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Global access and safety of robotic-assisted surgery for inguinal hernia and gallstone disease worldwide: A pooled multinational cohort study across 110 countries

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Abstract

Background: Robotic-assisted surgery (RAS) is rapidly expanding for common surgical procedures worldwide. This study aimed to measure global access and safety of this technology in patients undergoing inguinal hernia repair and cholecystectomy.

Methods: This analysis included patients undergoing cholecystectomy and inguinal hernia from two contemporary global prospective cohort studies (GECKO, n=52,163; HIPPO, n=18,041). Hierarchical multilevel logistic regression models were used to quantify associations between operative approach (open, laparoscopy, RAS, minimally invasive converted to open) and surgical safety, measured by 30-day postoperative complications, adjusting for hospital, patient, and operative-level factors.

Results: This study included 70,204 patients across 110 countries of whom 857 (1.2%) underwent RAS (high income, n=807; upper middle income, n=17; lower-middle or low income, n=33). Of RAS performed in high income countries, 480 (59.5%) were in the USA and 120 (14.9%) were in the United Kingdom. The overall 30-day complications were 15.0%, similar in patients undergoing laparoscopy (13.8%) and RAS (13.1%), but higher in open (16.8%) or minimally invasive converted to open (42.3%). In adjusted analysis compared to laparoscopy, there were no significant difference in 30-day complications with RAS (odds ratio 1.24, 95% confidence interval 0.98-1.56). However, open (2.56, 2.28-2.88) and minimally invasive converted to open surgery (3.92, 3.43-4.48) were associated with significantly higher 30-day complications.

Conclusion: Early phase implementation of robotic surgery for simple surgical procedures appears safe but is concentrated in wealthier settings. Avoiding conversion from minimally invasive surgery to open surgery requires careful patient selection. Future research should focus on wider health systems evaluation including productivity, equity of adoption, and cost-effectiveness of simple procedures within the lens of a whole robotic system.

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Introduction

Hernia repair and gallstone disease are the most common conditions requiring surgery around the world¹. The prevalence of both inguinal hernia and gallstone disease are estimated to be around 8% and 5% respectively^{2,3}. Each year, approximately

20 million inguinal hernia repairs are carried out globally⁴, compared to of 80,000 cholecystectomies performed in the United Kingdom and over 1,000,000 in America⁵. Therefore, these volumes highlight not only the clinical importance of these conditions but also the need to optimise resources and adopt safe innovations in surgical care.



Over the past two decades, the standard surgical approaches to these procedures have evolved over time. Laparoscopic cholecystectomy is regarded as the gold standard, while the HerniaSurge guidelines recommend laparo-endoscopic repair for inguinal hernia, where local expertise permits, due to faster recovery and reduced postoperative pain^{6,7}. Recently, robotic-assisted surgery (RAS) has gained traction, with low grade evidence suggesting potential advantages such as lower conversion rates and shorter hospital stays compared with laparoscopy, although a potentially higher risk of bile duct injury after cholecystectomy⁸. In the UK, the National Health Service (NHS) 10-year plan explicitly prioritises innovation, with digital technologies and artificial intelligence central to the future of patient care⁹. In 2025, the National Institute for Health and Care Excellence (NICE) approved five robotic systems for soft tissue and six for orthopaedic procedures¹⁰, highlighting an ambition to embed RAS into mainstream surgical practice.

Despite growing interest in adopting robotic surgery, its global implementation and safety remain unknown. For many countries, robotic platforms represent a symbol of inequity, limited by affordability, infrastructure, and training. The World Health Organization and the Society of Robotic Surgery have recently partnered to expand telesurgical capacity in low- and middle-income settings¹¹. Despite these efforts, there is little systematic evidence on worldwide access to robotic surgery, its safety, and its role in high-volume conditions such as inguinal hernia and gallbladder disease. To address this gap, we conducted a pooled multinational cohort study across 110 countries, evaluating the availability of robotic surgery and comparing 30-day mortality and Clavien-Dindo complications between laparoscopic and robotic approaches. Our primary aim was to measure global access and safety of this technology in patients undergoing inguinal hernia repair and cholecystectomy.

Methods

Data source, study design and participants

This secondary analysis included patients undergoing cholecystectomy and inguinal hernia surgery from two contemporary global prospective cohort studies (GECKO, n=52,163; HIPPO, n=18,041). No changes were made to existing care pathways in local hospitals for either study. Throughout the course of both studies, we collected only routine and anonymised data. Both studies were prospectively registered in ClinicalTrials.gov (NCT05748886 and NCT06223061) and the full protocols are available online^{12,13}. Ethical approval was obtained for each participating hospital by the local principal investigator for that centre, according to the individual regulations in place. Some hospitals required informed patient consent, whereas in others, this was waived by the local ethics committees. Full inclusion criteria can be found in the respective protocols. Consecutive patients who fulfilled the HIPPO and GECKO criteria were included, through a four-week collection period for HIPPO and up to eight two-week periods for GECKO. HIPPO collected data from January 30th to May 21st 2023, whereas GECKO collected data between July 31st and November 19th 2023.

Data management

The Research Electronic Data Capture (REDCap) web application¹⁴ was used for online data collection and storage. The service was managed by the Global Surgery REDCap system hosted at the University of Birmingham, UK. Security was governed by the policies of the University of Birmingham. Collaborators were given REDCap project server login details, allowing secure data entry and storage. Both the HIPPO and GECKO study had robust data validation methodology as previously validated^{15,16}. Each hospital lead was responsible for the accuracy and completeness of the collected and uploaded



data from their teams. In both studies, the data was checked centrally by investigators independent of the primary data collection process. When there was missing or invalid data, the hospital lead was contacted to complete and correct the data entered before the data lock. In both studies, hospitals with below 95% data completeness after the data lock were excluded.

Exposure and variables

The primary exposure is the surgical approach, defined as open, laparoscopic-assisted, robotic-assisted and minimally invasive converted to open surgery (i.e., including both laparoscopic- and robotic-assisted converted to open). To account for case-mix differences, and to limit risk of confounders, clinically relevant variables such as age at surgery, gender, body mass index (defined according to the WHO categories), American Society of Anaesthesiologists physical status grade (I-V) and urgency of surgery were collected. Collection of a wide range of variables and performing risk adjusted analysis reduces risk of bias and allows for comparison of outcomes.

Study outcomes

The primary outcomes of this study pertained to safety and access. Safety of the surgical approaches were defined as any post operative complication of the Clavien-Dindo classification as well as the 30-day mortality. Access was assessed by analysing the use of robotic surgery in countries of various income levels.

Sample size

Since this was a secondary analysis, there were no formal sample size calculation. However, sample sizes were evaluated for the original studies. For the HIPPO study, a minimum sample size of 10,000 patients was estimated for the HIPPO study¹⁷, based on a minimum of 30 patients included within 300 hospitals each from 70 countries, learning

from previous GlobalSurg¹⁶ and COVIDSurg¹⁵ cohort studies. For GECKO, sample sizes were estimated based on income groups. Estimates for 30-day postoperative complications following cholecystectomy were determined from the CholeS and CholeCOVID studies, in both high income (2.7% to 10.8%) and low- or middle- income (5.0% to 21.8%) countries. An indicative sample size calculation using the smaller of these estimates suggests around 587 per group at 80% power (2.0% vs 5.0%, $\alpha=0.05$) or 786 per group at 90% power would be required to conclude a difference in complication rate between income groups

Statistical analysis

Baseline characteristics were compared between participants in the two cohort studies as well as the various surgical approaches. Categorical data were described as counts and percentages while continuous data were written as medians, means and interquartile ranges. The values were compared using the Chi-Squared test. The analysis comparing the laparoscopic approach to other approaches used a hierarchical multilevel logistic regression model that quantified associations between operative approach (i.e., open, laparoscopy, robotic-assisted, minimally invasive converted to open) and surgical safety, measured by 30-day postoperative complications, adjusting for hospital, patient-, and operative-level factors.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The responsibility and decision to submit for publication was made by the corresponding author who had full access to the study data.

Results

Cohort characteristics



Table 1. Summary of countries and number of robotic-assisted surgery included in this secondary analysis.

Country	Patients	Hernia	Gallbladder
High income			
United States	480	34	446
United Kingdom	120	14	106
Switzerland	79	62	17
Italy	61	24	37
Spain	19	2	17
Sweden	12	0	12
United Arab Emirates	10	0	10
Austria	7	1	6
Malta	6	0	6
France	5	1	4
Australia	2	0	2
Germany	2	1	1
Greece	2	0	2
Hong Kong	1	0	1
Kuwait	1	0	1
Taiwan	1		
Upper middle income			
South Africa	4	4	0
Turkey	4	2	2
Russia	3	0	3
Mexico	2	0	2
Peru	2	0	2
Bosnia and Herzegovina	1	0	1
Ecuador	1	0	1
Lower middle or low income			
India	22	4	18
Pakistan	6	0	6
Sudan	2	0	2
Jordan	1	0	1
Sri Lanka	1	0	1
Ukraine	1	0	1

This study included 70,204 patients in total who had undergone surgery of inguinal hernia or gallstone disease across 110 countries. A flow chart of the patients included across both HIPPO and GECKO are presented in Figure 1 and baseline characteristics in Supplementary Table 1. Of these, 37,727 (53.7%) were from high-income, 14,916 (21.2%) from upper-middle, and 17,561 (25%) were from lower-middle- or low-income countries. A summary of RAS procedures by country is presented in Table 1. The distribution of operative approaches, postoperative outcomes and global distribution are illustrated in Figure 2 and 3. The cohort included a higher proportion of female patients (n=37,301; 53.1%), with the largest age group being 50-59 years (n=13090, 18.6%). Most procedures were performed laparoscopically (n=51,773; 73.7%), with a majority of the laparoscopic technique (n=48,105; 93.3%) being performed in GECKO compared to HIPPO. However, throughout the cohort, only a small proportion utilised a robotic approach (n=857; 1.2%).

Of the 857 patients who underwent RAS in the cohort, 154 (18%) were performed in HIPPO and 703 (82%) in GECKO. In those patients who underwent robotic surgery, 807 (94.2%) were from a high-income country, with the remaining 50 (5.8%) from upper-middle, lower-middle, or low-income countries. The robotic surgical approach was utilised more for those with ASA grades II - V, with 728 (84.9%) patients belonging to those categories and 111 (13%) patients recorded as ASA I. The open, laparoscopic, and open conversion approaches were utilised for ASA I patients 42.5%, 28.4%, and 17.9% of the time respectively. Baseline patient and operative characteristics by surgical approach are presented in Table 2 and 3.

Outcomes and robotic surgery

Overall, patients undergoing surgery in upper-middle income (OR:0.85; 95% CI: 0.52-1.38, p=0.503) and lower-middle income or low-income countries (OR: 1.17; 95% CI: 0.70-1.96, p=0.549) were associated with similar complications compared



Figure 1. Patient inclusion from the two cohort studies into the pooled analysis.

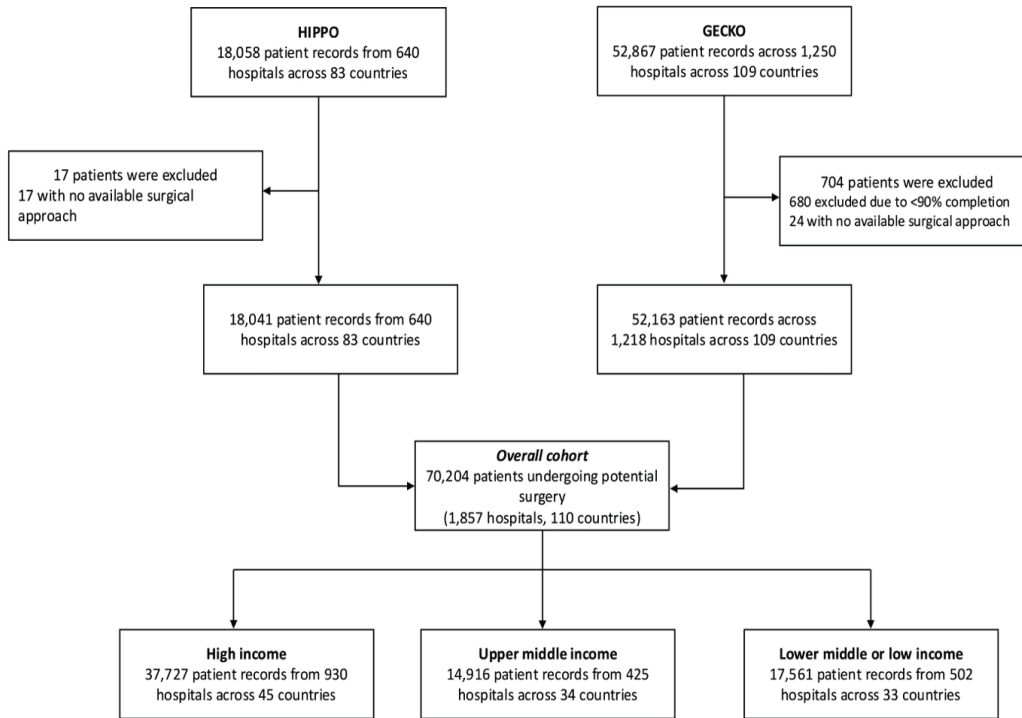


Figure 2. A- hospital type stratified by operative approach; B- 30-day postoperative complication rates (%)

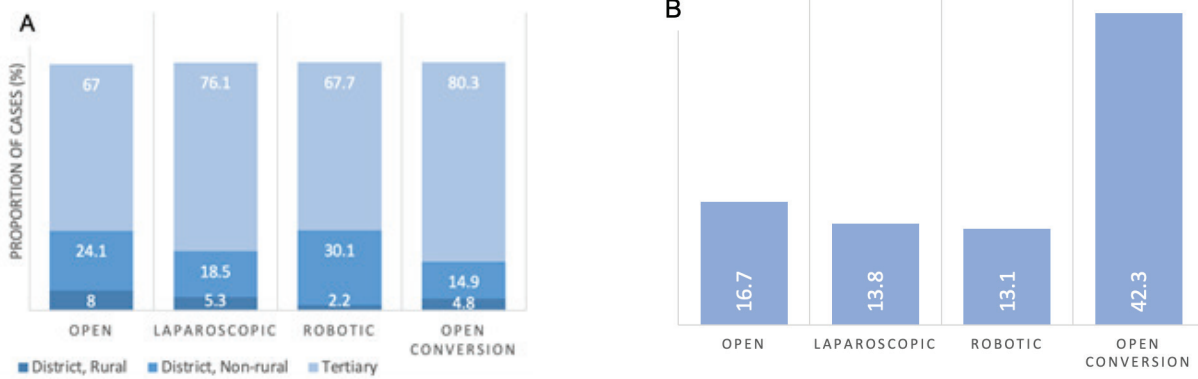


Figure 3. A- country ranking for number of robotic assisted operations; B- distribution of operative approaches across world bank income groups.

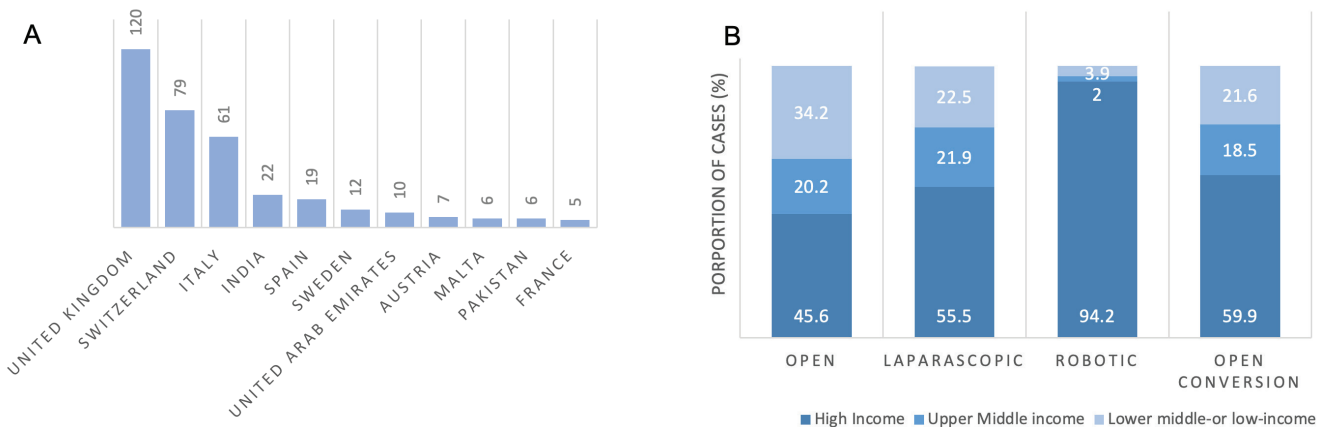




Table 2. Baseline hospital, and patient characteristics by surgical approach in patients undergoing cholecystectomy and inguinal hernia repair. Numbers are N and (%).

		Open	Laparoscopic	Robotic	Open conversion	Total	p-value
Total N (%)		16343 (23.3)	51773 (73.7)	857 (1.2)	1231 (1.8)	70204	
Country income	High income	7446 (45.6)	28737 (55.5)	807 (94.2)	737 (59.9)	37727 (53.7)	<0.0001
	Upper middle income	3309 (20.2)	11362 (21.9)	17 (2.0)	228 (18.5)	14916 (21.2)	
	Lower middle- or low-income	5588 (34.2)	11674 (22.5)	33 (3.9)	266 (21.6)	17561 (25.0)	
	(Missing)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	
Hospital type	District, Rural	1314 (8.0)	2731 (5.3)	19 (2.2)	59 (4.8)	4123 (5.9)	<0.0001
	District, Non-rural	3934 (24.1)	9595 (18.5)	258 (30.1)	183 (14.9)	13970 (19.9)	
	Tertiary	10956 (67.0)	39420 (76.1)	580 (67.7)	988 (80.3)	51944 (74.0)	
	(Missing)	139 (0.9)	27 (0.1)	0 (0.0)	1 (0.1)	167 (0.2)	
Hospital funding	Public	13763 (84.2)	37952 (73.3)	447 (52.2)	947 (76.9)	53109 (75.6)	<0.0001
	Private	1519 (9.3)	7939 (15.3)	282 (32.9)	112 (9.1)	9852 (14.0)	
	Mixed	922 (5.6)	5855 (11.3)	128 (14.9)	171 (13.9)	7076 (10.1)	
	(Missing)	139 (0.9)	27 (0.1)	0 (0.0)	1 (0.1)	167 (0.2)	
Age, years	<18 years	2045 (12.5)	189 (0.4)	0 (0.0)	3 (0.2)	2237 (3.2)	<0.0001
	18-29 years	1006 (6.2)	5643 (10.9)	86 (10.0)	42 (3.4)	6777 (9.7)	
	30-39 years	1282 (7.8)	9364 (18.1)	139 (16.2)	107 (8.7)	10892 (15.5)	
	40-49 years	1989 (12.2)	10090 (19.5)	138 (16.1)	165 (13.4)	12382 (17.6)	
	50-59 years	2752 (16.8)	9939 (19.2)	172 (20.1)	227 (18.4)	13090 (18.6)	
	60-69 years	3237 (19.8)	8816 (17.0)	166 (19.4)	287 (23.3)	12506 (17.8)	
	70-79 years	2777 (17.0)	5777 (11.2)	116 (13.5)	279 (22.7)	8949 (12.7)	
	80-89 years	1136 (7.0)	1815 (3.5)	35 (4.1)	112 (9.1)	3098 (4.4)	
	≥90 years	114 (0.7)	139 (0.3)	5 (0.6)	9 (0.7)	267 (0.4)	
(Missing)	5 (0.0)	1 (0.0)	0 (0.0)	0 (0.0)	6 (0.0)		
Gender	Male	13416 (82.1)	18448 (35.6)	364 (42.5)	668 (54.3)	32896 (46.9)	<0.0001
	Female	2923 (17.9)	33322 (64.4)	493 (57.5)	563 (45.7)	37301 (53.1)	
	(Missing)	4 (0.0)	3 (0.0)	0 (0.0)	0 (0.0)	7 (0.0)	
ASA grade	I	6943 (42.5)	14687 (28.4)	111 (13.0)	220 (17.9)	21961 (31.3)	<0.0001
	II	6876 (42.1)	28098 (54.3)	453 (52.9)	588 (47.8)	36015 (51.3)	
	III	2231 (13.7)	8252 (15.9)	252 (29.4)	371 (30.1)	11106 (15.8)	
	IV	190 (1.2)	376 (0.7)	22 (2.6)	41 (3.3)	629 (0.9)	
	V	91 (0.6)	25 (0.0)	1 (0.1)	1 (0.1)	118 (0.2)	
	(Missing)	12 (0.1)	335 (0.6)	18 (2.1)	10 (0.8)	375 (0.5)	
Body mass index, kg/m ²	<18.5 (underweight)	1668 (10.2)	713 (1.4)	5 (0.6)	27 (2.2)	2413 (3.4)	<0.0001
	18.5-24.9 (normal)	6543 (40.0)	16259 (31.4)	236 (27.5)	361 (29.3)	23399 (33.3)	
	25-29.9 (overweight)	5804 (35.5)	17714 (34.2)	284 (33.1)	453 (36.8)	24255 (34.5)	
	≥30 (obese)	1887 (11.5)	14202 (27.4)	327 (38.2)	337 (27.4)	16753 (23.9)	
	(Missing)	441 (2.7)	2885 (5.6)	5 (0.6)	53 (4.3)	3384 (4.8)	
Frailty	1-3	12141 (84.6)	44303 (85.9)	647 (75.5)	871 (70.9)	57962 (85.2)	<0.0001
	4-6	1714 (11.9)	4193 (8.1)	106 (12.4)	265 (21.6)	6278 (9.2)	
	7-9	129 (0.9)	257 (0.5)	4 (0.5)	25 (2.0)	415 (0.6)	
	Unknown	369 (2.6)	2815 (5.5)	100 (11.7)	67 (5.5)	3351 (4.9)	
Urgency	Elective	14407 (88.2)	40392 (78.0)	706 (82.4)	798 (64.8)	56303 (80.2)	<0.0001
	Emergency	1934 (11.8)	11366 (22.0)	151 (17.6)	433 (35.2)	13884 (19.8)	
	(Missing)	2 (0.0)	15 (0.0)	0 (0.0)	0 (0.0)	17 (0.0)	
Diabetes Mellitus	No	14426 (88.3)	44906 (86.7)	732 (85.4)	936 (76.0)	61000 (86.9)	<0.0001
	Yes	1911 (11.7)	6792 (13.1)	124 (14.5)	294 (23.9)	9121 (13.0)	
	(Missing)	6 (0.0)	75 (0.1)	1 (0.1)	1 (0.1)	83 (0.1)	



to those in high-income countries. The robotic surgical approach resulted in the lowest proportion of complications with 13.1% of patients having post-operative complications versus 16.7%, 13.8%, and 42.3% for the open, laparoscopic, and open conversion approaches respectively. Complications were defined as any post-operative complication of any Clavien-Dindo classification. There was no statistically significant difference between the rate of complications after robotic surgery, compared to that of laparoscopic surgery (OR 1.24; 95% CI 0.98-1.56; $p=0.072$). The open (OR: 2.56; 95% CI 2.28-2.88) and minimally invasive converted to open (OR: 3.92; 95% CI 3.43-4.48) approaches were both associated with increased odds of post-operative complications, respectively (Table 4). The 30-day mortality rates were low across all operative approaches and throughout both studies. 30-day mortality was 0.1% (16 patients) in HIPPO and 0.2% (120 patients) in GECKO totaling 136 patients with an overall rate of 0.2%. The open, laparoscopic, robotic, and open conversion approaches had mortality rates of 0.3% (57 patients), 0.1% (65 patients), 0.2% (2 patients), and 1% (12 patients) respectively.

Discussion

In this pooled analysis of more than 70,000 patients undergoing inguinal hernia repair or cholecystectomy across 110 countries, we found that robotic surgery was used in only 1.2% of cases. This figure is consistent with a recent retrospective cohort study which reported robotic surgery rates of 0.7% and 1.9% for cholecystectomy and inguinal hernia respectively⁸. The limited use of RAS is likely due to high costs and longer operative times¹⁸. Despite being deployed in patients who were younger, with lower ASA grades and comorbidity burden, robotic-assisted procedures demonstrated complication and mortality rates comparable with those of laparoscopic surgery. These findings, drawn from two of the largest global prospective surgical datasets, suggest that when access is available, robotic platforms can be

delivered safely for common procedures without compromising patient outcomes.

The analysis also highlights current inequalities in access with more than 94% of robotic procedures performed in high-income countries. This shows the capital intensity and running costs that restrict availability in resource-constrained settings. Current literature comparing robotic surgery to other surgical approaches were predominantly carried out in high- and middle-income countries such as the United States, Italy and Germany^{8, 19, 20}. This concentration of access mirrors broader patterns in surgical innovation, where low- and middle-income countries face barriers in infrastructure, maintenance, and training. Without targeted policy interventions or novel financing mechanisms, this gap is likely to persist. At the same time, adoption in high-income countries is accelerating, driven by strategic investment, regulatory approvals, and industry partnerships, reinforcing the need for balanced evaluation of value and sustainability.

We found a comparable 30-day complication rate for the robotic approach in relation to the laparoscopic approach and a significantly reduced rate of complications when compared to open or open conversion. The 30-day mortality was low across all operative approaches, with the highest in patients having conversion to open surgery, highlighting the overall safety of minimally invasive techniques. These effects are seen despite the robotic approach being utilised more for patients in generally poorer health pre-operatively. There is some evidence that RAS can allow surgeons to perform more difficult operations and operations on more comorbid patients compared to laparoscopic surgery^{21, 22}. In these cases, the ASA grade tended to be higher, BMI was less likely to be normal, and frailty scores were elevated when compared to the other approaches. This finding is congruous with other recent multicenter studies comparing the robotic and laparoscopic/open approaches for other general surgical procedures



Table 3. Baseline operative characteristics and outcomes by surgical approach in patients undergoing cholecystectomy and inguinal hernia repair. Numbers are N and (%).

		Open	Laparoscopic	Robotic	Open conversion	Total	p-value
Total N (%)		16343 (23.3)	51773 (73.7)	857 (1.2)	1231 (1.8)	70204	
Anaesthetic type	General (inhaled)	4733 (29.0)	29029 (56.1)	382 (44.6)	747 (60.7)	34891 (49.7)	<0.0001
	Other anaesthetic	10971 (67.1)	22341 (43.2)	453 (52.9)	480 (39.0)	34245 (48.8)	
	(Missing)	639 (3.9)	403 (0.8)	22 (2.6)	4 (0.3)	1068 (1.5)	
Intraoperative antibiotics	No	2906 (17.8)	10059 (19.4)	167 (19.5)	126 (10.2)	13258 (18.9)	<0.0001
	Yes	13432 (82.2)	41714 (80.6)	690 (80.5)	1104 (89.7)	56940 (81.1)	
	(Missing)	5 (0.0)	0 (0.0)	0 (0.0)	1 (0.1)	6 (0.0)	
Wound contaminations	Clean	13495 (82.6)	3602 (7.0)	151 (17.6)	101 (8.2)	17349 (24.7)	<0.0001
	Clean-Contaminated	2539 (15.5)	45617 (88.1)	655 (76.4)	901 (73.2)	49712 (70.8)	
	Contaminated or Dirty	307 (1.9)	2538 (4.9)	51 (6.0)	229 (18.6)	3125 (4.5)	
	(Missing)	2 (0.0)	16 (0.0)	0 (0.0)	0 (0.0)	18 (0.0)	
Any complications	No	13584 (83.1)	44637 (86.2)	744 (86.8)	710 (57.7)	59675 (85.0)	<0.0001
	Yes	2737 (16.7)	7133 (13.8)	112 (13.1)	521 (42.3)	10503 (15.0)	
	(Missing)	22 (0.1)	3 (0.0)	1 (0.1)	0 (0.0)	26 (0.0)	
30-day mortality	No	16264 (99.5)	51705 (99.9)	854 (99.6)	1219 (99.0)	70042 (99.8)	<0.0001
	Yes	57 (0.3)	65 (0.1)	2 (0.2)	12 (1.0)	136 (0.2)	
	(Missing)	22 (0.1)	3 (0.0)	1 (0.1)	0 (0.0)	26 (0.0)	

^{19,20,21,22} which have seen increased use of robotic surgery over the years and usefulness in older patients with several co-morbidities. This observation, however, may be due to one of the well-established utilities of robotic surgery, which is that RAS can allow surgeons to perform more difficult operations on more sick patients and patients with higher BMIs.

A large database study from the USA, including 737,908 Medicare cholecystectomies (2010-2021) reported approximately threefold higher bile duct injury after robotic-assisted versus laparoscopic cholecystectomy across low-, medium- and high-risk strata, while overall complications were similar²³. The authors suggest learning-curve effects and the use of cholecystectomy as a training case contributed, identifying the need for careful credentialing and case selection. Our study shows that more modern technologies and training programmes may overcome this, although we did not look at bile duct injury rates

separately.

The primary strength of this study lies in its large, globally diverse cohort, comprising 70,240 patients from 110 countries, providing a broadly representative sample of the wider surgical population. Besides that, the study uses multilevel logistic regression, uses country identifier as a random effect which ensures that our findings are not influenced by a particular country therefore increases the transferability of the data to a worldwide setting. Despite that, this study has several limitations that need to be addressed. Firstly, hospital, patient and operative characteristics were considered for the adjusted model. However, we failed to remove confounding factors such as surgeon experience, intraoperative decision making and adherence to peri- and postoperative protocols. Secondly, the study did not acquire data on the type of robotic systems used which may affect outcomes due to differences in availability and adaptability.



Table 4. Multilevel logistic regression of hospital, patient, and operative characteristics on overall complications in patients undergoing cholecystectomy and inguinal hernia repair. Multilevel model includes country identifier as a random effect. Numbers are N and (%).

		No	Yes	OR (univariable)	OR (multivariable full)
Operative approach	Laparoscopic	44637 (86.2)	7133 (13.8)	-	-
	Open	13584 (83.2)	2737 (16.8)	1.26 (1.20-1.32, p<0.001)	2.56 (2.28-2.88, p<0.001)
	Robotic	744 (86.9)	112 (13.1)	0.94 (0.77-1.15, p=0.559)	1.24 (0.98-1.56, p=0.072)
	Open conversion	710 (57.7)	521 (42.3)	4.59 (4.09-5.16, p<0.001)	3.92 (3.43-4.48, p<0.001)
Country income	High income	32036 (85.0)	5672 (15.0)	-	-
	Upper middle income	12756 (85.5)	2157 (14.5)	0.96 (0.91-1.01, p=0.093)	0.85 (0.52-1.38, p=0.503)
	Lower middle- or low-income	14883 (84.8)	2674 (15.2)	1.01 (0.97-1.07, p=0.565)	1.17 (0.70-1.96, p=0.549)
Hospital type	District, Rural	3538 (86.0)	577 (14.0)	-	-
	District, Non-rural	12067 (86.4)	1900 (13.6)	0.97 (0.87-1.07, p=0.493)	0.95 (0.83-1.10, p=0.499)
	Tertiary	43925 (84.6)	8012 (15.4)	1.12 (1.02-1.23, p=0.016)	1.06 (0.93-1.21, p=0.352)
Hospital funding	Public	45143 (85.0)	7949 (15.0)	-	-
	Private	8373 (85.0)	1478 (15.0)	1.00 (0.94-1.06, p=0.936)	0.86 (0.79-0.95, p=0.002)
	Mixed	6014 (85.0)	1062 (15.0)	1.00 (0.94-1.07, p=0.936)	1.06 (0.97-1.16, p=0.223)
Age, years	<18 years	2069 (92.5)	168 (7.5)	-	-
	18-29 years	5955 (87.9)	822 (12.1)	1.70 (1.43-2.02, p<0.001)	-
	30-39 years	9474 (87.0)	1414 (13.0)	1.84 (1.56-2.17, p<0.001)	1.04 (0.94-1.16, p=0.426)
	40-49 years	10685 (86.3)	1696 (13.7)	1.95 (1.66-2.31, p<0.001)	1.05 (0.94-1.16, p=0.402)
	50-59 years	11124 (85.0)	1962 (15.0)	2.17 (1.84-2.56, p<0.001)	1.13 (1.01-1.25, p=0.031)
	60-69 years	10516 (84.1)	1984 (15.9)	2.32 (1.97-2.74, p<0.001)	1.05 (0.94-1.17, p=0.389)
	70-79 years	7310 (81.7)	1634 (18.3)	2.75 (2.33-3.25, p<0.001)	1.21 (1.07-1.36, p=0.002)
	80-89 years	2348 (75.9)	747 (24.1)	3.92 (3.28-4.68, p<0.001)	1.41 (1.20-1.64, p<0.001)
≥90 years	191 (71.5)	76 (28.5)	4.90 (3.60-6.67, p<0.001)	1.46 (0.99-2.17, p=0.058)	
Gender	Male	27683 (84.2)	5193 (15.8)	-	-
	Female	31989 (85.8)	5309 (14.2)	0.88 (0.85-0.92, p<0.001)	0.93 (0.88-0.98, p=0.012)
ASA grade	I	19472 (88.7)	2484 (11.3)	-	-
	II	30748 (85.4)	5255 (14.6)	1.34 (1.27-1.41, p<0.001)	1.14 (1.06-1.23, p=0.001)
	III	8666 (78.1)	2436 (21.9)	2.20 (2.07-2.34, p<0.001)	1.46 (1.32-1.62, p<0.001)
	IV	383 (60.9)	246 (39.1)	5.03 (4.27-5.94, p<0.001)	2.15 (1.71-2.69, p<0.001)
	V	91 (78.4)	25 (21.6)	2.15 (1.38-3.36, p=0.001)	5.87 (1.74-19.81, p=0.004)
Body mass index, kg/m ²	<18.5 (underweight)	2154 (89.3)	257 (10.7)	-	-
	18.5-24.9 (normal)	20125 (86.0)	3266 (14.0)	1.36 (1.19-1.56, p<0.001)	0.76 (0.61-0.95, p=0.015)
	25-29.9 (overweight)	20584 (84.9)	3663 (15.1)	1.49 (1.30-1.71, p<0.001)	0.78 (0.62-0.97, p=0.023)
	≥30 (obese)	13897 (83.0)	2852 (17.0)	1.72 (1.50-1.97, p<0.001)	0.81 (0.65-1.01, p=0.059)
Frailty	1-3	49851 (86.0)	8090 (14.0)	-	-
	4-6	4643 (74.0)	1633 (26.0)	2.17 (2.04-2.30, p<0.001)	1.42 (1.30-1.55, p<0.001)
	7-9	239 (57.6)	176 (42.4)	4.54 (3.73-5.52, p<0.001)	2.22 (1.72-2.87, p<0.001)
	Unknown	2902 (86.6)	449 (13.4)	0.95 (0.86-1.06, p=0.360)	1.18 (1.03-1.35, p=0.014)
Urgency	Elective	48853 (86.8)	7427 (13.2)	-	-
	Emergency	10810 (77.9)	3071 (22.1)	1.87 (1.78-1.96, p<0.001)	1.58 (1.48-1.68, p<0.001)
Diabetes Mellitus	No	52542 (86.2)	8433 (13.8)	-	-
	Yes	7060 (77.4)	2060 (22.6)	1.82 (1.72-1.92, p<0.001)	1.34 (1.25-1.44, p<0.001)
Anaesthetic type	General (inhaled)	29644 (85.0)	5243 (15.0)	-	-
	Other anaesthetic	29058 (84.9)	5165 (15.1)	1.00 (0.96-1.05, p=0.815)	1.01 (0.95-1.07, p=0.715)
Intraoperative antibiotics	No	11635 (87.8)	1621 (12.2)	-	-
	Yes	48035 (84.4)	8881 (15.6)	1.33 (1.25-1.40, p<0.001)	1.01 (0.93-1.09, p=0.836)
Wound contaminations	Clean	15116 (87.3)	2207 (12.7)	-	-
	Clean-Contaminated	42360 (85.2)	7352 (14.8)	1.19 (1.13-1.25, p<0.001)	-
	Contaminated or Dirty	2184 (69.9)	941 (30.1)	2.95 (2.70-3.22, p<0.001)	1.80 (1.63-1.98, p<0.001)



Thirdly, there were only 857 robotic surgeries out of the total of 70,204. This is a small proportion of the total population with 737 robotic surgeries performed in high income countries, which restricts the representation of the results to middle and lower income countries. Fourthly, this study focuses solely on cholecystectomy and inguinal hernia repair. These are common general surgical procedures performed therefore the results do not highlight the safety and outcomes of other less commonly performed general surgical procedures hence limits the generalisability of the data. Another limitation presented by this study is the lack of long-term follow-up for our overall cohort. The GECKO study collected 1-year follow-up data, however HIPPO did not, therefore this could not be included in our present study. Long-term data on complications, including chronic pain and hernia recurrence for example, would provide valuable insights and result in stronger comparisons between operative approaches. Finally, hospitals that have participated in this study are likely to be better resourced and more research active, this does not reflect other hospitals with fewer resources. This introduces a component of selection bias in the study. Regardless of these limitations, our findings across various income settings suggest that the use of robotic surgery can achieve safer surgical outcomes globally.

Taken together, these findings suggest that early implementation robotic surgery for inguinal hernia and cholecystectomy has been safe. However, access is uneven and clinical benefit over standard laparoscopy is unproven. Future research should focus on proving where clinical benefit for robotic surgery in simple procedures lies, and how it can be made cost-effective. Health economics may need to focus on simple surgery within a matrix of more complex surgery, and how the robotic system as a whole becomes cost-effective. Prospective cohort studies with 30-day and one year outcomes, novel

health economic analyses, and carefully designed randomised trials are needed.

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