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Fundamental Strategies and Technical Perspectives in Bile Duct Anastomosis for Living Donor Liver Transplantation: Growth From Novice to Maturity

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Background: Biliary reconstruction is the most technically demanding step in living donor liver transplantation (LDLT), yet how a single surgeon's technique matures in the early career, and how this relates to clinical outcomes, remains incompletely characterized. This study evaluated whether the stepwise evolution of surgical technique was associated with a lower anastomotic biliary stricture (BS) rate.

Material/Methods: We retrospectively analyzed 382 consecutive right-lobe LDLTs with single-surgeon duct-to-duct biliary anastomosis performed between April 2020 and April 2024. Cases were grouped into 3 equal, consecutive time intervals (approximately 16 months each), and cumulative sum (CUSUM) analysis was applied to the learning trajectory. Independent risk factors for BS were identified by multivariable logistic regression, with separate models for surgical period and post-transition-point status.

Results: BS rates decreased across periods from 14.4% to 10.1% to 5.1% (P trend = 0.016). CUSUM identified a primary transition at case 33, ending the initial trial-and-error phase and coinciding with adoption of well-vascularized distal recipient duct selection, and a secondary inflection at case 210 coinciding with eversion-overlap anastomosis with hilar plate anchoring. Portal vein stenting (OR 6.515, P = 0.004) and ABO-incompatible transplantation (OR 2.462, P = 0.016) were independent risk factors. After adjustment, surgical period (OR 0.596, P = 0.027) and post-case-33 status (OR 0.291, P = 0.010) remained associated with lower BS odds.

Conclusions: In this single-surgeon cohort, the stepwise evolution of surgical technique was associated with a progressive reduction in BS rates, alongside the cumulative standardization of fundamental principles, but a concurrently evolving case mix precludes attribution to technique alone.

Keywords: **Anastomosis, Surgical • Bile Ducts • Learning Curve • Transplantation**

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Introduction

Liver transplantation, particularly living donor liver transplantation (LDLT), has become a vital treatment option for end-stage liver disease and select hepatic malignancies. Despite substantial advancements in surgical techniques, perioperative care, and immunosuppressive therapy, biliary complications remain among the most common and challenging issues following LDLT [1-4]. These complications, primarily bile leakage and biliary stricture (BS), can result in serious clinical outcomes, including increased morbidity, extended hospitalization, repeated interventions, and, in severe cases, re-transplantation, underscoring the critical importance of preventing BS at the time of the index operation.[5-7] BSs after LDLT are typically classified into anastomotic strictures (AS) and non-anastomotic strictures. The underlying mechanisms are multifactorial, involving ischemic injury, immunologic responses, infection, and technical factors during surgery. AS is generally associated with the technical aspects of biliary reconstruction, and its incidence varies widely across transplant centers, ranging from approximately 5% to over 30% [7-10]. This substantial inter-institutional variability indicates that surgical approach and intraoperative decision-making are crucial determinants of outcome.

Biliary reconstruction therefore demands not only technical proficiency but also a gradual understanding of essential surgical principles, often acquired through trial-and-error and iterative learning. However, longitudinal and objective documentation of how a single surgeon's technique matures during this process, and how this maturation relates to clinical outcomes, remains scarce in the LDLT literature. Most published studies report institutional outcomes or compare specific techniques, but few have traced the stepwise evolution of a single surgeon's practice along a systematically characterized learning trajectory.

In this retrospective, a single-surgeon cohort of 382 consecutive right-lobe LDLTs with duct-to-duct biliary reconstruction performed at a single center, we aimed to evaluate whether the stepwise evolution of surgical technique was associated with a lower incidence of anastomotic biliary stricture. As secondary aims, we applied cumulative sum (CUSUM) analysis to describe and locate transition points along the learning trajectory, identified independent risk factors for biliary stricture in the overall cohort, and described the technical details of the refinements that emerged through this process. By documenting the maturation of a single surgeon's technique in detail, this study also aims to describe a surgeon's experience, which may be informative for early-career surgeons in LDLT biliary reconstruction.

Material and Methods

Ethics Statement

This retrospective, single-center cohort study was approved by the Institutional Review Board of Asan Medical Center (AMC IRB 2025-0553; the identifier denotes the 2025 institutional approval of the retrospective study protocol, which postdates the clinical observation period of April 2020-April 2024; approval was obtained prior to data extraction and analysis). Because the study was retrospective and involved analysis of de-identified medical records, the requirement for written informed consent was waived. The study was conducted in accordance with the principles of the Declaration of Helsinki and its subsequent amendments.

Study Design

This study analyzed all adult patients who underwent right-lobe LDLT with duct-to-duct biliary reconstruction at Asan Medical Center between April 2020 and April 2024. The biliary anastomosis was performed by a single surgeon throughout the study period, while other surgical steps were shared among the transplant team. At our center, biliary reconstruction is performed by more than 1 surgeon; the present cohort was deliberately restricted to the consecutive cases in which the biliary anastomosis was performed by a single operator, so that that surgeon's individual learning trajectory could be documented without confounding by inter-operator variability. The study window (April 2020-April 2024) was divided into 3 consecutive, equal time intervals of approximately 16 months each (April 2020-July 2021, August 2021-November 2022, and December 2022-April 2024), so that outcomes were compared over comparable periods of time rather than over groups of equal case numbers. To confirm that the observed trend did not depend on this grouping, biliary stricture rates were additionally analyzed by individual calendar year as an equal-interval sensitivity analysis. The period-based changes reflect the individual surgeon's technical maturation of the anastomosis step rather than a team-wide protocol change, as the remaining operative steps were shared and unchanged. CUSUM analysis was applied independently as a continuous, case-by-case assessment that does not depend on this calendar grouping. Before the study period, the operating surgeon progressed through a graduated pathway in biliary reconstruction, assisting with biliary anastomoses during the early years of transplantation training, then performing deceased donor biliary anastomoses, and subsequently living donor anastomoses under supervision. The study cohort begins at the point at which the surgeon transitioned to independent LDLT duct-to-duct biliary anastomosis. The study period was pre-specified to end in April 2024, with data lock timed so that every included patient had at least 1 year of follow-up for ascertainment of the primary outcome (biliary stricture within 1 year);

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cases performed after this date had not completed the 1-year ascertainment window at data lock and were therefore not included, to avoid incomplete and differential outcome ascertainment. Two complementary analytic frameworks were applied to characterize the evolution of surgical technique: First, cases were grouped into the 3 equal time intervals defined above. This period-based grouping served as a descriptive framework, reflecting the surgeon's perceived phases of experience accumulation and technique refinement. Second, cumulative sum (CUSUM) analysis was applied across all consecutive cases as an objective, case-by-case assessment of the learning trajectory, with the aim of identifying transition points at which performance changed beyond expected variability. Independent risk factors for biliary stricture (BS) across the entire cohort were subsequently evaluated by multivariable logistic regression. The detailed analytic procedures for CUSUM and regression modeling are described in the Statistical Analysis section.

Study Population

During the study period, a single surgeon performed biliary reconstruction in 520 consecutive adult liver transplantation cases. To ensure a homogeneous cohort suitable for evaluating the learning curve of right-lobe duct-to-duct biliary anastomosis, several exclusions were applied sequentially. First, retransplantations, dual-graft transplantations, left-lobe grafts, and deceased donor liver transplantations were excluded, as their biliary anatomy and reconstruction strategies differ substantively from right-lobe duct-to-duct anastomosis. Sixteen patients who underwent hepaticojejunostomy (HJ) were also excluded, because HJ is performed at our center only in defined clinical contexts (eg, prior Kasai operation for biliary atresia, primary sclerosing cholangitis, re-transplantation, or dual grafts) and therefore does not reflect the technical learning curve of duct-to-duct reconstruction. Second, 3 patients who underwent duct-to-duct anastomosis in ABO-incompatible LDLT and subsequently developed diffuse-type intrahepatic biliary complications were excluded, as these complications are considered to be primarily immunologically mediated and are clinically and pathophysiologically distinct from anastomotic strictures attributable to surgical technique. Third, 12 patients who died within 1 year after transplantation from causes unrelated to the biliary anastomosis (eg, infection, intracranial hemorrhage, cardiomyopathy, or rapid hepatocellular carcinoma recurrence) were excluded, as early mortality precluded meaningful evaluation of biliary anastomosis-related outcomes. After these exclusions, 382 consecutive patients were included in the final analysis.

Surgical Techniques for Biliary Anastomosis

The standard surgical technique for duct-to-duct biliary reconstruction in this cohort is summarized below, with the sequential steps illustrated in **Figure 1**.

Briefly, the procedure begins with selection of an appropriate site on the recipient bile duct (BD). The recipient BD is trimmed distally after assessment of mucosal integrity, vascularity of the surrounding tissue, and size match with the donor BD. Hemostasis is kept minimal to avoid disrupting the local blood supply [11]. The axis of the donor BD is then defined by placing sutures at its lateral, medial, and anterior edges. A 1-mm coronary dilator is used to create a small opening below the cystic duct on the recipient common BD, through which a 5-0 black silk is passed for subsequent external stent placement. The anastomosis begins at the medial edges, corresponding to the patient's left side. The posterior wall is completed with externalized knots, except at the segment designated for stent fixation, where internal knots are used and the needle of the polydioxanone (PDS) suture is retained. After completion of the posterior wall, the black silk is threaded and connected to the external stent, which is then inserted into the graft BD and secured internally using the retained PDS suture. The anterior wall is subsequently completed, ensuring appropriate alignment, tension, and stability. The exteriorized portion of the stent is fixed to the peritoneum, and a leak test with indigo carmine followed by intraoperative cholangiography is performed through the stent [12].

Key Points for Successful Duct-to-Duct Anastomosis

Five technical principles guided the performance and progressive refinement of duct-to-duct biliary anastomosis during the study period. Among these, 2 principles—well-vascularized distal recipient duct selection and eversion-overlap anastomosis with hilar plate anchoring—were progressively standardized as experience accumulated and are therefore highlighted as the fundamental principles underlying the outcomes reported in this study.

1. *Bile Duct Size Adjustment:* The recipient duct is preferably at least 1.5 times larger in diameter than the graft duct. This size disparity allows the recipient duct to partially envelop the graft duct, which reduces anastomotic tension and helps to prevent bile leakage even under tension-free suturing.
2. *Three-directional tagging of the graft bile duct:* At the start of the anastomosis, the graft BD is tagged with sutures placed at 3 positions: lateral, medial, and anterior. Lateral and medial tags, placed along the horizontal axis of the hilar plate, provide traction and maintain axial alignment between the donor and recipient ducts, preventing twisting or kinking. The anterior tag ensures clear visualization of the graft duct lumen for accurate needle placement during suturing.
3. *Well-vascularized distal recipient duct selection (fundamental principle):* The recipient BD is aligned with the tagged graft BD without torsion or excessive tension, and proper alignment is confirmed by gentle saline inflation before anastomosis. Adequate vascular supply of the recipient duct is a critical determinant of anastomotic healing, as inadequate

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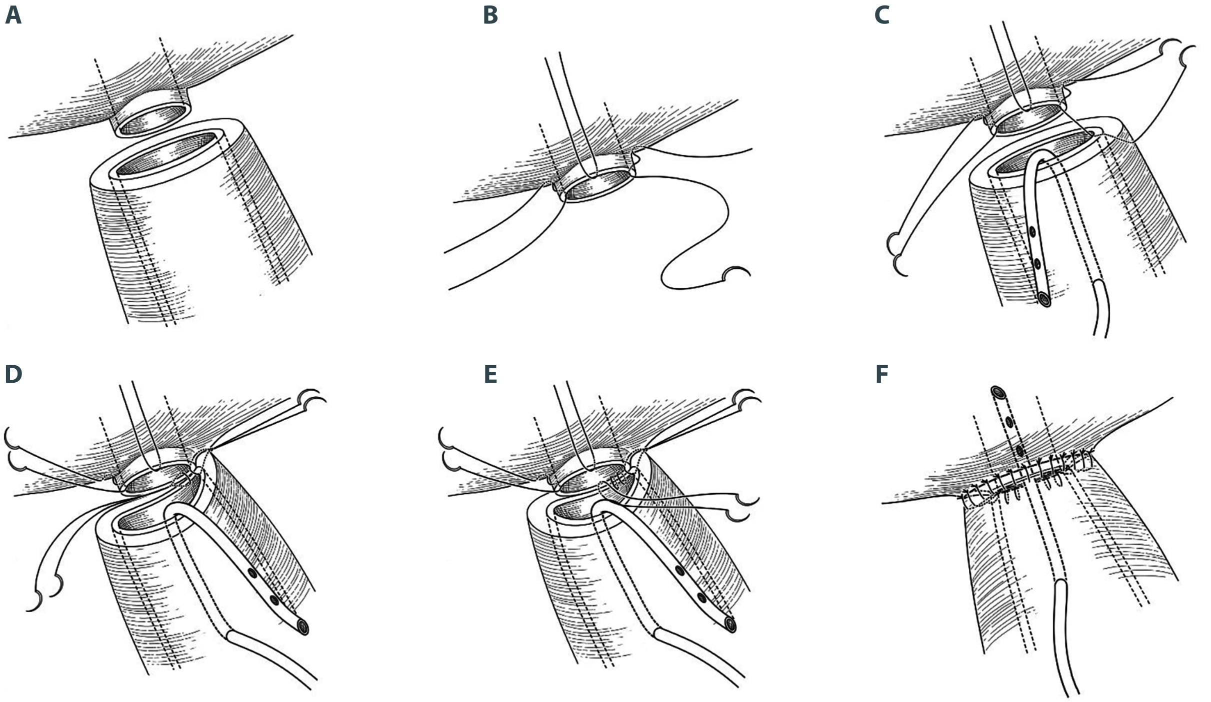

Figure 1. Step-by-step schematic of the biliary anastomosis technique. (**A**) A recipient bile duct with a larger diameter and robust blood supply is selected. (**B**) The graft bile duct is marked at 3 points—lateral, medial, and anterior—with sutures intentionally incorporating the hilar plate for secure anchoring and anastomotic stability. (**C**) On the recipient side, sutures are placed with a thick bite through the outer wall and a thin bite through the mucosal layer to create an overlapping configuration. (**D**) During posterior wall suturing, external knots are positioned outside the bile duct. (**E**) The external stent is secured internally using a retained suture. (**F**) After completing both walls, the external stent is additionally fixed externally to enhance stability.

perfusion can result in ischemic inflammation and subsequent stricture or leakage. When a single graft duct is present, or when a unified orifice is created by ductoplasty, the common hepatic duct is preferentially selected on the recipient side because of its larger diameter and superior vascularity. In cases with multiple graft ducts in which the interductal distance is excessive or the orientation is unfavorable for ductoplasty, separate duct-to-duct anastomoses are performed using first-order recipient BD branches selected for optimal size, orientation, and perfusion. In all cases, distal trimming of the recipient duct—rather than anastomosis at the initial transection level from recipient hepatectomy—is preferred, so that healthy, well-perfused mucosa is exposed. Intraluminal exploration with curved instruments such as a Mixter or right-angle clamp is used to assess the internal branching pattern and determine the optimal transection level and orientation, which is particularly important when multiple anastomoses are required.

4. *Eversion-overlap anastomosis with hilar plate anchoring (fundamental principle):* This principle concerns the handling of tissues and the needle path during suturing. Because the graft BD is typically thin and fragile, sutures incorporate not only the duct wall but also a portion of the surrounding hilar soft tissue, which reinforces the anastomosis, reduces the risk of duct tearing, and produces a beneficial eversion effect on the graft side. On the recipient side, the needle is passed from the thicker outer layer to the thinner mucosal layer, promoting eversion in the same direction. Because the recipient duct is generally larger in diameter, this symmetric eversion creates a partial overlap between the recipient duct and the graft duct together with the hilar plate, widening rather than narrowing the anastomotic lumen and enhancing mechanical stability.
5. *Suture material, interval, and knot positioning:* Absorbable 6-0 PDS is used for its adequate tensile strength and progressive biodegradability. An interrupted suture technique allows individualized tension adjustment, with suture intervals typically maintained at approximately 0.8 to 1.0 mm and adjusted according to BD wall thickness and hemostatic requirements. Knots are placed on the external surface of the BD to minimize intraluminal foreign-body reaction and reduce the risk of stricture formation.

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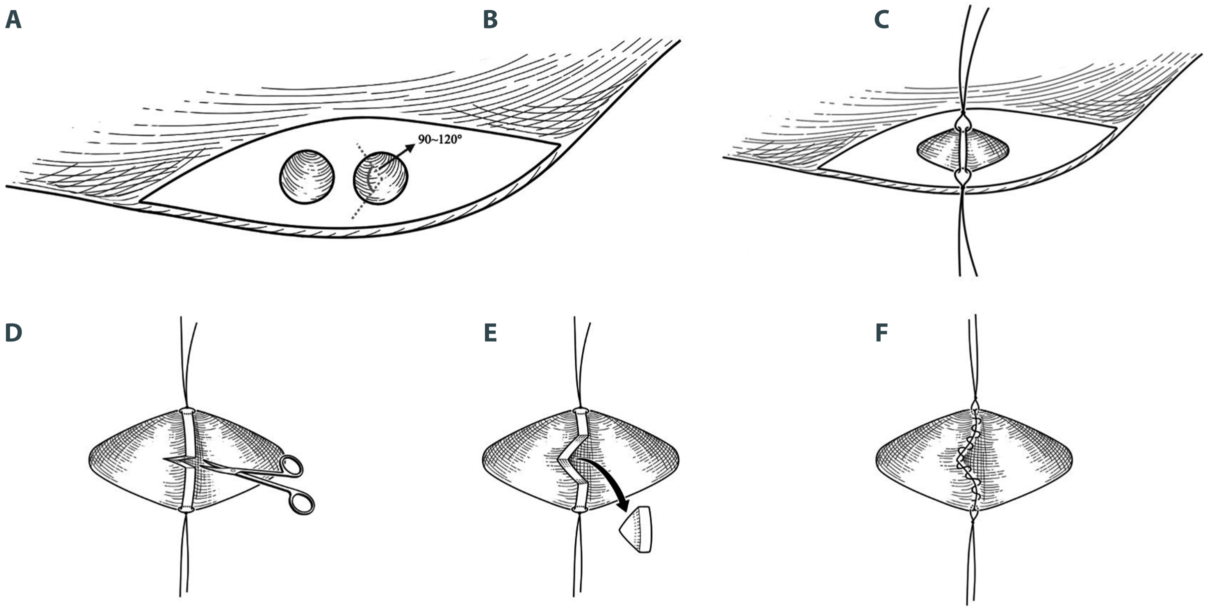

Figure 2. Sequential steps of back-table ductoplasty for multiple bile duct openings. (**A**) Two bile duct orifices are identified, and approximation points are planned at 90° to 120° from the center of each duct. (**B**) Approximation sutures are placed at the anterior and posterior aspects to bring the 2 orifices into close contact. (**C**) A simple vertical septotomy—the prior/alternative approach, shown here for comparison and now reserved for cases in which the duct orifices are too small to accommodate a wedge excision (not a routine step of the current sequence). (**D**) A wedge-shaped septotomy—the current preferred approach when duct size permits. Panels **C** and **D** depict 2 alternative septotomy options, not 2 consecutive steps of a single procedure. (**E**) The ductoplasty is completed with tight, mucosa-to-mucosa suturing to form a single, unified orifice.

Back-Table Ductoplasty for Multiple Bile Duct Openings

When the graft contains multiple BD openings, back-table ductoplasty is performed whenever appropriate to create a single, unified orifice suitable for a single anastomosis. The decision to perform ductoplasty is based on comprehensive assessment of the inter-ductal distance, the diameter of each orifice, and the internal orientation of the ducts. In general, ductoplasty is indicated when the inter-ductal distance is shorter than the diameter of the larger orifice [13,14]. In selected cases, ductoplasty may remain feasible even when the ducts lie slightly farther apart if they run in parallel. Conversely, when the inter-ductal distance is excessive or when a marked size discrepancy would require undue stretching of the smaller duct or could compromise its blood supply, ductoplasty is not attempted; instead, individual duct-to-duct anastomoses are performed using first-order recipient BD branches, as described in the preceding section.

The standardized ductoplasty procedure, illustrated step-by-step in **Figure 2**, is as follows. Suture tags are first placed at the lateral edges of the 2 duct orifices (**Figure 2A**). Approximation sutures are then positioned on the anterior and posterior aspects, ideally at 90° to 120° from the center of each duct, to preserve a sufficient anteroposterior luminal diameter after unification (**Figure 2B**). The angle can be modified according to the spacing and orientation of the ducts so that a circular rather than elliptical unified orifice is achieved. Approximation is completed with 7-0 PDS sutures tied to bring the 2 orifices into close contact. The septotomy at the medial septum between the 2 ducts is then performed. A simple vertical septotomy (**Figure 2C**) was the original approach and is still applied in selected cases in which the duct orifices are too small to accommodate a wedge excision. In current standard practice, however, a wedge-shaped septotomy (**Figure 2D**) is preferred whenever duct size permits, as it allows a more three-dimensional expansion of the common lumen. In the deep central area, the needle is passed through the full thickness of both mucosal layers and secured with a tight internal knot; the suture is then advanced in repeated vertical (superior–inferior) passes, brought out externally, and tied together with the previously placed approximation suture (**Figure 2E**). Accurate inclusion of the mucosal layers and secure stitching are essential to prevent hemobilia, internal stricture, and bile leakage at the ductoplasty site.

External biliary stent

External biliary stents were used routinely in this cohort. Clear, flexible plastic stents with an internal diameter of approximately

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0.5 to 1 mm were used to stabilize the anastomosis, allow intraoperative leak testing with indigo carmine and cholangiography, and enable early postoperative monitoring of bile drainage.

Stent placement was tailored to the graft biliary anatomy and recipient conditions. For grafts with a single orifice, a stent was placed at the anastomotic site. For grafts with 2 orifices, stents were placed in both ducts whenever feasible. When the graft had 3 or more orifices or when the ductal lumen was too small to safely accommodate a stent, stent placement was limited to avoid luminal narrowing. In cases where the recipient common bile duct (CBD) harbored a choledochal varix with bleeding risk along the potential exit tract, or when severe adhesions from previous surgery precluded a safe exit site, the stent was not exteriorized but maintained as an internal stent only. When exteriorized, the stent was brought out through the exposed portion of the CBD below the cystic duct and secured at 3 points: the anastomotic site, the CBD exit site, and the skin. External stents were generally removed approximately 1 year after transplantation.

Outcomes and Definitions

The primary outcome was anastomotic biliary stricture (BS). In line with previously reported definitions, [3,4,15,16] BS was defined as a clinically significant narrowing at the biliary anastomosis occurring within 1 year after transplantation and requiring interventional treatment. The diagnosis required the combination of biochemical abnormalities (such as elevation of liver enzymes), radiologic evidence of anastomotic narrowing with upstream intrahepatic bile duct dilatation on computed tomography, ultrasonography, or direct cholangiography, and therapeutic intervention by endoscopic retrograde cholangiopancreatography (ERCP) or percutaneous transhepatic biliary drainage (PTBD). Only cases meeting all 3 criteria within 1 year were classified as BS. Early postoperative cholangiography through the external biliary stent was routinely used to detect anastomotic narrowing, allowing early ERCP when progression was suspected.

As complementary procedural observations, 2 biliary leak-related events were separately recorded: postoperative anastomotic bile leakage, defined as bile leakage from the duct-to-duct anastomosis identified postoperatively by bilious drain output or radiologic perianastomotic bile collection; and stent-related exit-site bile leakage, defined as delayed-onset intraperitoneal bile leakage presenting weeks to months after transplantation with sudden abdominal pain and radiologic bile collection, presumed to result from partial or complete dislodgement of the external stent at its intra-abdominal exit site. All events were ascertained from the medical records during follow-up up to 1 year after transplantation.

Statistical Analysis

Continuous variables are presented as mean (SD) or median [IQR] and compared using the *t* test or Mann-Whitney U test; categorical variables are presented as n (%) and compared using the chi-square or Fisher exact test. The period-based trend in BS rate was assessed using the Cochran-Armitage test, and 95% confidence intervals were calculated using the Wilson score method. Univariable 95% confidence intervals were estimated by profile likelihood; multivariable intervals and all *P* values are Wald-based.

For CUSUM analysis, a reference failure rate (p_0) of 0.136, corresponding to the biliary stricture rate observed early in the series, was used. The CUSUM statistic was computed as the running sum of ($x_i - p_0$) across consecutive cases ordered by operation date, where $x_i = 1$ for a biliary stricture and 0 otherwise; the curve rises while the observed failure rate exceeds p_0 and falls once performance surpasses it. The primary transition point was defined as the global maximum of the curve, and the secondary inflection as the local maximum beyond which the curve entered its steepest sustained descent (the mean per-case CUSUM decrement increased from approximately 0.03 to 0.08 units beyond case 210).

Risk factors for BS were assessed by univariable and multivariable logistic regression. Each candidate variable in **Table 1** was first assessed univariably, and variables associated with BS at a likelihood-ratio $P < 0.05$ were entered into the main multivariable model; this yielded a 3-variable model (recipient sex, ABO incompatibility, and portal vein stenting). Recipient sex qualified on this basis (likelihood-ratio $P = 0.037$) despite a Wald *P* of 0.051. Given the limited number of BS events (36), the model was intentionally capped at 3 covariates to maintain an events-per-variable ratio of 12 and minimize overfitting. Two additional models incorporating either surgical period (ordered categorical) or post-transition-point status (binary) were separately fitted to assess the association of accumulated experience with BS, each adjusted for the 3 confirmed clinical risk factors (recipient sex, ABO incompatibility, and portal vein stenting). All statistical analyses were performed by an independent biostatistician (see Acknowledgments). A 2-sided $P < 0.05$ was considered significant.

Results

Technical Improvement and Surgical Outcomes

Patients were divided into the 3 consecutive, equal time intervals defined in the Methods section above. In Period 1 (April 2020-July 2021), anastomoses were performed preferentially in patients with relatively favorable single bile duct openings of

Table 1. Baseline characteristics by biliary stricture and multivariable logistic regression.

Characteristic	No BS (n=346)	BS (n=36)	*P* value	Univariable OR (95% CI)	*P*	Multivariable OR (95% CI)	*P*
Recipient sex			0.069				
Male	221 (63.9)	29 (80.6)					
Female	125 (36.1)	7 (19.4)		0.427 (0.168-0.950)	0.051	0.378 (0.157-0.914)	**0.031**
Donor sex			0.962				
Male	224 (64.7)	24 (66.7)					
Female	122 (35.3)	12 (33.3)		0.918 (0.430-1.866)	0.818	—	—
Underlying disease			0.674				
Others	35 (10.1)	4 (11.1)					
Alcoholic	102 (29.5)	7 (19.4)		0.600 (0.171-2.405)	0.437	—	—
Cryptogenic	33 (9.5)	4 (11.1)		1.061 (0.233-4.819)	0.937	—	—
HBV	158 (45.7)	20 (55.6)		1.108 (0.389-3.985)	0.860	—	—
HCV	18 (5.2)	1 (2.8)		0.486 (0.024-3.594)	0.532	—	—
Number of graft BD openings			0.639				
1	233 (67.3)	26 (72.2)					
2	108 (31.2)	9 (25.0)		0.747 (0.321-1.593)	0.470	—	—
≥3	5 (1.4)	1 (2.8)		1.792 (0.092-11.685)	0.601	—	—
Ductoplasty			0.790				
None (single duct)	233 (67.3)	26 (72.2)					
Done (multiple ducts)	85 (24.6)	7 (19.4)		0.738 (0.287-1.678)	0.494	—	—
Impossible (multiple ducts)	28 (8.1)	3 (8.3)		0.960 (0.219-2.960)	0.949	—	—
Portal vein stent			**0.042**				
No	336 (97.1)	32 (88.9)					
Yes	10 (2.9)	4 (11.1)		4.200 (1.103-13.363)	**0.021**	6.515 (1.806-23.498)	**0.004**
ABO type			0.053				
Compatible	259 (74.9)	21 (58.3)					
Incompatible	87 (25.1)	15 (41.7)		2.126 (1.034-4.284)	**0.036**	2.462 (1.184-5.122)	**0.016**

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Table 1 continued. Baseline characteristics by biliary stricture and multivariable logistic regression.

Characteristic	No BS (n=346)	BS (n=36)	*P* value	Univariable OR (95% CI)	*P*	Multivariable OR (95% CI)	*P*
Donor hepatectomy			0.601				
Open	241 (69.7)	23 (63.9)					
Laparoscopic	105 (30.3)	13 (36.1)		1.297 (0.617-2.624)	0.477	—	—
External biliary stent			1.000				
No	9 (2.6)	1 (2.8)		0.935 (0.168-17.488)	0.950	—	—
Yes	337 (97.4)	35 (97.2)					
Recipient age (y)	56.71 (9.38)	58.11 (7.24)	0.386	1.018 (0.980-1.062)	0.384	—	—
Donor age (y)	32.36 (9.37)	34.47 (8.86)	0.196	1.024 (0.987-1.060)	0.196	—	—
MELD	12.00 [9.00-17.00]	9.00 [8.00-14.25]	0.062	0.952 (0.888-1.008)	0.125	—	—
Minimal diameter of graft BD opening (mm)	5.00 [3.00-6.00]	4.50 [3.00-6.00]	0.507	0.945 (0.804-1.101)	0.480	—	—
GRWR	1.13 (0.28)	1.04 (0.27)	0.099	0.307 (0.068-1.157)	0.100	—	—
CIT (min)	83.09 (22.04)	82.00 (18.92)	0.776	0.998 (0.982-1.013)	0.775	—	—
WIT (min)	45.51 (10.00)	48.61 (10.09)	0.078	1.030 (0.996-1.064)	0.079	—	—
Surgical period (ordered categorical)[a]			**0.016[b]**	0.578 (0.367-0.909)	**0.018**	0.596 (0.377-0.942)	**0.027**
Period 1 (Apr 2020-Jul 2021)	83 (24.0)	14 (38.9)					
Period 2 (Aug 2021-Nov 2022)	134 (38.7)	15 (41.7)					
Period 3 (Dec 2022-Apr 2024)	129 (37.3)	7 (19.4)					
Post-learning curve (case > 33)[a]			**0.002**	0.273 (0.113-0.660)	**0.002**	0.291 (0.114-0.742)	**0.010**
≤33 cases	25 (7.2)	8 (22.2)					
>33 cases	321 (92.8)	28 (77.8)					

Data are presented as mean (standard deviation), median [interquartile range], or n (%). Bold values indicate statistical significance ($p<0.05$). [a] Multivariable model adjusted for recipient sex, ABO incompatibility, and portal vein stenting; [b] Cochran-Armitage trend test; [c] Univariable 95% confidence intervals were estimated by profile likelihood; multivariable intervals and all *P* values are Wald-based. Abbreviations: BD, bile duct; BS, biliary stricture; CI, confidence interval; CIT, cold ischemic time; GRWR, graft-to-recipient weight ratio; HBV, hepatitis B virus; HCV, hepatitis C virus; MELD, Model for End-Stage Liver Disease; OR, odds ratio; WIT, warm ischemic tim.

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Table 2. Patient demographics according to operative period (3 equal consecutive time intervals).

Characteristic	Period 1 Apr 2020-Jul 2021 (n=97)	Period 2 Aug 2021-Nov 2022 (n=149)	Period 3 Dec 2022-Apr 2024 (n=136)	*P* value
Recipient sex				0.238
Male	70 (72.2)	92 (61.7)	88 (64.7)	
Female	27 (27.8)	57 (38.3)	48 (35.3)	
Recipient age (y)	56.03 (9.33)	56.48 (10.09)	57.82 (7.99)	0.286
MELD	12.00 [9.00-17.00]	11.00 [8.00-15.00]	12.00 [9.00-17.00]	0.262
Donor sex				0.577
Male	67 (69.1)	96 (64.4)	85 (62.5)	
Female	30 (30.9)	53 (35.6)	51 (37.5)	
Donor age (y)	30.90 (7.85)	32.93 (9.42)	33.32 (10.10)	0.121
Original disease				0.802
HBV	46 (47.4)	68 (45.6)	64 (47.1)	
Alcoholic	30 (30.9)	38 (25.5)	41 (30.1)	
Cryptogenic	7 (7.2)	18 (12.1)	12 (8.8)	
HCV	6 (6.2)	6 (4.0)	7 (5.1)	
Others	8 (8.2)	19 (12.8)	12 (8.8)	
GRWR	1.12 (0.30)	1.10 (0.27)	1.14 (0.29)	0.449
CIT (min)	80.06 (21.12)	87.13 (22.85)	80.53 (20.33)	**0.011**
WIT (min)	48.10 (9.94)	44.84 (9.55)	45.22 (10.42)	**0.031**
Minimal diameter of graft BD opening (mm)	6.00 [3.00-7.00]	5.00 [3.00-6.00]	4.00 [3.00-5.25]	**<0.001**
Number of graft BD openings				0.112
1	66 (68.0)	104 (69.8)	89 (65.4)	
2	27 (27.8)	43 (28.9)	47 (34.6)	
≥3	4 (4.1)	2 (1.3)	0 (0.0)	
Ductoplasty				0.268
None (single duct)	66 (68.0)	104 (69.8)	89 (65.4)	
Done (multiple ducts)	27 (27.8)	34 (22.8)	31 (22.8)	
Impossible (multiple ducts)	4 (4.1)	11 (7.4)	16 (11.8)	
Portal vein stent				0.712
No	93 (95.9)	145 (97.3)	130 (95.6)	
Yes	4 (4.1)	4 (2.7)	6 (4.4)	
ABO type				0.678
Compatible	68 (70.1)	112 (75.2)	100 (73.5)	
Incompatible	29 (29.9)	37 (24.8)	36 (26.5)	

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Table 2 continued. Patient demographics according to operative period (3 equal consecutive time intervals).

Characteristic	Period 1 Apr 2020-Jul 2021 (n=97)	Period 2 Aug 2021-Nov 2022 (n=149)	Period 3 Dec 2022-Apr 2024 (n=136)	*P* value
Donor hepatectomy				0.649
Open	69 (71.1)	105 (70.5)	90 (66.2)	
Laparoscopic	28 (28.9)	44 (29.5)	46 (33.8)	
External biliary stent				0.628
No	2 (2.1)	3 (2.0)	5 (3.7)	
Yes	95 (97.9)	146 (98.0)	131 (96.3)	

Data are presented as mean (standard deviation), median [interquartile range], or n (%). Bold values indicate statistical significance ($P<0.05$). Abbreviations: BD, bile duct; CIT, cold ischemic time; GRWR, graft-to-recipient weight ratio; HBV, hepatitis B virus; HCV, hepatitis C virus; MELD, Model for End-Stage Liver Disease; WIT, warm ischemic time.

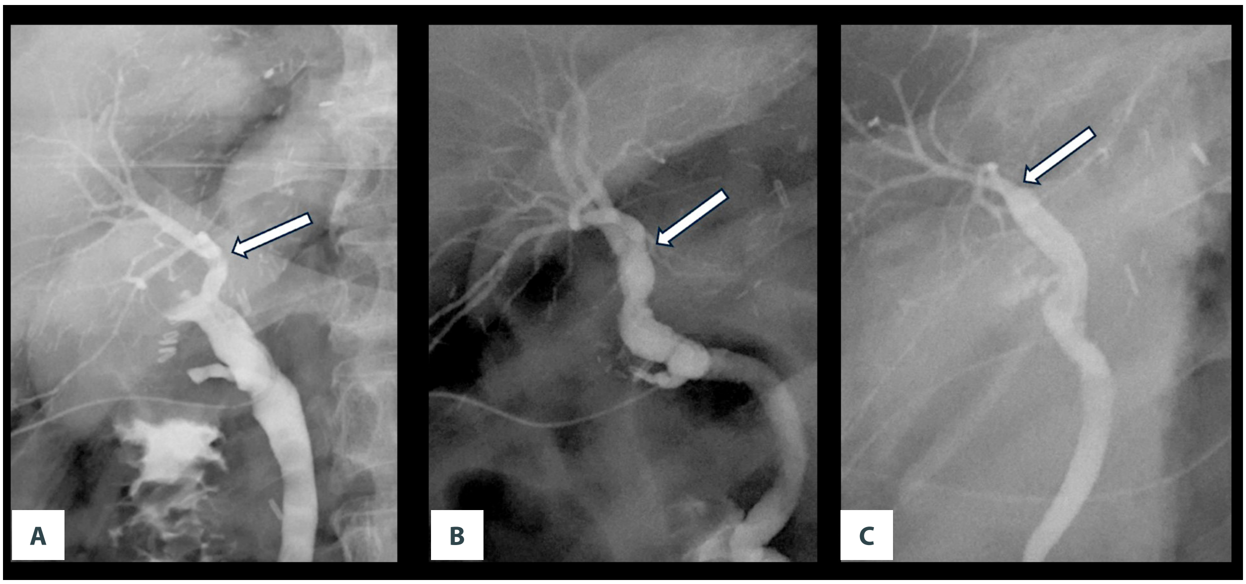

Figure 3. Intraoperative cholangiogram after biliary anastomosis. (**A**) Period 1: Reconstruction using the first-order branch of the bile duct following total hepatectomy. (**B**) Period 2: Anastomosis using the well-vascularized recipient bile duct after additional distal transection. (**C**) Period 3: Anastomosis using the well-vascularized recipient bile duct with the eversion-overlapping technique. White arrows indicate the anastomotic site.

larger diameter. Beginning in Period 2 (August 2021-November 2022), the surgeon managed an increasing share of the team's biliary anastomoses and increasingly complex anatomical features, which is reflected in **Table 2**: the minimal graft BD diameter decreased progressively across the 3 periods (median 6.0, 5.0, and 4.0 mm; $P<0.001$), and the proportion of multiple-duct grafts requiring separate first-order branch anastomoses (rather than ductoplasty-based single anastomosis) increased across the 3 periods (4.1%, 7.4%, and 11.8%). Cold and warm ischemic times differed across periods ($P=0.011$ and $P=0.031$, respectively); other baseline demographic and operative variables did not differ significantly across periods.

During Period 1, anastomoses were typically performed using the exposed bile duct orifice following total hepatectomy (**Figure 3A**). In the latter part of this period, emphasis gradually shifted toward distal recipient BD transection, with anastomosis performed only after healthy, well-perfused mucosa was confirmed under direct visualization (**Figure 3B**). In Period 2, well-vascularized distal recipient duct selection was applied more consistently, with recipient ducts of larger diameter and better perfusion than the graft duct preferentially chosen whenever feasible. In the latter half of Period 2, the eversion-overlap anastomosis with hilar plate anchoring was progressively introduced, and intraoperative cholangiography

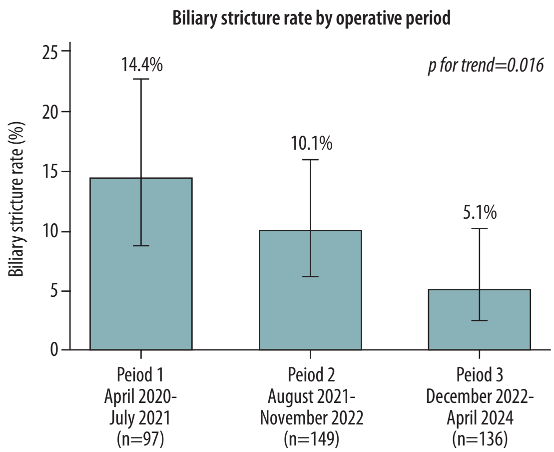

Figure 4. Biliary stricture rates by surgical period. Rates decreased from 14.4% (April 2020-July 2021) to 5.1% (December 2022-April 2024), reflecting progressive improvements in surgical technique over time. Error bars represent 95% confidence intervals calculated using the Wilson score method. *P* trend = 0.016 (Cochran-Armitage trend test).

often showed a mildly bulging configuration at the anastomotic site consistent with this overlap (**Figure 3C**). By Period 3, both principles were routinely employed. The BS rate across the 3 periods was 14.4% (14/97), 10.1% (15/149), and 5.1% (7/136), respectively (**Figure 4**). As an equal-interval sensitivity analysis, the biliary stricture rate by individual calendar year (20.0%, 10.9%, 10.1%, 5.6%, and 0.0% for 2020 through 2024) showed a consistent monotonic decline (*P* for trend = 0.003),

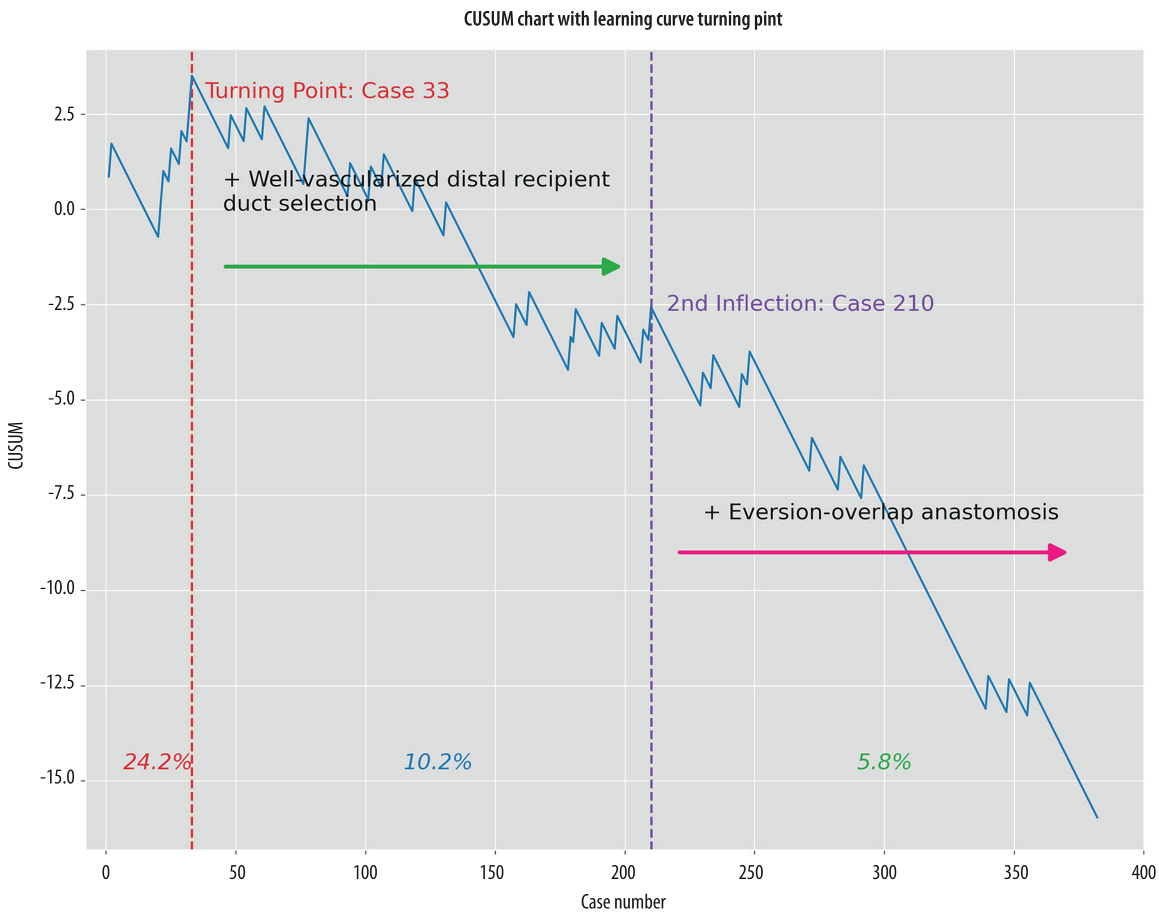

Figure 5. CUSUM chart showing the learning curve for biliary anastomosis in LDLT. Using a predefined reference failure rate of $p_0 = 13.6\%$, a primary turning point was identified at case 33, representing the transition beyond the initial learning phase. A secondary inflection point was identified at case 210, corresponding to the period during which eversion-overlap anastomosis with hilar plate anchoring was routinely employed. The introduction of well-vascularized distal recipient duct selection (green arrow) and eversion-overlap anastomosis with hilar plate anchoring (pink arrow) were observed alongside stepwise reductions in BS rates. CUSUM, cumulative sum.

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confirming that the observed reduction was not an artifact of the period grouping.

On CUSUM analysis, the cumulative curve reached its first local maximum at case 33 (CUSUM = 3.51), corresponding to the transition beyond the initial trial-and-error phase. A secondary inflection was observed at case 210 (late 2022), which coincided with the period during which the eversion-overlap anastomosis with hilar plate anchoring was routinely used. After case 210, the cumulative curve showed a steeper downward slope, and the BS rate was lower in cases 211 to 382 (5.8%) than in cases 34 to 210 (10.2%) (**Figure 5**).

An external biliary stent was placed in 372 patients (97.4%), and in all stented cases intraoperative leak testing with indigo carmine was performed through the stent before abdominal closure. Postoperative anastomotic bile leakage was recorded in 1 patient (0.26%). Stent-related exit-site bile leakage, presenting as delayed-onset abdominal pain with radiologic intraperitoneal bile collection weeks to months after transplantation, occurred in 37 patients (9.7%) during the 1-year follow-up.

Risk Assessment in Biliary Stricture

Risk factors for BS were evaluated across all 382 patients (**Table 1**), including recipient and donor demographics, MELD score, graft BD characteristics, ductoplasty, portal vein stenting, ABO compatibility, donor hepatectomy method, external biliary stent use, cold ischemia time (CIT), warm ischemia time (WIT), and graft-to-recipient weight ration (GRWR).

In the main multivariable logistic regression model for clinical risk factors, portal vein stent placement (OR 6.515, 95% CI 1.806-23.498; $P = 0.004$) and ABO-incompatible transplantation (OR 2.462, 95% CI 1.184-5.122; $P = 0.016$) were independently associated with a higher risk of BS, whereas female recipient sex was associated with a lower risk (OR 0.378, 95% CI 0.157-0.914; $P = 0.031$). None of the remaining candidate variables—including graft BD diameter, number of graft BD openings, ductoplasty, donor hepatectomy method, external biliary stent use, CIT, WIT, and GRWR—reached statistical significance (all $P \geq 0.05$; **Table 1**).

To describe whether accumulated experience was associated with BS in addition to these clinical risk factors, 2 additional multivariable models were separately fitted, each adjusted for recipient sex, ABO incompatibility, and portal vein stenting. In the first additional model, surgical period (as an ordered categorical variable) was associated with a lower BS rate (OR 0.596, 95% CI 0.377-0.942; $P = 0.027$). In the second additional model, procedures performed after the CUSUM-identified primary transition point (post-case 33, binary) showed lower odds of BS (OR 0.291, 95% CI 0.114-0.742; $P = 0.010$). The Cochran-Armitage trend test further demonstrated a linear decrease in BS rates across surgical periods ($Z = -2.414$, $P = 0.016$).

Discussion

In this single-surgeon cohort of 382 consecutive right-lobe LDLTs with duct-to-duct biliary reconstruction, the stepwise evolution of surgical technique was associated with a progressive reduction in the anastomotic biliary stricture (BS) rate, from 14.4% in the earliest period to 5.1% in the most recent period. These changes coincided with the gradual standardization of 2 fundamental principles—well-vascularized distal recipient duct selection and eversion-overlap anastomosis with hilar plate anchoring—and with a parallel increase in anatomically more demanding reconstructions. Although cold and warm ischemic times also differed across the 3 periods, neither was associated with biliary stricture in the risk factor analysis (**Table 1**), making it unlikely that these differences account for the observed trend. Below, we discuss these observations in the context of the learning trajectory and the identified risk factors.

The initial BS rate of 14.4% in Period 1 falls within the wide range of 5% to 30% previously reported for adult right-lobe LDLT with duct-to-duct reconstruction [7-10], reflecting both the inherent difficulty of the procedure and the well-recognized variability in outcomes across centers and surgeons. Two technical principles were progressively emphasized over the course of this cohort: well-vascularized distal recipient duct selection, motivated by the recognition that adequate mucosal perfusion is essential for anastomotic healing, and eversion-overlap anastomosis with hilar plate anchoring, which reinforces the thin graft duct wall with surrounding periductal tissue and places all knots externally. These refinements are broadly in line with principles previously advocated by others, including the importance of vascularity preservation and minimal hilar dissection [15-17], mucosal eversion and corner-sparing sutures described by Vij and Ikegami [18,19], and the all-knots-outside concept reported by Pamecha and Fan [14,20]. The lower BS rates observed in the later periods (10.1% and 5.1%) are consistent with the gradual standardization of these principles, although other concurrent changes, including accumulated team experience and evolving case mix, may also have contributed in this observational cohort.

CUSUM analysis was used to describe the trajectory of BS occurrence over the full cohort, complementing the period-based grouping with a continuous, case-by-case perspective. The first local maximum at case 33 corresponded to the transition beyond the initial trial-and-error phase rather than the attainment of technical mastery, a distinction worth emphasizing in the context of early-career surgical training. The

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secondary inflection around case 210 was observed during the latter half of Period 2, the same timeframe in which eversion-overlap anastomosis with hilar plate anchoring was routinely used; whether this temporal coincidence reflects the effect of the technique itself, further consolidation of earlier principles, or broader contextual factors cannot be determined from this descriptive analysis. Taken together, the 2 inflection points and the stepwise reduction in BS rates across periods support a view of the learning trajectory as a gradual process rather than a single-point event, which may be relevant to how mentorship and standardization are structured in early LDLT practice.

The main multivariable model identified portal vein stent placement (OR 6.515) and ABO-incompatible transplantation (OR 2.462) as independent risk factors for BS, while female recipient sex was associated with a lower risk (OR 0.378). In 2 separately fitted models adjusted for these clinical risk factors, accumulated experience remained associated with lower BS odds, both when operationalized as surgical period (OR 0.596; $P=0.027$) and as post-transition-point status (OR 0.291; $P=0.010$). This consistency of the association across 2 different operationalizations of experience, and its persistence after adjustment for the strongest clinical risk factors, suggests that the period-related reduction in BS is not driven solely by shifts in case mix or by any single covariate, and aligns with the stepwise trajectory described by CUSUM analysis.

The strong association with portal vein stenting is consistent with a previous report linking stent proximity to the biliary anastomosis with impaired anastomotic outcomes [21], and a plausible but not formally tested mechanism is mechanical pressure from the stent on the adjacent suture line during early healing. Regardless of the precise mechanism, this observation suggests that closer postoperative biliary surveillance may be warranted in patients who require portal vein stenting. For ABO-incompatible transplantation, diffuse intrahepatic biliary injury is the most characteristic biliary complication, with a reported incidence of approximately 5% [22]. In the present cohort, even after excluding cases with diffuse intrahepatic involvement, the anastomotic stricture rate was higher in the ABO-incompatible group, raising the possibility that immunological factors may also affect anastomotic-level healing; this suggests that heightened biliary surveillance may be prudent in ABO-incompatible recipients regardless of whether diffuse intrahepatic injury is clinically evident. The lower BS risk observed with female recipient sex is more difficult to interpret, as no specific biological or anatomical determinant was identified in the present dataset and the confidence interval was wide; this association should therefore be regarded as hypothesis-generating.

Several traditionally cited risk factors for BS—including small graft BD diameter, multiple BD orifices, ductoplasty, donor hepatectomy method, and external biliary stent use—did not reach statistical significance in this cohort. The null finding for duct number and ductoplasty is noteworthy given the progressive shift toward more complex biliary anatomy across periods. This observation may reflect homogeneous surgical handling within a single-surgeon cohort, together with selective use of ductoplasty only when inter-ductal distance and orientation were judged favorable. CIT and WIT were likewise not associated with BS, which may reflect the relatively narrow range of ischemic times achievable in LDLT rather than an absence of biological effect. GRWR showed a non-significant trend toward lower values in the BS group ($P=0.100$).

Beyond the quantitative risk factor analysis, this cohort also illustrates how ductoplasty was applied in practice. When multiple bile duct openings were closely positioned and ran in parallel, back-table ductoplasty was used to create a single unified orifice, enabling a single duct-to-duct anastomosis rather than 2 separate anastomoses. When the inter-ductal distance was excessive or the orientation was unfavorable, however, ductoplasty was not attempted. In these anatomically demanding cases, individual anastomoses to first-order recipient bile duct branches were performed, with each anastomosis requiring the same principles of vascularity preservation and tension-free apposition applied to single-duct reconstructions. The observation that ductoplasty was not associated with increased BS risk in this cohort is consistent with these selective indications, and suggests that the decision of whether to unify multiple graft ducts should be guided by the local anatomy rather than by a uniform preference for a single anastomosis.

The role of external biliary stents in LDLT remains a subject of ongoing debate, with reported advantages and potential drawbacks varying across series [4,13,23-25]. In this cohort, the stent served 2 practical purposes: it enabled intraoperative confirmation of anastomotic integrity by leak testing and cholangiography before abdominal closure, and it provided access for early postoperative cholangiography when anastomotic narrowing was suspected. Although these procedural benefits did not translate into a statistically significant risk reduction for BS in the present dataset (**Table 1**), they may nonetheless have been useful in the early phase of this surgeon's learning curve, when a low threshold for detecting and correcting technical problems was helpful.

The principal drawback observed was delayed stent-related exit-site bile leakage, which should not be conflated with postoperative anastomotic bile leakage, as the 2 differ in timing, mechanism, and clinical course; in this cohort, all such events resolved with conservative treatment or ERCP without progression to life-threatening complications. On balance, these

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observations describe external biliary stenting as a pragmatic adjunct in our own early-learning-curve practice, rather than endorse it as routine guidance for others, provided that recipients are counseled about and monitored for the possibility of delayed stent-related leakage. Whether and when this routine approach should be tapered as experience accumulates warrants further evaluation.

The principal strengths of this study are its detailed longitudinal documentation of how duct-to-duct biliary reconstruction evolved within a single-surgeon practice, and the use of 2 complementary analytic frameworks—period-based grouping and CUSUM analysis—to describe the learning trajectory. Rather than proposing a novel technique, this study traces how the progressive standardization of 2 fundamental principles—well-vascularized distal recipient duct selection and eversion-overlap anastomosis with hilar plate anchoring—developed alongside a parallel shift toward more complex biliary anatomy. The honest reporting of both successful refinements and early-phase difficulties is not offered as a generalizable training protocol, but rather as 1 surgeon's experience that other teams may find useful when reflecting on how to structure early-career practice in LDLT biliary reconstruction. The specific, supported contribution of this work is 3-fold: (1) longitudinal documentation of a single surgeon's learning trajectory in right-lobe LDLT duct-to-duct biliary reconstruction; (2) CUSUM-based description of transition points temporally linked to specific technical refinements; and (3) contextual integration, rather than invention, of previously established principles. We do not claim to present a novel technique.

The trajectory described here unfolded within a high-volume program that provided dense case exposure and structured mentorship; these environmental factors are inseparable enablers of the observed improvement and are themselves part of what the learning curve reflects. Consequently, the specific numeric trajectory is unlikely to transfer directly to lower-volume settings. What may be transferable is not the rate of improvement but the underlying principles and the value of deliberately structuring early-career biliary reconstruction—graduated hands-on transfer, isolation of the anastomosis step for focused skill acquisition, and early feedback through routine intraoperative cholangiography—which lower-volume centers could adapt to their own context.

Several limitations should be acknowledged. First, this was a retrospective single-surgeon analysis in a single center; the observed association between accumulated experience and lower BS rates cannot be disentangled from parallel changes in team experience, institutional workflow, and case mix, and no causal attribution should be drawn from the period- or transition-point-related associations. More broadly, the observed reduction in biliary stricture rate cannot be attributed to surgical technique alone, given the concurrent evolution of instrumentation, anesthesia, perioperative care, and team experience over the 4-year observation period. Second, BS was defined as a clinically significant stricture requiring intervention within 1 year, and mild strictures not requiring intervention or those presenting later may have been missed, potentially underestimating the true BS incidence. Third, the cohort was restricted to right-lobe duct-to-duct reconstruction, so the findings may not generalize to left-lobe grafts, dual grafts, or hepaticojejunostomy. Finally, the CUSUM analysis was applied as a descriptive visualization of the learning trajectory rather than as a formal statistical test; the identified transition points should therefore be regarded as interpretive landmarks rather than validated thresholds. Furthermore, as a single-surgeon experience from a high-volume center, these findings cannot be generalized to other surgeons or to lower-volume settings, and the limited number of biliary stricture events (36 events) further constrains statistical power; the analysis should therefore be read as a descriptive learning trajectory report rather than as confirmatory evidence of a reproducible effect. Extension of this experience into a prospectively followed, more recent cohort—once the one-year ascertainment window is complete—would allow confirmation of whether the observed trajectory continues.

Conclusions

In this single-surgeon cohort of 382 right-lobe LDLTs, the anastomotic biliary stricture rate declined from 14.4% to 5.1% across 3 periods, alongside the progressive standardization of well-vascularized distal recipient duct selection and eversion-overlap anastomosis with hilar plate anchoring. Although causal attribution is limited by the observational design, these fundamental principles and the gradual learning trajectory they reflect may inform early-career practice in LDLT biliary reconstruction.

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Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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