

Review

Leak-Stratified Management of Early Bile Leaks After Liver Transplantation: A Narrative Review of Leak Characteristics, Patient Stability, and the Limited Evidence on Intervention Timing in the First 14 Postoperative Days

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Abstract

Background: Bile leaks complicate 5–25% of liver transplants and are among the most common early postoperative biliary events. Their management within the first 14 postoperative days has traditionally been framed around the timing of intervention. **Objective:** To evaluate whether leak characteristics and patient stability provide more consistent guidance than intervention timing for early post-transplant bile leaks. **Methods:** A structured narrative review using a dual-source search (AI-assisted semantic search [Elicit Plus] and PubMed/MEDLINE) was conducted. A PICO-informed (Population, Intervention, Comparator, Outcome) framework guided inclusion; two independent reviewers preformed screening, with senior adjudication, yielding 37 sources. Because “early” was defined heterogeneously—by leak onset in most studies (definitions exceeding 14 days) and by intervention timing in others—and no study compared timing within a 14-day window, quantitative pooling was not undertaken. **Results:** No included study directly compared intervention timing within the first 14 postoperative days. In the largest available analysis of ERCP timing, resolution and adverse event rates did not differ by whether endoscopy was performed within one day, on days two to three, or after three days; endoscopic success was consistently high (80–98%) across temporal windows. Leak type was a consistent correlate of management intensity and resolution: anastomotic leaks were associated with higher surgical-intervention rates (40% vs. 8.3% for T-tube exit-site leaks in one cohort) and lower resolution rates (58–69%) than non-anastomotic leaks (90–100%). Within endoscopic



Academic Editor: Consolato M. Sergi

Received: 24 June 2026

Revised: 16 July 2026

Accepted: 17 July 2026

Published: 21 July 2026

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therapy, bridging stent placement—not leak location—was the strongest independent predictor of resolution, and any bile leak, irrespective of subtype, independently predicted subsequent biliary stricture (pooled adjusted OR $\approx$ 4). Ultra-early leaks ($\leq$ 72 h), frequently technical failures, formed the one subset favoring early surgical re-exploration. Conclusions: The absence of a demonstrated timing effect reflects a lack of direct comparative data rather than proof that timing is unimportant. Leak type, patient stability, and management modality offer more consistent and actionable guidance than temporal urgency, forming the basis for a leak-stratified framework. Prospective multicenter registries with standardized timing strata and leak type stratification are needed to test whether timing independently influences outcomes.

Keywords: liver transplantation; bile leak; biliary complications; postoperative complications; ERCP; leak-stratified management

1. Introduction

Biliary complications remain a significant source of morbidity and mortality following liver transplantation and are often referred to as the “Achilles heel” of the procedure [1,2]. Among these complications, bile leaks represent one of the most common early postoperative challenges, with reported incidence rates ranging from 5% to 25% depending on transplant type, surgical technique, and institutional experience [2–4]. The consequences can be severe and include biloma formation, secondary infection, sepsis, and the need for prolonged hospitalization and multiple interventions [1,5]. Management has evolved substantially over the past two decades, with endoscopic retrograde cholangiopancreatography (ERCP) emerging as first-line therapy for most cases [6–8]. Endoscopic techniques, including sphincterotomy, biliary stent placement, and nasobiliary drainage, have achieved consistently high success rates ranging from 80% to 98% [9,10].

Several factors influence the decision to intervene: leak severity and output volume, leak location and type (anastomotic versus non-anastomotic), associated complications, patient hemodynamic stability, graft type, and the method of biliary reconstruction [11,12]. The distinction between ultra-early and later-presenting leaks has pathophysiological relevance: anastomotic failure within the first 72 h typically reflects a technical defect amenable to surgical repair in fresh tissue, whereas leaks presenting after day three to five occur in increasingly edematous, friable tissue that generally favors endoscopic management [13,14]. Importantly, a proportion of bile leaks may resolve without intervention [15], raising the question of whether immediate intervention is always necessary.

These observations have frequently been framed around a single organizing question: does earlier intervention improve outcomes? This review re-examines that framing. Rather than asserting that timing is unimportant, a claim that the available evidence cannot support, we ask whether the more defensible and clinically useful organizing principle is stratification by leak characteristics and patient stability. Accordingly, the objective of this structured narrative review was to synthesize the available evidence on intervention timing for bile leaks during the first 14 postoperative days, to place that evidence alongside data on leak type, patient stability, and management modality, and to derive a clinically actionable, leak-stratified framework while explicitly delineating the boundaries of what the current evidence can and cannot establish.

2. Materials and Methods

2.1. Information Sources and Search Strategy

A dual-source strategy was employed. A semantic search was performed via the Elicit platform (which indexes the Semantic Scholar and OpenAlex databases, comprising over 138 million records) using the query: “What is the impact of early versus delayed intervention on patient outcomes for bile leaks in liver transplant recipients during the first 14 postoperative days?”; the 500 most semantically relevant records were carried forward for screening. In parallel, PubMed/MEDLINE was searched using Medical Subject Headings (MeSH) and free-text terms, including “bile leak,” “liver transplantation,” “biliary complications,” “ERCP,” and “intervention timing,” returning 845 records. Records were retrieved from database inception through February 2026, with the final search executed in February 2026.

2.2. Eligibility Criteria and Study Selection

Studies were included per predefined, PICO-informed (Population, Intervention, Comparator, Outcome) criteria: adult liver transplant recipients (≥ 18 years) with postoperative bile leaks; interventions comprising surgical, endoscopic, percutaneous, or conservative management; and studies directly comparing early versus delayed timing (early defined as within 24–48 h, delayed as beyond 48 h), with studies lacking direct timing comparisons but reporting relevant timing or outcome data retained for contextual synthesis. Eligible designs included randomized controlled trials (RCTs), prospective and retrospective cohorts, case-control studies, and systematic reviews. Case reports, series of fewer than 10 patients, editorials, and abstracts were excluded. Retrieval was further restricted to peer-reviewed sources in Q2-or-higher journals with full-text availability. All included studies provided explicit diagnostic criteria for bile leak identification.

The 500 records retained from the semantic search were combined with the deduplicated PubMed/MEDLINE records, yielding 935 records for screening. These were screened by two reviewers (M.S. and T.N.), with uncertain or discordant cases resolved through discussion and, where necessary, adjudication by a senior reviewer (F.K.). A total of 898 records were excluded during title, abstract, and full-text screening for the following reasons: off-topic or non-therapeutic focus; pediatric populations or animal models; unsuitable study design (e.g., case reports or series of fewer than 10 patients); and publication in journals below the Q2 quartile. This process yielded 37 sources for narrative synthesis (Figure 1).

2.3. Data Extraction, Evidence Appraisal, and Synthesis

Data were extracted using a large language model–assisted structured protocol with subsequent manual verification by the research team. Extracted variables included intervention-timing parameters, leak type and severity, intervention modality and success rates, patient outcomes, and transplant-type-specific data. Each included study was appraised for its design-based level of evidence using the Oxford Centre for Evidence-Based Medicine (CEBM) framework; the resulting distribution is summarized in Table 1. Owing to the definitional heterogeneity in intervention timing across studies and the absence of timing-comparative studies within the 14-day window, evidence was synthesized narratively rather than pooled.

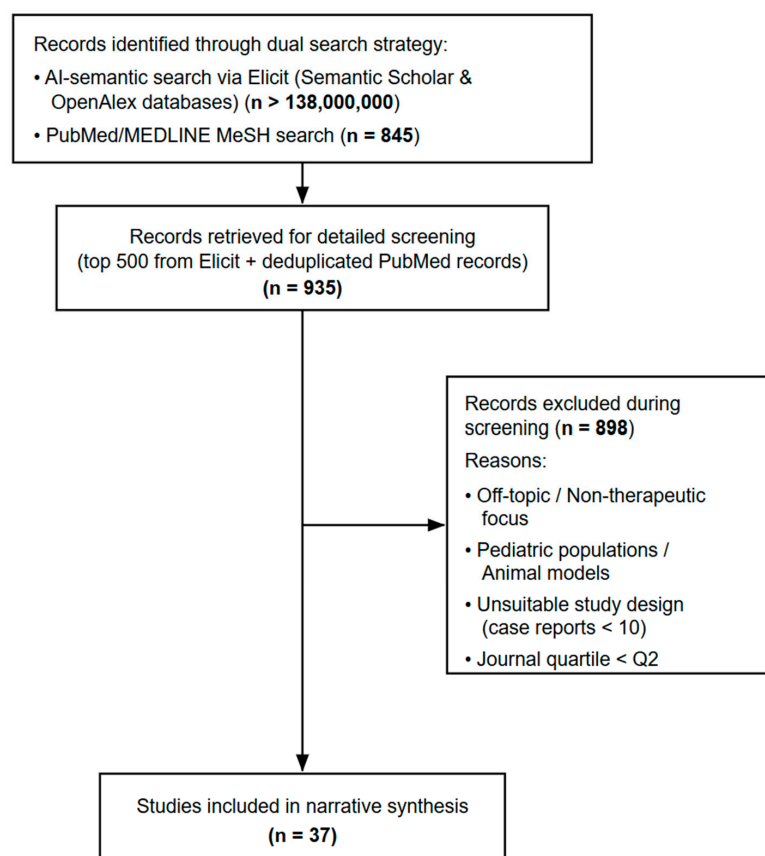


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-style flow diagram of the study selection process. The diagram illustrates the dual-search strategy incorporating both the AI-assisted semantic search (Elicit) and the parallel PubMed/MEDLINE MeSH search, detailing the automated deduplication and subsequent manual exclusion of irrelevant, pediatric, and non-timing-specific records by two independent reviewers, resulting in the final 37 included studies.

Table 1. Characteristics and design-based level of evidence of the included studies (N = 37).

Study Design	N (%)	Representative Sources (First Author, Year)	Primary Focus Areas	CEBM Level of Evidence
Systematic Review/ Meta-analysis	13 (35.1%)	Raza 2019 [9]; Riediger 2010 [12]; Wan 2014 [16]; Boteon 2018 [17]; Jia 2020 [18]	Biliary reconstruction, machine perfusion vs. cold storage, T-tube use, LDLT vs. DDLT outcomes, thrombolytic therapy, split-liver transplantation	Level 1 (of RCTs) to Level 3 (of observational studies)
Narrative/Literature Review	9 (24.3%)	Fasullo 2022 [1]; Kochhar 2013 [2]; Boraschi 2014 [3]; Arain 2013 [6]; Lee 2017 [7]	Endoscopic management, biliary complications overview, MR cholangiography, bile-duct-injury classification	Level 5
Retrospective Cohort	11 (29.7%)	Khan 2021 [19]; Bohorquez 2017 [20]; Wang 2023 [21]; Yu 2024 [22]	Surgical techniques, preservation protocols, learning curves, and reconstruction in specific populations	Level 3–4
RCT/Prospective Trial	2 (5.4%)	Mathew 2019 [23]; Huang 2020 [24]	Ischemia-free transplantation, dual-perfusion techniques, arterial-first reperfusion	Level 1–2
Case-Control/ Commentary	2 (5.4%)	Eid 2010 [5]; Chon 2020 [25]	Predictive markers for infected collections; endoscopic-outcomes commentary	Level 3–4; Level 5

CEBM, Oxford Centre for Evidence-Based Medicine; DDLT, deceased donor liver transplantation; LDLT, living donor liver transplantation; RCT, randomized controlled trial.

3. Results

The search yielded 37 sources meeting the inclusion criteria (Figure 1), comprising 13 systematic reviews or meta-analyses (35.1%) [9,11,12,17,18,26–32], 9 narrative or literature reviews (24.3%) [1–3,6,7,10,13–15], 11 retrospective cohort studies (29.7%) [19–22,33–38], two RCTs including one protocol (5.4%) [22,23], one case-control study (2.7%) [5], and one commentary (2.7%) [25]. None were specifically designed to compare intervention timing within the first 14 postoperative days. The design-based level of evidence for the included sources is summarized in Table 1.

3.1. Intervention Timing and Reported Outcomes

Endoscopic intervention was reported to achieve success rates of 80–98% across the temporal windows described in the included studies [6,7,9,10,39]. In the largest identified analysis of ERCP timing for bile duct leaks of mixed etiology (including transplant recipients), endotherapy was classified by timing relative to leak recognition—within one day, on days two to three, and beyond three days—and leak resolution and adverse event rates did not differ significantly across these groups [40]. This study indexed timing to leak recognition rather than to transplantation and was not confined to the first 14 post-transplant days. No included study directly compared intervention timing within the first 14 postoperative days.

Definitions of “early” were heterogeneous and referred to two distinct constructs (Table 2). Most sources defined “early” by leak onset, most commonly within four weeks of transplantation [2,3,7,15]. Only Wellner et al. [13] and Symeonidis et al. [14] specified thresholds falling within the first postoperative days, and both defined early intervention—anchored to the index operation and to leak diagnosis, respectively—rather than early leak onset. Shin et al. [10] classified leaks by mechanism rather than time.

Table 2. Definitions of “early” bile leak and of early versus delayed intervention across the included studies.

Source	Construct Defined	Index Event	Early Definition	Delayed/Late Definition
Wellner et al. 2017 [13]	Intervention timing	Index operation	Within the first three days post-operation	≥5 days post-operation
Symeonidis et al. 2023 [14]	Intervention timing	Leak diagnosis	Within 48–72 h from diagnosis	Beyond 72 h from diagnosis
Lee et al. 2017 [7]	Leak onset	Transplantation	Within four weeks of LT	More than four weeks after LT
Kochhar et al. 2013 [2]	Leak onset	Transplantation	Within four weeks of OLT	Beyond four weeks post-OLT
Boraschi et al. 2014 [3]	Leak onset	Transplantation	Within four weeks post-transplant	Beyond four weeks post-transplant
Lisotti et al. 2015 [15]	Leak onset	Transplantation	Within the first few months	Late complications
Shin et al. 2016 [10]	Leak mechanism (non-temporal)	Not applicable	At the anastomotic site, the technical origin	Associated with T-tube removal

Definitions are anchored to different index events (index operation, leak diagnosis, transplantation, or leak mechanism) and are therefore not directly comparable. Only Wellner et al. [13] and Symeonidis et al. [14] define a threshold falling within the 14-day window addressed by this review; Shin et al. [10] classify leaks by mechanism rather than time and are included here for completeness. LT, liver transplantation; OLT, orthotopic liver transplantation.

3.2. Leak Type, Management Modality, and Reported Resolution

Reported resolution rates differed by leak type: anastomotic leaks were reported at 58–69% versus 90–100% for T-tube site and cut-surface leaks (Table 3) [10,12,41,42]. In a contemporary high-acuity transplant cohort, anastomotic leaks required surgical intervention in approximately 40% of cases versus 8.3% for T-tube exit-site leaks, with the remainder managed endoscopically or conservatively [43].

Table 3. Reported intervention success rates by modality and leak type.

Intervention Type	Overall Success	Anastomotic Leaks	Non-Anastomotic Leaks	Ref.
Biliary stents (plastic)	82.4%	69.2%	90.9% (T-tube), 92.8% (cut-surface)	[1]
Nasobiliary tubes	87.2%	58.3%	100% (T-tube/cut-surface)	[1]
ERCP with sphincterotomy	80–100%	64–76%	>90%	[2,4,6]
Self-expanding metal stents	94%	— ^a	— ^a	[6]
Combined endoscopic approach	91.5% at 6 weeks	— ^a	— ^a	[2]
Percutaneous drainage	Variable ^b	20.7% required PTBD	Reserved for ERCP failure	[4]

^a Leak type-stratified data not separately reported in the cited source; an em dash denotes data not reported, not a value of zero. ^b A single pooled success rate was not reported; ERCP, endoscopic retrograde cholangiopancreatography; PTBD, percutaneous transhepatic biliary drainage. Percutaneous drainage was used predominantly after ERCP failure or in patients with bilioenteric anatomy.

In an analysis of two high-volume transplant centers, plastic stent placement achieved complete resolution in 94% of cases versus 58% with sphincterotomy alone, and bridging stent placement was the only independent predictor of leak resolution on multivariable analysis [44].

In a meta-analysis of living donor recipients, the presence of a postoperative bile leak was among the strongest independent predictors of subsequent biliary stricture (pooled adjusted OR $\approx$ 4) [45]. Published multivariable models analyzed bile leak as a single binary variable; none tested leak subtype as a separate predictor.

3.3. Spontaneous Resolution and the Ultra-Early Subset

A subset of low-output leaks resolved without procedural intervention [15,46], and reported closure in treated cases occurred over a period of weeks to months (e.g., 92% closure by six months in living donor recipients; median stent-free status at $\sim$ 1.3 months) [10]. Reported complications of endoscopic intervention included post-ERCP pancreatitis (5.6%) and post-sphincterotomy bleeding (1.4%) (Table 4).

Table 4. Complications and mortality associated with biliary complications and endoscopic interventions.

Source	Complication Type	Incidence/Rate	Mortality
Chon et al. 2020 [25]	Post-ERCP pancreatitis	5.6%	Not reported
Chon et al. 2020 [25]	Post-sphincterotomy bleeding	1.4%	Not reported
Lee et al. 2017 [7]	Secondary sepsis	Variable	$\sim$ 1%
Fasullo et al. 2022 [1]	All biliary complications	Variable	Up to 20%
Boteon et al. 2018 [17]	ITBL requiring retransplant/death	$\sim$ 50%	$\sim$ 50%
Pereira et al. 2025 [31]	Hepatic artery pseudoaneurysm with bile leak	66.7%	Up to 78%

ITBL, ischemic-type biliary lesions.

Leaks presenting within 72 h were described as technical failures (e.g., suture dehiscence, missed accessory ducts); Wellner et al. [13] recommended surgical re-exploration for this subset, and Symeonidis et al. [14] supported surgical repair within 48–72 h when technical failure was identifiable.

Bile leaks were categorized across studies into anastomotic leaks at the biliary-enteric or duct-to-duct anastomosis; T-tube site leaks; cut-surface leaks in split or living donor grafts; cystic duct stump leaks; and leaks from damaged accessory ducts. Reported timing varied: the median interval from living donor transplantation to leak detection was 21 days (range, postoperative day one to six months), and in recipients of grafts donated after circulatory death (DCD), the mean interval to first ERCP was 81 days [10,36].

3.4. Graft Type, Reconstruction, and Peri-Transplant Factors

Reported biliary complication rates differed by graft type (Table 5). Living donor liver transplantation (LDLT) carried higher rates than deceased-donor liver transplantation (DDLT) (OR 2.23–3.08) [4,16,29], and split-liver transplantation carried higher rates than whole-graft transplantation (OR 4.30, 95% CI 2.97–6.23) [27,28,47]. Machine perfusion was associated with lower biliary complication rates than static cold storage (OR 0.53, 95% CI 0.34–0.83) [18]; a network meta-analysis of randomized trials reported reduced biliary complications with hypothermic oxygenated perfusion versus cold storage (RR 0.52, 95% CI 0.43–0.75) [48], and a randomized trial reported reduced non-anastomotic strictures with hypothermic machine perfusion (HMP) in DCD recipients [49]. Arterial-first reperfusion was associated with a threefold lower rate of (ITBL) (6.1% vs. 18.1%) [38]; thrombolytic flush in DCD transplantation was associated with fewer ischemic-type lesions and improved one-year graft survival [20,30]; two-surgeon operative workflows were associated with lower leak (12% to 4%) and reintervention (21% to 11%) rates [37]; and accumulating institutional experience was associated with lower bile leak rates (10.3% to 5.5%) [19]. T-tube use was reported as protective against strictures in pre-2010 studies (OR 0.62) and associated with higher overall biliary complications in post-2010 studies (OR 1.49) [12,26].

Table 5. Reported biliary outcomes by graft type, reconstruction, and peri-transplant factors.

Factor	Comparison	Reported Association	Ref.
Graft type	LDLT vs. DDLT	Higher biliary complication rate with LDLT (OR 2.23–3.08)	[4,16,29]
Graft type	Split vs. whole graft	Higher rate with split grafts (OR 4.30, 95% CI 2.97–6.23)	[27,28,47]
Time to detection	LDLT	Median interval ~21 days (range, day one to six months)	[10]
Time to first ERCP	DCD	Mean interval ~81 days	[36]
Preservation	Machine perfusion vs. cold storage	Lower biliary complications (OR 0.53; RR 0.52 in RCT network meta-analysis)	[18,48]
Preservation	HMP vs. cold storage (DCD)	Reduced non-anastomotic strictures (RCT)	[49]
Reperfusion	Arterial-first	~three-fold fewer ischemic-type lesions (6.1% vs. 18.1%)	[38]
Operative workflow	Two-surgeon (before/after)	Lower leak (12% → 4%) and reintervention (21% → 11%) rates	[37]
Institutional experience	Learning curve (before/after)	Lower leak rate (10.3% → 5.5%)	[19]
Reconstruction	T-tube use (pre- vs. post-2010)	Protective for strictures (OR 0.62) → higher overall complications (OR 1.49)	[12,26]

4. Discussion

Within the early postoperative period, the synthesized evidence indicates that leak characteristics and patient stability provide more consistent and actionable guidance than intervention timing. This is a statement about the relative interpretability and clinical

utility of these variables, not a causal claim: no included study directly compared intervention timing within a 14-day window, and the data therefore cannot establish that timing has no effect. Endoscopic management achieved high success rates (80–98%) across variable temporal windows [6,7,9,10,39], and the one large analysis to examine ERCP timing directly—albeit in mixed-etiology leaks indexed to leak recognition—found no significant difference in resolution or adverse events across timing groups [40]. Together, these observations support a practice-relevant reframing: urgency of intervention has not been shown to be the dominant determinant of outcome for the broad category of early post-transplant bile leaks, while its role cannot be formally excluded based on current evidence.

The leak-type gradient is mechanistically plausible. Anastomotic leaks arise at a site of reduced vascularity, ischemia, and tension—conditions less favorable to spontaneous or endoscopic closure than better-perfused non-anastomotic sites—which is consistent with both their higher reported surgical-intervention rate [43] and their lower reported resolution rates [10,12,41,42]. Management modality is a further correlate of outcome: within endoscopic therapy, bridging stent placement rather than leak location was the strongest reported independent predictor of resolution [44]. A coherent reading of the evidence is therefore hierarchical—leak type and patient stability inform the choice among surgical, endoscopic, and conservative pathways, while within the endoscopic pathway, bridging stent placement is associated with the probability of success.

A fundamental definitional problem limits direct evidence in this field. Most studies classify “early” leaks as those within four weeks of transplantation [2,3,7]—substantially exceeding the clinically critical 14-day window—and definitions of “early” and “delayed” are markedly inconsistent across studies (Table 2). The inconsistency operates at two levels—what qualifies as an early leak and what qualifies as an early intervention—and these are not interchangeable; their conflation is addressed as a limitation in Section 5. The only within-window distinction supported by the evidence is between ultra-early presentations (≤ 72 h, frequently technical failures) and later presentations.

Contemporary evidence reinforces the prognostic weight of leak type while also delimiting it. Updated data confirm that endoscopic management—including combined ERCP and percutaneous drainage—resolves the large majority of post-transplant bile leaks, and that anastomotic leaks are associated with inferior resolution [39,41,46,50]. The robust adjusted finding in the stricture literature, however, is that the presence of *any* bile leak predicts subsequent stricture (pooled adjusted OR ≈ 4) [45]; whether specific leak subtypes carry differential adjusted stricture risk has not been established. Two claims of unequal evidentiary strength should therefore be distinguished: (i) leak type is a consistent correlate of management intensity and reported resolution, supported largely by unadjusted data; and (ii) any leak is an adjusted predictor of downstream stricture, supported by pooled multivariable data.

Graft type and reconstruction modulate baseline risk substantially. LDLT and split transplantation carry two- to four-fold higher complication rates than DDLT owing to complex, small-caliber, multi-duct reconstructions and parenchymal cut surfaces [16,27,29,47,51]. Because these populations differ in biliary anatomy, reconstruction complexity, ischemia-related injury, and leak mechanism, the evidence on early bile leaks is best interpreted with attention to graft type rather than pooled across graft types (Table 5).

The greatest opportunity for outcome improvement appears to lie upstream of leak occurrence. Machine perfusion was associated with lower odds of biliary complications (OR 0.53) [18] and, in randomized-trial syntheses, with reduced biliary complications and non-anastomotic strictures relative to cold storage (RR 0.52) [48,49]; arterial-first reperfusion was associated with fewer ischemic-type lesions [38]; two-surgeon workflows were associated with lower leak rates [37]; and accumulated institutional experience was associated with fewer complications over the learning curve [19]. Several of these

findings derive from uncontrolled before-after comparisons and are therefore hypothesis-generating; collectively, they suggest that prevention through graft preservation, surgical technique, and institutional protocols may influence biliary outcomes more than the timing of post-complication intervention.

The study design required to answer the timing question directly is inherently challenging: many leaks present after the 14-day window; a proportion close spontaneously; baseline endoscopic success is already high (80–98%), requiring large samples to detect small differences; and confounding by indication complicates observational comparison, because severe early leaks differ fundamentally from those amenable to delayed management.

5. Limitations and Strengths

The principal limitation is inherent to the available evidence: no existing study was designed to compare intervention timing directly within the 14-day window. This absence means that a timing effect within this window has neither been established nor excluded; accordingly, the central conclusion of this review is framed as a decision framework grounded in the more consistently reported variables—leak type, patient stability, and management modality—rather than as a causal claim about timing. The inclusion of sources addressing broader aspects of biliary complications reflects this evidence landscape and the need to triangulate an understudied question.

A further limitation concerns the definition of “early” bile leak itself, which was not standardized across the included sources. Two conceptually distinct constructs were used interchangeably: the interval from transplantation to leak onset—defined as within four weeks in most studies [2,3,7], within the first postoperative days in one [13], and as the first few postoperative months in another [15]—and the interval from leak recognition to intervention [14,40]. Definitions were thus anchored to different index events (Table 2), and diagnostic ascertainment differed further (drain bilirubin thresholds, cross-sectional imaging, cholangiography, or preoperative findings), with International Study Group of Liver Surgery (ISGLS) severity grading reported inconsistently. Three consequences follow for the present synthesis. First, cohorts labeled “early” are not exchangeable: a cohort defined by a four-week threshold contains a substantial proportion of patients presenting outside the 14-day window of interest, so its aggregate resolution rates cannot be attributed to the early period specifically. Second, because later-presenting leaks are enriched for ischemic and non-anastomotic mechanisms, the direction of the resulting bias is not predictable a priori; the leak-type gradient reported here (58–69% versus 90–100%) derives from cohorts assembled under different temporal definitions and may therefore partly reflect case-mix and follow-up duration rather than leak anatomy alone. Third, and most consequentially, this variability means that the exposure variable is not consistently measured across studies—which is why quantitative pooling was not undertaken, and why the absence of an observed timing effect is uninformative rather than reassuring. Standardized definitions that anchor leak onset to the date of transplantation, intervention timing to the date of leak recognition, and severity to the ISGLS grade are a prerequisite for any future pooled analysis.

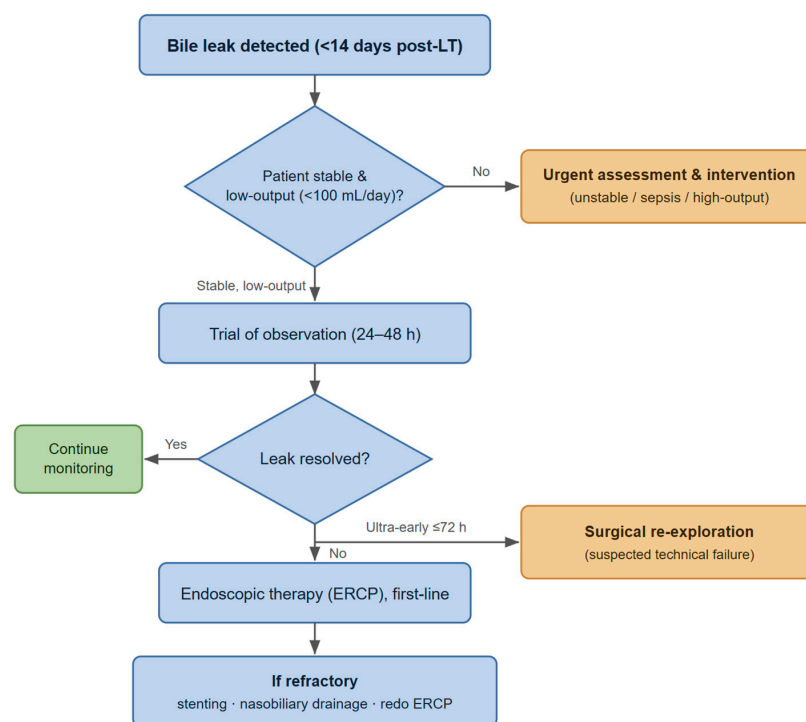
Additional limitations warrant mention. The retrieval filters—restriction to Q2-or-higher journals and to full-text records—may have excluded relevant work, particularly single-center series from specialized transplant units publishing in institutional or lower-indexed journals. Much of the leak-type and resolution data derive from heterogeneous, unadjusted case series; the cross-study proportions reported here (e.g., 58–69% vs. 90–100%) are correlational and confounded by leak severity, graft type, and institutional practice, and should not be read as adjusted effect estimates. Living-donor and deceased-donor populations differ materially, and pooled interpretation across graft types risks obscuring

clinically important differences; graft-stratified data have therefore been presented separately where possible (Table 5). Many studies did not report outcomes stratified by timing; publication bias may inflate apparent success rates; and large language model-assisted extraction, although manually verified, may have missed nuanced information.

This review has several strengths. To our knowledge, it is the first structured synthesis in the English literature to explicitly examine whether leak characteristics and patient stability provide more consistent guidance than intervention timing within the early 14-day window, and to translate that examination into a stratified, clinically actionable framework. Consistent with a narrative design, its conclusions are descriptive and hypothesis-generating.

6. Directions for Future Research

To validate the proposed clinical framework, the most feasible approach is a multicenter prospective registry incorporating predefined timing strata—ultra-early (<24 h), early (24–72 h), intermediate (3–7 days), and delayed (7–14 days)—with mandatory stratification by leak type (anastomotic vs. non-anastomotic), International Study Group of Liver Surgery (ISGLS) severity grade, graft type, and biliary reconstruction method. Primary outcomes should include time to complete leak resolution, total intervention burden, and 30- and 90-day mortality. Given success rates of 80–98%, detecting a 10-percentage-point difference requires approximately 200 patients per timing group; with a 10% leak incidence and 50% presenting within 14 days, approximately 10,000 transplants across centers would be needed. Propensity score methods should be applied where randomization is infeasible; death and graft failure should be modeled as competing risks in time-to-resolution analyses [7,9,10,39]. Key unanswered questions include whether anastomotic and non-anastomotic leaks respond differently to timing strategies, whether contemporary machine perfusion modifies timing–outcome relationships in DCD recipients [18,30], and which clinical parameters predict spontaneous resolution versus the need for intervention in stable patients (Figure 2) [15,46].



Endoscopic resolution varies by leak type (lower for anastomotic leaks); bridging-stent placement is the strongest reported predictor of endoscopic success.

Figure 2. Proposed clinical decision algorithm for early post-transplant bile leaks (<14 days), stratified by timing, patient stability, and leak type. Expected success rates stratified by leak anatomy.

Furthermore, as the management of complex biliary complications requires highly specialized expertise, future paradigms may increasingly rely on advanced technological integration. The rapid evolution of robotic platforms and artificial intelligence holds the potential to redefine these complex hepatobiliary interventions. Emerging concepts in AI-augmented telesurgery and intelligent robotics could eventually facilitate remote, expert-guided ERCP or precision robotic re-explorations for ultra-early technical failures, thereby standardizing high-level care across diverse transplant centers [52,53].

7. Clinical Implications

In the absence of evidence supporting a specific early versus delayed intervention strategy within the first 14 postoperative days, clinical decision-making should not be driven by rigid temporal thresholds alone. Management should be individualized and guided primarily by bile leak characteristics, graft perfusion status, and patient clinical stability. Anastomotic leaks, which are reported to have lower resolution rates across endoscopic modalities, warrant closer surveillance and a lower threshold for escalation, whereas non-anastomotic leaks such as T-tube or cut-surface leaks may be more amenable to endoscopic management or short periods of observation in clinically stable patients. The high success rates of endoscopic intervention across studies, without demonstrated dependence on timing, support a measured and multidisciplinary approach rather than reflexive early intervention. Until robust timing-specific evidence becomes available, a patient-centered strategy integrating surgical judgment, endoscopic expertise, and institutional protocols remains the most clinically sound approach.

8. Conclusions

Within the early postoperative period, leak characteristics and patient stability appear to offer more consistent and clinically actionable guidance than chronological timing for post-transplant bile leaks. The available evidence supports a practice-relevant reframing in which management is anchored to the anatomical type of the leak, patient clinical stability, and the selected management modality—most notably bridging stent placement within endoscopic therapy. A limited subset of ultra-early technical failures (≤ 72 h) may warrant prompt surgical re-exploration, whereas stable patients with later-onset or non-anastomotic leaks are generally well served by selective observation or elective endoscopic management, which achieves high success rates (80–98%) across temporal windows. Crucially, the absence of a demonstrated timing effect reflects a lack of direct comparative evidence rather than proof that timing is irrelevant; this remains an open question. Upstream prevention strategies—machine perfusion, arterial-first reperfusion, and optimized surgical workflows—show associations with improved biliary outcomes that may exceed the influence of post-complication timing. Future clinical pathways and prospective research should shift from rigid temporal thresholds toward anatomical classification and leak-specific management algorithms, while directly testing whether timing independently affects outcomes.

Author Contributions: Conceptualization, M.S. and F.K.; methodology, M.S., A.G.L. and F.K.; validation, M.S., F.K. and E.N.; investigation, M.S., H.O., V.D., R.H., S.H., Y.B.A., T.N., K.A., R.J.O. and N.Z.; resources, A.G.L., E.N. and F.K.; data curation, M.S.; writing—original draft preparation, M.S.; writing—review and editing, A.G.L., H.O., V.D., R.H., S.H., Y.B.A., T.N., K.A., R.J.O., N.Z., E.N. and F.K.; visualization, M.S.; supervision, E.N. and F.K.; project administration, M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study.

Acknowledgments: This review was conducted via the Elicit research platform for literature search and AI-assisted data extraction. The authors acknowledge the limitations inherent in AI-assisted review methodologies while recognizing their utility for comprehensive literature synthesis under rigorous human validation, and the authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

DCD	Donation after Circulatory Death
DDLT	Deceased Donor Liver Transplantation
ERCP	Endoscopic Retrograde Cholangiopancreatography
ISGLS	International Study Group of Liver Surgery
ITBL	Ischemic-Type Biliary Lesions
LDLT	Living Donor Liver Transplantation
OLT	Orthotopic Liver Transplantation
PTBD	Percutaneous Transhepatic Biliary Drainage

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