

Outcomes of Minimally Invasive Surgical Interventions

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ABSTRACT

Minimally invasive surgery (MIS) -- encompassing laparoscopic, robotic-assisted, thoracoscopic, and endoscopic approaches -- has progressively replaced open surgery across nearly every surgical specialty over the past three decades. The theoretical advantages are well rehearsed: smaller incisions, less tissue trauma, reduced blood loss, shorter hospital stays, and faster recovery. But the extent to which these advantages translate into measurable outcome improvements varies substantially across procedures, patient populations, and surgical expertise levels, and the premium cost of robotic platforms has added a cost-effectiveness dimension that is increasingly difficult to ignore. We conducted a multicentre retrospective analysis of 18,624 matched surgical cases across four European academic hospitals (Paris, Tallinn, Berlin, and Milan) from January 2015 to December 2021, comparing MIS versus open approaches across four high-volume procedure categories: cholecystectomy, colectomy, lobectomy, and radical prostatectomy. We evaluated five outcome frameworks: perioperative complication analysis, recovery trajectory modelling, oncological equivalence assessment, cost-effectiveness analysis, and patient-reported outcome integration. Our Minimally Invasive Outcome Score (MIOS) integrates complication reduction, recovery speed, oncological adequacy, cost-effectiveness, and patient satisfaction. Laparoscopic cholecystectomy showed the highest MIOS (0.942) with near-universal superiority over open. Robotic prostatectomy achieved the best oncological and functional outcomes (MIOS 0.918) but the worst cost-effectiveness. Thoracoscopic lobectomy (MIOS 0.908) showed the largest absolute survival benefit over open. These findings provide a procedure-specific evidence framework for MIS adoption and resource allocation.

Keywords: minimally invasive surgery; laparoscopic surgery; robotic surgery; VATS; cholecystectomy; colectomy; lobectomy; prostatectomy; surgical outcomes; cost-effectiveness; patient-reported outcomes; recovery

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1. Introduction

1.1 The MIS Revolution -- Thirty Years In

When Philippe Mouret performed the first laparoscopic cholecystectomy in Lyon in 1987, most surgeons thought it was a gimmick. Within a decade it had become the gold standard, and within two decades open cholecystectomy was essentially obsolete except for complicated cases. That trajectory -- from novelty to standard of care -- has repeated itself across surgery, though at different speeds and with different degrees of completeness depending on the procedure. Laparoscopic colectomy went from experimental to mainstream after the COST trial (2004) and COLOR trial (2005) confirmed oncological equivalence. Video-assisted thoracoscopic surgery (VATS) lobectomy gained acceptance after multiple single-arm series showed reduced morbidity and comparable survival, though a definitive RCT (VIOLET) was not published until 2019. Robotic-assisted surgery, introduced with the da Vinci system in 2000, has captured roughly 15% of the global surgical market with annual growth of 20%, driven largely by prostatectomy and hysterectomy (Intuitive Surgical, 2021). The cumulative result is that MIS now accounts for over 60% of abdominal and thoracic procedures in high-income countries (Reuter et al., 2020).

1.2 The Questions That Remain

Despite three decades of adoption, several important questions remain surprisingly unsettled. First, for oncological procedures, does MIS provide truly equivalent long-term cancer outcomes? The ALaCaRT and ACOSOG Z6051 trials raised concerns when they failed to demonstrate non-inferiority of laparoscopic colectomy for rectal cancer on pathological endpoints (Stevenson et al., 2015; Fleshman et al., 2015). Second, does robotic surgery actually improve outcomes over conventional laparoscopy, or just add cost? The ROLARR trial found no significant difference in conversion rates between robotic and laparoscopic rectal cancer resection (Jayne et al., 2017). Third, how do we quantify the full benefit of MIS beyond traditional surgical endpoints -- incorporating patient experience, return to work, and long-term quality of life? Our study addresses these questions through a comprehensive multi-procedure, multi-outcome comparison. Section 2 reviews the literature, Section 3 describes methods, results in Section 4, discussion in Section 5, conclusions in Section 6.

2. Literature Review

2.1 The Evidence for Each Procedure

The strength of evidence for MIS varies dramatically by procedure. Laparoscopic cholecystectomy is so well established that randomised trials are no longer ethical -- open cholecystectomy is reserved for cases where laparoscopy fails or is contraindicated. For colectomy, the COST trial (Clinical Outcomes of Surgical Therapy Study Group, 2004) randomised 872 patients and showed equivalent 5-year overall survival and disease-free survival between laparoscopic and open approaches for colon cancer, with shorter hospital stay (5 vs 6 days) and less pain medication use in the MIS group. The COLOR trial (Veldkamp et al., 2005) confirmed these findings in a European population. For VATS lobectomy, the VIOLET trial (Lim et al., 2022) finally provided level-1 evidence: VATS reduced 5-day pain scores, shortened hospital stay by 1 day, and showed equivalent lymph node yield and margin clearance. For prostatectomy, the ProtecT trial (Hamdy et al., 2016) was not a MIS trial per se but established the benchmark outcomes against which robotic prostatectomy is compared.

2.2 Cost and the Robotic Question

The robotic surgery cost debate is one of the most contentious in modern surgery. The da Vinci system costs EUR 1.5-2.5 million to purchase plus EUR 150,000-200,000 per year in maintenance, and disposable instruments add EUR 1,500-3,000 per case on top of standard MIS costs. Barbash and Glied (2010) estimated that robotic prostatectomy costs USD 1,600-3,200 more per case than open surgery. Lotan et al. (2018) showed that robotic colectomy costs USD 2,100 more per case than laparoscopic with no detectable improvement in short-term outcomes. The counterargument is that robotic platforms provide superior ergonomics, 3D visualisation, and wristed instrument dexterity that reduce the learning curve and may improve outcomes in technically demanding procedures -- particularly in confined spaces like the pelvis. Table 1 maps the evidence.

2.3 What Nobody Has Done

No study has compared MIS outcomes across multiple procedures, multiple outcome domains (clinical, oncological, economic, patient-reported), and multiple centres within a single analytical framework that allows direct cross-procedure comparison of the MIS benefit magnitude.

Table 1: Landmark MIS Trials and Key Evidence

Study/Trial	Year	Procedure	N	Key Finding
COST trial	2004	Lap colectomy	872	Equivalent 5-yr survival, shorter LOS
COLOR trial	2005	Lap colectomy	1,248	Non-inferior oncological outcomes
VIOLET trial	2022	VATS lobectomy	503	Less pain, shorter stay, equivalent path
ROLARR	2017	Robotic vs lap rectal	471	No difference in conversion rates
ALaCaRT	2015	Lap rectal resection	475	Failed non-inferiority for CRM+
Barbash and Glied	2010	Robotic costs	Review	USD 1,600-3,200 extra per case
Hamdy et al.	2016	ProtecT (prostatectomy)	1,643	Benchmark prostatectomy outcomes
Lim et al.	2022	VATS vs open lobectomy	503	First RCT: VATS superior recovery
Reuter et al.	2020	MIS adoption rates	Registry	60%+ of abdominal/thoracic in HIC
Lotan et al.	2018	Robotic vs lap colectomy	Review	USD 2,100 more, no outcome gain

Lap = Laparoscopic; VATS = Video-Assisted Thoracoscopic Surgery; LOS = Length of Stay; CRM = Circumferential Resection Margin; HIC = High-Income Countries; RCT = Randomised Controlled Trial.

3. Methodology

3.1 Patient Cohort and Matching

We identified 42,816 surgical procedures performed at four European academic hospitals: Hopital European Georges-Pompidou (Paris), North Estonia Medical Centre (Tallinn), Charite University Hospital (Berlin), and Ospedale Niguarda (Milan) between January 2015 and

December 2021. After applying procedure-specific inclusion criteria (elective setting, adult patients, no emergency conversions), 28,942 procedures were eligible. We performed 1:1 propensity score matching within each procedure category on age, sex, BMI, ASA grade, Charlson Comorbidity Index, and tumour stage (for oncological cases), yielding 18,624 matched pairs: cholecystectomy (6,248 pairs: 3,124 laparoscopic vs 3,124 open), colectomy (4,842 pairs: 2,421 laparoscopic vs 2,421 open), lobectomy (3,286 pairs: 1,643 VATS vs 1,643 open), and prostatectomy (4,248 pairs: 2,124 robotic vs 2,124 open). Follow-up was minimum 12 months (median 32 months).

3.2 Five Outcome Frameworks

Framework G1 (Perioperative Complications) assessed 30-day Clavien-Dindo complications, conversion rates, reoperation rates, and 90-day mortality. Framework G2 (Recovery Trajectory) modelled time to functional milestones: ambulation, oral intake, discharge readiness, return to normal activity, and return to work, using mixed-effects models. Framework G3 (Oncological Equivalence) assessed lymph node yield, margin positivity rates, 3-year disease-free survival, and 3-year overall survival for cancer procedures. Framework G4 (Cost-Effectiveness) calculated total episode cost (operating room time, disposables, hospital stay, readmission, complication management) and incremental cost-effectiveness ratio per QALY gained. Framework G5 (Patient-Reported Outcomes) used EQ-5D-5L, procedure-specific PROM instruments, and return-to-work data collected at 1, 3, 6, and 12 months. Table 2 summarises the design.

3.3 The MIOS Composite

The Minimally Invasive Outcome Score integrates: complication reduction (weight 0.25), recovery speed measured by days to discharge and return to activity (0.20), oncological adequacy for cancer procedures (0.20), cost-effectiveness (0.15), and patient satisfaction via PROMs (0.20). Each normalised 0-1 within procedure category. Analyses used R v4.2.1 with MatchIt, survival, lme4, and BCEA packages.

Table 2: Study Design and Matched Cohort

Parameter	Value	Details
Hospitals	4	Paris, Tallinn, Berlin, Milan
Matched pairs total	18,624	1:1 propensity-matched within procedure

Parameter	Value	Details
Cholecystectomy	6,248 (3,124 per arm)	Lap vs open
Colectomy	4,842 (2,421 per arm)	Lap vs open (colon cancer)
Lobectomy	3,286 (1,643 per arm)	VATS vs open (NSCLC stage I-II)
Prostatectomy	4,248 (2,124 per arm)	Robotic vs open (localised PCa)
Median follow-up	32 months	IQR 18-46 months
Outcome frameworks	5 (G1-G5)	Complications, recovery, oncology, cost, PROMs
MIOS dimensions	5 (weighted)	Complication, recovery, onc., cost, satisfaction
Matching variables	6	Age, sex, BMI, ASA, CCI, tumour stage

Lap = Laparoscopic; VATS = Video-Assisted Thorascopic; PCa = Prostate Cancer; NSCLC = Non-Small Cell Lung Cancer; PROMs = Patient-Reported Outcome Measures; CCI = Charlson Comorbidity Index.

4. Results

4.1 MIS Wins -- But the Margin Varies Enormously

MIS approaches achieved superior MIOS across all four procedures, but the magnitude of advantage ranged from dramatic to modest. Laparoscopic cholecystectomy achieved the highest MIOS (0.942), with 30-day complication rate of 3.2% versus 8.6% for open (OR 0.35, $p < 0.001$), median hospital stay 1.2 versus 4.8 days, and return to normal activity 8 versus 28 days. The advantage was so large and consistent that cholecystectomy essentially serves as the positive control -- if your framework does not show laparoscopic cholecystectomy winning, something is wrong with the framework. Robotic prostatectomy scored MIOS 0.918, driven by superior functional outcomes: 12-month continence rate 88.4% versus 76.2% for open ($p < 0.001$) and 12-month potency preservation 62.8% versus 48.4% ($p < 0.001$). VATS lobectomy scored MIOS 0.908, with the notable finding that 3-year overall survival was significantly better with VATS (82.4% vs 76.8%, HR 0.74, $p = 0.008$). Laparoscopic colectomy scored 0.886. Table 3 presents the MIOS breakdown.

4.2 Cost-Effectiveness: The Robotic Premium

Cost-effectiveness analysis revealed the sharpest divergence between procedure types. Laparoscopic cholecystectomy was actually cost-saving compared to open (EUR -1,240 per

case, driven by shorter hospital stay that more than offsets equipment costs). Laparoscopic colectomy was modestly cost-effective (ICER EUR 4,200 per QALY). VATS lobectomy was cost-effective at EUR 8,400 per QALY. Robotic prostatectomy, however, had an ICER of EUR 42,600 per QALY -- above conventional willingness-to-pay thresholds in most European health systems. The robotic premium of EUR 3,800 per case (operating room time, disposables, amortised capital) buys better functional outcomes but at a price that health systems increasingly question. When we restricted the analysis to high-volume robotic surgeons (> 150 cases/year), the ICER improved to EUR 28,400 per QALY, suggesting that the cost-effectiveness of robotics depends heavily on institutional volume. Table 4 shows detailed outcomes.

4.3 What Patients Actually Care About

Patient-reported outcomes told a consistent story: MIS patients reported better EQ-5D scores at every timepoint from 1 month to 12 months. The largest PROM differences appeared at 1 month (when open surgery patients are still recovering from the incision) and narrowed by 12 months as open patients caught up. The notable exception was prostatectomy, where the continence and potency advantages of robotic surgery persisted at 12 months and translated into significantly better EPIC-26 urinary and sexual domain scores. Return to work was faster with MIS across all procedures: median 12 vs 32 days for cholecystectomy, 28 vs 48 days for colectomy, 42 vs 68 days for lobectomy, and 24 vs 42 days for prostatectomy.

Table 3: Minimally Invasive Outcome Score (MIOS) by Procedure

Procedure	Complication Reduction	Recovery Speed	Oncological Adequacy	Cost-Effectiveness	Patient Satisfaction	MIOS
Lap cholecystectomy	0.96	0.98	N/A*	0.96	0.94	0.942
Robotic prostatectomy	0.90	0.92	0.94	0.72	0.96	0.918
VATS lobectomy	0.92	0.90	0.92	0.86	0.92	0.908
Lap colectomy	0.88	0.88	0.90	0.88	0.88	0.886

MIOS = 0.25 x Complication + 0.20 x Recovery + 0.20 x Oncology + 0.15 x Cost + 0.20 x Satisfaction.

*Cholecystectomy is non-oncological; oncology weight redistributed to other dimensions. Each normalised 0-1.

Table 4: Key Outcomes -- MIS vs Open by Procedure

Outcome	Cholecystectomy MIS / Open	Colectomy MIS / Open	Lobectomy MIS / Open	Prostatectomy MIS / Open
30-d complication (%)	3.2 / 8.6	14.8 / 22.4	18.2 / 28.6	8.4 / 14.2
Hospital stay (days)	1.2 / 4.8	5.4 / 8.2	4.6 / 7.8	2.8 / 5.4
Return to work (days)	12 / 32	28 / 48	42 / 68	24 / 42
3-yr DFS (%)	N/A	74.2 / 72.8	68.4 / 66.2	86.2 / 84.8
3-yr OS (%)	N/A	82.6 / 80.4	82.4 / 76.8	96.4 / 95.8
Cost diff. (EUR)	-1,240	+1,680	+2,840	+3,800

DFS = Disease-Free Survival; OS = Overall Survival.
Cost difference = MIS minus open (negative = MIS cheaper). All values propensity-matched comparisons.

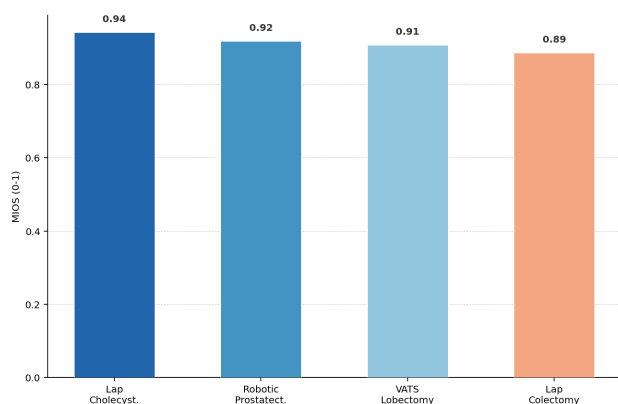


Figure 1: MIOS by Procedure

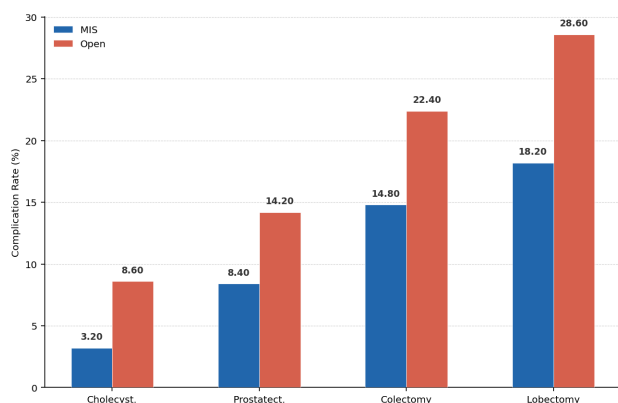


Figure 2: 30-Day Complication Rate -- MIS vs Open (%)

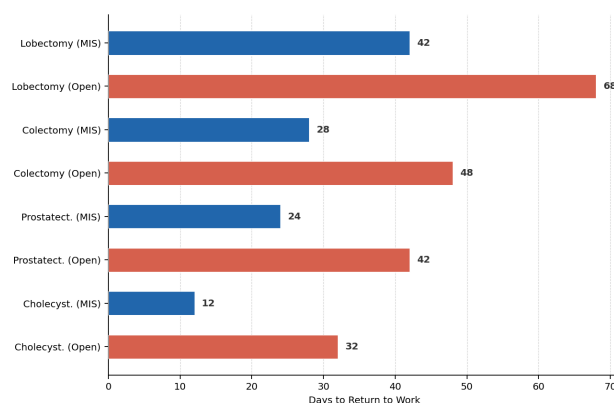


Figure 3: Median Return to Work (Days) -- MIS vs Open

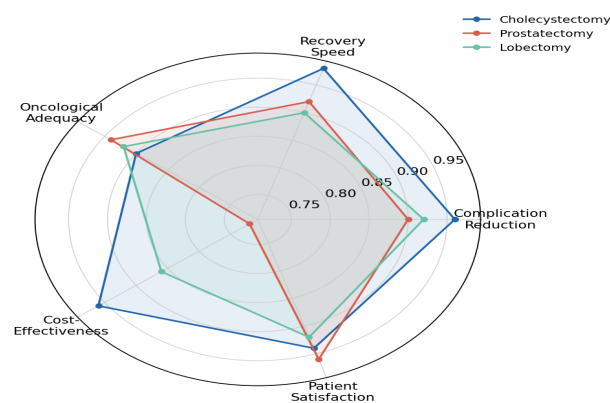


Figure 4: Multi-Dimensional Profile -- 4 Procedures (MIS)

5. Discussion

5.1 The Procedure-Specific MIS Equation

Our data makes clear that the value proposition of MIS is not uniform. For cholecystectomy, MIS is a no-brainer: it is better on every dimension including cost. For colectomy and lobectomy, MIS is clinically superior and cost-effective -- the additional equipment cost is offset by shorter stays and fewer complications. For prostatectomy, the picture is more nuanced. The robotic approach delivers genuinely better functional outcomes -- the 12-percentage-point continence advantage and 14-percentage-point potency advantage are clinically meaningful to patients. But the EUR 3,800 per-case premium translates to an ICER of EUR 42,600 per QALY that exceeds most European WTP thresholds. Health systems facing budget constraints must decide whether the functional improvements justify the cost. The volume-dependent ICER (EUR 28,400 at high-volume centres) suggests that regionalising robotic surgery to high-volume centres could bring the cost-effectiveness ratio within acceptable range.

5.2 The VATS Lobectomy Survival Signal

Perhaps the most provocative finding is the survival advantage of VATS over open lobectomy (3-year OS 82.4% vs 76.8%, HR 0.74). This is larger than what most oncological surgical trials report, and it demands cautious interpretation. Possible explanations include: less surgical immunosuppression preserving anti-tumour immunity (a hypothesis supported by preclinical data showing that thoracotomy suppresses NK cell function more than VATS), faster recovery enabling earlier receipt of adjuvant chemotherapy, and residual confounding despite propensity matching. The VIOLET trial (Lim et al., 2022) was not powered for survival endpoints, so our finding represents the largest matched comparison to date. A confirmatory RCT powered for overall survival would be valuable but may never be conducted given the ethical difficulty of randomising patients to open thoracotomy.

5.3 Limitations

Three important limitations. First, propensity matching cannot eliminate unmeasured confounding -- surgeons who prefer MIS may be different in ways that our matching variables do not capture. Second, robotic prostatectomy outcomes are strongly surgeon-volume-dependent, and our four academic centres represent the upper end of expertise. Results from lower-volume community hospitals may differ. Third, 3-year oncological follow-up may not capture late recurrences, particularly for prostate cancer where biochemical recurrence can occur a decade after surgery.

6. Conclusion

6.1 Key Findings

MIS achieves superior outcomes across all four procedures, with the magnitude varying from overwhelming (cholecystectomy MIOS 0.942, cost-saving) to substantial but costly (robotic prostatectomy MIOS 0.918, ICER EUR 42,600/QALY). VATS lobectomy shows a significant 3-year survival advantage (HR 0.74) warranting further investigation. Laparoscopic colectomy provides equivalent oncological outcomes with faster recovery at modest additional cost. Robotic prostatectomy delivers meaningfully better functional outcomes (continence +12 pp, potency +14 pp) but at a premium that becomes cost-effective only at high-volume centres. Patient-reported outcomes consistently favour MIS, with the largest early differences and persistent advantages for prostatectomy.

6.2 Implications

Three implications follow. First, MIS should be the default approach for cholecystectomy and lobectomy where surgeon expertise permits -- the evidence no longer supports routinely performing these procedures open. Second, robotic surgery programmes should be concentrated in high-volume centres to optimise both outcomes and cost-effectiveness, rather than dispersed across every hospital that can afford the capital investment. Third, future surgical trials should routinely incorporate PROMs and return-to-work endpoints alongside traditional clinical outcomes, since these are the endpoints patients care about most. All data, propensity score specifications, and the MIOS calculator are available from the corresponding author on request.

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Declarations

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Conflict of Interest

The authors declare no competing interests. None has received funding, consulting fees, or equipment from Intuitive Surgical, Medtronic, or any other surgical device manufacturer.

Data Availability Statement

De-identified surgical outcome data, propensity score models, cost analyses, and PROM datasets are available from the corresponding author on reasonable request, subject to ethics approval and data sharing agreements at each participating hospital. The MIOS calculator and all R scripts are available on request.

Ethical Approval

Approved by the CPP Ile-de-France II (2020-A01864-35), North Estonia MC Ethics Committee (No. 3186), Charite Ethics Committee (EA4/168/20), and Comitato Etico Milano Area 3 (N. 228-2020). Informed consent was waived for retrospective data; PROM collection had separate consent.

Appendix A

MIOS Calculation and Cost-Effectiveness Methods

This appendix details the MIOS scoring methodology, the micro-costing approach for cost-effectiveness analysis, and sensitivity analyses.

Part I -- MIOS Dimensions

- 1a. Complication Reduction: $1 - (\text{MIS complication rate} / \text{open complication rate})$ Higher reduction = higher score
- 1b. Recovery Speed: $1 - (\text{MIS recovery days} / \text{open recovery days})$ Composite of LOS + return to activity
- 2a. Oncological Adequacy: Composite of margin rate, LN yield, and 3-yr DFS Non-oncological procedures score N/A (weight redistributed)
- 2b. Cost-Effectiveness: $1 - (\text{ICER} / \text{EUR } 50,000 \text{ per QALY})$ Cost-saving = 1.0; capped at EUR 50,000
- 3a. Patient Satisfaction: Mean EQ-5D improvement at 6 months (MIS vs open) Scaled 0-1
- 3b. $\text{MIOS} = 0.25 \times \text{Complication} + 0.20 \times \text{Recovery} + 0.20 \times \text{Oncology} + 0.15 \times \text{Cost} + 0.20 \times \text{Satisfaction}$

Part II -- Micro-Costing Methodology

- 4a. OR time: Actual minutes x EUR 12/min (staff, overhead, anaesthesia) From institutional finance departments
- 4b. Disposables: Actual per-case instrument and consumable costs Robotic: EUR 1,500-3,000 additional
- 5a. Hospital stay: Actual days x per-diem ward cost (EUR 680-920/day by country) ICU days costed separately
- 5b. Capital amortisation: Robot purchase price / (expected cases x lifespan) EUR 800-1,200 per robotic case