

Research Article

Single-incision Laparoscopic Cholecystectomy: Technical Challenges, Clinical Breakthroughs, and a New Chapter for the Future

Zhui Ke, Peng Ji, Huanwen Li, Yi Chen, Fang Wang, Guobao Yang*

Department of Critical Care Medicine, Xiangshui County People's Hospital, Yancheng, China

Abstract

Single-incision laparoscopic cholecystectomy (SILC) represents a significant direction in the evolution of minimally invasive surgery. Performed through a single umbilical incision, SILC offers the distinct advantage of achieving a "scarless" abdominal wall and significantly improving patient cosmetic satisfaction. However, this technique faces considerable technical challenges, including the "chopstick effect" inherent to coaxial instrument manipulation, limited visual field, and a steep learning curve. These factors may contribute to an elevated risk of complications such as bile duct injury and incisional hernia. Currently, SILC is primarily indicated for carefully selected patients with low-to-moderate surgical complexity benign gallbladder diseases. While it achieves comparable major clinical outcomes to conventional laparoscopic cholecystectomy (LC), debates persist regarding its operative duration, postoperative pain profiles, and health economic implications. To address these technical bottlenecks, innovative modifications such as suspension exposure techniques, magnetic anchor technology, and robotic single-port platforms continue to emerge. This review contends that SILC serves not as a replacement for conventional LC, but as a valuable complement, specifically designed to meet the higher demands for aesthetics and minimal invasiveness in particular patient populations. Future advancement of SILC urgently requires robust high-quality evidence, establishment of standardized training protocols, and systematic progress in instrument innovation and healthcare reimbursement policies. Such developments are essential to steer SILC towards a more precise and personalized surgical paradigm.

Keywords

Single-incision Laparoscopic Cholecystectomy, Cholecystectomy, Minimally Invasive Surgery, Learning Curve

1. Introduction

The evolution of surgical procedures has consistently centered on the dual objectives of minimizing trauma and maximizing patient benefits. In this continuum, laparoscopic cholecystectomy (LC) stands as a pivotal milestone, having unequivocally replaced open surgery as the gold standard for treating benign gallbladder diseases due to its pronounced

minimally invasive advantages [1]. However, the pursuit of refinement in minimally invasive techniques has continued unabated. Following the widespread adoption and maturation of LC, the surgical community has turned its attention to a more profound exploration of the "minimally invasive" concept: whether it is possible to further reduce abdominal wall

*Corresponding author: ygb19970712@sina.com (Guobao Yang)

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trauma, conceal surgical scars, and optimize the patient experience without compromising safety and efficacy. It is within this context that single-incision laparoscopic cholecystectomy (SILC) has emerged. By consolidating the multiple ports of traditional LC into a single umbilical incision, SILC represents a conceptual leap towards the ideal of "scarless" surgery in the field of minimally invasive surgery [2].

The development of SILC commenced with the pioneering report by Navarra et al. in 1997 [3], and since then, it has captured global surgical attention due to its revolutionary cosmetic outcomes. The umbilicus, a natural scar fold of the human body, serves as an ideal portal to the abdominal cavity, enabling the abdominal wall to recover to a nearly scar-free state postoperatively. This significantly addresses the strong demand for physical aesthetics and psychosocial well-being among patients, particularly young women and individuals in specific occupations. However, alongside this remarkable advantage, persistent debates surround its clinical value and safety profile. On one hand, multiple studies have confirmed that SILC yields significantly superior cosmetic scores and patient satisfaction compared to conventional LC [4, 5]. On the other hand, substantial evidence highlights that due to inherent technical limitations—such as the "chopstick effect" arising from instruments and the laparoscope sharing a single entry channel, challenges in surgical field exposure, and the lack of triangulation—SILC is confronted with considerable challenges, including substantially increased technical difficulty, a steep learning curve, and potentially elevated risks of specific complications such as bile duct injury and incisional hernia [6-8]. This coexistence of distinct advantages and notable risks constitutes the fundamental and core academic tension within the field of SILC.

To standardize the healthy development of this technique and guide clinical practice toward maximizing benefits and minimizing risks, China released the "Chinese Expert Consensus on Single-incision Laparoscopic Cholecystectomy" in 2024 [9], which provides authoritative guidance for appropriate case selection, standardized procedures, and complication prevention in SILC. At this critical transitional phase, this review aims to conduct a systematic review and critical appraisal of SILC based on the latest global research advancements. Moving beyond mere procedural descriptions of "how to perform" the technique, this article delves into the inherent logic and challenges of its technical framework, objectively evaluates the efficacy and limitations of its clinical application, and prospectively explores potential future developmental pathways. Thereby, it seeks to provide a solid academic foundation for the precise positioning and rational adoption of SILC within the field of minimally invasive surgery.

2. Overview of SILC Technical System: From Concept to Practice

Single-incision laparoscopic cholecystectomy (SILC) represents an evolution in minimally invasive surgery from "reduced trauma" toward "ultimate minimally invasive and cosmetic outcomes." Its core technical principle involves consolidating all procedural steps—including visualization, retraction, and dissection—traditionally performed in multi-port laparoscopic cholecystectomy (LC) through a single umbilical access point [10]. This approach not only poses technical challenges for surgeons but also fundamentally reconfigures the spatial arrangement and operational logic of conventional laparoscopic surgery.

2.1. Core Operational Platforms and Access Strategies

The successful implementation of SILC begins with establishing a stable and efficient single-access approach. With the patient in the supine position, a 2.5–3.0 cm curvilinear or vertical incision is typically made along the superior or inferior edge of the umbilicus to leverage its natural folds for optimal scar concealment and cosmetic outcomes. Following pneumoperitoneum establishment, the surgical access methods are primarily categorized into two types:

The first involves integrated multi-channel single-port access systems, which are specialized devices for SILC such as the SILS™ Port and TriPort® [11-13]. These platforms often utilize flexible materials and integrate multiple instrument channels along with an insufflation port into a single unit, facilitating the formation of a relatively stable operative triangle for coordinated instrument use. However, the mobility of instruments remains constrained by the physical boundaries of the device itself.

The second approach employs a multiple-trocar array configuration, representing a more flexible, self-assembled platform strategy. In this method, three conventional trocars [14] (typically two 5 mm and one 10–12 mm trocar) are positioned adjacent to each other within the same incision to create operational channels. While this configuration offers advantages such as lower cost and adaptability to surgeon preference regarding trocar types and arrangement, its drawback lies in the proximity of the trocars. This close arrangement often leads to crowding and interference between instruments—commonly referred to as "instrument clashing"—which can significantly compromise procedural fluency [15].

2.2. Inherent Technical Challenges and Physical Limitations

The coaxial operating paradigm of SILC fundamentally deviates from the "triangulation principle" of conventional laparoscopy, giving rise to a series of inherent technical

challenges rooted in the physical convergence of operational channels [16]. The primary challenge manifests as instrument interference and the "chopstick effect": when all instruments and the laparoscope share a single or closely adjacent entry tract, their external handles inevitably collide (external interference), crowd at the abdominal wall entry point (entry-level interference), and move in parallel within the abdominal cavity due to insufficient angulation (internal interference). This phenomenon, collectively termed the "chopstick effect," significantly diminishes instrument tactile feedback and exponentially increases the difficulty of precise dissection and suturing [17].

Secondly, this approach presents substantial challenges in surgical field exposure and visuomotor coordination. In traditional LC, the laparoscope and operating instruments approach the target area from different angles, creating a stereoscopic "panoramic view" [18]. In contrast, SILC produces a narrow "tunnel vision" due to the near-parallel alignment of the scope and instruments, severely compromising depth perception and three-dimensional awareness. This not only complicates the anatomical exposure of Calot's triangle but also disrupts the surgeon's visuomotor coordination—the natural alignment between hand movement direction and instrument movement on the screen. Surgeons must exert considerable cognitive effort to compensate for this discrepancy, substantially increasing mental workload and operative fatigue [19, 20].

Furthermore, the physical constraints and ergonomic trade-offs of the limited operating space cannot be overlooked. To accomplish tissue dissection within this confined environment, surgeons frequently employ unconventional crossed-hand instrument manipulation (cross-hand technique). While this can somewhat improve instrument tip angulation, it does so at the expense of intuitive operation and ergonomic positioning, thereby further compounding the technical difficulty [20, 21].

2.3. Learning Curve and Skill Acquisition

The aforementioned technical challenges collectively contribute to the characteristically steep and prolonged learning curve associated with SILC. According to the Chinese Expert Consensus on Single-incision Laparoscopic Cholecystectomy (2024 Edition) [9], surgeons typically require approximately 20 to 50 procedures to overcome the initial learning phase and reach a plateau of proficiency where complication rates stabilize. This developmental trajectory can be delineated into three sequential stages: the cognitive adaptation phase, the technical integration phase, and the mastery phase. The initial cognitive adaptation phase is primarily focused on overcoming visuomotor discoordination, acclimating to the "tunnel vision," and establishing fundamental skills such as single-handed traction and counter-intuitive manipulation. This progresses to the technical integration phase, where surgeons begin to proficiently utilize techniques like the crossed-hand

maneuver and learn to leverage the instrument shafts for indirect exposure, leading to stabilized operative times. Finally, the mastery phase is characterized by the ability to proactively manage diverse anatomical variations and exercise sound clinical judgment to either safely complete the procedure or decisively convert to an alternative approach in complex situations [22, 23].

2.4. Current Status of Technical Modifications

In response to these persistent challenges, technical innovations are advancing along multiple fronts. Beyond the suspension techniques, specialized instruments, and robotic platforms mentioned in the original text, the underlying rationale of these modifications consistently aims to overcome the physical constraints inherent to coaxial operation. For instance, robotic single-port platforms (e.g., the da Vinci SP) utilize their multi-articulated instruments to reconstruct dexterous "wrist-like" maneuvers intra-corporeally. This fundamentally circumvents the "chopstick effect" and represents a significant direction for future development in this field [24-26].

3. Clinical Application and Comprehensive Evaluation of SILC

The transition of single-incision laparoscopic cholecystectomy (SILC) from a technical concept to routine clinical practice has been accompanied by rigorous evaluation of its benefits and risks. This section conducts a comprehensive "clinical audit" of SILC across multiple dimensions, including patient selection, clinical outcomes, complications, and economic considerations.

3.1. Precise Delineation of Indications and Contraindications: From "What Can Be Done" to "What Should Be Done"

While the indications for SILC broadly overlap with those of conventional LC [27], encompassing most benign gallbladder diseases such as symptomatic cholelithiasis, gallbladder polyps, and chronic cholecystitis, its technical limitations necessitate careful patient stratification and selection in clinical practice. Specifically, ideal candidates include: patients with Tokyo Guidelines 2018(TG18) Grade I or II acute cholecystitis with good overall health status [(American Society of Anesthesiologists (ASA) classification ≤ 2 , Charlson Comorbidity Index (CCI) ≤ 5], controlled inflammatory response (white blood cell count $<18 \times 10^9/L$), and symptom duration <72 hours; those with chronic cholecystitis or gallstones demonstrating clear Calot's triangle anatomy on imaging, gallbladder wall thickness $<4\text{mm}$ on ultrasonography, absence of gallbladder atrophy, and no extensive pericholecystic adhesions; and patients with benign gallbladder

polyps >1cm in diameter or those requiring prophylactic resection due to malignant potential. Additionally, the technique is particularly suitable for patients with strong cosmetic concerns who understand the procedure's potential risks and limitations, such as young women. In the exploratory domain, carefully selected intermediate-difficulty cases (e.g., filtered Grade II or III acute cholecystitis with $\text{CCI} \leq 3$ and $\text{ASA} \leq 2$) may be considered for SILC when performed by experienced senior surgical teams with thorough preoperative assessment and preparedness for conversion, representing a safe expansion of technical boundaries [28]. Regarding contraindications, SILC maintains clear demarcations. Absolute contraindications represent non-negotiable boundaries, including suspected or confirmed gallbladder malignancy, preoperative or intraoperative suspicion of common bile duct stones requiring exploration, severe cardiopulmonary insufficiency or other systemic conditions precluding pneumoperitoneum tolerance, and cirrhosis with portal hypertension (due to increased bleeding risk and restricted operating space). Relative contraindications signal substantially elevated conversion risk and demand heightened surgical vigilance, primarily including acute suppurative or gangrenous cholecystitis, Mirizzi syndrome, "frozen" dense pericholecystic adhesions from chronic inflammation, and patients with severe obesity [(Body Mass Index (BMI) >35 kg/m²)] or markedly enlarged gallbladders, as abdominal wall thickness and liver position further compromise the already constrained operating space [9, 29, 30]. Dynamic risk assessment forms the cornerstone of clinical decision-making. For teams initiating SILC programs, adherence to ideal indications remains fundamental to ensuring patient safety and building technical confidence.

3.2. Comprehensive Evaluation of Clinical Outcomes: Balancing Advantages, Challenges, and Controversies

The assessment of SILC's clinical value presents a multi-dimensional challenge characterized by coexisting advantages and limitations, with ongoing debates in several areas. The most well-established advantage of SILC lies in its superior cosmetic outcomes. By concealing the incision within the umbilicus, SILC achieves a virtually scarless abdominal wall. Multiple randomized controlled trials and patient-reported outcome measures (PROMs) studies have consistently demonstrated significantly better cosmetic satisfaction and overall surgical experience with SILC compared to conventional LC [31]. Additionally, a single incision theoretically reduces the risk of puncture injury, bleeding, and infection associated with multiple incisions. The relatively sparse innervation of the umbilical region (T10 dermatome) may contribute to reduced subjective pain perception in some patients during the early postoperative period [32].

However, these benefits must be weighed against objective challenges in efficiency and specific risks. The technical complexity of SILC directly translates to prolonged operative

time, with meta-analyses indicating an average increase of approximately 10 minutes compared to conventional LC [33]. More significantly, SILC demonstrates a distinct complication profile requiring careful consideration: the rate of bile duct injury (0.72%) approaches twice that of conventional LC (0.4%-0.5%) [34], while the larger umbilical incision serving as the main operating channel contributes to a substantially higher risk of incisional hernia (13.3% vs. 4.7%) [35].

Notable controversies persist regarding postoperative pain and recovery quality. Contrary to the theoretical pain advantage, high-quality systematic reviews have reported slightly higher pain scores at 24 hours postoperatively in SILC groups compared to multiport approaches, along with potentially increased wound infection rates and marginally extended hospital stays [36]. These findings suggest that the potential benefits of reduced invasiveness in SILC may be partially offset by greater tissue traction trauma inherent to its technical execution.

From a health economic perspective, SILC faces challenges in cost-value alignment. Within the diagnosis-related groups (DRGs) payment system, SILC typically falls within the same category as conventional LC, resulting in comparable total hospitalization costs and insurance reimbursements. However, the specialized commercial single-port access devices required for SILC increase direct surgical costs by approximately 455 RMB [37]. Although this cost increment is partially offset by reduced postoperative wound care expenses, creating no significant additional burden for patients or insurers, this "cost inversion" phenomenon highlights the dissemination challenge SILC faces within the current healthcare economic framework—where its technical added value fails to translate into reimbursement advantages [38].

3.3. Complication Analysis and Technical Modification Strategies: From Passive Response to Active Problem-solving

Confronted with the unique complication risks and technical bottlenecks of SILC, the surgical community's response strategy has evolved from initial cautious attempts to systematic, multi-faceted active technical innovation. Most SILC complications stem from its restricted visual field and unconventional operating angles, leading to difficulties in identifying and protecting key anatomical structures such as the cystic duct and common bile duct. Therefore, establishing a safety-oriented conversion culture is paramount. Whenever intraoperative situations arise involving unclear anatomy, difficult hemorrhage control, or extremely poor exposure, the threshold for intervention should be immediately lowered, decisively adding auxiliary ports or converting to open surgery. This represents not technical failure but the embodiment of professional judgment and the principle of prioritizing patient safety.

Technical modifications primarily advance along three directions. In the realm of visual field exposure techniques,

basic methods like "grasping and retracting" have evolved into more stable active suspension exposure systems. Techniques such as percutaneous fundal suture suspension, ligamentum teres hepatis suspension, and the emerging magnetic anchor technique [39] utilize external abdominal wall traction to continuously and stably rotate the gallbladder and liver toward the cephalad direction, significantly improving exposure of Calot's triangle, effectively creating an "invisible retractor" within the body.

Regarding specialized instruments and operational platforms, pre-bent instruments, flexible laparoscopes, and articulating surgical instruments have emerged to address the "chopstick effect." Further advancing this, integrated platforms like the SymphonX single-incision laparoscopic system facilitate non-interfering operation of multiple instruments through a 15mm single port, enhancing efficiency [40]. The current pinnacle of this technological evolution is embodied in robotic single-port platforms (e.g., da Vinci SP), whose internal wristed instruments achieve 540 degrees of articulation within the abdominal cavity, fundamentally overcoming the physical limitations of coaxial operation and representing a crucial future direction for SILC, despite high costs remaining a significant barrier to widespread adoption [41].

In terms of perioperative management refinement, targeted analgesic strategies such as continuous local anesthetic infiltration devices have been investigated to address the potentially more significant postoperative incision pain in SILC. These approaches have proven effective in reducing postoperative pain and accelerating patient recovery, demonstrating the specific application of Enhanced Recovery after Surgery (ERAS) principles in SILC practice [42].

4. Limitations and Future Perspectives

Despite its cosmetic appeal and potential benefits, single-incision laparoscopic cholecystectomy (SILC) carries inherent limitations that must be acknowledged. The technique remains constrained by the physical and ergonomic challenges of coaxial operation, contributing to a steep learning curve and a distinct complication profile, including elevated risks of bile duct injury and incisional hernia compared to conventional laparoscopic cholecystectomy (LC). Current evidence, while affirming its safety in selected populations, is often derived from heterogeneous studies with limited long-term follow-up, particularly regarding hernia rates and patient-reported quality of life years after surgery [43-45]. Furthermore, the lack of standardized training pathways and the higher procedural costs within current healthcare reimbursement frameworks pose significant barriers to its widespread and equitable adoption.

Future progress hinges on a multi-faceted strategy. There is an urgent need for high-quality, prospective, multi-center trials with extended follow-up to definitively establish the long-term safety, cost-effectiveness, and quality-of-life ben-

efits of SILC within enhanced recovery pathways. Simultaneously, the development of structured, simulation-based training curricula is essential to flatten the learning curve and ensure procedural standardization. Technological innovation must continue to focus on overcoming the "chopstick effect" through more intelligent and miniaturized instruments, cost-reduction in robotic single-port platforms, and the integration of augmented reality and 3D navigation. Finally, health policy should evolve to recognize the added technical value of SILC through thoughtful reimbursement adjustments, fostering a sustainable environment for its responsible advancement.

5. Conclusion

Single-incision laparoscopic cholecystectomy represents a significant refinement in minimally invasive surgery, successfully transitioning from a novel concept to a viable clinical option. It achieves comparable major clinical outcomes to conventional LC while offering superior cosmetic results, fulfilling a specific patient demand for "scarless" abdominal surgery. SILC does not replace multi-port LC as the gold standard but serves as an important complementary technique within the surgical arsenal for benign gallbladder disease. Its future as a mature and widely adopted procedure depends on converging advancements in robust clinical evidence, systematic training, and supportive techno-economic policies.

Abbreviations

ASA	American Society of Anesthesiologists
BMI	Body Mass Index
CCI	Charlson Comorbidity Index
DRG	Diagnosis-Related Group
ERAS	Enhanced Recovery After Surgery
LC	Laparoscopic Cholecystectomy
PROMs	Patient-Reported Outcome Measures
SILC	Single-incision Laparoscopic Cholecystectomy
TG18	Tokyo Guidelines 2018
VBP	Value-Based Payment

Author Contributions

Zhui Ke: Writing – original draft

Peng Ji: Project administration, Data curation

Huanwen Li: Project administration, Data curation

Yi Chen: Formal analysis, Investigation

Fang Wang: Methodology, Supervision

Guobao Yang: Writing – review & editing, Funding acquisition

Conflicts of Interest

All authors declare no conflicts of interest.

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