints	Some concerns Adequate randomization uncertain; lack of pre-registration raises selective reporting concerns
Brescia et al., 2015 [12]	Brazil	RCT	Low Explicit computer-generated randomization and sequentially-numbered	Low Deviation from assigned technique not reported; VVB always	Low 28-day renal follow-up complete for all 32 patient	Low AKI assessed using RIFLE criteria from serum creatinine	Some concerns Trial registered (RBR-8n4yvk); however, primary/secondary	Some concerns Well-conducted small RCT; primary concern is

			opaque sealed envelopes (SNOSE); allocation concealment adequate	used in conventional arm per protocol; no evidence of non-adherence	s; 0% missing primary outcome data	(objective biomarker); blinding of outcome assessors not explicitly described but little scope for bias on hard laboratory endpoints	endpoints not fully listed in registry; risk of outcome-reporting bias cannot be excluded	possible selective outcome reporting given incomplete registry pre-specification

Two randomized controlled trials were assessed across five domains: (D1) randomization process; (D2) deviations from intended interventions; (D3) missing outcome data; (D4) outcome measurement; and (D5) selection of reported results. Each domain was rated as Low, Some Concerns, or High risk of bias, with an overall judgment assigned per trial. Jovine et al. (1997) and Brescia et al. (2015) both received an overall rating of Some Concerns, primarily due to uncertainty around allocation concealment and incomplete pre-registration of outcome endpoints, respectively. Yellow: some concerns; Green: Low concerns. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

Table 4. Risk of bias assessment of included observational studies using the ROBINS-I tool.

Study	Country	Design	D1: Confounding	D2: Participant Selection	D3: Classification of Interventions	D4: Deviations from Intended Interventions	D5: Missing Data	D6: Outcome Measurement	D7: Selection of Reported Results	Overall RoB
Hannon et al., 2020 [16]	USA	Retrospective cohort	Serious Major confounders (MELD, DCD rate, era) differ between groups; DCD 10.7% PB vs 7.4% CR; no multivariable adjustment for all confounders	Serious non-randomized allocation; selection criteria for PB vs CR not stated; temporal bias (technique evolution over study period)	Low Techniques clearly defined; standard PB and caval replacement; no ambiguity in group assignment	Low Deviation from intended IVC technique unlikely once operative decision made; VVB not used in either group	Low Large retrospective cohort with complete AKI and RRT data; minimal attrition reported	Low AKI criteria not explicitly stated (labelled 'Other'); no validated tool (KDIGO/RIFLE) mentioned; potential misclassification	Moderate Retrospective design; unclear if AKI endpoint was pre-specified; selective reporting of outcomes cannot be excluded	Serious Serious confounding and selection bias; AKI definition non-standardized

Khan et al., 2006 [9]	United Kingdom	Prospective cohort	Moderate VVB used in 100% of CR vs 0% PB; MELD difference (13.8 vs 15); prospective design reduces some confounder risk	Moderate Prospective allocation though not randomized; selection criteria for technique not fully described; potential operator preference bias	Low Techniques explicitly defined (PC-LT vs CON-LT); VVB use clearly documented	Low VVB imbalance is a significant co-intervention but inherent to the technique comparison	Low Prospective design; minimal missing data; limited loss to follow-up	Moderate AKI criteria labelled 'Other'; no KDIGO/RIFLE; renal outcomes likely extracted from clinical notes	Low Study predates mandatory trial registration but all major stated outcomes reported	Moderate Moderate bias overall; VVB imbalance complicates causal inference; renal endpoint not validated
Sakai et al., 2010 [10]	USA	Retrospective cohort	Moderate DCD rates differ (8.0% PB vs 4.8% CR); cold ischemia longer in CR; MELD not reported; some adjustment may exist	Moderate non-randomized; indication for VVB in CR arm introduces selection pressure; era effect possible	Low Techniques clearly separated (PB-Only vs RCR+VVB); third arm (PB+VVB) excluded from this extraction	Low VVB mandatory in CR; not used in PB-Only; co-intervention inherent to study question	Moderate Retrospective design; some missing data in AKI denominators (169/174 PB; 95/104 CR)	Low RIFLE criteria used; standardized and reproducible; objective creatinine-based classification	Moderate Retrospective; not pre-registered; outcomes appear clinically motivated. Post-hoc selection possible	Moderate Moderate risk overall; RIFLE adds credibility; confounding by DCD rate and ischemia times remains

Laroche et al., 2021 [15]	France	Retrospective cohort	Serious Re-transplantation cohort: PB feasibility depended on prior anastomosis type; groups differ in baseline IVC anatomy; no propensity adjustment	Serious Technique determined by feasibility (prior PB → PB retransplant); selection not independent of anatomy; major selection bias	Low Techniques clearly defined (caval preservation vs caval replacement at retransplant)	Low No evidence of deviation from intended technique; VVB excluded from this subgroup by design	Low Complete case data for primary KDIGO endpoint; small sample (n=46) limits precision	Low KDIGO criteria applied; standardized; objective creatinine-based	Moderate Retrospective, not pre-registered; AKI chosen as primary outcome post-hoc likely	Serious Serious: selection bias is fundamental. Groups differ in anatomy, not just technique preference
Nishida et al., 2006 [19]	USA	Retrospective cohort	Serious CR arm enriched for tumor proximity to cava (32.2% tumor vs 5.9% PB); selection for CR was indication-driven; no propensity	Serious CR selected for anatomically complex cases; groups structurally incomparable; large imbalance in n (918 vs 149)	Low Techniques clearly defined; three PB subtypes combined as PB group	Low VVB used more in CR (79.2%) than PB (19.7%); co-intervention imbalance significant but technique-inherent	Moderate AKI/RRT data not reported; only operative time and ICU data extracted; missing primary outcome	NI AKI criteria not reported; primary renal outcome data absent from extraction	Moderate Key primary outcomes not reported; major reporting gap	Serious Serious: indication-driven selection bias and missing primary renal outcome data

			matching							
Hesse et al., 2000 [8]	Belgium	Prospective cohort	Moderate Three-arm study: PB (n=15), LLC (n=72), ETE (n=75) combined; groups differ in VVB use (53%/8%/67%); MELD not reported	Moderate Technique allocation not randomized; operator preference likely; LLC patients selected for newer technique era	Moderate Three techniques combined into 2 groups for this extraction; some heterogeneity within 'PB' group (PB+LLC)	Low VVB use differs substantially across arms; co-intervention imbalance	Low Prospective design; no explicit missing data reported	Moderate AKI criterion not stated; 'Other' classification; no validated tool used	Moderate Prospective design; outcomes appear pre-specified in study protocol	Moderate Moderate: technique heterogeneity within groups and VVB imbalance limit comparability
Nikeghbalian et al., 2014 [11]	Iran	Retrospective cohort	Moderate MELD similar (21.3 vs 20.6); VVB not used in either group (eliminates key co-intervent	Moderate non-randomized; allocation criteria not specified; single-center operator preference	Low Techniques clearly defined; VVB excluded from both groups; standard PB vs classic CR	Low Neither group received VVB; co-intervention balance is a strength of this comparison	Low Retrospective; AKI data complete; no explicit missing data reported	Moderate AKI criteria 'Other'; no KDIGO/RIFLE; endpoint definition unclear	Moderate Retrospective; not pre-registered; unclear if AKI was pre-specified primary endpoint	Moderate Moderate: reasonable baseline comparability but non-standardized AKI

			ion); age difference (37 vs 40); no multivariable adjustment stated							definition
Reddy et al., 2000 [18]	USA	Retrospective cohort	Moderate VVB used in 100% CR vs 22% PB; small sample (n=76); no formal confounder adjustment	Moderate Non-randomized; VVB use selective in PB group; technique choice not randomized	Low PT vs ST clearly defined; anastomosis technique documented	Moderate Selective VVB in 22% of PB introduces co-intervention imbalance within PB arm	Moderate Primary renal endpoint not explicitly reported; blood loss data available	NI Not Reported	Moderate Small retrospective study; outcomes appear clinically motivated	Moderate Moderate: limited by small sample, VVB imbalance, and missing primary renal outcome
Widmer et al., 2018 [13]	United Kingdom	Retrospective cohort	Moderate MELD similar (16 vs 15); DBD only in both groups (major strength); no VVB in either group; some era bias possible (not	Moderate non-randomized; technique choice not described; VVB exclusion across center reduces co-intervention bias	Low PB subtypes (side-to-side 67%, end-to-side 33%) and CR clearly defined	Low Neither group received VVB (institutional policy); important co-intervention balance	Low Retrospective; complete AKI and RRT data available; no explicit missing data	Low KDIGO criteria applied; standardized; strongest AKI definition in this review	Low Retrospective; outcomes appear pre-specified consistent with institutional audit design	Moderate Moderate: well-controlled for VVB and donor type; main limitation is non-randomized design

			adjusted)							
Cabezuelo et al., 2003 [7]	Spain	Retrospective cohort	Serious Temporal comparison (PB era 1995+ vs CR era 1991-1995); era effect strongly confounds; practice improvements over time not separable from technique	Serious Historical control group (CR 1991-1995 vs PB 1995-2003); technique change over time = non-concurrent controls; major selection bias	Moderate CR group includes standard + selective VVB (20/104, 19.2%); heterogeneous CR arm; unclear how classified	Low VVB selectively used in CR (19.2%); limited co-intervention imbalance within CR arm	Low Retrospective; AKI data available; no missing data explicitly reported	Moderate AKI defined as Cr>1.5mg/dL or 50% rise or oliguria; non-standardized but explicitly defined	Moderate Retrospective; not pre-registered; historical comparison design introduces unmeasured confounding	Serious Serious: temporal/historical control design introduces irresolvable confounding
Vieira de Melo et al., 2011 [17]	Brazil	Retrospective cohort	Moderate MELD similar (15.3 vs 16.0); VVB not used in either group; age	Moderate non-randomized; allocation criteria not described; single-	Low PB and CR techniques clearly described; VVB exclusion in both arms	Low Neither group received VVB; co-intervention balance.	Moderate Primary AKI endpoint not reported in extracted data; RRT	NI Not reported	Moderate Retrospective; primary renal outcome underreported	Moderate Moderate: reasonable baseline balance but AKI primary endpoint

			difference (53 vs 49, p not reported); no formal propensity adjustment	center consecutive series may reduce selection bias			data available			not formally reported
Sutherasan et al., 2022 [14]	Thailand	Retrospective cohort	Serious Very small CR arm (n=11) vs PB (n=90); major imbalance in group size and age (54.8 vs 44.9 years); no multivariable analysis; MELD similar	Moderate non-randomized; technique choice not described; 3rd arm (CCA, n=113) excluded from extraction; selection within remaining groups unclear	Low Techniques clearly defined per centre protocol; RIFLE/KDIGO-derived AKI definition	Low Neither group received VVB (institutional unavailability); important co-intervention balance	Low Complete AKI and ICU data; no missing data explicitly reported	Moderate RIFLE-derived criteria applied; reasonable standardization though labelled as RIFLE/KDIGO hybrid	Moderate Retrospective, not pre-registered; 3-arm study with selective 2-group reporting.	Serious Serious: underpowered CR arm (n=11) and age imbalance severely limit validity of comparisons
Schmitz et al., 2014 [20]	Germany	Retrospective cohort	Moderate CR combined from two subgroups (CR-no-bypass n=126, CR-	Moderate Non-randomized; VVB allocation within CR based on hemodynamic	Low PB (Belghiti side-to-side) and CR (with/without VVB) clearly defined; subgrou	Moderate VVB in 47.1% of CR arm (112/238) based on hemodynamic response	Low 14-day primary renal follow-up complete; no explicit missing data	Low RIFLE criteria applied; standardized and objective	Moderate Retrospective; not pre-registered; 14-day observation window may	Moderate Moderate: RIFLE strengthens outcome; but VVB within CR and

			bypass n=112); MELD higher in CR-bypass subgroup (p=0.008); PB vs CR overall MELD similar (18.8 vs ~19.7)	tolerance (trial clamping); adds selection within CR arm	p heterogeneity within CR noted	; significant co-intervention imbalance within CR; confounds overall PB vs CR comparison			under-capture delayed AKI	heterogeneous CR arm limit inference

Thirteen observational studies were assessed across seven domains: (D1) confounding; (D2) participant selection; (D3) classification of interventions; (D4) deviations from intended interventions; (D5) missing data; (D6) outcome measurement; and (D7) selection of reported results. Each domain was rated as Low, Moderate, Serious, or Critical risk of bias, with an overall judgment assigned per study. The predominant sources of bias were indication-driven technique allocation, heterogeneous or non-validated AKI definitions, and temporal confounding in studies using historical control groups. Dark Yellow: Serious concerns; Pale Yellow: Moderate concerns; Green: Low concerns; Grey: Not reported. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

Table 5. GRADE certainty of evidence assessment for all pooled outcomes.

Outcome (follow-up)	No. of Studies	No. of Patients	Risk of Bias (ROBINS-I/RoB2)	Inconsistency (I^2)	Indirectness	Imprecision	Publication Bias	Certainty of Evidence	Effect Estimate (95% CI) & Comments
AKI (any stage) [All studies; non-validated criteria included]	11	PB:1669 CR:979	Serious (–1): majority of studies have serious confounding or selection bias; AKI criteria heterogeneous	Serious (–1): I^2=25%; substantial variation across studies	Not serious: direct liver transplant populations	Serious (–1): wide 95%CI; many small studies	Suspected (–1): publication bias plausible given predominance of single-center retrospective series	⨁○○○ Very low	OR 0.565 (95% CI 0.408–0.783), z = –3.43, p = 0.0006. Favors PB [Start: Low – observational; –1 ROB; –1 inconsistency; –1 imprecision; –1 pub bias]
AKI (validated criteria only) [High-quality studies: Brescia	3	PB:363 CR:311	Not serious: 1 RCT (some concerns) + 2 Moderate-ROB	Not serious: I^2=48%; low-to-moderate heterogeneity	Not serious	Serious (–1): small event numbers; wide CI does not exclude clinically	Undetected: small subset; funnel plot not feasible	⨁⨁○○ Low	OR 0.65 (95%CI 0.37–1.15); I^2=48%; Favors PB [Start:

2015, Sakai 2010, Widmer 2018]			cohorts using RIFLE/KDIGO			important difference			Low – observational (RCT upgraded partially); –1 imprecision]
Renal Replacement Therapy (RRT) [All studies]	6	PB:1053 CR:897	Serious (–1): includes studies with serious confounding (Hannon et al. 2020 [16])	Moderate: I^2=0%; some unexplained variance	Not serious	Not serious: large combined sample; CI excludes no-effect direction	Suspected (–1)	⨁○○○ Very low	OR 0.86 (95%CI 0.68–1.09); I^2=0% Favors PB [Start: Low; –1 ROB; –1 pub bias]
Renal Replacement Therapy (RRT) [High-quality studies]	3	PB:370 CR:454	Not serious: all Moderate ROB or better	Not serious: I^2=0%	Not serious	Not serious: n>600 per arm combined	Undetected	⨁⨁○○ Low	OR 0.89 (95%CI 0.66–1.19); I^2=0% Favors PB [Start: Low; no further downgrades]
Operative Time (min) [All	7	PB:765 CR:765	Not serious for this outcome: studies	Serious (–1): I^2=91%	Not serious	Not serious: effect size large	Suspected (–1)	⨁⨁○○ Low	MD -27 min (95%CI -60 to 5); I^2=91%

studies with SD]			with SD reported tend to be better-documented			relative to CI			PB shorter operative time [Start: Low; –1 inconsistency; –1 pub bias]
Operative Time (min) [High-quality studies]	5	PB:603 CR:603	Not serious: all Moderate ROB or better	Not serious: I^2=93%	Not serious	Not serious	Undetected	⨁⨁○○ Low	MD -31 min (95%CI -77 to 15); I^2=93% PB associated with shorter operative time [Start: Low; no further downgrades → Low]
Warm Ischemia Time (min) [Narrative; no pooling – mixed measurement methods]	9	~2300 total	Serious (–1): varies by study	Serious (–1): anastomosis vs total WIT variously reported	Not serious	Serious (–1): data not poolable	Suspected (–1)	⨁○○○ Very low	All 9 reporting studies favor PB (shorter WIT) but methods heterogeneous; pooling not appropriate

									[Start: Low; –1 inconsistency; –1 imprecision; –1 pub bias → Very low]
Blood Loss (mL) [Narrative only – inadequate SD reporting]	4	~350 total	Serious (–1)	Serious (–1): very wide variance, SD missing in most	Not serious	Very serious (–2): data not poolable; SD absent	Suspected (–1)	⨁○○○ Very low	Trend toward lower blood loss with PB; no reliable pooled estimate possible [Start: Low; –1 ROB; –1 inconsistency; –2 imprecision → Very low]
ICU Stay (days) [Narrative only – inadequate SD reporting]	4	~590 total	Serious (–1)	Not serious	Not serious	Very serious (–2): SD largely missing	Suspected (–1)	⨁○○○ Very low	No consistent difference in ICU stay; data too sparse for pooling [Start: Low; –1 ROB; –2 imprecisi

									on; –1 pub bias → Very low]

Certainty of evidence was independently rated by two reviewers using the Grading of Recommendations, Assessment, Development and Evaluations (GRADE) framework, applied to each pooled outcome. Ratings were downgraded for risk of bias, inconsistency (I^2), indirectness, imprecision, and suspected publication bias. Outcomes assessed include: AKI incidence (all studies and high-quality subset), renal replacement therapy (all studies and high-quality subset), operative time, warm ischemia time, blood loss, and ICU stay. Certainty ranged from Very Low to Low across all outcomes, reflecting the predominantly observational evidence base, heterogeneity in AKI definitions, and small study sample sizes. AKI: acute kidney injury; CI: confidence interval; CR: conventional caval replacement; KDIGO: Kidney Disease Improving Global Outcomes; MD: mean difference; OR: odds ratio; PB: piggyback; RIFLE: Risk, Injury, Failure, Loss, End-stage renal disease; ROB: risk of bias; RRT: renal replacement therapy. ⨁○○○: Very low; ⨁⨁○○: Low. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds

Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

Table 6. Leave-One-Out Sensitivity Analysis for AKI

Omitted study	Pooled OR [95% CI]	I^2
Hannon et. al. 2020	0.54 [0.35–0.82]	56.6%
Khanet. al. 2006	0.53 [0.36–0.78]	54.8%
Jovine et. al. 1997	0.58 [0.42–0.80]	53.5%
Sakai et. al. 2010	0.61 [0.44–0.86]	46.8%
Laroche et. al. 2021	0.60 [0.45–0.81]	42.7%
Hesse et. al. 2000	0.55 [0.39–0.78]	56.2%
Nikeghbalian et. al. 2014	0.54 [0.37–0.77]	54.9%
Brescia et. al. 2015	0.58 [0.41–0.81]	55.6%
Widmer et. al. 2018	0.52 [0.37–0.74]	49.3%
Cabezuelo et. al. 2003	0.62 [0.45–0.85]	46.1%
Sutherasan et. al. 2022	0.55 [0.40–0.76]	53.3%

Sensitivity analysis for the AKI outcome performed by sequentially omitting each of the 11 studies [6–16] to evaluate the robustness of the pooled odds ratio and the impact of individual trials on overall heterogeneity. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

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Figures

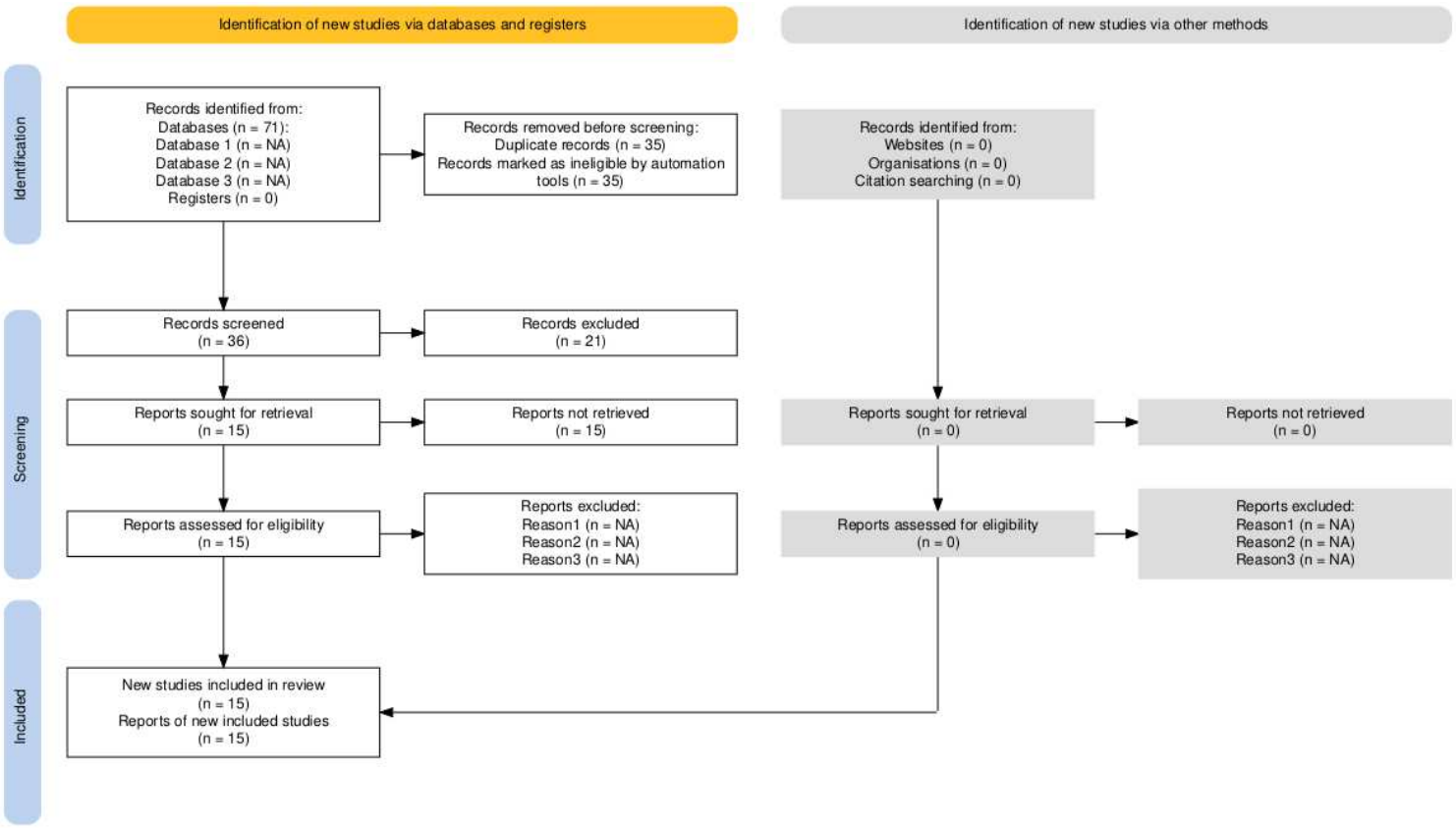


Figure 1

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Prisma) flow diagram

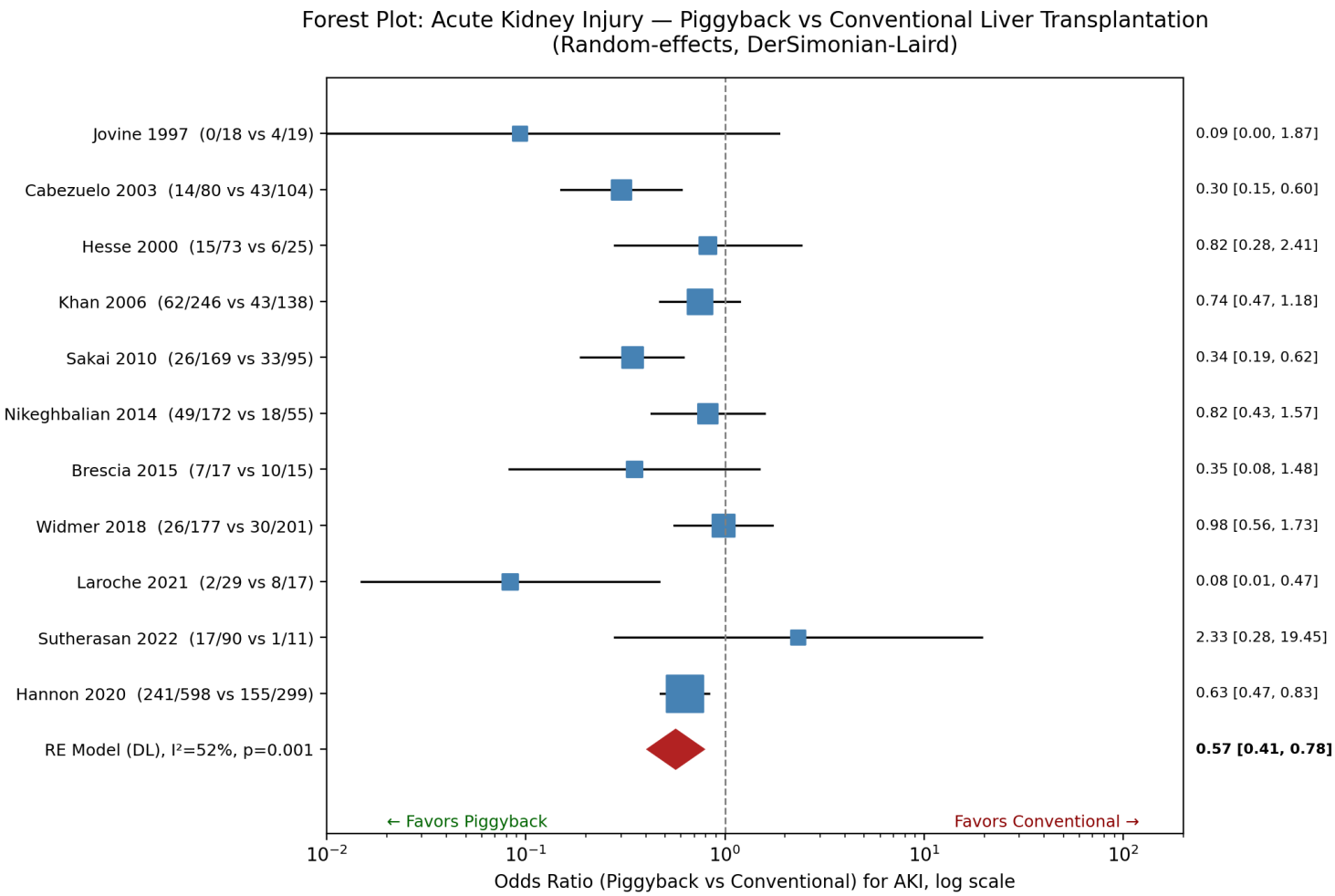


Figure 2

Forest plot displaying the comparison of Acute Kidney Injury (AKI) incidence between the Piggyback (PB) technique and the Conventional/Standard technique in liver transplantation. The analysis pools data from 11 studies: Jovine et al. 1997 [6], Cabezuelo et al. 2003 [7], Hesse et al. 2000 [8], Khan et al. 2006 [9], Sakai et al. 2010 [10], Nikeghbalian et al. 2014 [11], Brescia et al. 2015 [12], Widmer et al. 2018 [13], Laroche et al. 2021 [15], Sutherasan et al. 2022 [14], and Hannon et al. 2020 [16]. Results are presented as odds ratios (OR) with 95% confidence intervals (CI), using a random-effects model. A 0.5 continuity correction was applied to studies with zero events. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

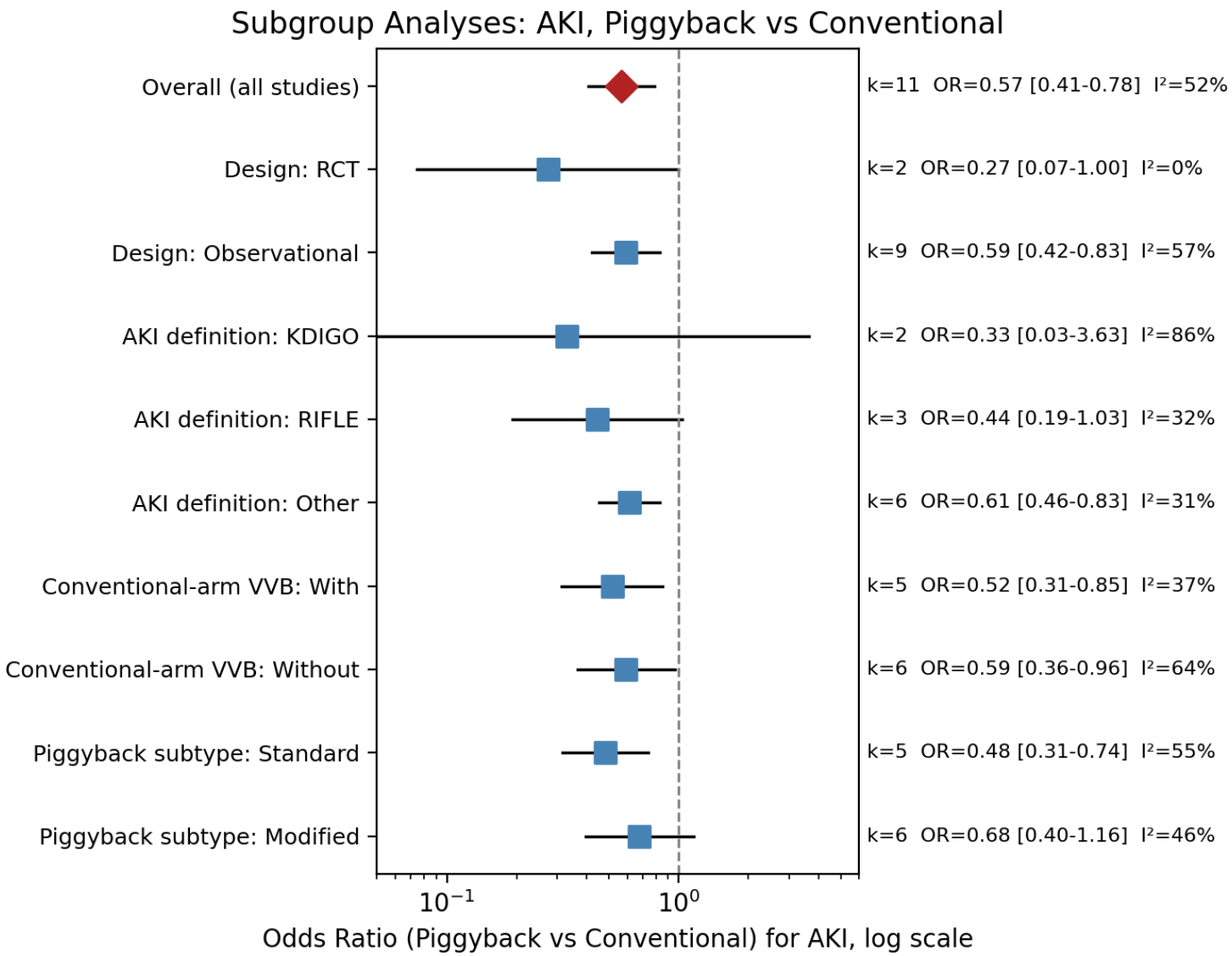


Figure 3

Forest plots illustrating subgroup analyses for the risk of AKI based on study design (RCT vs. Observational), AKI definition (KDIGO, RIFLE/AKIN, Other), use of veno-venous bypass (VVB) in the conventional arm, and piggyback subtype (Standard vs. Modified). These analyses incorporate the same 11 primary studies [6–16] to identify potential sources of heterogeneity and modifiers of the treatment effect. Abbreviations: KDIGO: The Kidney Disease Improving Global Outcomes; RIFLE: Risk, Injury, Failure, Loss of kidney function, and End-stage kidney disease; AKIN: Acute Kidney Injury Network; AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

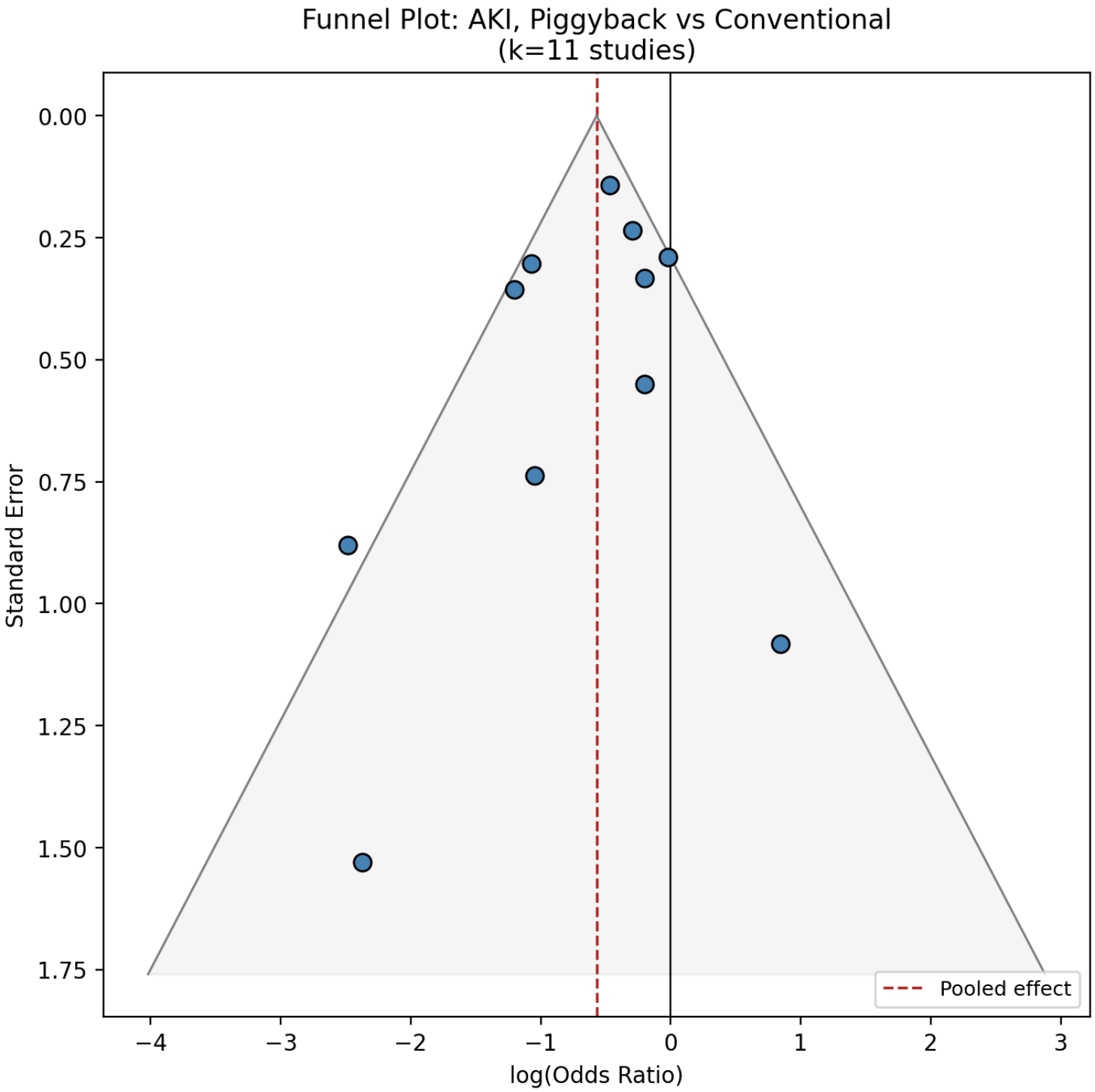


Figure 4

Each data point represents one of the 11 included studies [6–16] contributing to the primary pooled analysis of AKI incidence. The x-axis displays the log odds ratio (OR) for AKI (piggyback vs. conventional caval replacement), and the y-axis displays the standard error of the log OR as a measure of study precision. The vertical dashed line represents the pooled effect estimate (OR 0.565). Mild asymmetry was noted on visual inspection; however, Egger's linear regression test revealed no statistically significant evidence of publication bias (intercept −0.78, SE 0.80, t = −0.98, p = 0.354). Interpretation

should be made cautiously given the limited number of included studies (k = 11). OR: odds ratio; SE: standard error. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

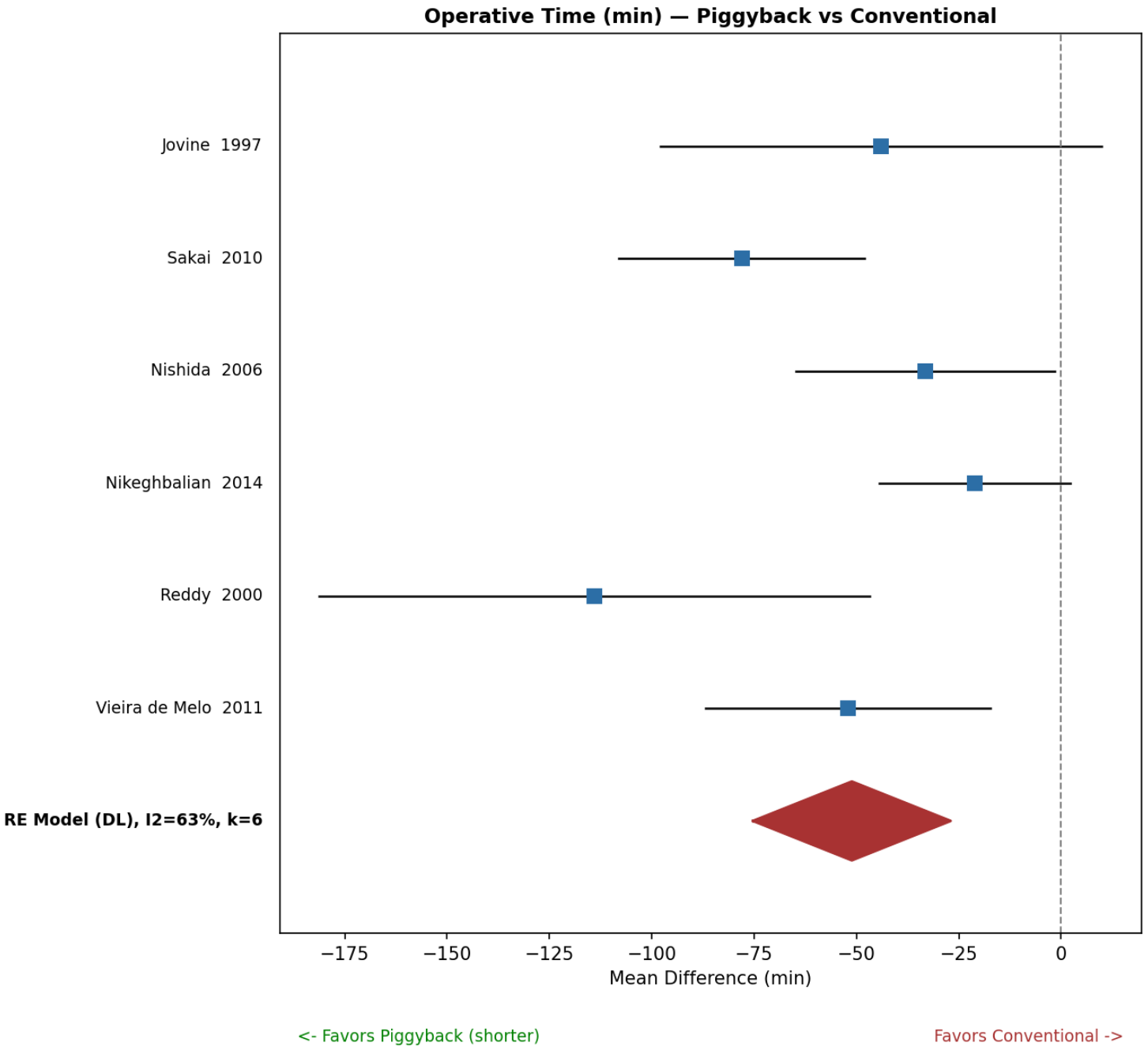


Figure 5

Forest plot comparing total operative time (in minutes) between the Piggyback and Conventional techniques. This meta-analysis includes 6 studies: Jovine et al. 1997 [6], Sakai et al. 2010 [10], Nishida et

al. 2006 [19], Nikeghbalian et al. 2014 [11], Reddy et al. 2000 [18], and Vieira de Melo et al. 2011 [17]. Results are expressed as mean difference (MD) with 95% CI. Abbreviations: AKI = Acute Kidney Injury; RE= Random effects ; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

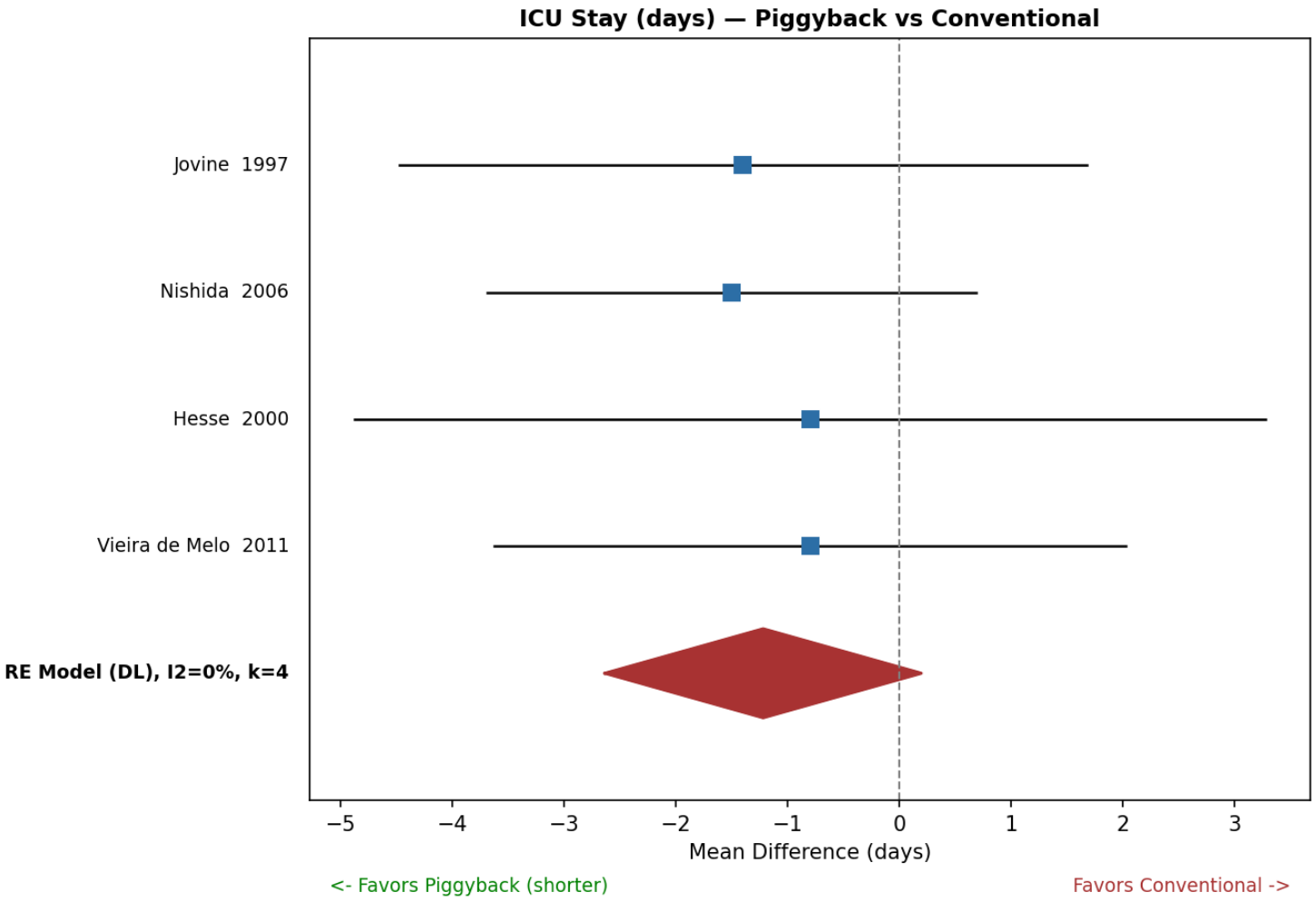


Figure 6

Forest plot illustrating the difference in Intensive Care Unit (ICU) length of stay (in days) between the Piggyback and Conventional techniques. The analysis incorporates data from 4 studies: Jovine et al. 1997 [6], Nishida et al. 2006 [19], Hesse et al. 2000 [8], and Vieira de Melo et al. 2011 [17]. Results are presented as MD with 95% CI. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass; RE= Random effects

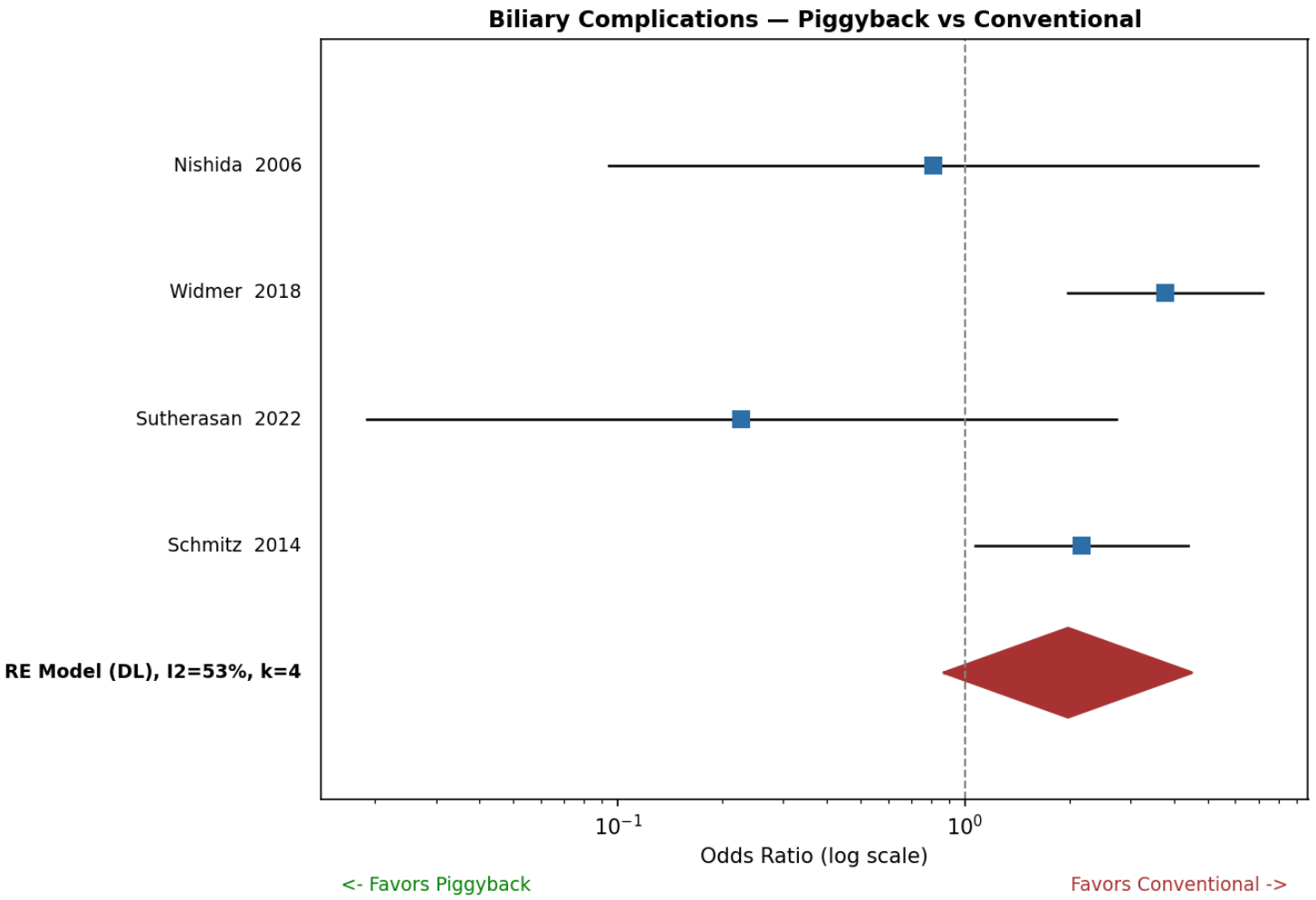


Figure 7

Forest plot comparing the incidence of postoperative biliary complications between the Piggyback and Conventional techniques. The analysis incorporates 4 studies: Nishida et al. 2006 [19], Widmer et al. 2018 [13], Sutherasan et al. 2022 [14], and Schmitz et al. 2014 [20]. Results are presented as OR with 95% CI. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass.

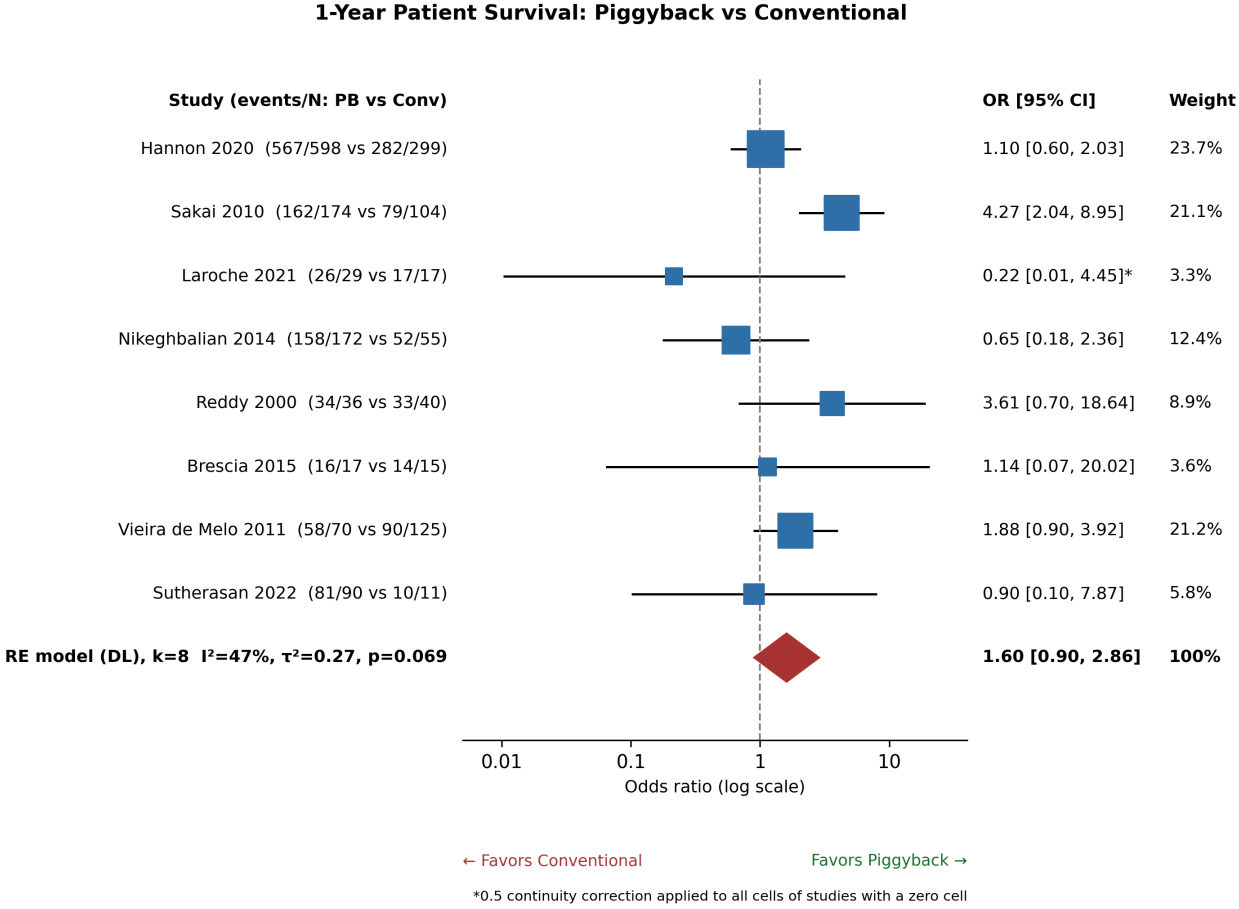


Figure 8

Forest plot for 1-year patient survival rates comparing Piggyback and Conventional techniques. This analysis includes 8 studies: Hannon et al. 2020 [16], Sakai et al. 2010 [10], Laroche et al. 2021 [15], Nikeghbalian et al. 2014 [11], Reddy et al. 2000 [18], Brescia et al. 2015 [12], Vieira de Melo et al. 2011 [17], and Sutherasan et al. 2022 [14]. Results are shown as OR with 95% CI. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass; RE= Random effects.

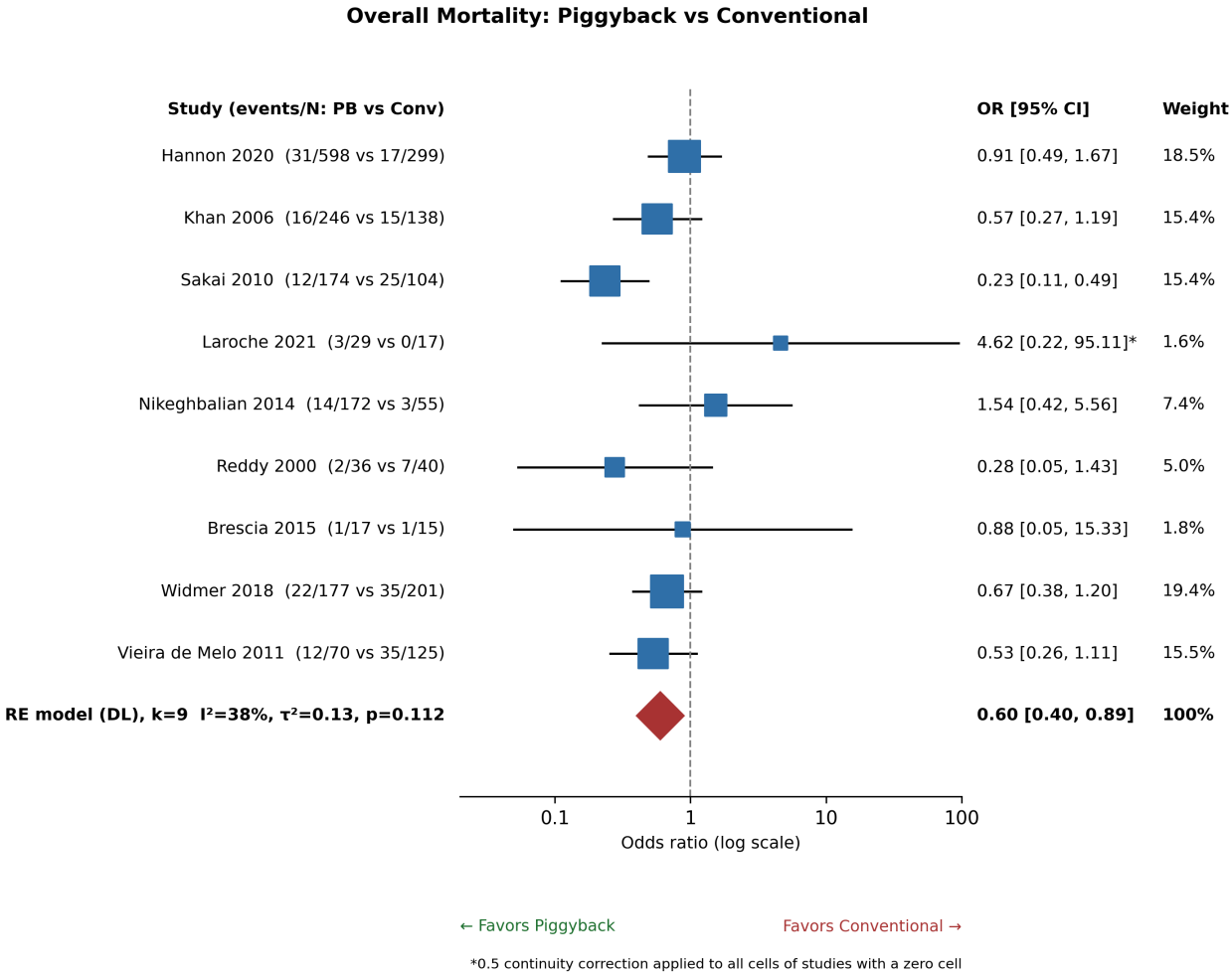


Figure 9

Forest plot comparing overall mortality rates between the Piggyback and Conventional techniques. The analysis pools data from 9 studies: Hannon et al. 2020 [16], Khan et al. 2006 [9], Sakai et al. 2010 [10], Laroche et al. 2021 [15], Nikeghbalian et al. 2014 [11], Reddy et al. 2000 [18], Brescia et al. 2015 [12], Widmer et al. 2018 [13], and Vieira de Melo et al. 2011 [17]. Results are expressed as OR with 95% CI. Abbreviations: AKI = Acute Kidney Injury; CI = Confidence Interval; CR = Caval Replacement; GRADE = Grading of Recommendations Assessment, Development and Evaluation; ICU = Intensive Care Unit; MD = Mean Difference; OR = Odds Ratio; PB = Piggyback; RCT = Randomized Controlled Trial; RoB / ROBINS-I = Risk of Bias; RRT = Renal Replacement Therapy; SD = Standard Deviation; VVB = Veno-venous bypass; RE= Random effects.

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