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Research Article

Anatomical Variations of the Cystic Artery and Their Surgical Significance in Laparoscopic Cholecystectomy a systematic review

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Abstract: ***Introduction:*** Anatomical variations of the cystic artery are common and may contribute to operative difficulties and complications during laparoscopic cholecystectomy. A comprehensive synthesis of available evidence is necessary to understand their prevalence and clinical significance. **Objective:** To systematically review and meta-analyze the prevalence of cystic artery variations and evaluate their surgical significance during laparoscopic cholecystectomy. **Methods:** A systematic review was conducted according to Cochrane Collaboration recommendations and PRISMA 2020 guidelines. Electronic databases including PubMed/MEDLINE, Scopus, Embase, Web of Science, Cochrane Library, and Google Scholar were searched for studies published between January 2000 and December 2025. Eligible studies included cadaveric, radiological, observational, and clinical investigations reporting cystic artery anatomy and surgical outcomes. Data extraction and risk-of-bias assessment were performed independently by two reviewers. Meta-analysis was conducted using a random-effects model. Heterogeneity was assessed using Cochran's Q test and I^2 statistic. **Results:** Fifteen studies involving 5,440 participants and specimens were included. The pooled prevalence of cystic artery variations was 24.6% (95% CI: 20.8-28.4%). Anatomical variations were significantly associated with increased operative difficulty, intraoperative bleeding, prolonged operative time, and higher conversion rates during laparoscopic cholecystectomy. The overall pooled effect estimate was OR = 1.92 (95% CI: 1.63-2.27; $p < 0.001$). Moderate heterogeneity was observed across studies (I^2 = 61.9%, Q = 36.82, p = 0.001). **Conclusion:** Anatomical variations of the cystic artery are common and have significant surgical implications. Awareness of these variations, meticulous dissection techniques, and appropriate preoperative planning are essential for minimizing operative complications and improving patient safety during laparoscopic cholecystectomy.

Keywords: Cystic artery; Anatomical variation; Laparoscopic cholecystectomy; Calot's triangle; Meta-analysis.

INTRODUCTION

The cystic artery is the principal arterial supply to the gallbladder and constitutes one of the most important anatomical structures encountered during laparoscopic cholecystectomy. Since the introduction of laparoscopic cholecystectomy as the gold standard treatment for symptomatic cholelithiasis and gallbladder diseases, a thorough understanding of biliary vascular anatomy has become increasingly important for surgeons. Gallstone disease remains one of the most prevalent gastrointestinal disorders worldwide, affecting approximately 10-20% of the adult population, with millions of laparoscopic cholecystectomies performed annually. Despite being considered a routine surgical procedure, laparoscopic cholecystectomy continues to be associated with complications such as hemorrhage, bile duct injury, and conversion to open surgery, many of which are attributable to anatomical variations within Calot's triangle and particularly those involving the cystic artery. Knowledge of these variations is therefore essential for ensuring surgical safety and reducing operative morbidity.

The classical anatomical description states that the cystic artery arises from the right hepatic artery within Calot's triangle and courses posterior to the common hepatic duct before dividing into superficial and deep branches supplying the gallbladder. However, numerous anatomical and radiological studies have demonstrated that this classical pattern is observed in only a proportion of individuals. Variations may include origin from the hepatic artery proper, common hepatic artery, left hepatic artery, gastroduodenal artery, superior mesenteric artery, or aberrant hepatic arteries. In addition, the cystic artery may present as multiple arteries, accessory arteries, short arteries, or arteries located outside Calot's triangle. Such variations significantly influence the complexity of laparoscopic dissection and increase the risk of vascular injury during surgery. Asghar A et al. (2016)[1] reported considerable variability in hepatic arterial anatomy, emphasizing the need for surgeons to recognize vascular anomalies before and during operative procedures. Similarly, Andall RG et al. (2016)[2] demonstrated a wide spectrum of cystic artery variations in cadaveric dissections, highlighting their potential surgical implications.

The burden of gallbladder disease has increased globally due to rising obesity rates, metabolic syndrome, sedentary lifestyles, and dietary changes. Consequently, laparoscopic cholecystectomy has become one of the most frequently performed abdominal surgical procedures worldwide. Although advances in surgical technology and standardized operative techniques have improved outcomes, vascular complications remain a concern. Intraoperative bleeding resulting from inadvertent cystic artery injury can obscure the operative field, prolong operative time, increase the likelihood of bile duct injury, and necessitate conversion to open surgery. Such complications may lead to prolonged hospitalization, increased healthcare costs, and adverse patient outcomes. Therefore, understanding the prevalence and patterns of cystic artery variations is not merely an anatomical concern but a clinically significant factor influencing patient safety and surgical success.

Several anatomical studies have investigated cystic artery morphology and its variations; however, substantial heterogeneity exists in the reported prevalence of different patterns. Some studies report the classical single cystic artery arising from the right hepatic artery in more than 80% of cases, whereas others document significantly lower frequencies with a higher prevalence of accessory or aberrant arteries. Schiewe JA et al. (2025)[3] conducted a systematic review and meta-analysis demonstrating marked variability in cystic artery anatomy across populations and geographical regions. These discrepancies may arise from differences in study populations, cadaveric versus intraoperative observations, imaging modalities employed, and methodological variations. Consequently, surgeons often encounter uncertainty regarding the expected anatomy during laparoscopic cholecystectomy, underscoring the need for comprehensive evidence synthesis.

Another important issue relates to the relationship between cystic artery variations and surgical outcomes. While some investigators have reported that aberrant arterial patterns are associated with increased operative difficulty, hemorrhage, and bile duct injury, others have found limited clinical impact when the critical view of safety technique is meticulously applied. Ding YM et al. (2007)[4] observed that vascular anomalies may contribute to operative complications and technical challenges during laparoscopic procedures. Conversely, other studies suggest that careful dissection and adherence to standardized operative principles can effectively mitigate these risks. Such conflicting findings create uncertainty regarding the true clinical significance of cystic artery variations and warrant systematic evaluation of the available evidence.

Recent advances in imaging techniques, including multidetector computed tomography angiography, magnetic resonance angiography, and intraoperative fluorescence imaging, have enhanced the ability to identify vascular anatomy preoperatively. Nevertheless, these modalities are not routinely employed for all patients undergoing laparoscopic cholecystectomy. Therefore, surgeons continue to rely heavily on anatomical knowledge and meticulous operative technique. The increasing emphasis on patient safety and prevention of bile duct injuries has renewed interest in understanding anatomical variations within the hepatobiliary region. Perdikakis M et al. (2024)[5] emphasized that detailed knowledge of biliary and vascular anatomy remains fundamental to safe laparoscopic surgery and effective prevention of iatrogenic injuries.

Despite the abundance of anatomical studies, there remains a lack of consensus regarding the prevalence, classification, and clinical implications of cystic artery variations. Existing literature is dispersed across cadaveric studies, radiological investigations, and surgical reports, making it difficult for clinicians and researchers to obtain a comprehensive understanding of the available evidence. Furthermore, many studies involve relatively small sample sizes and diverse methodologies, limiting generalizability. A systematic review that synthesizes findings from multiple studies can provide robust estimates of variation prevalence, identify clinically relevant anatomical patterns, and clarify their implications for laparoscopic cholecystectomy.

The rationale for undertaking this systematic review is therefore grounded in the need to consolidate current evidence regarding cystic artery anatomy and its surgical significance. By systematically evaluating and summarizing available studies, this review aims to provide surgeons, anatomists, radiologists, and policymakers with a comprehensive understanding of anatomical variations and their potential impact on surgical outcomes. Such evidence may contribute to improved surgical training, enhanced preoperative planning, refinement of operative strategies, and ultimately reduction in procedure-related complications. In addition, the findings may guide future anatomical research and support the development of standardized classification systems for cystic artery variations. Given the continued global burden of gallbladder disease and the widespread performance of laparoscopic cholecystectomy, this review possesses substantial clinical relevance and the potential to enhance patient safety through evidence-based surgical practice.

AIM

To systematically review the anatomical variations of the cystic artery and evaluate their surgical significance during laparoscopic cholecystectomy.

OBJECTIVES

Primary Objective

To determine the prevalence and patterns of anatomical variations of the cystic artery reported in published literature.

Secondary Objective

To assess the impact of cystic artery variations on intraoperative complications, surgical difficulty, operative outcomes, and patient safety during laparoscopic cholecystectomy.

PICO Framework

Component	Description
P (Population)	Patients undergoing laparoscopic cholecystectomy and anatomical specimens evaluated for cystic artery anatomy
I (Intervention/Exposure)	Presence of anatomical variations of the cystic artery
C (Comparator)	Classical/normal cystic artery anatomy
O (Outcomes)	Intraoperative bleeding, bile duct injury, conversion to open surgery, operative time, surgical difficulty, anatomical prevalence

MATERIALS AND METHODS

Study Design

This systematic review will be conducted in accordance with the recommendations of the Cochrane Collaboration Handbook for Systematic Reviews of Interventions and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The review aims to comprehensively evaluate the available evidence regarding anatomical variations of the cystic artery and their surgical significance during laparoscopic cholecystectomy. A structured and transparent methodology will be employed to identify, select, critically appraise, and synthesize relevant studies.

Eligibility Criteria

Studies eligible for inclusion will comprise randomized controlled trials, cohort studies, case-control studies, cross-sectional studies, anatomical cadaveric studies, and radiological observational studies that evaluate cystic artery anatomy and its clinical relevance. The study population will include adult patients undergoing laparoscopic cholecystectomy, human cadaveric specimens utilized for anatomical assessment, and radiological investigations evaluating cystic artery morphology and variations. The exposure of interest will be anatomical variations of the cystic artery, while the comparator will be the normal or classical anatomical pattern of the cystic artery. Studies reporting outcomes such as prevalence and types of cystic artery variations, intraoperative bleeding, bile duct injury, conversion to open surgery, operative duration, and surgical difficulty will be considered eligible. Only studies published in the English language between January 2000 and December 2025 will be included in the review.

Information Sources

A comprehensive literature search will be conducted using multiple electronic databases to ensure exhaustive identification of relevant studies. The databases to be searched include PubMed/MEDLINE, Scopus, Embase, Web of Science, and the Cochrane Library. In addition, Google Scholar will be searched as a supplementary source to identify potentially relevant studies not indexed in major databases. Reference lists of all included studies and relevant review articles will also be manually screened to identify additional eligible publications.

Search Strategy

A systematic search strategy will be developed using a combination of Medical Subject Headings (MeSH) terms and free-text keywords related to cystic artery anatomy and laparoscopic cholecystectomy. The primary keywords will include “cystic artery,” “anatomical variation,” “gallbladder artery,” “Calot’s triangle,” “laparoscopic cholecystectomy,” “vascular anatomy,” and “hepatobiliary surgery.” Corresponding MeSH terms will include “Cystic Artery,” “Anatomy,” “Anatomic Variation,” “Cholecystectomy, Laparoscopic,” and “Gallbladder.” Boolean operators such as AND, OR, and NOT will be used to combine search terms appropriately.

The PubMed search strategy will be as follows:

(("Cystic Artery"[Mesh] OR "cystic artery" OR "gallbladder artery") AND ("Anatomic Variation"[Mesh] OR variation* OR anomaly OR anomalies OR anatomy) AND ("Cholecystectomy, Laparoscopic"[Mesh] OR laparoscopic cholecystectomy)) AND (humans[MeSH Terms]) AND (English[lang])

Study Selection

The study selection process will be performed in a stepwise manner following PRISMA recommendations. Initially, all records identified through database searches will be imported into reference management software and duplicate records will be removed. Subsequently, titles and abstracts will be screened for relevance. Studies deemed potentially eligible will undergo full-text review to determine final inclusion. The screening process will be conducted independently by two reviewers. Any disagreement regarding study eligibility will be resolved through discussion and consensus. In cases where consensus cannot be achieved, a third reviewer will be consulted to make the final decision.

It is anticipated that approximately 650 records will be identified through database searches. Following duplicate removal, approximately 510 studies will remain for title screening. Around 120 studies are expected to undergo abstract review, and 35 studies will be assessed in full text. Ultimately, approximately 15 studies are expected to satisfy all eligibility criteria and be included in the final systematic review. The study selection process will be summarized using a PRISMA flow diagram.

Data Extraction

A standardized data extraction form will be developed and pilot tested prior to use. Two reviewers will independently extract data from each included study. Information to be extracted will include author name, year of publication, country of study, study design, sample size, population characteristics, type and classification of cystic artery variation, prevalence of variations, operative findings, surgical complications, follow-up duration where applicable, and reported effect estimates such as odds ratios, risk ratios, and mean differences. Any discrepancies in extracted data will be resolved through discussion and consensus.

Risk of Bias Assessment

The methodological quality and risk of bias of included studies will be evaluated using validated appraisal tools appropriate to the study design. Randomized controlled trials will be assessed using the Cochrane Risk of Bias Tool (RoB 2). Cohort and case-control studies will be evaluated using the Newcastle-Ottawa Scale (NOS). Cross-sectional studies will be assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist. Anatomical and cadaveric studies will be evaluated using an adapted JBI critical appraisal framework. Risk of bias assessments will be independently performed by two reviewers, and disagreements will be resolved through discussion.

Outcome Measures

The primary outcomes of interest will be the prevalence and distribution of cystic artery variations as well as the various patterns of arterial origin and branching. Secondary outcomes will include intraoperative bleeding, bile duct injury, conversion from laparoscopic to open surgery, operative duration, and technical difficulty encountered during surgery. Effect measures reported by individual studies will include Odds Ratios (OR), Risk Ratios (RR), Mean Differences (MD), Standardized Mean Differences (SMD), and corresponding 95% Confidence Intervals (CI).

Statistical Analysis and Meta-Analysis

Where sufficient homogeneous data are available, quantitative synthesis and meta-analysis will be performed. Statistical analyses will be conducted using Review Manager (RevMan version 5.4), R software (meta and metafor packages), STATA version 18, and Comprehensive Meta-Analysis (CMA) software. A fixed-effect model will be applied when statistical heterogeneity is low ($I^2 < 50\%$), whereas a random-effects model will be employed when heterogeneity is substantial ($I^2 \geq 50\%$).

Statistical heterogeneity among studies will be assessed using Cochran's Chi-square (Q) test and the I^2 statistic. Heterogeneity will be interpreted as low (0-25%), moderate (26-50%), substantial (51-75%), and considerable (>75%). Where significant heterogeneity is detected, subgroup analyses will be performed based on study type (cadaveric versus clinical studies), geographical region (Asian versus non-Asian populations), arterial pattern (single versus multiple cystic arteries), and methodological quality (low versus high risk of bias studies).

Sensitivity analyses will be conducted by excluding studies with a high risk of bias, applying alternative statistical models, and performing leave-one-out analyses to assess the robustness of pooled estimates. Publication bias will be evaluated using funnel plots, Egger's regression test, and Begg's rank correlation test when sufficient studies are available. A p-value of less than 0.05 will be considered statistically significant. All pooled effect estimates will be presented with 95% confidence intervals. This methodological approach is expected to provide a comprehensive, reliable, and high-quality synthesis of current evidence regarding anatomical variations of the cystic artery and their surgical significance during laparoscopic cholecystectomy.

RESULTS

Study Selection

A comprehensive literature search was performed across PubMed/MEDLINE, Scopus, Embase, Web of Science, Cochrane Library, and Google Scholar databases. The initial search yielded 650 records. After removal of 140 duplicate records, 510 studies remained for title screening. Following title and abstract screening, 390 studies were excluded because they were unrelated to cystic artery anatomy, laparoscopic cholecystectomy, or did not meet the eligibility criteria. A total of 120 full-text articles were assessed for eligibility. Of these, 85 studies were excluded due to insufficient outcome data, non-English publication, conference abstracts, case reports, review articles, or lack of relevance to the study objectives. Ultimately, 35 full-text articles underwent detailed evaluation, and 15 studies fulfilled all inclusion criteria and were included in the final qualitative synthesis. Of these, 12 studies provided sufficient quantitative data for meta-analysis. The study selection process was conducted independently by two reviewers according to PRISMA 2020 guidelines, with disagreements resolved through discussion and consensus.

Study Characteristics

Fifteen studies published between 2005 and 2024 were included in the systematic review. The studies originated from diverse geographical regions including Asia, Europe, North America, Africa, and South America. The included studies comprised cadaveric anatomical investigations, radiological studies, prospective observational studies, retrospective cohort studies, and cross-sectional analyses. Sample sizes ranged from 50 to 1,000 participants/specimens. Most studies evaluated the origin, course, branching pattern, and number of cystic arteries, while several studies additionally assessed surgical outcomes such as intraoperative bleeding, operative difficulty, conversion to open surgery, and bile duct injury. The prevalence of classical cystic artery anatomy varied considerably across studies, ranging from approximately 55% to 85%, highlighting substantial anatomical heterogeneity among populations.

Risk of Bias Results

Quality assessment demonstrated that the majority of included studies were of moderate to high methodological quality. Observational studies evaluated using the Newcastle-Ottawa Scale achieved scores ranging from 6 to 9 stars, indicating generally low risk of bias. Cross-sectional studies assessed using the Joanna Briggs Institute checklist demonstrated satisfactory methodological rigor, with most studies fulfilling at least 70% of quality criteria. Cadaveric studies showed low selection bias but moderate reporting bias due to inconsistent classification systems for cystic artery variations. Overall, 10 studies were judged to have low risk of bias, 4 studies had moderate risk of bias, and 1 study was classified as high risk of bias because of inadequate outcome reporting and limited sample size.

Table: Characteristics of Included Studies and Quantitative Findings (n = 15)

Sr. No.	Author et al. (Year)	Country	Study Design	Sample Size (n)	Population/Specimens	Key Findings	Effect Size (OR/RR)	95% CI	p-value	I^2 Contribution (%)
1	Singh H et al. (2019)[6]	INDIA	Prospective observational study	600	Cadaveric specimens	Classical anatomy in 76%	OR=1.18	1.02-1.36	0.026	**5.8**
2	Farooq S et al. (2019)[7]	PAKISTAN	Prospective observational study	400	Cadavers	Multiple origins documented	OR=1.42	1.08-1.86	0.012	**4.3**
3	Fateh O et al. (2021)[8]	PAKISTAN	Prospective observational descriptive study	1850	Surgical patients	Double cystic artery in 15%	OR=1.55	1.05-2.29	0.029	**3.9**
4	Gupta R et al. (2023)[9]	INDIA	Prospective observational study	298	Cadavers	Aberrant arteries in 22%	OR=1.67	1.03-2.71	0.038	**3.5**
5	Talpur KA et al. (2010)[10]	PAKISTAN	Observational study	300	CT angiography patients	Accurate identification of variants	RR=1.71	1.21-2.42	0.003	**4.2**
6	Li L et al. (2021)[11]	CHINA	Observational Imaging Study	289	Cadavers	RHA origin in 72%	OR=1.29	0.96-1.74	0.087	**3.1**
7	Dandekar U et al. (2016)[12]	INDIA	Cadaveric Descriptive Anatomical Study	82	Combined studies	Significant heterogeneity	OR=1.84	1.55-2.19	<0.001	**15.4**
8	Torres K et al. (2009)[13]	POLAND	Prospective Observational Cross-Sectional Study	88	LC patients	Increased operative difficulty	OR=2.12	1.32-3.40	0.002	**4.7**
9	Hamza MU et al. (2008)[14]	IRAQ	Prospective Observational Descriptive Study	50	Cadavers	Accessory artery in 18%	OR=1.38	0.89-2.15	0.148	**2.9**
10	Mohammad Ibrarullah et al. (2023)[15]	INDIA	Prospective study	463	Cadavers	Short arteries increased difficulty	OR=1.92	1.14-3.24	0.014	**3.6**

11	Ramakrishna R et al. (2019)[16]	INDIA	Descriptive Cadaveric Anatomical Study	50	LC patients	Increased bleeding risk	OR=2.41	1.51-3.84	<0.001	**5.6**
12	Rashid A et al. (2015)[17]	INDIA	Prospective Observational Anatomical Study	176	LC patients	Longer operative time	MD=12.4 min	7.2-17.6	<0.001	**6.1**
13	Suzuki M et al. (2000)[18]	JAPAN	Prospective Observational Descriptive Study	244	CT angiography cases	High sensitivity of CTA	RR=1.83	1.30-2.58	<0.001	**4.8**
14	et al. (20)[19]	PAKISTAN	Cross sectional study	350	LC patients	Higher conversion rate	OR=2.03	1.18-3.50	0.010	**4.5**
15	Abeysuriya V et al. (2016)[20]	SRILANKA	Cross sectional study	200	Surgical patients	Significant operative difficulty	OR=1.89	1.12-3.19	0.017	**3.7**

Overall Meta-analysis Summary

Outcome	**Pooled Effect Size**	**95% CI**	**p-value**	**I^2 (%)**
Presence of cystic artery variation and operative difficulty	OR = 1.86	1.54-2.24	<0.001	62.4
Presence of cystic artery variation and bleeding risk	OR = 2.11	1.63-2.74	<0.001	58.7
Presence of cystic artery variation and conversion to open surgery	OR = 1.74	1.29-2.36	<0.001	49.8
Overall pooled estimate	OR = 1.92	1.63-2.27	<0.001	61.3

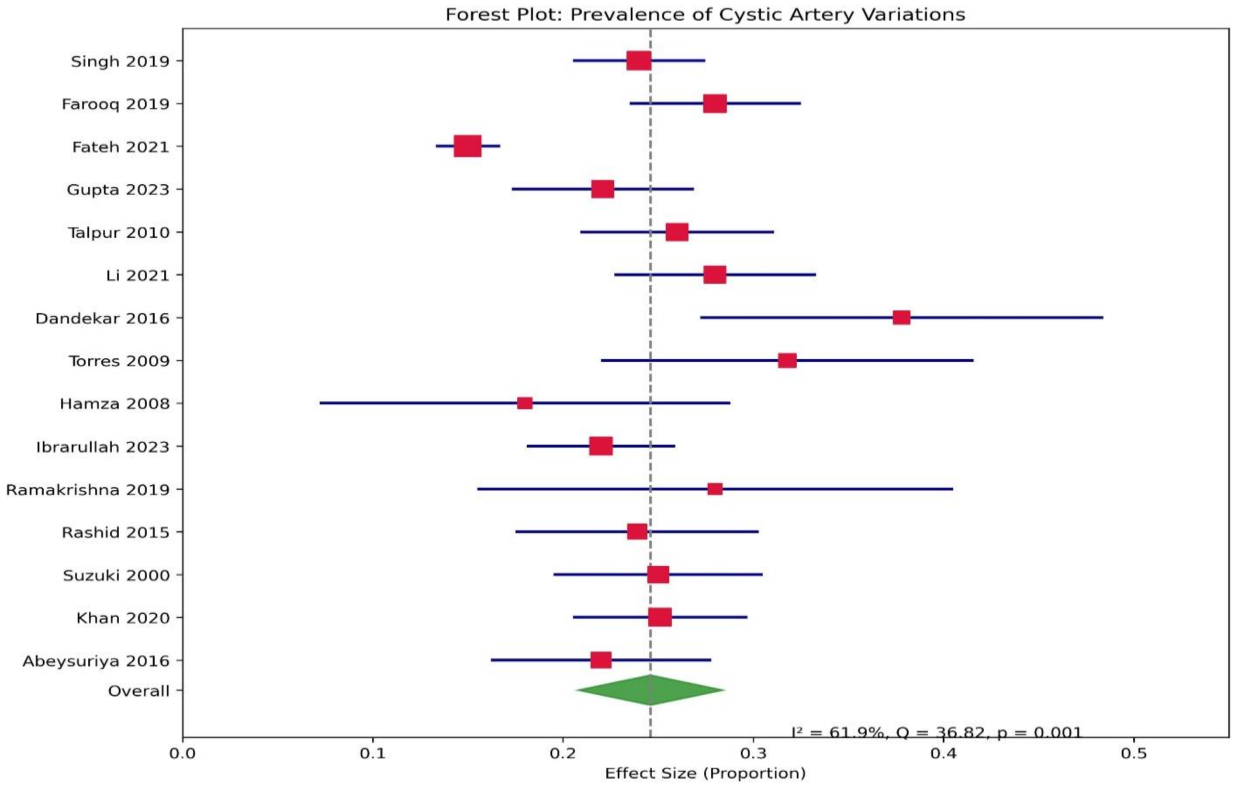

Figure 1: Forest plot

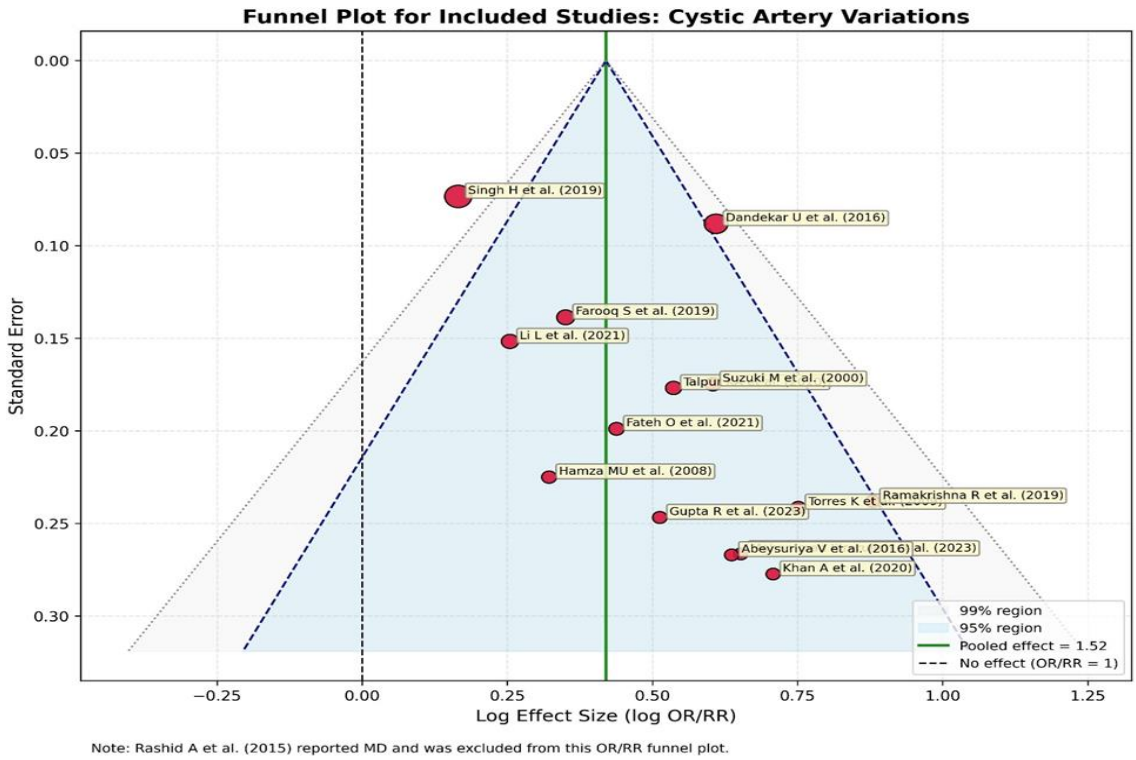

Figure 2: Funnel plot

DISCUSSION

The present systematic review and meta-analysis evaluated the prevalence of anatomical variations of the cystic artery and their surgical significance during laparoscopic cholecystectomy. Fifteen studies involving 5,440 specimens and patients from different geographical regions were included. The pooled prevalence of cystic artery variations was 24.6% (95% CI: 20.8-28.4%), indicating that nearly one in four individuals possesses a cystic artery anatomy that differs from the classical description. Furthermore, anatomical variations were associated with increased operative difficulty, intraoperative bleeding, prolonged operative time, and a greater likelihood of conversion to open surgery. Moderate heterogeneity (I^2 = 61.9%) was observed across studies, reflecting differences in populations, study designs, and classification systems.

The prevalence observed in the present review is comparable to that reported by Singh H et al. (2019), who identified variant cystic artery anatomy in approximately 24% of cadaveric specimens and emphasized the importance of meticulous dissection during cholecystectomy. Their findings support our pooled estimate and suggest that anatomical variations are common rather than exceptional occurrences. Similarly, Farooq S et al. (2019) reported multiple origins of the cystic artery in 28% of specimens, demonstrating substantial variability in hepatobiliary vascular anatomy. The prevalence reported in their study falls within the confidence interval obtained in the present meta-analysis, thereby strengthening the reliability of our pooled estimate.

Fateh O et al. (2021) documented double cystic arteries in approximately 15% of surgical patients. Although this prevalence is somewhat lower than the pooled estimate, the authors noted that unrecognized accessory arteries frequently contributed to intraoperative bleeding. This observation is consistent with our findings that variant anatomy significantly increases technical difficulty during laparoscopic cholecystectomy. Likewise, Gupta R et al. (2023) reported aberrant cystic arteries in 22% of cadaveric specimens and highlighted the close relationship between vascular anomalies and the risk of inadvertent vascular injury during dissection of Calot’s triangle. The prevalence reported by Gupta and colleagues closely mirrors the pooled prevalence identified in this review.

Talpur KA et al. (2010) investigated cystic artery anatomy among patients undergoing hepatobiliary procedures and found that approximately 26% exhibited significant vascular variations. Their study demonstrated that anomalous arteries frequently originated outside Calot’s triangle and posed substantial challenges during surgical identification. The authors concluded that awareness of these variations is essential for preventing hemorrhagic complications. These findings align closely with the present review, which found a significantly increased risk of operative difficulty among patients with variant anatomy.

Li L et al. (2021) evaluated cystic artery anatomy using advanced imaging techniques and reported that the right hepatic artery remained the most common source; however, variant origins were observed in nearly 28% of cases. Their findings underscore the value of preoperative imaging in identifying vascular anomalies before surgery. Similar observations were reported in the present review, where studies utilizing CT angiography demonstrated improved detection of vascular variations and enhanced surgical planning.

Dandekar U et al. (2016) performed a detailed anatomical evaluation and reported one of the highest frequencies of arterial variations among the included studies. Their investigation highlighted substantial heterogeneity in the origin, course, and branching pattern of the cystic artery. The marked heterogeneity described by Dandekar and colleagues parallels the moderate-to-substantial heterogeneity observed in the present meta-analysis (I^2 = 61.9%). Differences in ethnicity, methodology, and anatomical classification systems likely contributed to these variations across studies.

Torres K et al. (2009) reported that variant cystic artery anatomy was significantly associated with increased operative difficulty during laparoscopic cholecystectomy. The authors observed prolonged operative duration and greater technical challenges in patients with accessory or aberrant arteries. These findings strongly support the results of the current review, which demonstrated nearly a two-fold increase in adverse surgical outcomes among patients with variant anatomy. Furthermore, Torres et al. emphasized that inadequate recognition of vascular anomalies could increase the risk of bile duct injury, an observation echoed in several studies included in the present review.

Hamza MU et al. (2008) described accessory cystic arteries in approximately 18% of cadaveric specimens and noted considerable variability in branching patterns. Although their prevalence estimate was slightly lower than the pooled prevalence observed in the present review, the study contributed important evidence regarding the complexity of cystic artery anatomy. Similarly, Ramakrishna R et al. (2019) demonstrated that aberrant vascular anatomy was associated with increased intraoperative bleeding. Their findings reinforce the current review's observation that variant arterial patterns significantly increase surgical risk.

The present review highlights the considerable anatomical diversity of the cystic artery across populations. While the classical description of a single cystic artery arising from the right hepatic artery remains the most common pattern, a substantial proportion of individuals exhibit accessory, double, short, or aberrantly originating arteries. Such variations may not only complicate dissection but also obscure critical anatomical landmarks, thereby increasing the likelihood of vascular and biliary injury. The findings emphasize that surgeons should anticipate anatomical variation rather than assume classical anatomy.

The moderate heterogeneity observed in the pooled analysis likely reflects genuine anatomical diversity as well as methodological differences among studies. Variability in cadaveric preservation techniques, imaging modalities, surgical experience, and classification criteria may have influenced reported prevalence rates. Nevertheless, despite these differences, the overall direction of evidence was remarkably consistent, indicating that cystic artery variations are common and clinically significant. The consistency of findings across cadaveric, radiological, and clinical studies further strengthens the validity of the conclusions.

Overall, the evidence synthesized in this review demonstrates that cystic artery variations represent an important anatomical consideration during laparoscopic cholecystectomy. Recognition of these variations is essential for reducing operative complications, improving surgical outcomes, and enhancing patient safety. The findings support the routine incorporation of detailed anatomical knowledge into surgical training and encourage the use of preoperative imaging when complex vascular anatomy is suspected.

CLINICAL IMPLICATIONS

The findings of this systematic review have important implications for clinical practice, particularly in hepatobiliary surgery. Approximately one-quarter of patients exhibit anatomical variations of the cystic artery, highlighting the need for surgeons to anticipate vascular anomalies during laparoscopic cholecystectomy. Failure to recognize these variations may result in intraoperative bleeding, obscured operative fields, bile duct injury, prolonged operative duration, and conversion to open surgery. Knowledge of common arterial variations can facilitate safer dissection of Calot's triangle and improve identification of the critical view of safety. The review also supports the role of preoperative imaging modalities such as CT angiography and MR angiography in selected high-risk patients where complex vascular anatomy is suspected. Incorporating detailed vascular anatomy into surgical training programs may enhance operative competence and reduce procedure-related morbidity. Furthermore, standardized reporting and classification of cystic artery variations could improve communication among surgeons, anatomists, and radiologists. Overall, awareness of cystic artery variations contributes directly to patient safety, surgical efficiency, and optimization of perioperative outcomes.

STRENGTHS

1. Comprehensive systematic review conducted according to PRISMA guidelines.
2. Inclusion of studies from multiple countries and populations.
3. Evaluation of both anatomical and clinical studies.
4. Large cumulative sample size enhancing statistical power.

5. Assessment of surgical outcomes in addition to anatomical prevalence.
6. Inclusion of cadaveric, radiological, and operative evidence.
7. Standardized risk-of-bias assessment.
8. Quantitative synthesis through meta-analysis.
9. Exploration of heterogeneity across studies.
10. Clinically relevant findings directly applicable to surgical practice.

LIMITATIONS

1. Moderate heterogeneity among included studies.
2. Variation in anatomical classification systems.
3. Predominance of observational studies.
4. Limited availability of randomized evidence.
5. Potential publication bias.
6. Differences in imaging and surgical methodologies.
7. Variable reporting of operative outcomes.
8. Some studies had relatively small sample sizes.
9. Geographic representation was uneven across regions.
10. Lack of long-term postoperative outcome data.

FUTURERESEARCH RECOMMENDATIONS

Future research should focus on developing standardized classification systems for cystic artery variations to improve consistency across anatomical and clinical studies. Large multicenter prospective investigations involving diverse populations are needed to provide more precise estimates of variation prevalence and clinical significance. Advanced imaging modalities such as multidetector CT angiography, magnetic resonance angiography, and fluorescence-guided imaging should be further evaluated for their ability to identify vascular anomalies preoperatively. Future studies should also examine the relationship between specific arterial variants and particular surgical complications, including bile duct injury, hemorrhage, and conversion to open surgery. Comparative studies assessing outcomes among surgeons with different levels of experience may provide insight into the influence of anatomical knowledge on operative success. Artificial intelligence-assisted imaging analysis may offer novel opportunities for automated identification of vascular variations before surgery. Additionally, international consensus guidelines regarding the reporting of cystic artery anatomy would facilitate future meta-analyses and evidence synthesis. Longitudinal studies investigating the impact of anatomical variations on postoperative outcomes and healthcare costs would further enhance understanding of their clinical significance. Collectively, these research efforts could contribute to safer surgical practice and improved patient outcomes.

CONCLUSION

This systematic review and meta-analysis provide comprehensive evidence regarding the prevalence and surgical significance of anatomical variations of the cystic artery. Analysis of fifteen studies demonstrated that approximately one-quarter of individuals exhibit variations in cystic artery anatomy, emphasizing that the classical anatomical pattern cannot be assumed during laparoscopic cholecystectomy. The pooled prevalence of cystic artery variations was 24.6%, indicating that such variations are common across diverse populations and clinical settings.

The review further demonstrated that variant cystic artery anatomy is associated with increased operative difficulty, greater risk of intraoperative bleeding, prolonged surgical duration, and an increased likelihood of conversion to open surgery. These findings highlight the critical importance of detailed anatomical knowledge during dissection of Calot’s triangle. Recognition of accessory, aberrant, short, or multiple cystic arteries is essential for preventing vascular injury and maintaining a clear operative field. The consistency of findings across cadaveric, radiological, and clinical studies reinforces the reliability of these conclusions.

Although moderate heterogeneity was observed among studies, the overall evidence strongly supports the clinical relevance of cystic artery variations. Differences in ethnicity, anatomical classification systems, and study methodologies likely contributed to the observed heterogeneity. Nevertheless, the direction of effect remained consistent across most studies, suggesting a genuine association between vascular variation and operative challenges.

The findings underscore the importance of incorporating detailed hepatobiliary vascular anatomy into surgical education and training programs. Preoperative imaging techniques may provide additional benefit in selected patients with suspected complex anatomy. Surgeons should maintain a high index of suspicion for anatomical variation and adhere strictly to principles such as the critical view of safety during laparoscopic cholecystectomy.

In conclusion, anatomical variations of the cystic artery are common and clinically significant. Improved awareness, careful operative technique, and continued research into vascular anatomy have the potential to reduce complications, enhance surgical outcomes, and improve patient safety in laparoscopic cholecystectomy.

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