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ORIGINAL ARTICLE

# Inpatient Choledocholithiasis Management: a Cost-Effectiveness Analysis of Management Algorithms

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## Abstract

**Background** Choledocholithiasis is commonly encountered. It is frequently managed with laparoscopic common bile duct exploration or endoscopic retrograde cholangiopancreatography (either preoperative, intraoperative, or postoperative relative to laparoscopic cholecystectomy). The purpose of this study is to determine the most cost-effective method to manage inpatient choledocholithiasis.

**Methods** A decision tree model was created to evaluate the cost-effectiveness of laparoscopic common bile duct exploration and preoperative, intraoperative, and postoperative endoscopic retrograde cholangiopancreatography. The primary outcome was incremental cost-effectiveness ratio with a ceiling willingness to pay threshold assumed of $100,000 per quality-adjusted life year. Model parameters were determined through review of published literature and institutional data. Costs were from the perspective of the healthcare system with a time horizon of 1 year. Sensitivity analyses were performed on model parameters.

**Results** In the base case analysis, laparoscopic common bile duct exploration was cost-effective, resulting in 0.9909 quality-adjusted life years at an expected cost of $18,357. Intraoperative endoscopic retrograde cholangiopancreatography yielded more quality-adjusted life years (0.9912) at a higher cost ($19,717) with an incremental cost-effectiveness ratio of $4,789,025, exceeding the willingness to pay threshold. Both preoperative and postoperative endoscopic retrograde cholangiopancreatographies were eliminated for being both more costly and less effective. Laparoscopic common bile duct exploration remained cost-effective if the probability of successful biliary clearance was above 0.79, holding all other variables constant. If its base cost remained below $18,400 and intraoperative endoscopic retrograde cholangiopancreatography base cost rose above $18,200, then laparoscopic common bile duct exploration remained cost-effective.

**Conclusion** Laparoscopic common bile duct exploration is the most cost-effective method to manage choledocholithiasis. Efforts to ensure availability of local expertise and resources for this procedure are warranted.

**Keywords** Choledocholithiasis · Endoscopic retrograde cholangiopancreatography · Biliary tract surgical procedures · Cost-effectiveness analysis · Decision analysis

## Introduction

Laparoscopic cholecystectomy (LC) is one of the most commonly performed surgical procedures in the USA, with an estimated 503,000 ambulatory laparoscopic cholecystectomies performed in 2006.[1–3] Among patients undergoing laparoscopic cholecystectomy, the prevalence of choledocholithiasis has been reported to range from 3.4 to 18.8%.[4–8] As a result, choledocholithiasis is commonly encountered in general surgical practice.

Two methods for clearance of the biliary tree have emerged to manage choledocholithiasis: laparoscopic common bile duct exploration (LCBDE) and endoscopic retrograde cholangiopancreatography (ERCP). There is variability in the timing of ERCP relative to LC in clinical practice, as it could be performed preoperatively, intraoperatively, or postoperatively. Selection of one of these methods of biliary ductal clearance is typically driven by available expertise and local resources. Presently, ERCP overwhelmingly represents the most common management method, with 86% of

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patients with choledocholithiasis managed with this modality in the USA in 2013.[9]

Given the frequent presentation of choledocholithiasis in surgical practice, it has been studied extensively. Several meta-analyses detail the management of this common diagnosis.[10–12] Of these, the meta-analysis by Ricci et al. [10] summarized the four most common contemporary management strategies using a network meta-analysis with a total of 2,489 patients in 20 studies. The authors demonstrated that LC with intraoperative ERCP (intra-ERCP) had the highest probability of ductal clearance followed by LC with LCBDE. LC with LCBDE also had the highest probability of resulting in the least total cost, while LC with intra-ERCP had the lowest probability of morbidity. A recent decision analysis further supported the conclusions of that meta-analysis demonstrating that single-stage management (e.g., LCBDE or intra-ERCP) of choledocholithiasis resulted in higher duct clearance and lower morbidity.[13] That study, however, did not include cost as an outcome.

Despite the utility of these existing studies to begin to address differences in costs for these strategies, dedicated cost-effectiveness analysis is necessary. To date, no cost-effectiveness analysis has been performed to compare all four common management strategies for choledocholithiasis in a single study with prior analyses comparing preoperative ERCP (pre-ERCP) to intra-ERCP or postoperative ERCP (post-ERCP) to LCBDE.[14,15] Without a single analysis comparing all four common management strategies, the relative cost-effectiveness of these strategies remains unclear. The purpose of this study, therefore, is to determine the most cost-effective strategy to address choledocholithiasis in patients undergoing LC comparing pre-ERCP, intra-ERCP, LCBDE, and post-ERCP.

## Materials and Methods

The Consolidated Health Economic Evaluation Reporting Standards (CHEERS) statement was used to guide this study.[16]

### Decision Analysis Definitions and Model

A decision tree was used to model the therapeutic approach for choledocholithiasis during inpatient admission. This model was developed after review of published decision trees and was supplemented by the authors' judgment where existing model pathways were insufficient for the current study.[13,14] The reference population was patients undergoing inpatient management of choledocholithiasis with LC during that same admission. Four management strategies for choledocholithiasis were evaluated: (1) pre-ERCP; (2) intra-ERCP; (3) LCBDE; and (4) post-ERCP. The timing of the procedure to clear the bile ducts for each of these strategies is relative to the LC. The time horizon for the model was 1 year.

The decision tree model describes the pathway of decision-making during inpatient management of choledocholithiasis (Fig. 1). The decision node represents the choice to manage choledocholithiasis with pre-ERCP, intra-ERCP, LCBDE, or post-ERCP. In all management strategies following failed stone extraction, a repeat attempt at duct clearance would be attempted prior to proceeding with open common bile duct exploration (OCBDE). For both pre-ERCP and post-ERCP, this entailed a repeat ERCP. For intra-ERCP and LCBDE, this also entailed an ERCP; however, the ERCP occurred in the postoperative period subsequent to completion of the LC.

In the pre-ERCP management pathway, stone clearance from the bile ducts is attempted prior to LC via ERCP (Fig. 1A). Failed stone clearance results in another attempt at clearance by ERCP preoperatively. Two failed attempts at ERCP clearance of the bile ducts resulted in OCBDE with cholecystectomy. In cases of successful duct clearance by ERCP, the patient would then undergo a LC.

In the intra-ERCP management pathway, stone clearance from the bile ducts is attempted concurrently with LC (Fig. 1B). If intraoperative clearance is unsuccessful, the LC is completed, and a repeat attempt at ERCP clearance is made in the postoperative period. If the repeat attempt fails, the patient undergoes OCBDE for definitive clearance of the bile ducts.

In the LCBDE management pathway, stone clearance from the bile ducts is attempted concurrently with LC (Fig. 1C). If laparoscopic intraoperative clearance is unsuccessful, the LC is completed, and an attempt at clearance by ERCP is made in the postoperative period. If the repeat attempt fails, the patient undergoes OCBDE for definitive clearance of the bile ducts. In the model, the method of laparoscopic bile duct clearance was not specified and encompassed both transcystic and transductal approaches.

In the post-ERCP management pathway, stone clearance from the bile ducts is attempted in the postoperative period after the patient undergoes LC (Fig. 1D). If duct clearance fails, a repeat attempt at clearance by ERCP would be made. Two failed attempts at ERCP clearance of the bile ducts resulted in OCBDE for definitive duct clearance.

### Probabilities

Probability parameters in the model were obtained from literature review (Table 1). Of note, several meta-analyses have recently investigated the success rate of choledocholithiasis stone extraction and include several overlapping randomized clinical trials in their pooled analyses.[10–12] For our model parameters, the probability for LCBDE came from the study

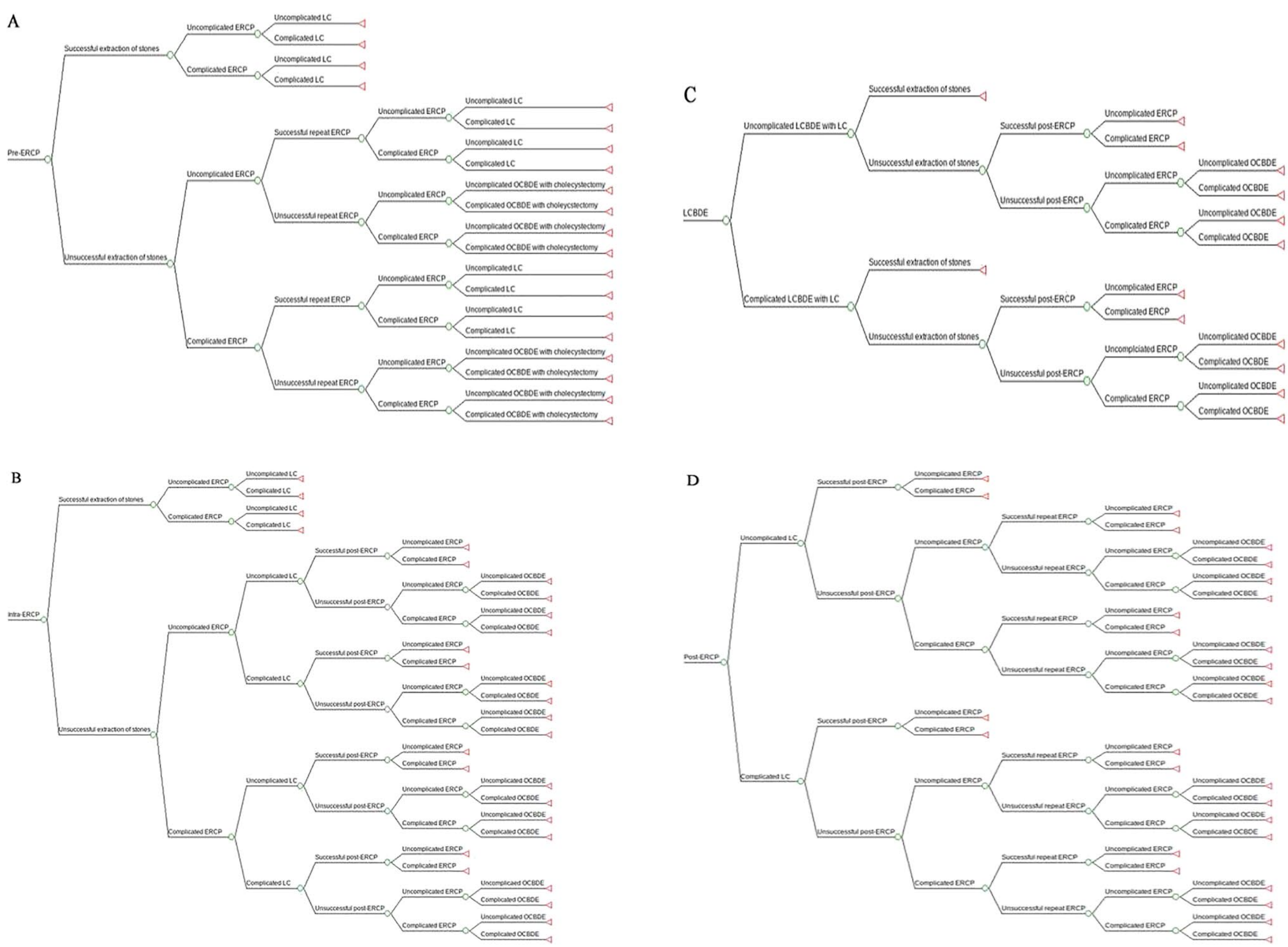



**Fig. 1** Decision tree model of inpatient management of choledocholithiasis modeling outcomes following the decision to manage choledocholithiasis via pre-ERCP, intra-ERCP, LCBDE, or post-ERCP. Square at the beginning of the model represents a decision node, with each successive circle representing chance nodes with all branches of the model ending with a triangle representing the terminal node. Outcomes of each branch of the decision tree are detailed in the subfigures: **A** pre-ERCP branch; **B** intra-ERCP branch; **C** LCBDE branch; **D** post-ERCP branch

by Singh et al. given that its pooled analysis included more studies for LCBDE than the other meta-analyses.[12] All other probabilities for stone extraction were calculated using the probability for LCBDE (given greatest number of patients out of all four methods) in combination with the odds ratios from the network meta-analysis performed by Ricci et al..[10] This study by Ricci et al. had the greatest number of included studies for the remaining management strategies (pre-ERCP, intra-ERCP, post-ERCP).

## Costs

Costs were estimated from the perspective of the healthcare system. Costs were obtained from retrospective review of our institution's electronic medical record (EMR) for patients who underwent inpatient management of choledocholithiasis. The EMR was queried for all patients with an inpatient diagnosis of choledocholithiasis (ICD-10 codes K80.40, K80.50, and K80.41) and a cholecystectomy during that admission (CPT codes 47,600, 47,605, 47,610, 47,562, or 47,563) between September 2015 and February 2020. The associated costs with that admission were pulled from the institutional cost accounting database, which estimates costs using a standard ratio of cost-to-charge method. Patients presenting with choledocholithiasis complicated by pancreatitis or cholangitis prior to procedural intervention were excluded as were patients undergoing planned open cholecystectomy. Given that no OCBDE procedures were encountered in the data set, the additional cost of that procedure was extrapolated from patients with LC procedures converted to open. Costs were adjusted for inflation to 2020 US dollars using the medical care component of the US Bureau of Labor Statistics Consumer Price Index (Table 1).[17]

**Table 1** Model parameters used in the comparative effectiveness analysis

| Variable | Baseline value | Range for sensitivity analysis | | Source |
|---|---|---|---|---|
| | | *Lower* | *Upper* | |
| *Probabilities* | | | | |
| Successful extraction of stones | | | | |
| Pre-ERCP | 0.871 | 0.44 | 1.00 | Meta-analysis [10,12] |
| Intra-ERCP | 0.915 | 0.46 | 1.00 | Meta-analysis [10,12] |
| LCBDE | 0.881 | 0.44 | 1.00 | Meta-analysis [12] |
| Post-ERCP | 0.743 | 0.37 | 1.00 | Meta-analysis [10,12] |
| Procedural complication | | | | |
| ERCP | 0.0685 | 0.03 | 0.10 | Systematic review [31] |
| Laparoscopic cholecystectomy | 0.035 | 0.01 | 0.06 | Meta-analysis [32] |
| LCBDE* | 0.045 | 0.02 | 0.07 | NSQIP study [33] |
| Open CBDE | 0.188 | 0.09 | 0.28 | NSQIP study [33] |
| *Utility* | | | | |
| Laparoscopic cholecystectomy | 0.900 | 0.45 | 1.00 | CEA Registry [14,17] |
| Complicated laparoscopic cholecystectomy | 0.774 | 0.38 | 1.00 | CEA Registry [17,34] |
| ERCP | 0.95 | 0.47 | 1.00 | CEA Registry [15,17,35,36] |
| Complicated ERCP | 0.85 | 0.42 | 1.00 | CEA Registry [17,36,37] |
| LCBDE | 0.90 | 0.45 | 1.00 | CEA Registry [15,17,37] |
| Complicated LCBDE | 0.774 | 0.38 | 1.00 | CEA Registry [15,17,37] |
| Open CBDE | 0.81 | 0.40 | 1.00 | CEA Registry [17,36–38] |
| Complicated open CBDE | 0.774 | 0.38 | 1.00 | CEA Registry [17,36–38] |
| *Duration of health states* | | | | |
| Laparoscopic cholecystectomy | 4 weeks | 2 weeks | 6 weeks | Author estimate |
| Complicated laparoscopic cholecystectomy | 6 weeks | 3 weeks | 9 weeks | Author estimate |
| ERCP | 1 day | 0 days | 1 week | Author estimate |
| Complicated ERCP | 1 week | 0 days | 2 weeks | Author estimate |
| LCBDE | 4 weeks | 2 weeks | 6 weeks | Author estimate |
| Complicated LCBDE | 6 weeks | 3 weeks | 9 weeks | Author estimate |
| Open CBDE | 6 weeks | 3 weeks | 9 weeks | Author estimate |
| Complicated open CBDE | 8 weeks | 4 weeks | 12 weeks | Author estimate |
| Pre-ERCP | $18,508.53 | $9,250 | $27,750 | Institutional data |
| Intra-ERCP | $17,441.80 | $8,750 | $26,250 | Institutional data |
| LCBDE | $16,206.64 | $8,000 | $24,250 | Institutional data |
| Post-ERCP | $26,485.36 | $13,250 | $39,750 | Institutional data |
| *Additional Costs* | | | | |
| Laparoscopic cholecystectomy complication | $7,633.83 | $3,750 | $11,500 | Institutional data |
| Open CBDE | $10,965.45 | $5,500 | $16,500 | Institutional data |
| Open CBDE complication | $7,633.83 | $3,750 | $11,500 | Institutional data |
| ERCP complication | $10,485.32 | $5,250 | $15,750 | Institutional data |
| Repeat ERCP | $6,133.40 | $3,000 | $9,250 | Institutional data |
| Post-ERCP after failed intraoperative clearance | $11,276.64 | $5,750 | $17,000 | Institutional data |

*ERCP*, endoscopic retrograde cholangiopancreatography

*Pre-ERCP*, preoperative ERCP

*Intra-ERCP*, intraoperative ERCP

*LCBDE*, laparoscopic common bile duct exploration

*Post-ERCP*, postoperative ERCP

*CBDE*, common bile duct exploration

*complication rate for both LCBDE and laparoscopic cholecystectomy

*CEA*, cost-effectiveness analysis

### Utilities

Utility weights were obtained from a search of the Cost-Effectiveness Analysis Registry (Table 1).[18] The duration of disease states and post-procedural recovery periods was estimated by the study authors. Effectiveness was measured as quality-adjusted life years (QALY) during the 1-year postoperative period.

### Baseline Cost-Effectiveness Analysis

The cost-effectiveness of the four management algorithms was evaluated using an incremental approach.[19] Incremental costs and incremental QALYs were calculated to generate the incremental cost-effectiveness ratio (ICER). Strategies which were strictly dominated (i.e., both more costly and less effective) were eliminated. The willingness to pay threshold for declaring cost-effectiveness was defined as an ICER of $100,000/QALY or less.

### Additional Assumptions

Additional assumptions of the decision analysis included (1) all patients with choledocholithiasis had a gallbladder; (2) for patients undergoing pre-ERCP, no procedural complications were preclusive of undergoing LC; (3) all LC procedures were successful with no conversions to open procedures; (4) institutions lacked the expertise and resources to attempt LCBDE following failed intra-ERCP and vice versa; and (5) OCBDE resulted in complete clearance of the common bile duct in all instances. The model did not account for outpatient management of choledocholithiasis or methods to diagnose choledocholithiasis.

### Sensitivity Analysis

One-way sensitivity analyses were performed for all model parameters to assess robustness of results to the baseline parameters. Sensitivity of the analysis was tested using variations of ± 50% from the base case value. If the results did not change within the range of values used in the analysis, then the model was considered robust for that variable. Two-way sensitivity analyses were performed to test the costs of all management strategies as well as the probability of successful duct clearance for LCBDE and intra-ERCP. The range of costs tested for the two-way sensitivity analyses was $10,000–30,000 which was deemed a plausible range for the cost of uncomplicated inpatient choledocholithiasis management. The range of probabilities tested was 0.75–1 for the two-way sensitivity analysis which was also deemed a plausible range. All analyses were performed using TreeAge Pro (TreeAge Software Inc., Williamstown, MA) and R (version 3.6.1, R Foundation for Statistical Computing, Vienna, Austria).

## Results

### Expected Costs and Effectiveness

The results of the base case analysis are presented in Table 2. Of the four management strategies, LCBDE was the least costly, with an expected cost of $18,357 to the healthcare system and resulting in 0.9909 QALYs. Intra-ERCP was the second least costly with an expected cost of $19,717, resulting in 0.9912 QALYs and an ICER of $4,789,025. Both pre-ERCP ($20,580 cost, 0.9910 QALY) and post-ERCP ($30,051 cost, 0.9904 QALY) were dominated for being more costly and less effective. Although intra-ERCP resulted in the greatest effectiveness (0.9912 vs 0.9909 QALY), its ICER of $4,789,025 exceeded our willingness

**Table 2** Base case analysis

| Strategy | Cost ($) | Marginal cost ($) | Effectiveness (QALY) | Marginal effectiveness (QALY) | ICER ($/QALY) |
|---|---|---|---|---|---|
| LCBDE | 18,357 | | 0.99092 | | |
| Intra-ERCP | 19,717 | 1,360 | 0.99120 | 0.00028 | 4,789,025 |
| Pre-ERCP | 20,580 | 863 | 0.99104 | −0.00016 | Dominated |
| Post-ERCP | 30,051 | 9,921 | 0.99037 | −0.00083 | Dominated |

*QALY*, quality-adjusted life years

*ICER*, incremental cost-effectiveness ratio

*LCBDE*, laparoscopic common bile duct exploration

*ERCP*, endoscopic retrograde cholangiopancreatography

*Intra-ERCP*, interoperative ERCP

*Pre-ERCP*, preoperative ERCP

*Post-ERCP*, postoperative ERCP

to pay threshold of $100,000/QALY. As a result, LCBDE was the most cost-effective management strategy in the base case analysis.

## Sensitivity Analysis

Sensitivity analyses were performed for all model parameters. Key one-way sensitivity analyses are summarized in Fig. 2. Table 3 summarizes the results of the one-way sensitivity analyses with variables where LCBDE remained the cost-effective option for the entire range tested excluded from the table. Holding all other variables constant, LCBDE remains the most cost-effective if the probability of successful stone extraction remains above 79%. For the utility experienced by patients following LCBDE, that value must remain above 0.71, and for cost of uncomplicated LCBDE management, it must remain below $17,539. LCBDE remains the most cost-effective if the cost of uncomplicated management for pre-ERCP remains above $16,285, intra-ERCP remains above $16,110, and post-ERCP remains above $14,791.

**Table 3** One-way sensitivity analysis

| Parameter | Threshold value for WTP of $100,000[a] |
|---|---|
| Probability successful extraction of stones (LCBDE) | > 0.79[b] |
| LCBDE utility | > 0.71[b] |
| Pre-ERCP cost | > $16,285[b] |
| Intra-ERCP cost | > $16,110[b] |
| LCBDE cost | < $17,539[b] |
| Post-ERCP cost | > $14,791[b] |

*WTP*, willingness to pay

*a*, variables where LCBDE is the cost-effective option for the entire range tested were not included

*b*, the value indicates the parameter values at which LCBDE remains cost-effective compared with other strategies

*ERCP*, endoscopic retrograde cholangiopancreatography

*Pre-ERCP*, preoperative ERCP

*Intra-ERCP*, intraoperative ERCP

*LCBDE*, laparoscopic common bile duct exploration

*Post-ERCP*, postoperative ERCP

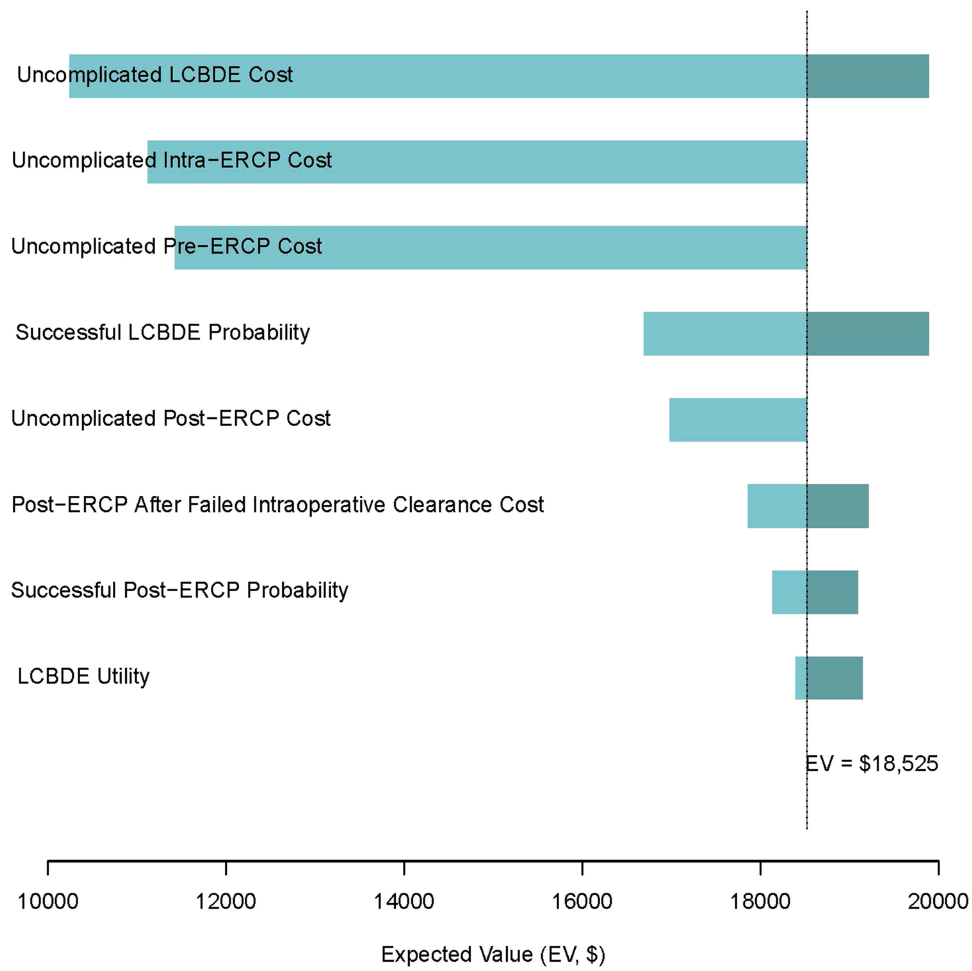



**Fig. 2** Tornado diagram of the results of one-way sensitivity analyses of model variables (only variables generating a risk percentage greater than 0.1% are included in the diagram). Model variables are arranged in descending order of impact on cost-effectiveness with cost of an uncomplicated LCBDE having the greatest impact

A two-way sensitivity analysis was performed for the probability of success of intra-ERCP and LCBDE (Fig. 3). For the range of 0.75 to 1 for the probability of successful stone clearance, LCBDE was the preferred method and was cost-effective in most instances. LCBDE remains the most cost-effective if its probability of success is above 0.875. In turn, its probability of success can drop to 0.75 if the probability of success for intra-ERCP also drops to 0.875.

Figure 4 presents results of a two-way sensitivity analysis of the base costs of LCBDE and intra-ERCP. If the base cost of LCBDE is above $18,400 and the base cost of intra-ERCP is above $18,200, then pre-ERCP is the most cost-effective method. If the base cost of LCBDE remains below $18,400 and the base cost of intra-ERCP is above $18,200, then LCBDE is the most cost-effective method. If the base cost of intra-ERCP is below $18,200 and the base cost of LCBDE is above $18,400, then intra-ERCP is the most cost-effective method.

Finally, we performed a two-way sensitivity analysis of the base costs of pre-ERCP and post-ERCP (Fig. 5). LCBDE was the most cost-effective if the base cost of pre-ERCP was above $16,200 and post-ERCP was above $14,600. For pre-ERCP to be the most cost-effective, the base cost must be less than $11,400 and post-ERCP greater than $10,000 or for the base cost to be less than $16,200, while the base cost of post-ERCP was greater than $14,600. For post-ERCP to be the most cost-effective, the base cost must be less than $14,600, while the base cost of pre-ERCP is greater than $16,200.

## Discussion

Laparoscopic cholecystectomy with laparoscopic common bile duct exploration is the most cost-effective management strategy for inpatient choledocholithiasis. Although current inpatient management depends heavily on available local expertise and resources, the results of this study support efforts to ensure availability of LCBDE expertise and resources. Expanded implementation of LCBDE in general surgical residency training is necessary to support efforts to increase availability of LCBDE as a management option for inpatient choledocholithiasis.

Given that the effectiveness of the four methods was very similar, our model is particularly sensitive to the cost of each management strategy. As a result, it is very likely that the least costly management strategy is the most cost-effective. In our model, LCBDE was the least costly by $1,360 based

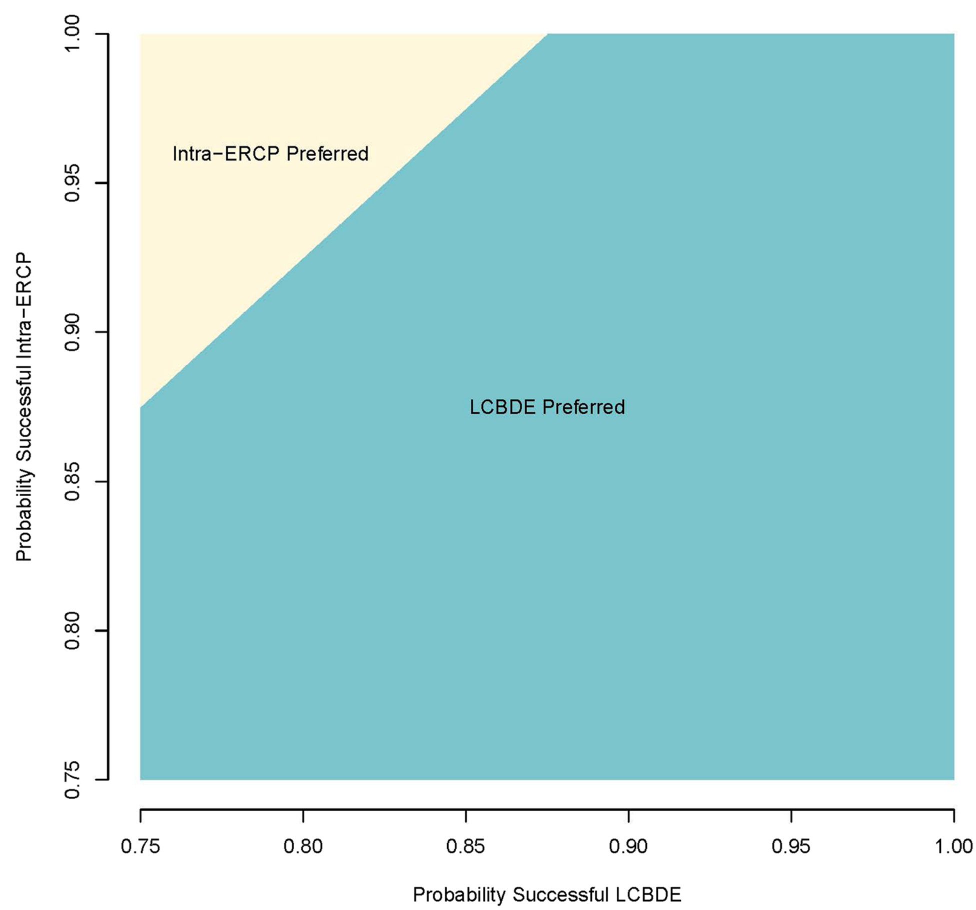



**Fig. 3** Two-way sensitivity analysis of the probability of successful stone extraction for intra-ERCP and LCBDE. LCBDE remains cost-effective in the majority of the analyzed range of probabilities of successful stone extraction

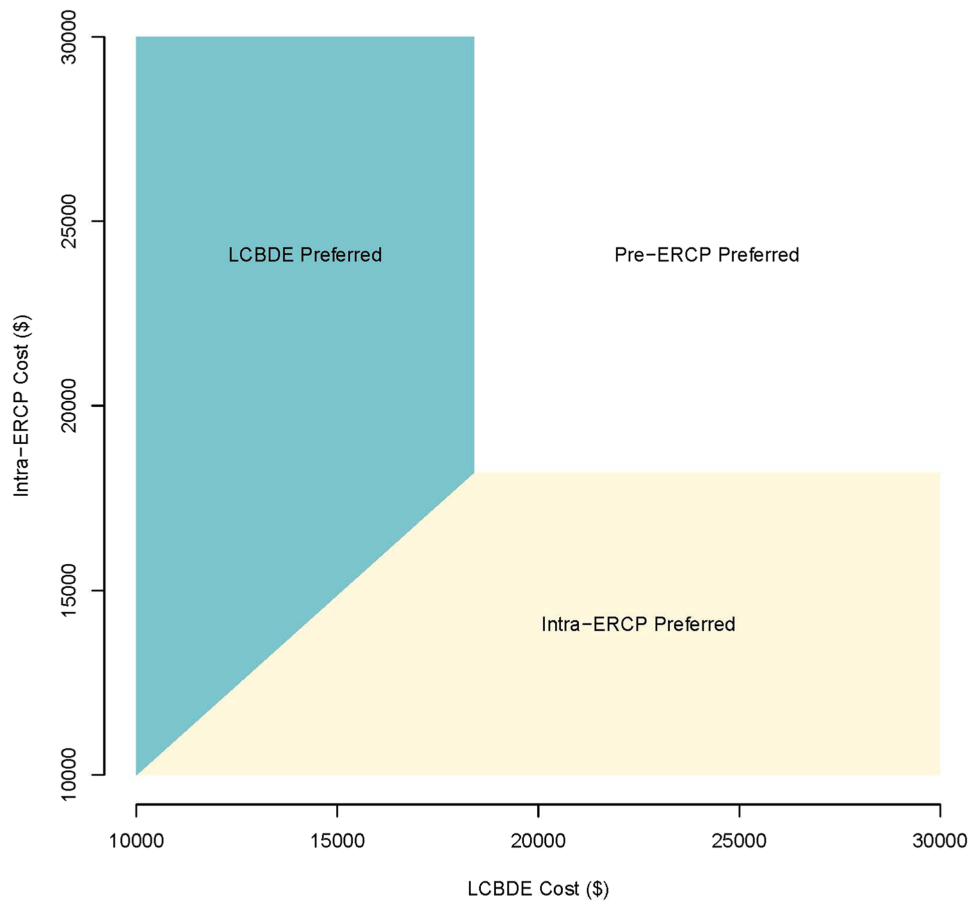



**Fig. 4** Two-way sensitivity analysis of the cost of intra-ERCP and LCBDE. LCBDE remains cost-effective when its base cost is below $18,400 and does not exceed the base cost of intra-ERCP by more than $200

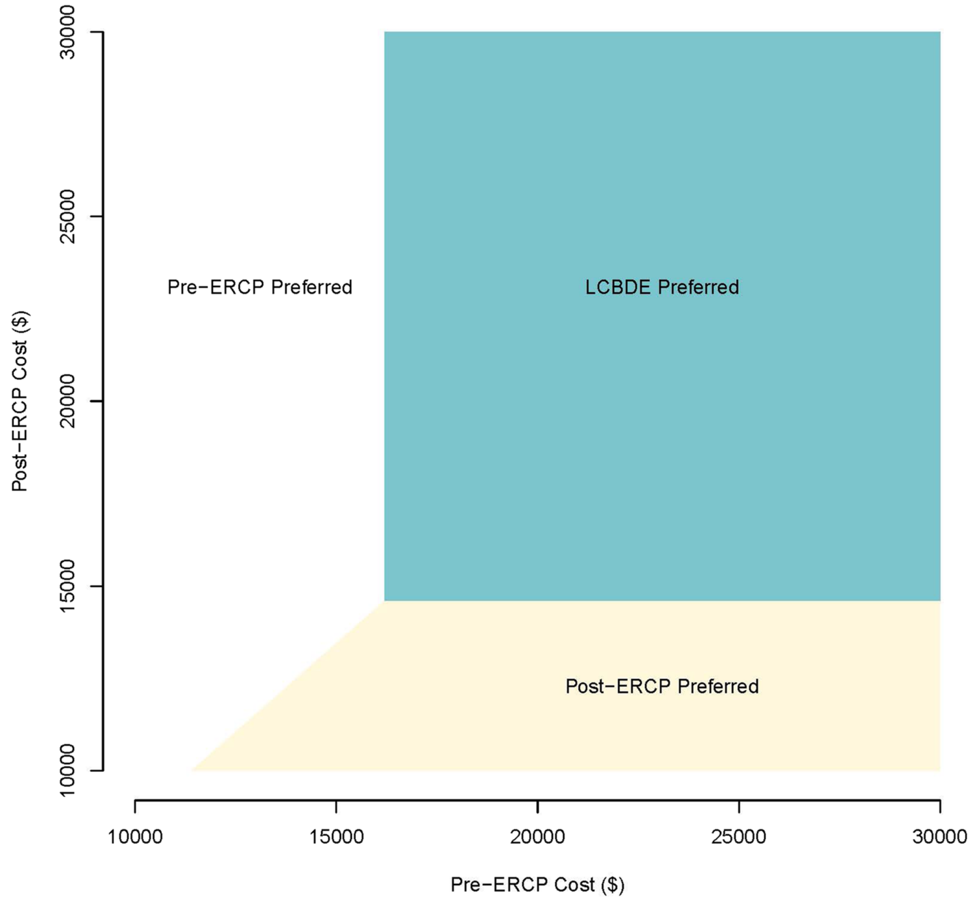
on retrospective analysis of our institutional cost accounting database. In the network meta-analysis by Ricci et al.,[10] LCBDE had the greatest odds of being the least costly management strategy. This lends further support to the conclusion of our model that LCBDE is the most cost-effective management option for inpatient choledocholithiasis management. Furthermore, the robustness of our model was assessed through the use of sensitivity analysis of the costs of these management strategies as noted previously. We believe our model to be reflective of the relative costs of these procedures and capture their inherent cost variability in clinical practice through the use of sensitivity analysis.

All patients in the model were presumed to have choledocholithiasis. As such, the costs associated with diagnosing choledocholithiasis were accounted for in the base costs of each management method and considered to be inherent to those costs. Diagnostic studies (e.g., intraoperative cholangiogram [IOC], magnetic resonance cholangiopancreatography) are commonly employed as part of the management of choledocholithiasis. Although ERCP procedures can be both diagnostic and therapeutic, we do not believe that avoiding other diagnostic studies (e.g., IOC) through routine management of choledocholithiasis with ERCP necessarily precludes LCBDE from being cost-effective. In fact, LCBDE had the lowest base cost of the management strategies despite the potential for increased costs from more routine utilization of diagnostic studies.

Our model assumed that all LC procedures were successful and conversion to an open procedure was avoided. This decision was made recognizing that approximately 10% of all cholecystectomies in North America are performed via an open approach.[20] This assumption was to focus our analysis on the cost-effectiveness of the methods of bile duct clearance at the time of cholecystectomy for choledocholithiasis. There are circumstances where surgeons may convert to an open cholecystectomy specifically for management of choledocholithiasis; however, this appears to be a rare occurrence. Open cholecystectomy with common bile duct exploration comprises less than 1% of cholecystectomies performed in North America, and in a systematic review of cholecystectomies converted to open procedures, choledocholithiasis was cited as the reason for conversion in 0.4% of cases.[20,21] In our model, OCBDE was utilized as the definitive management strategy when attempts at bile duct clearance via LCBDE or ERCP failed with the additional costs of the open procedure accounted for in the study parameters.

Our model did not specify the method of biliary clearance for LCBDE and encompasses both transcystic and

**Fig. 5** Two-way sensitivity analysis of the cost of pre-ERCP and post-ERCP. LCBDE becomes preferred if the base cost of pre-ERCP is above $16,200 and post-ERCP is above $14,600




transductal approaches. In our review of the literature, the meta-analysis by Singh et al. [12] included more studies for LCBDE in their pooled analysis than other existing meta-analyses and was used for the probability parameter of successful LCBDE in our model. In that study, both methods of laparoscopic bile duct clearance were included in the analysis, and therefore, our model parameter is reflective of both methods of LCBDE. Notably, the network meta-analysis by Ricci et al. [10] also included both laparoscopic transcystic and transductal exploration in the pooled analysis, and their study found that LCBDE had the greatest odds of being the least costly management strategy — mirroring the base cost parameters from the institutional data used in our model. We believe the selection of either a transcystic or transductal LCBDE will influence procedural cost and success rates of biliary clearance; however, as noted, the model parameters came from data including a mix of both methods. Existing literature includes a meta-analysis by Bekheit et al. [22] which suggests that transcystic LCBDE has a higher rate of successful duct clearance but is associated with longer procedural times and length of stay. Subsequent to this meta-analysis, three large cohort studies have shown similar rates of successful duct clearance between transcystic and transductal approaches with more complications and longer length of stay associated with transductal exploration.[23–25] As a result, we believe that analyzing the impact on cost-effective choledocholithiasis management of selecting either a transcystic or transductal LCBDE on the cost-effectiveness of choledocholithiasis management is beyond the scope of the current study.

Relatively high rates of bile duct clearance were observed in the meta-analyses used as sources for the parameters of all four management methods studied in our model (pre-ERCP 87%, intra-ERCP 92%, LCBDE 88%, and post-ERCP 74%).[10,12] The referenced meta-analyses represent the largest pooled outcomes of randomized controlled trials for each of the management methods as previously noted. It is possible that the high rate of bile duct clearance following LCBDE and ERCP procedures reported in the literature may be reflective of the expertise of the authors reporting outcomes included in the pooled studies. Such high rates of bile duct clearance may not be witnessed in clinical practice where similar expertise is be lacking. Any alteration in existing management algorithms must be done with caution and understanding of an institution's own outcomes with these procedures.

Cost parameters for the model were obtained from retrospective review of our institution's cost accounting database. As such, these costs may not be reflective of the costs incurred by other institutions when utilizing these methods of bile duct clearance. As previously noted, we do believe the relative costs of these procedures witnessed at our institution are reflective of existing literature as our costs mirrored the results from the meta-analysis by Ricci et al..[10] Despite this, it is possible that not all institutions will have similar costs associated with these procedures. This underscores the need for familiarity with institutional costs before altering existing management algorithms at individual institutions.

Although current inpatient management depends heavily on available institutional expertise, the results of our study argue strongly for ensuring surgical trainee exposure and competence in LCBDE with increased utilization of LCBDE in the management of choledocholithiasis by practicing surgeons. Increased emphasis on this procedure is particularly pressing given the historical trend of decreasing utilization since the introduction of ERCP as demonstrated by an analysis of the trends of choledocholithiasis management from 1998 to 2013, with a decrease from 9.2% of patients with choledocholithiasis undergoing LCBDE to 3.0% of patients during that period.[9] Despite decreased utilization, there has been renewed emphasis on LCBDE given decreased rates of postoperative pancreatitis with 82% decreased odds relative to pre-ERCP and the highest probability of avoiding pancreatitis compared to pre-ERCP, intra-ERCP, and post-ERCP.[10,26,27] Increasing numbers of patients with surgically altered anatomy (e.g., Roux-en-Y gastric bypass) that prevent standard ERCP methods have additionally driven interest in LCBDE.[28] Nevertheless, without prompt changes in LCBDE utilization nationwide, local expertise in this uncommon procedure will become increasing limited and may no longer represent a viable management option at most centers.

In our practice, LCBDE has become the primary method of choledocholithiasis management. Despite this, we continue to utilize ERCP in patients we deem to be inappropriate candidates for LCBDE such as those with large gallstones or those with multiple stones within the common bile duct. We believe our model supports that practice as ERCP was still demonstrated to be an effective management strategy. Although LCBDE would appear to be the most cost-effective management strategy, careful patient selection for these procedures remains paramount.

There are several factors driving the difference in costs for each of the respective management strategies. The relatively low cost of LCBDE in our institutional dataset as well as in the network meta-analysis by Ricci et al. [10] may be explained by a single physician performing both the cholecystectomy and duct clearance, resulting in lower fees for physician services as well as decreased operating room time with no period of transition between providers in the operating room. Additionally, the length of stay will be shortened with a single anesthetic exposure, which decreases costs for the healthcare system. It is possible that the other intraoperative bile duct clearance strategy, intra-ERCP, which is typically performed by a different physician than the surgeon performing the cholecystectomy may have lower costs if performed by a single provider.

As demonstrated in this study, intra-ERCP appears to be slightly more effective at bile duct clearance compared to LCBDE but more costly. As noted, this cost may be decreased with a single provider performing both LC and intra-ERCP. The previously described method of laparoendoscopic rendezvous ERCP is a potential candidate to facilitate localized expertise in intra-ERCP to allow for a single provider to perform both LC and intra-ERCP.[29] However, expertise in this procedure among surgeons performing LC remains more limited than LCBDE with limited utilization of this method of intra-ERCP since it was first described in 1998.

Though not studied, laparoendoscopic rendezvous ERCP likely carries a less severe learning curve than traditional ERCP given the presence of a guidewire through the bile ducts into the duodenum via the ampulla of Vater. With a flatter learning curve, it is possible that surgeons could become proficient and eligible for credentialing for ERCP on the limited basis of rendezvous-only intraoperative ERCP as part of a LC. Consideration for increased exposure to laparoendoscopic rendezvous ERCP in surgical trainees may be beneficial in the further refinement of existing management algorithms for choledocholithiasis. However, whether such exposure is feasible in enough trainees to drive change in choledocholithiasis management is unclear.

Post-ERCP is considered an acceptable management option when ERCP resources are lacking or limited.[30] Perhaps because of those limited resources, a nationwide survey of general surgeons indicated that 64% prefer post-ERCP when choledocholithiasis is first diagnosed intraoperatively.[31] Our analysis demonstrates how the lack of those resources and/or expertise is costly from a healthcare system perspective. As such, we believe that post-ERCP should be the management option of last resort in choledocholithiasis when viewed from the perspective of cost-effectiveness.

Finally, our model attempts to capture the wide variation of inpatient choledocholithiasis management and account for the most common algorithms currently used in the USA. The substantial variation in institutional expertise and resources makes one model that is applicable to all choledocholithiasis management in the USA impossible. As a result, the conclusions of this study may not be broadly applicable and should be interpreted cautiously. The implementation of the findings of this study requires careful evaluation of available expertise and outcomes at each respective institution prior to changing existing management algorithms. The parameters utilized in this study reflect previously published outcomes that may not be reflective of outcomes at every institution, and the expertise necessary to achieve these outcomes may also not be present at every institution.

## Conclusion

Laparoscopic common bile duct exploration is the most cost-effective management option for choledocholithiasis in patients undergoing laparoscopic cholecystectomy. Efforts to incorporate laparoscopic common bile duct exploration into surgical training are warranted to drive increased expertise in this currently uncommon procedure. Further efforts to ensure local availability of both expertise in and resources for laparoscopic common bile duct exploration are necessary.

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Data collection: Morrell
Data analysis and interpretation: Morrell, Pauli, and Hollenbeak
Manuscript drafting: Morrell
Critical revisions of manuscript: Morrell, Pauli, and Hollenbeak

### Declarations

**Conflict of Interest** David J. Morrell and Christopher S. Hollenbeak have no conflicts of interest. Eric M. Pauli reports consultant fees and Data and Safety Monitoring Board membership for Becton, Dickinson and Company (BD); consultant fees from Boston Scientific Corp.; consultant fees from Cook Biotech, Inc.; royalties from Springer; royalties from UpToDate, Inc.; consultant fees from Wells Fargo & Company; consultant fees from CMR Surgical; consultant fees from Medtronic, PLC; consultant fees from Ovesco Endoscopy, AG; and consultant fees from Baxter International, Inc., unrelated to this report.

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