

Using Artificial Intelligence to Enable Safer Laparoscopic Cholecystectomy: A Step Toward a Standardized Critical View of Safety and Reduced Bile Duct Injuries

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Introduction

Laparoscopic cholecystectomy (LC) is among the most common surgical procedures employed worldwide. Bile duct injuries (BDIs) are among its most serious complications, with an incidence between 0.4% and 1.5% [1]. Most BDIs result from anatomical misidentification, particularly during dissection of the hepatocystic triangle. The Critical View of Safety (CVS) remains the gold standard for safe cholecystectomy, yet consistent and accurate identification in real time is still a challenge in daily surgical practice [2,3].

Artificial Intelligence (AI), particularly in the form of computer vision (CV) and deep learning (DL), is emerging as a promising tool for enhancing intraoperative decision-making. Several systems are now capable of identifying anatomical structures, classifying procedural steps, and highlighting safe and dangerous dissection zones [4–6]. These technologies are not designed to replace the surgeon but to assist in realizing the CVS and minimizing subjectivity, ultimately helping to improve safety and reduce the incidence of BDIs.

AI and CVS Recognition: Standardizing What We See

Real-time AI systems trained on thousands of annotated surgical videos can now detect critical anatomical structures with high accuracy. The cystic duct, the cystic artery, the common bile duct, Rouvière's sulcus, and the gallbladder infundibulum have been detected with a mean precision above 90% and F1/Dice scores above 0.75 [4,5,7].

Studies evaluating intraoperative use of AI tools have shown that AI-corrected annotations differ from surgeons' interpretations in approximately 25–30% of cases and that these corrections align better with CVS principles in most instances [8,9]. AI platforms can now assess whether the

three CVS criteria have been met and alert the surgeon accordingly. Some systems go a step further, defining “Go” vs. “No-Go” zones within the operative field, thereby enhancing real-time safety during dissection [10].

By introducing this layer of probabilistic safety, AI enables a standardized, reproducible evaluation of CVS that mitigates the cognitive variability seen among operators, especially under complex or inflammatory conditions [6].

Impacts on Patient Safety and Healthcare Costs

BDIs often require complex management: Endoscopic Retrograde Cholangiopancreatography (ERCP), reintervention, biliary reconstruction, or even liver transplantation. These outcomes not only harm patients but also result in significant healthcare expenditures and medico-legal consequences [1,11]. Even a modest reduction in BDIs incidence through AI-guided identification of CVS could yield measurable benefits in cost containment and surgical quality [12].

Moreover, AI-assisted workflows have demonstrated improved procedural efficiency. In some implementations, CVS adherence increased from approximately 40% to nearly 70% over time [5,13]. Enhanced accuracy in identifying anatomy could also reduce operative time, postoperative complications, and the need for conversion to open surgery.

AI in Surgical Education: Cognitive Augmentation for Trainees

Training surgeons in laparoscopic anatomy and safe techniques is a cornerstone of surgical education. AI systems capable of annotating anatomy and classifying operative phases in real-time offer an unparalleled opportunity to accelerate learning curves. Annotated videos allow residents to compare their performance against objective feedback, increasing awareness of dissection planes and anatomical landmarks [9,14].

Recent studies have shown that AI-supported tools help trainees perform at levels closer to those of experts when recognizing key anatomical landmarks during an LC. In terms of identifying safe dissection zones, metrics such as precision and recall significantly improve under the guid-

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ance of AI, underscoring its value in structured training [8]. Importantly, this educational function complements, rather than replaces, the mentorship provided by senior surgeons. It ensures consistency in how anatomical safety is taught and practiced.

Ethical Considerations and Surgical Responsibility

The deployment of AI in the operating room must be grounded in clear ethical principles. The surgeon remains the only agent responsible for intraoperative decisions and outcomes. AI can support clinical judgment, but it must never override it.

Informed consent must include disclosure of AI assistance, particularly in systems that provide visual prompts or real-time alerts. Legal and ethical frameworks will need to evolve alongside these technologies, especially concerning liability in the rare event that an AI-assisted suggestion contributes to harm [15].

Additionally, most current AI models are trained on datasets derived from specific populations or institutions, raising concerns about generalizability. Their performance may decrease when confronting complex anatomies, unexpected variations, or conditions such as severe inflammation. Therefore, ongoing validation and refinement are essential for broad clinical reliability [7,10].

Limitations and Future Perspectives

While early data are promising, several challenges remain before AI can be fully embedded in everyday surgical workflows:

- **Lack of prospective trials:** Most evidence is based on retrospective or simulated environments; few prospective clinical studies have evaluated BDIs incidence reduction.
- **Dataset bias:** Limited diversity in training data may cause current AI systems to underperform when dealing with patients with an abnormal anatomy or severe inflammation.
- **Integration challenges:** Real-time video processing must be fast, reliable, and seamlessly incorporated into the surgical workflow.
- **Cost and accessibility:** While cost savings from prevented complications are possible, the initial investment in AI infrastructure may be a barrier in resource-limited settings.

Future directions include multimodal AI systems that integrate intraoperative video with preoperative imaging (e.g., Computed Tomography and Magnetic Resonance Imaging) as well as the use of adjunct technologies like indocyanine green (ICG) fluorescence imaging. Additionally, AI-assisted platforms could evolve to provide personalized surgical roadmaps based on patient-specific risk profiles [13,14].

Conclusions

AI holds substantial promise for improving the safety, efficiency, and educational quality of laparoscopic cholecystectomy. By assisting in the identification of the Critical View of Safety, AI can act as a probabilistic defense against a bile duct injury, one of the most feared complications in general surgery.

The surgeon, however, must remain at the center of operative decision-making. AI is a tool that should be used for guidance, not replacement. The future of surgical safety lies not in automation but in intelligent collaboration between humans and machines. Embracing this partnership responsibly will allow us to raise the standard of care while preserving the irreplaceable role of surgical expertise.

Availability of Data and Materials

Not applicable.

Author Contributions

GQ conceived the editorial and drafted the initial manuscript. GB critically revised the content and contributed to the literature review. AF supervised the overall work. All authors contributed to the conception and have been involved in revising it critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

Not applicable.

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Conflict of Interest

Gennaro Quarto is serving as one of the Editorial Board members of this journal. We declare that Gennaro Quarto had no involvement in the peer review of this article and has no access to information regarding its peer review. Other authors declare no conflict of interest.

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