Review

Clinical Decision-Making in Laparoscopic Common Bile Duct Exploration: Choosing Between Primary Closure and T-Tube Drainage

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AIM: Choledocholithiasis, or common bile duct (CBD) stones, is increasingly prevalent in aging populations worldwide. Laparoscopic common bile duct exploration (LCBDE) is a well-established minimally invasive procedure; however, the optimal method for choledochotomy closure—primary closure (PC) versus T-tube drainage (TTD)—remains controversial.

METHODS: This narrative review summarizes the available evidence from randomized controlled trials, meta-analyses, and observational studies to compare perioperative practices, clinical outcomes, and patient-specific variables associated with PC and TTD following LCBDE.

RESULTS: Quantitative data from meta-analyses and recent clinical studies indicate that when complete stone clearance is achieved and patient conditions permit, PC is associated with significantly shorter operative time (by approximately 20 minutes), reduced hospital stay (by 1–2 days), and lower overall complication rates (e.g., 5.2% vs. 12.1% in selected series), without increasing the risks of bile leakage or biliary stricture. TTD remains valuable in scenarios involving residual stone risk, biliary tract inflammation, uncertain ductal anatomy, or limited institutional resources. Key determining factors include CBD diameter, infection status, choledochoscopic visualization quality, and operator expertise.

CONCLUSIONS: Both PC and TTD are valid therapeutic options following LCBDE, with PC preferred in uncomplicated cases and TTD indicated for high-risk scenarios. An individualized, patient-centered strategy based on intraoperative findings and institutional resources is essential to optimize clinical outcomes.

Keywords: choledocholithiasis; laparoscopic common bile duct exploration; primary closure; T-tube drainage; intraoperative decision-making; surgical outcomes

Introduction

Choledocholithiasis, defined as the presence of stones within the common bile duct (CBD), occurs in approximately 10%~15% of patients with gallstone disease. Its prevalence is rising, particularly among older adults, due to increased life expectancy and a higher incidence of comorbidities [1,2]. This condition can lead to severe complications such as jaundice, cholangitis, and pancreatitis. The projected global increase in CBD stones cases underscores the need to refine and optimize treatment protocols for choledocholithiasis across diverse healthcare settings.

Historically, the management of CBD stones has relied on a two-stage approach: endoscopic retrograde cholangiopancreatography (ERCP) for stone extraction followed by laparoscopic cholecystectomy. This strategy was long regarded as the gold standard of practice for the management of choledocholithiasis management [3]. However, with advances in minimally invasive surgical techniques, increasing numbers of centers have begun to implement a one-stage procedure with laparoscopic common bile duct exploration (LCBDE) and cholecystectomy in the same operation. It allows for simultaneous clearance of stones and gallbladder removal and thereby eliminates having to do ERCP separately [3]. A recent meta-analysis of randomized controlled trials of single-stage (LCBDE plus cholecystectomy) versus two-stage (ERCP followed by surgery) methods has shown that single-stage treatment yields equivalent or superior results, with extra benefits of reducing the number of procedures per patient [4]. Consequently, LCBDE has thus emerged as a safe, effective, and increasingly popular alternative to sequential ERCP, offering superior stone clearance rates and favorable perioperative outcomes [5].

In LCBDE, one of the most important intraoperative decisions is choosing the optimal method of closure of the choledochotomy (surgical incision into the CBD) following

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stone removal. The two broad choices for surgeons are primary closure (PC) of the duct or external bile drainage using a T-tube. Classically, T-tube drainage (TTD) was the standard in open bile duct surgery, employed primarily to drain the biliary tree and permit intraoperative and postoperative cholangiography. However, T-tube use is associated with complications, including bile leakage, tract infection, tube dislodgment, and electrolyte–fluid imbalances [6]. With advent of advanced laparoscopic techniques, PC without the requirement of T-tube has gained universal acceptability, facilitated by enhanced intraoperative visualization and superior suturing methods. This paradigm shift in practice change has sparked ongoing debate regarding the necessity of routine T-tube insertion in the laparoscopic era [7].

Despite extensive clinical experience, the surgical community has not reached a consensus on the optimal CBD closure technique following LCBDE. There is still controversy regarding indications for TTD and under what conditions PC can be safely performed [3,6]. The major controversy is whether PC carries a greater risk of long-term complications, e.g., postoperative bile leakage or biliary stricture, compared with TTD. There remains controversy regarding whether TTD reduces recurrence of bile duct stones or improves long-term result in high-risk settings. New evidence from recent reports progressively refutes the prevalent use of T-tubes, instead promoting PC as a rational and in some instances better alternative in most scenarios [8]. As a result, the selection between PC and TTD is often guided by individual surgeon preference, patient anatomy, and intraoperative considerations, leading to practice variability.

High-quality research published in 2025 has further reinforced the preferential use of PC over TTD in LCBDE. A 2025 propensity score matching investigation of 433 patients confirmed that PC is associated with reduced operation times, decreased blood loss, and lower postoperative infection rates, without increasing the risks of bile leakage or stricture [9]. In elderly patients, PC also demonstrated superior recovery profiles compared to TTD [10].

This review aims to address this persistent clinical dilemma by proposing an individualized, evidence-based strategy that enables surgeons to select the optimal closure technique based on patient-specific and operative considerations.

Literature Search and Study Selection

A structured literature search was conducted to identify all relevant studies comparing PC and TTD following LCBDE. Electronic databases including PubMed, Embase, Web of Science, and the Cochrane Library were searched from their inception through May 2025. The search strategy employed a combination of keywords and Medical Subject Headings (MeSH) terms, including: ("laparoscopic common bile duct exploration" OR LCBDE) AND ("primary closure" OR "primary suture" OR "duct closure") AND ("T-tube" OR "T-tube drainage" OR "biliary drainage") AND ("choledocholithiasis" OR "bile duct stones"). Reference lists of retrieved articles and relevant review papers were also manually screened to identify additional eligible studies.

Studies were included if they met the following criteria: (1) population: patients undergoing LCBDE for choledocholithiasis; (2) intervention and comparison: direct comparison of PC versus TTD for choledochotomy closure; (3) outcomes: reporting of at least one perioperative or clinical outcome (e.g., operative time, bile leakage, hospital stay, biliary stricture, complications); (4) study design: randomized controlled trials (RCTs), cohort studies (prospective or retrospective), and meta-analyses. Exclusion criteria included case reports, narrative reviews, non-comparative studies, non-English publications, and duplicate publications.

The study selection process followed these steps: first, titles and abstracts of identified records were screened for relevance. Subsequently, the full texts of potentially eligible studies were assessed against the inclusion and exclusion criteria. This screening and selection process was conducted independently by two authors to minimize bias. Any discrepancies regarding study eligibility were resolved through discussion or consultation with a third author until a consensus was reached.

The initial database search yielded 687 records. After removing duplicates, 452 unique records remained. Following title and abstract screening, 78 articles were selected for full-text review. Of these, 42 studies met the predefined eligibility criteria and were included in this narrative review. Although a PRISMA flow diagram is not provided, the selection process strictly adhered to the stages of identification, screening, eligibility, and inclusion.

Risk of Bias and Data Synthesis

As this is a narrative review rather than a meta-analysis, no formal risk-of-bias assessment tools (e.g., RoB 2.0, Cochrane) were applied. However, the methodological quality and potential biases of the included studies were critically evaluated using a structured qualitative approach. Assessment criteria included study design (with RCTs and large prospective cohorts considered higher quality), sample size and statistical power, clarity of inclusion/exclusion criteria, completeness of outcome reporting, appropriateness of statistical methods, and internal consistency of results.

Comparative Outcomes and Technical Rationale: Weighing PC vs. TTD

Primary Closure

PC refers to the closure of the choledochotomy following stone removal during LCBDE without the use of an external biliary drain. This procedure typically involves a single-layer closure of the CBD using absorbable sutures under laparoscopic visualization, with opposition of the duct walls in a careful manner to ensure a watertight closure. In certain cases, a temporary internal stent or nasobiliary drain may be inserted to enable bile drainage and reduce intraductal pressure; however, in true PC, no T-tube or long-term drainage catheter is used. The success of this technique depends on adequate ductal clearance and meticulous examination of the bile duct, preferably acquired during intraoperative choledochoscopy, to confirm that no stones are left behind prior to closure [3].

A key advantage of PC, as demonstrated in recent meta-analyses, is the significant reduction in T-tube-related morbidities, including electrolyte abnormalities and tract infections [5]. The absence of an external biliary drain improves patient comfort and abolishes the need for postoperative drain management or requirement for subsequent removal interventions [11]. Several clinical trials have demonstrated that PC is associated with reduced operating time, reduced hospital stay, and faster return to normal activity compared with TTD [5,12]. Interestingly, more recent evidence confirms that, in well-selected patients-typically those with a CBD diameter $\geq$8 mm, confirmed complete stone clearance intraoperatively (e.g., via choledochoscopy), absence of severe acute cholangitis or significant ductal inflammation, and clear biliary anatomy-PC carries no increased risk of bile leakage or long-term biliary stricture complication compared to TTD [5].

By the removal of the T-tube, PC also avoids tube-related complications, including dislodgement, tract infection, and fluid loss. The principal disadvantage of PC is technical, in that it involves intracorporeal CBD suturing and complete exploration of the duct, procedures that necessitate advanced laparoscopic skill and intraoperative resources such as fluoroscopy and choledochoscopy [3]. If inadvertently a residual stone is left behind, postoperative ERCP or even surgical reoperation may be needed. Therefore, PC is ideally reserved for cases where complete stone clearance can be definitely confirmed intraoperatively.

T-Tube Drainage

TTD involves to placing a T-shaped tube typically of silicone or latex into the CBD following choledochotomy. The transverse limb of the tube is left within the duct lumen and the longitudinal limb is taken out through a small incision in the abdomen for external drainage. The choledochotomy is also left partially open over the tube to keep it in place, forming a continuous tract for bile to drain into a collection bag. Postoperatively, the T-tube serves as a biliary stent, maintaining ductal patency and decompressing the biliary tree-particularly useful in the setting of widespread edema or recurrent inflammation. In addition, it allows for postoperative contrast cholangiogram via the tube tract, typically 1~2 days after surgery, for better clearance of stones. T-tube also offers a pathway through which remaining stones can be flushed or removed, potentially preventing the need for early reoperation.

Historically, T-tube placement was utilized to decompress the biliary system and reduce intraductal pressure, with the theoretical goal of reducing bile leakage postoperatively [6]. As noted by Jiang *et al*. [8], TTD provides a useful postoperative safeguard, whereby both cholangiography and stone extraction can be performed via the tube tract. If a residual stone is detected on the postoperative cholangiogram, it may be extracted through the T-tube tract or addressed with ERCP, while the tube continues to provide effective biliary drainage [8]. However, recent evidence-including data from meta-analyses-indicates that, despite its theoretical advantages, routine use of T-tubes introduces notable clinical drawbacks, including a longer postoperative hospital stay, increased patient discomfort due to the external drain and its management, persistent fluid and electrolyte losses from bile drainage (often several hundred milliliters daily), and specific T-tube-related complications such as tube dislodgement (which can lead to bile peritonitis), tract infection, and issues related to its subsequent removal [5,6]. The presence of an external drain for 1~2 weeks postoperatively is associated with patient discomfort and an increased burden of at-home care requirements [11]. Moreover, the continuous loss of bile through the T-tube-often amounting to several hundred milliliters per day-can cause fluid and electrolyte disturbances and temporarily deprive the patient of digestive bile flow. T-tube removal is usually obtained 10~14 days after surgery. Once a matured tract has formed, thereby extending the patient's total convalescence.

As Al-Qudah and Tuma [6] noted, TTD can lead to several complications like tract infection, bile leakage, tube dislodgment, and, in some rare cases, biliary peritonitis-more frequently when the tube gets dislodged early. A meta-analysis by Zhu *et al*. [5] also demonstrated that T-tube use is associated with longer hospital stay and postoperative complication rate compared with PC. Supported by a growing number of papers, routine T-tube placement is increasingly questioned, especially in the context of complete ductal clearance and PC being technically feasible [7,8]. In the hope of reducing the morbidity of external drainage, Dong *et al*. [13] investigated alternative internal biliary drainage. They found comparable rates of stone clearance with improved patient comfort in comparison to T-tube insertion [13]. Such options remain to be confirmed, however, and the core surgical dilemma—whether to perform primary closure or place a drain remains a major consideration in CBD stone management.

Evidence From Trials and Meta-Analyses

There is a growing body of evidence from randomized controlled trials and meta-analyses comparing the safety and efficacy of PC and TTD following LCBDE. In a comprehensive meta-analysis of 6 RCTs and 10 observational studies encompassing approximately 1865 patients in 2021, Zhu *et al*. [5] provided quantitative evidence favoring PC. Their analysis demonstrated that PC was associated with a significant reduction in operative time (mean difference [MD] approximately 20 minutes), lower overall postoperative complication rates (risk ratio [RR] often reported in the range of 0.5–0.7, indicating a 30–50% reduction), and a shorter postoperative hospital stay (MD approximately 2 to 3 days), without increasing the risks of bile leakage, retained stones, or late biliary strictures (RR for these specific complications typically not significant, with 95% CI spanning 1.0). These findings were reinforced by Ma and Cai [14] in their meta-analysis, which confirmed that PC significantly improved operative efficiency (e.g., reduced operative time) and accelerated recovery (shorter hospital stay), while maintaining comparable safety outcomes, particularly showing non-inferiority in bile leakage rates (RR often around 0.8–1.2 with 95% CI including 1.0) and other major complications. Further studies in 2025 upheld the same findings. Chen *et al*. [9] conducted a propensity score–matched study of 433 patients and demonstrated that PC had less operation time, no intraoperative blood loss, and less postoperative infection with no increase in bile leakage or biliary stricture rates. La *et al*. [10] also contrasted elderly patients with hepatolithiasis or choledocholithiasis and validated PC had shorter operation time and hospital stay without increasing the rate of complications against TTD.

These findings are further supported by high-quality retrospective studies. Zheng *et al*. [15] employed propensity score-matched analysis and found similar safety profiles in patients treated with TTD and LCBDE without drainage, prompting abolition of routine drainage in most cases. Teng *et al*. [16] also compared synchronous CBD and gallstones patients' results with those of synchronous CBD and TTD patients and concluded no difference in the PC group and TTD group, a demonstration of the extended use of PC even among synchronous biliary disease patients. Even in complex presentations of big, multiple, or impacted stones, laparoscopic examination of CBD has been shown to be comparable to open surgery when performed with appropriate technique [17].

A number of institutional series and cohort series have independently validated the effectiveness and utility of PC. Yin *et al*. [18] published a retrospective analysis stating that PC was associated with accelerated recovery and comparable postoperative complication rates compared to TTD. Single-institution series have shown outstanding ductal clearance rates and comparable bile leak rates (no significant difference) for PC and TTD [19,20]. A multicenter study by Cawich *et al*. [21] also confirmed homogenous outcomes of PC in multiple practice settings with its replicability. Geographic variations in evidence from Egypt and the Caribbean further highlight the broad applicability of laparoscopic PC [22,23]. Notably, as early as 2013, a Cochrane systematic review indicated that routine TTD after open CBD exploration did not confer significant long-term benefits over PC, thereby challenging the traditional default T-tube use [24].

Considered together, these collective inferences-from classical systematic reviews to the modern comparative real-world analyses-support PC as the go-to approach following LCBDE if intraoperative status is ideal and technical success is feasible.

While cumulative evidence strongly supports the safety and efficacy of PC, a critical appraisal reveals substantial heterogeneity across studies that must be considered when interpreting these findings. Variations in patient selection criteria-such as differing CBD diameter thresholds for PC (ranging from 6 mm to 10 mm across institutions)-inherently influence postoperative outcomes like bile leakage and stricture rates. Furthermore, the outcomes are significantly confounded by surgeon expertise and the institutional learning curve for advanced laparoscopic suturing. Meta-analyses pooling data from both high-volume specialized centers and community hospitals may underestimate the complication rates of PC in less experienced hands. Similarly, the definition of "complete stone clearance" is highly dependent on the availability and quality of intraoperative choledochoscopy, a variable not consistently reported in all included studies. This heterogeneity underscores that the favorable results of PC are most reproducible in settings with optimal patient selection, advanced surgical skills, and robust intraoperative resources.

Critical Appraisal of Determinants for Surgical Decision-Making

Bile Duct Diameter (≥8 mm)

Bile duct diameter is a key factor in closure selection after LCBDE. While a larger duct (≥8 mm) has traditionally been preferred for PC due to perceived lower stricture risk, evidence shows that with optimal conditions and technique, PC in ducts <8 mm does not increase stricture risk [25]. Traditionally, a CBD diameter of 6~8 mm has been considered as the safe limit for PC, assuming smaller ducts are more likely to form strictures and are technically more challenging to perform intracorporeal suturing on. This conventional threshold of 8 mm is supported by several studies that have identified it as a practical cutoff associated with successful primary closure and a lower risk of postoperative complications, particularly biliary stricture [25,26]. Indeed, wider ducts facilitate easier placement of sutures and are associated with greater confidence of the surgeon for long-term patency of the duct. Nevertheless, recent evidence points towards the conventional 8 mm "safe threshold" not being absolute. Xiong *et al*. [26] have already reported that PC can be safely performed in ducts of diameter less than 8 mm without increased risk of stricture or bile leakage, if careful technique is employed. Therefore, even ≥8 mm diameter is ideal, a reduced diameter should never preclude primary repair if the other intraoperative conditions are favorable. The strength of evidence for a rigid 8-mm cutoff is moderate at best, primarily based on observational data and historical precedent rather than high-level RCTs. Therefore, while a larger duct diameter facilitates PC, a smaller diameter should not be an absolute contraindication if other conditions (excellent visualization, minimal inflammation, expert technique) are favorably met.

Inflammation and Infection Severity

The severity of biliary tract inflammation and cholangitis significantly impacts intraoperative management. For example, edematous or inflamed tissue can compromise suture strength and healing potential [26]. When severe infection is suspected-based on significantly increased levels of inflammatory markers (e.g., C-reactive protein, procalcitonin) and visible edema of the CBD-drainage via T-tube has a preference from surgeons in order to achieve adequate biliary drainage and reduce risk of postoperative bile leakage. The primary concern is friable, inflamed ductal tissue may not accept sutures well, and is thus at risk for leaks, as well as the fact that ongoing infection can be more easily managed by external drainage. Despite this, Wang *et al*. [27] and Zhuang *et al*. [28] have demonstrated in their research that PC is still feasible and safe even in the acute cholangitis setting if and when patients are well selected and preoperatively managed. Even in the setting of acute choledocholithiasis (which often presents with cholangitis), some studies have reported comparable rates of bile leakage and overall complications between PC and TTD groups [27,28]; however, these findings are based on selected patient cohorts and may not be generalizable to all patients with moderate to severe cholangitis without careful intraoperative assessment. Aggressive antibiotic therapy and careful surgical technique are most important in these patients for good results. Of note, active infection of bile with specific pathogens (e.g., Enterococcus) has been identified in a recent review as a potential risk factor for postoperative bile leakage following PC, highlighting the role of infectious burden in ductal healing [26]. Overall, being so inflamed or septic should be managed with caution and might make one consider the use of a T-tube or, at least, a temporary drain. However, if the infection is adequately controlled and the bile duct tissue is viable, PC can be done safely.

Residual Stones or Uncertain Anatomy

When residual stones are suspected or ductal visualization is incomplete, most surgeons opt for T-tube insertion to enable postoperative cholangiography and potential nonsurgical stone removal if necessary [6]. The T-tube acts as a safeguard, especially when there is suspicion of small calculi remaining in the intrahepatic ducts or that a piece of stone has been inadvertently overlooked during intraoperative exploration. Via the T-tube tract, contrast imaging can be performed postoperatively to detect retained stones, and in some instances, residual stones can be flushed out or extracted through the tract, thereby avoiding reoperation. In contrast, with PC, any undetected stone would likely require a repeat intervention, typically via ERCP or even reoperation. So, when intraoperative cholangiogram or choledochoscopy cannot provide complete visualization of the biliary tree-due to technical reasons or challenging anatomy-surgery can fall back on a T-tube for management of potential residual lithiasis [6]. The risk of retained stones is especially high in the case of multiple or intrahepatic stones, making TTD a prudent precautionary measure in such scenarios [29]. Precise demarcation of ductal anatomy with identification of tapering, strictures, or anomalous ducts is essential; indeterminate results require more conservative measures with T-tube insertion. Notably, a recent comparative study noted that patients with more numerous or larger CBD stones often present a more complex scenario, and in such challenging cases (e.g., suspected residual stones, intrahepatic stones), T-tube drainage remains a viable management option, as it provides a route for postoperative assessment and intervention [29].

Choledochoscopic Clarity

The availability and quality of intraoperative choledochoscopy-endoscopic visualization of the CBD are critical factors influencing the decision between PC and TTD. In centers equipped with advanced imaging technologies, surgeons can directly confirm complete stone clearance by inspecting the ductal lumen in real time. If choledochoscopic visualization is excellent and wide, and all stone fragments are successfully evacuated, surgeons are more inclined to proceed with PC. Without high-quality choledochoscopy, X-ray cholangiography alone may fail to detect minute or intrahepatic retained stones, leading to a more conservative approach of T-tube insertion [3].

Inadequate visualization-due to factors such as intraluminal bleeding, debris, or narrow ducts impeding scope passage-also introduces diagnostic uncertainty. Under these conditions, TTD provides a "second-look" opportunity via the tube tract for postoperative ductal reassessment and potential stone retrieval. Therefore, the routine use of intraoperative choledochoscopy is strongly recommended to reduce the risk of missed stones [3], and the decision to omit a T-tube often hinges on the surgeon's confidence in the completeness of ductal inspection and clearance.

Patient Comorbidities and Risk Profile

Patient overall health of the patient as well as comorbidities are also important factors to weigh when selecting a closure method after LCBDE. In the elderly or medically compromised patient, clinical data support avoiding additional manipulation, and multiple studies have demonstrated PC to be associated with good results as long as patients are appropriately selected [30,31]. While on the one hand LCBDE with PC eliminates the need for cholangiography or tube removal after surgery and therefore spares patients the inconvenience and discomfort of an external drain, it is conceivable that this may enhance early mobilization and overall recovery postoperatively. Importantly, studies have also confirmed that even in elderly groups, PC can be performed safely and can speed up recovery when performed with sound surgical judgement [30,31]. Yet another study more recently highlighted that older age and greater comorbidity scores are predictive of increased rates of post-LCBDE complication, highlighting the need for meticulous preoperative evaluation and optimization of patient-related factors to mitigate overall procedural risk [32]. This is consistent with earlier reports illustrating that even octogenarians could safely and successfully undergo single-stage laparoscopic bile duct exploration with PC without needing staged procedures [33]. On the other hand, in critically ill cardiopulmonary patients or with long or highly technical intraoperative time, a surgeon will opt to shorten the procedure by placing a T-tube and thereby limit anesthesia time. In this case, the disadvantage of procedural time against the postoperative burden of care for a T-tube needs to be considered on an individual basis. Interestingly, even among nonagenarians and the so-called "oldest old", LCBDE has been shown to be both safe and feasible [34]. Accordingly, while advanced age and comorbidities are by no means absolute contraindications to PC, they do underscore the need for a risk-adjusted, personalized surgical approach.

Determinants and a Clinical Decision Framework for Closure Strategy

The technical capability and experience of the operating team and the institutional infrastructure are major deciding factors in selecting the appropriate closure technique following LCBDE. Nassar *et al*. [35] shared a grading system for difficulty in LCBDE that highlights the importance of surgeon experience and technical skills in determining PC versus TTD. Less experienced surgeons may utilize T-tube placement as a protective measure, while experienced biliary surgeons are more likely to perform PC, leveraging their expertise in comprehensive ductal exploration and safe closure [35]. This grading system further facilitates stratification of operative complexity, allowing prediction by surgeons when adjunct procedures can be expected or when conversion to open or staged procedure would be appropriate [35]. Institutional factors also need to be considered. The availability of interventional radiology, endoscopic facilities, and multidisciplinary team rooms means that more institutions are likely to manage postoperative issues of PC-such as bile leak, which can be managed with ERCP and stenting. Where resources do not exist, perceived safety of T-tube may be the option where postoperative circumstances are unclear and hard to manage in the absence of standby facilities [35]. Ultimately, sound surgical judgment founded on the technical skill of the operating personnel and available surroundings is ultimately most crucial in determining the optimal closure method for the individual patient.

Combining the above parameters, surgeons require a risk-adapted algorithmic strategy to guide intraoperative decision-making between PC and TTD, as in Fig. 1. Step-by-step analysis of four operative parameters maximizes intraoperative decision-making following LCBDE. Start with CBD assessment, prioritizing diameter and integrity of the wall. A CBD diameter $\geq$8 mm with hard wall sustains PC, whereas a friable, stenotic, or inflamed duct may necessitate TTD [25]. Second, confirm clearance of stone intraoperatively by cholangiography and/or choledochoscopy. In the case of intraoperative imaging evidencing complete biliary tree visualization and absence of residual stone, PC can safely be done [3,36]. In cases with suspected residual stones (e.g., due to difficult anatomy or large stone burden), TTD may be employed, providing a tract for potential postoperative management [29]. The leaves space for postoperative cholangiographic evaluation and potential non-operative management, if necessary [6]. Third, evaluate for severe inflammation. In the presence of purulence, uncontrolled cholangitis, or systemic evidence of infection, TTD is generally preferred to ensure safe decompression and prevention of bile leakage risk. This is particularly relevant when inflammatory markers are significantly elevated, specifically a C-reactive protein (CRP) level $\geq$100 mg/L, which indicates a substantial systemic inflammatory response, or a procalcitonin (PCT) level $>$0.5 ng/mL, which suggests a high likelihood of bacterial infection [26]. In contrast, in low-inflammatory load elective settings, PC is a suitable option.

Intraoperative decision also needs to be based on real-time patient physiology and surgery course. If the operation is running too long or the patient is becoming unstable, the surgeon may select TTD as a means to restrict operative time and reduce procedural stress [30]. Conversely, when the patient is stable and all safe closure criteria are met, PC may be continued with the advantage of preventing morbidity from external drainage [11,31]. In practice, experienced surgeons are likely to use these parameters in an implicit mental algorithm-a decision tree in which PC is performed if all intraoperative checkpoints are positive, and TTD is chosen when multiple risk factors occur intraoperatively.

It is also essential for surgeons to be dynamic and adaptive intraoperatively-willing to make what is oft referred to as the "switch decision". The operation can be planned initially with PC in mind; however, if there are unforeseen intraoperative findings—i.e., a greater-than-anticipated stone burden, difficult biliary clearance, or excessive edema or bleeding-the surgeon should not hesitate to intraoperatively convert to TTD [8,35]. Conversely, if the operation proceeds more easily than anticipated, it is appropriate for a surgeon to omit an initial T-tube in favor of PC, provided all safe closure requirements are met. This adaptable strategy allows the final decision to be based upon the immediate intraoperative circumstances and not to be hampered by an inflexible preoperative protocol. While flowcharts and algorithmic models have been proposed to formalize decision-making [36], in clinical practice, success often hinges on the surgeon's judgment, balancing all intraoperative variables in real time. Ultimately, the guiding principle remains constant: to maximize patient safety and optimize surgical outcomes by selecting the closure strategy that best fits the individualized risk profile and operative findings of each patient.

To support this intraoperative strategy, Fig. 1 presents a stepwise, risk-adjusted algorithm merging ductal anatomy, stone clearance, inflammatory severity, and operative context to guide closure selection. In concept, this is connected to the difficulty grading system of Nassar *et al*. [35] for LCBDE, which permits real-time decision regarding closure and supports training and standardization.

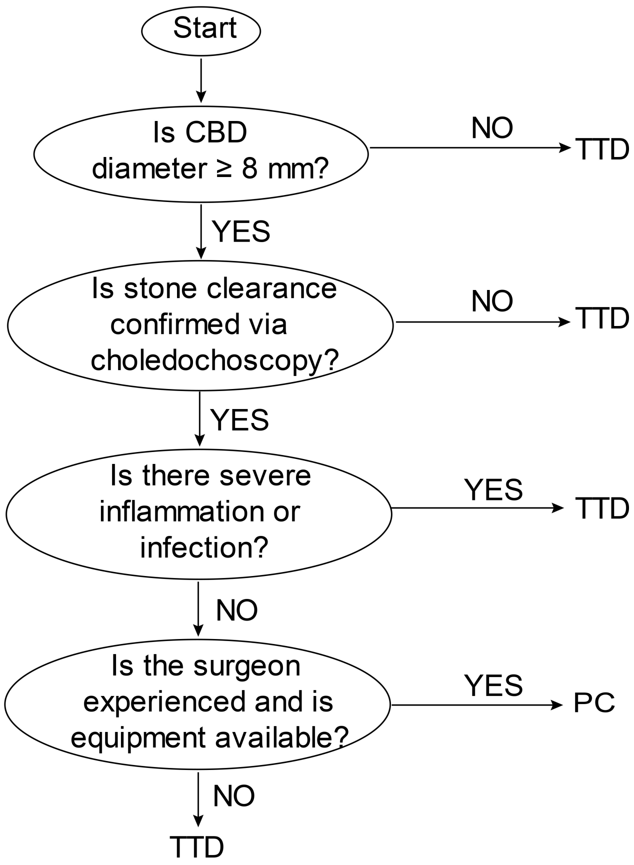

Fig. 1. Clinical decision-making algorithm for closure strategy after laparoscopic common bile duct exploration (LCBDE). CBD, common bile duct; TTD, T-tube drainage; PC, primary closure.

Start: after complete stone removal during LCBDE, assess the following parameters sequentially:

1. Bile duct diameter & integrity: if CBD diameter $\geq$8 mm AND duct wall is healthy/non-friable $\rightarrow$ proceed to next parameter (Step 2). If CBD diameter <8 mm OR duct wall is friable, stenotic, or severely inflamed $\rightarrow$ consider TTD.
2. Confidence in complete stone clearance: if intraoperative cholangiography and/or choledochoscopy confirm complete clearance (full visualization of biliary tree, no residual stones) $\rightarrow$ proceed to next parameter (Step 3). If uncertainty exists regarding complete clearance (e.g., poor visualization of distal CBD, suspected residual fragments, multiple/intrahepatic stones) $\rightarrow$ recommend TTD.
3. Severity of inflammation/infection: if no signs of severe systemic infection (CRP <100 mg/L AND PCT $\leq$0.5 ng/mL) AND no local purulence/uncontrolled cholangitis $\rightarrow$ proceed to next parameter (Step 4). If signs of severe systemic infection (CRP $\geq$100 mg/L AND/OR PCT >0.5 ng/mL) OR local purulence/uncontrolled cholangitis $\rightarrow$ recommend TTD.
4. Operative context & resources: If patient is physiologically stable AND operative time is acceptable AND surgical expertise for laparoscopic suturing is available AND institutional support (e.g., ERCP backup) exists $\rightarrow$ favorable for PC. If patient becomes unstable, operation is prolonged, OR requisite surgical expertise/institutional support is lacking $\rightarrow$ consider TTD to expedite procedure and ensure safety.

This algorithm provides a proposed intraoperative flowchart to guide surgeons in choosing between primary closure and TTD based on stepwise evaluation of key operative variables. These include bile duct diameter, confidence of stone clearance, inflammation/infection severity, and availability of intraoperative imaging and surgical expertise. Systemic infection is defined as CRP $\geq$100 mg/L and/or procalcitonin (PCT >0.5 ng/mL). Dilatation of CBD is important at $\geq$8 mm. This decision-making algorithm is based on the already existing published guidelines on LCBDE procedural difficulty grading and closure-related risk stratification [32,35].

Postoperative Outcomes

The choice between PC and TTD has implications for postoperative outcomes, however, contemporary studies suggest that both techniques can yield excellent results when applied to appropriately selected patients. A primary outcome of concern is bile leakage. Luckily, with either technique, bile leakage after LCBDE is rare-typically in the order of a few percent or so-and the comparative study is not demonstrating any statistically significant difference between PC and TTD groups as regards leak rates [5]. Zhang *et al*. [11] said that bile leaks following PC are typically trivial and can be successfully managed by conservative management or ERCP-guided stenting. In contrast, Al-Qudah and Tuma [6], on the other hand, said that bile leaks complicating TTD most often occur at the point of tube placement or following premature tube removal but are uncommon with meticulous technique. Importantly, long-term biliary stricture following LCBDE is exceedingly rare and has not been shown to increase with PC [5].

Evidence supporting the long-term safety, particularly concerning biliary stricture, is promising but must be interpreted with caution. While a study with follow-up up to

18 months report no strictures [27], the available literature is characterized by a lack of long-term (e.g., >5 years) prospective data. The risk of late-onset stricture following PC, though believed to be very low, cannot be fully ascertained without longer follow-up. Most existing studies, including favorable meta-analyses, are limited by their intermediate-term follow-up periods. Therefore, while PC appears safe in the mid-term, the possibility of long-term sequelae requires confirmation through more rigorous, long-term surveillance studies.

According to recent cohort analyses, infectious complication rates are more closely associated with patient condition and intraoperative factors than with the closure method itself [26]. Nonetheless, T-tube placement introduces specific risks-including ascending cholangitis, tract contamination, and fluid loss-which have been cited as key disadvantages in multiple comparative studies [5,6]. Intraoperatively, all these tube-related complications are avoided by PC. The limitation of PC, however, is that impacted stones, unless diagnosed intraoperatively, may subsequently lead to symptoms of biliary obstruction such as postoperative abdominal pain, jaundice, or cholangitis. A T-tube, in such a situation, would have allowed a preoperative diagnosis or decompression. In short, comparative series demonstrate that PC is associated with equivalent or fewer overall complication rates, mainly due to removal of T-tube-associated complications [5]. Meta-analyses, on the other hand, demonstrate consistently that patients with PC have shorter hospital stays and earlier return to normal function compared with T-tubes [14].

Use of ERAS protocols contributes to the enhancement of recovery rates. One trial demonstrated that the use of ERAS in the care of LCBDE decreased hospital stay significantly and accelerated functional recovery [37]. These benefits are partly a result of avoiding delay due to T-tube care, such as waiting for maturation of the tract and interval cholangiograms. Patients without an external drainage system also are more likely to report increased comfort, improved mobility, and higher overall satisfaction. In a comparative study, PC patients experienced less postoperative pain, and comparable incidence of referred shoulder pain, and their scores of patient satisfaction were higher than in patients with TTD [11].

Regarding long-term outcomes, neither PC nor TTD has demonstrated inherent superiority with regard to preventing CBD stone recurrence. The rates of recurrence are low and are largely dependent on patient-specific factors, such as stone diathesis or intrinsic biliary strictures, rather than the closure method. According to this, a follow-up study reports no significant difference in recurrence rates between PC and TTD groups [5]. With good patient selection and proper follow-up, both techniques are able to achieve long-term biliary drainage and high success rates, though PC offers greater efficiency and patient convenience during recovery.

Future Perspectives

Recent reports further highlight the requirement for patient-anatomy and intraoperative-informed individualized surgical decision-making for the treatment of CBD stones to optimize outcomes [32]. A key area of future development would be to develop formalized scoring systems or risk stratification algorithms to assist surgeons in being able to objectively quantify the factors that tip the scales in favor of PC versus TTD. For instance, points-based scoring system using the variables of CBD diameter, stone burden, inflammatory markers, and comorbidities can help in choosing the optimal closure in a given clinical scenario. Efforts along this line are already in progress-like the LCBDE difficulty grading system, which classifies cases according to anticipated procedural difficulty [35], and recent research that identifies predictive risk factors for complications, such as the association between some pathogens and bile leaks after surgery [26]. The next critical step is the prospective, multicenter validation of such a model to assess its impact on clinical outcomes and decision-making consistency across different practice settings. Furthermore, future studies should focus on identifying and validating novel predictive biomarkers, such as specific biliary pathogens or molecular markers of tissue repair capacity, which could further refine risk assessment for complications like bile leakage.

In parallel, Zhang *et al*. [38] investigated human fibrin sealant usage versus choledochotomy closure, with a reduced postoperative bile leakage rate. Advances in highly advanced intraoperative imaging technologies-including high-definition choledochoscopy and intraoperative real-time fluorescence cholangiography-have also enhanced the accuracy of ductal evaluation and confidence of surgeons in closure decisions [36]. Further refinement of predictive models represents a key future direction. The integration of artificial intelligence (AI) and machine learning (ML) holds promise for developing sophisticated decision-support tools. Such systems could analyze preoperative and intraoperative data-including imaging, inflammatory markers, and patient comorbidities-to provide real-time, individualized risk assessments for complications like bile leakage, thereby offering evidence-based guidance on the optimal closure choice (PC vs. TTD) for each patient [32,39,40]. These tools would augment, not replace, surgical judgment, helping to standardize and optimize decision-making.

Pioneering specialists have advocated for the development of consensus guidelines based on current evidence and standardized training modules to harmonize LCBDE practice across institutions [24]. Variable practice exists at the center level as well as between surgeons due to the absence of standardized protocols. The establishment of collaborative research networks and the execution of multicenter randomized controlled trials are essential to generate high-level evidence that can inform clinical guidelines and best practice recommendations [24]. With a stronger evidence base, professional societies would be positioned to issue standardized criteria for patient selection and closure method choice, thereby reducing inter-institutional variation. Standardization will also extend to surgical training so that trainees are skilled both in T-tube and choledochotomy closure so that they can provide balanced, patient-guided decisions.

In summary, the future of LCBDE lies in personalized, evidence-driven, data-driven care founded on predictive tools, technical improvements, and robust clinical evidence. Optimizing decision-making and standardizing practice guidelines will allow surgeons to improve outcomes, promote uniformity of care, and improve the general quality of biliary surgery.

Conclusions

Both PC and TTD are established techniques in the management of CBD following laparoscopic stone removal, each with a valuable role in the surgeon's armamentarium. The choice, however, is nuanced by the heterogeneity of the evidence base, where outcomes are modulated by patient factors, surgical expertise, and institutional protocols. PC is advantageous in providing an internal, tubeless recovery course and has been shown to be safe and effective in a wide range of clinical contexts. It has become the procedure of preference when anatomical status, stone removal, and patient status are all optimal. However, the enthusiasm for PC must be tempered by a candid acknowledgment of its limitations and potential failures.

TTD, as a second alternative, although more invasive in the postop management context, is nonetheless of important value in complicated cases-providing an element of security in the environment of residual stone risk, sepsis, or biliary anatomy problems. Therefore, the decision between PC and TTD is not to be followed by a universal algorithm but needs to be tailored based on the patient's ductal anatomy, pathology of disease, intraoperative circumstances, and the experience of the surgeon.

Finally, individualized and patient-specific treatment is imperative for the best outcomes with LCBDE. PC should be attempted by surgeons in those cases that have proper anatomical and procedural indications so that a safe closure can result in faster recovery, less postoperative morbidity, and avoidance of unnecessary external drainage. Conversely, TTD should be selectively reserved for cases involving residual stone risk, active infection, or problematic ductal anatomy, where it provides a safety margin. A wise, case-by-case policy derived from clinical evidence and gained through surgical practice is required to modulate the closure technique to the individual patient's situation.

Looking ahead, additional high-quality studies and rigorous clinical trials will further strengthen the evidence base and lay the groundwork for the development of formalized, evidence-based guidelines to drive institutional standardization. Meanwhile, however, the surgeon's careful, intraoperative clinical exam and judicious clinical judgment remain the primary determinants of the optimal decision between PC and TTD for each patient.

Availability of Data and Materials

Not applicable.

Author Contributions

KL: data collection, manuscript drafting. ZL, JG, ZFL and YQL: formal analysis, manuscript editing. All authors have been involved in revising the manuscript critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

Not applicable.

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Conflict of Interest

The authors declare no conflict of interest.

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