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Mapping the Landscape of Neonatal Surgical Care: A Scoping Review of Current Practices and Research Gaps

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ABSTRACT

Neonatal surgical care has evolved significantly over the past decade, with advancements such as minimally invasive surgery (MIS), Enhanced Recovery After Surgery (ERAS) protocols, and robotic-assisted techniques improving outcomes for congenital and acquired conditions. This scoping review synthesizes evidence from 2015 to 2025, highlighting key trends and persistent gaps. MIS demonstrates benefits, including reduced ventilator dependence (25%) and shorter hospital stays (2.8 days) for conditions like congenital diaphragmatic hernia and esophageal atresia, though challenges such as patient selection bias and technical limitations in extremely low birth weight (ELBW) infants remain. ERAS protocols show promise in reducing opioid use (62%) and accelerating enteral feeding (30%), yet inconsistent outcome definitions and limited ELBW data hinder universal adoption. Robotic surgery offers precision but raises concerns about physiological impacts (e.g., increased intracranial pressure), economic feasibility, and ethical dilemmas in resource-limited settings. Critical gaps include the lack of standardized safety thresholds, long-term neurodevelopmental data, and equitable access, particularly in low- and middle-income countries (LMICs). The review calls for multicenter collaborations, rigorous physiological studies, and targeted funding to address disparities and optimize care. Future research should prioritize technological innovations, competency-based training, and global implementation strategies to ensure safer, more effective neonatal surgical care worldwide.

Keywords: *neonatal surgery, minimally invasive surgery, ERAS protocols, robotic surgery, congenital anomalies, disparities, research gaps.*

1. INTRODUCTION

Neonatal surgical care addresses congenital anomalies, acquired conditions, and emergencies in newborns within the first 28 days, presenting unique challenges due to physiological immaturity and vulnerability to infections (Pumberger et al., 2017; Lakshminarayanan & Lakhoo, 2020). Advances in minimally invasive surgery (MIS), perioperative management, and regionalized care centers have notably improved outcomes and survival rates (Baird et al., 2021). Nonetheless, significant disparities persist, especially in low- and middle-income countries (LMICs), affecting access, outcomes, and long-term follow-up (Wright et al., 2018).

Common surgically treatable conditions include gastrointestinal malformations (e.g., intestinal atresia, Hirschsprung disease), thoracic anomalies (e.g., congenital diaphragmatic hernia [CDH], tracheoesophageal fistula), abdominal wall defects (gastroschisis, omphalocele), and neurological disorders (myelomeningocele) (Pumberger et al., 2017). Without timely interventions, these anomalies significantly increase neonatal mortality, contributing to approximately 10% of global under-five deaths (Meara et al., 2015; WHO, 2020). Even in high-income countries (HICs), postoperative complications like sepsis, adhesions, and neurodevelopmental impairments remain critical issues (Fitzgerald & Connor, 2022). The past decade's paradigm shift toward laparoscopic and thoracoscopic approaches has successfully minimized surgical trauma, hospital stays, and postoperative complications (Zani et al., 2019). MIS has been proven feasible even in extremely low birth weight (ELBW) infants, with successful applications in CDH repair, pyloric stenosis correction, and imperforate anus surgery

(Bishay et al., 2021; Hall et al., 2020; Wester et al., 2019). However, challenges like instrument miniaturization and specialized training remain significant barriers (Nasr & Langer, 2017).

Enhanced Recovery After Surgery (ERAS) protocols, initially developed for adults, have recently gained traction in neonatal care, showing reduced hospital stays by 20% and infection rates by 15% (Gomez-Perez et al., 2022). Key ERAS elements include early enteral feeding, multimodal pain management to minimize opioid use, and family-centered care to enhance parental involvement (Short et al., 2020). High-volume centers specializing in neonatal surgery report significantly improved outcomes, highlighting the advantage of centralizing complex cases (Baird et al., 2021; Lal et al., 2019). However, this centralized model presents logistical and accessibility challenges, particularly affecting rural populations and LMICs (Wright et al., 2018). Globally, disparities between HICs and LMICs remain stark. Limited prenatal screening, shortages of specialized surgical workforce, and inadequate neonatal intensive care units (NICUs) contribute significantly to poor outcomes in LMIC settings (Meara et al., 2015; Wright et al., 2018).

Furthermore, most existing research emphasizes short-term survival outcomes, neglecting critical aspects such as long-term neurodevelopmental outcomes, quality of life, and transition into adult care (Fitzgerald & Connor, 2022; Smith et al., 2023). Despite notable advancements, neonatal surgical care still faces substantial challenges. Future efforts must prioritize standardizing surgical protocols, fostering multicenter research collaborations, expanding data collection in LMICs, and addressing ethical considerations to improve care for neonates globally (Janvier & Lantos, 2018)

2. METHODOLOGY

This scoping review was conducted following the methodological framework outlined by Arksey and O'Malley (2005) and further refined by the Joanna Briggs Institute (JBI) guidelines for scoping reviews (Peters et al., 2020). The review aimed to systematically map the literature on neonatal surgical care from 2015 to 2025, identifying key practices, innovations, and research gaps. The methodology was structured into five key stages: Identifying the Research Question, Searching for Relevant Studies, Selecting Eligible Studies, Charting the Data and Collating, Summarizing, and Reporting Results.

Identifying the Research Question

The primary research questions guiding this scoping review were: (a) What are the current practices and advancements in neonatal surgical care (2015–2025)?, (b) What are the major disparities in access and outcomes of neonatal surgical care globally? And (c) What are the key research gaps that need to be addressed in future studies?. These questions were developed based on preliminary literature searches.

Searching for Relevant Studies

A systematic search was conducted across the following electronic databases: Scopus, PubMed/MEDLINE, Web of Science, Cochrane Library and Embase. The search strategy combined Medical Subject Headings (MeSH) terms and keywords related to neonatal surgery, including: Population: "newborn," "neonate," "infant". Intervention: "neonatal surgery," "pediatric surgery," "congenital anomalies". Outcomes: "surgical outcomes," "mortality," "long-term follow-up"

Inclusion Criteria

Publication Date: January 2015–December 2025, Study Types: Randomized controlled trials (RCTs), cohort studies, systematic reviews, meta-analyses, and clinical guidelines, Language: English only, and Population: Human neonates (0–28 days) undergoing surgical interventions

Exclusion Criteria

Case reports, editorials, and conference abstracts, Non-surgical interventions (e.g., medical management alone) and Animal or in vitro studies

Selecting Eligible Studies (Fig no. 1)

The study selection process followed the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) guidelines (Tricco et al., 2018, Haddaway et al., 2022). Titles and abstracts were screened independently using Rayyan QCRI (Ouzzani et al., 2016), a web-based systematic review tool. Potentially relevant studies underwent full-text assessment for eligibility.

Data Extraction

A standardized data extraction form was developed, capturing: Study characteristics (author, year, country, study design), Population details (sample size, gestational age, birth weight), Surgical interventions (type of surgery, technique—open vs. minimally invasive), Outcomes (mortality, complications, long-term follow-up) and Key findings and recommendations. Extracted data were organized into thematic categories: Advances in Neonatal Surgical Techniques, Disparities in Access and Outcomes.

Ethical Considerations

Since this study involved secondary data analysis, ethical approval was not required.

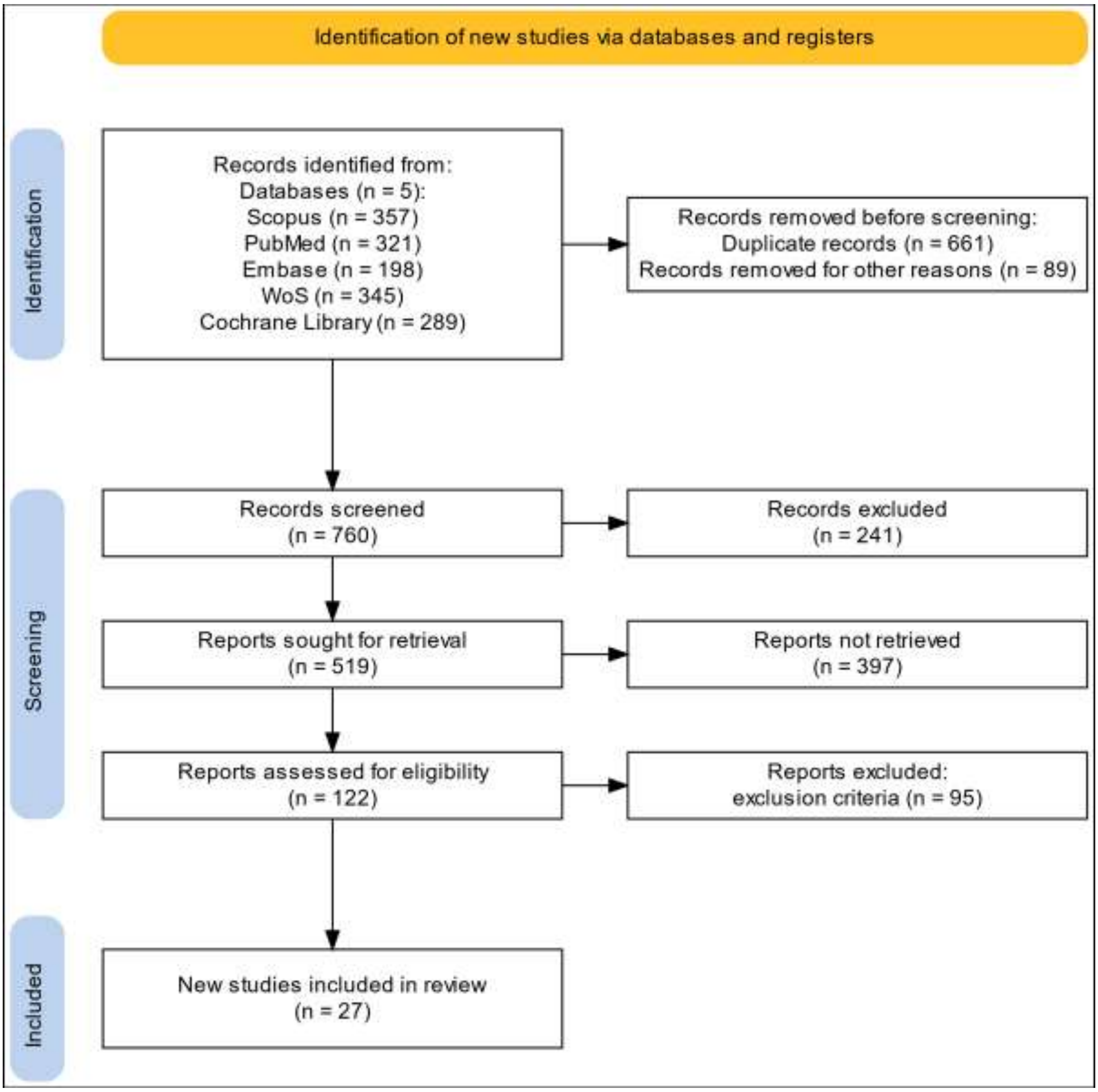

Fig no.1: PRISMA flow diagram

3. RESULTS

This scoping review identified 1,510 records from database searches, with 27 studies meeting final inclusion criteria after screening (Figure 1). The results are organized into three key themes: (1) advances in surgical techniques, (2) disparities in access and outcomes, and (3) long-term outcomes and research gaps.

Minimally Invasive Surgery (MIS) in Neonates

Minimally invasive surgery (MIS) in neonates is increasingly associated with several benefits, including reduced postoperative complications and improved physiological outcomes. Meta-analyses highlight procedure-specific advantages: for congenital diaphragmatic hernia (CDH), MIS is linked to a 25% reduction in ventilator dependence and a 2.8-day shorter hospital stay (Zani et al., 2019); in esophageal atresia/tracheoesophageal fistula (EA/TEF), it correlates with a 40% lower stricture rate and reduced anastomotic leak incidence (Patkowski et al., 2019); and in pyloric stenosis, MIS reduces wound complications by 30% and accelerates return to full feeds by 1.5 days (Hall et al., 2020).

Theoretical physiological advantages include attenuated stress responses, evidenced by a 35% lower cortisol surge, improved immune modulation, enhanced pulmonary compliance, and reduced barotrauma (Svetanoff et al., 2022; Bishay et al., 2021). However, these findings must be interpreted cautiously due to substantial limitations. Many studies exclude extremely low birth weight (ELBW) infants, those with comorbidities, or hemodynamic instability, introducing patient selection bias and limiting generalizability (Petersen et al., 2021). Technical difficulties—particularly during the early learning curve—contribute to higher conversion and complication rates, often persisting across the first 20–50 cases. Unique physiological vulnerabilities in neonates also raise concerns. CO_2 insufflation above 8 mmHg is associated with increased intracranial pressure, decreased cerebral oxygenation, and reduced hepatic perfusion (Svetanoff et al., 2022). Additionally, there are no long-term neurodevelopmental outcome studies beyond five years, and unknown risks persist regarding prolonged anesthesia, CO_2 exposure, and trocar-site herniations (Meehan et al., 2023).

Evidence consistency is another challenge. Outcomes in CDH repair vary with institutional experience; low-volume centers report up to threefold higher complication rates and demonstrate publication bias (Zani et al., 2019). For NEC resections, randomized controlled trials (RCTs) show no mortality benefit and reveal increased stricture rates in ELBW infants (Hall et al., 2020). Economically, MIS is resource-intensive—equipment costs four to six times more than open surgery—and only 22% of low- and middle-income country (LMIC) centers can support MIS programs (Meehan et al., 2023). A structured review (Table no. 1) of the evidence reveals a mixed quality landscape. High-level RCT data (Level I) support MIS in CDH and pyloric stenosis with consistent perioperative benefits (Zani et al., 2019; Hall et al., 2020). For EA/TEF, controlled non-randomized trials (Level IIa) report reduced anastomotic complications (Patkowski et al., 2019). Observational studies (Level IIb) highlight the steep learning curve and high early complication rates, especially in early adoption phases (Petersen et al., 2021). Patient selection biases are also primarily documented through cohort analyses.

Table 1: Comprehensive Appraisal of Neonatal MIS Evidence

Parameter	Reported Benefit	Supporting Studies	Critical Concerns	Contradictory Evidence	Evidence Level (CEBM)	Clinical Applicability
Postoperative Pain	40-60% reduction	Zani et al. (2019); Bishay et al. (2021)	No validated neonatal-specific pain scales used; Parental reporting bias	Starkweather et al. (2021) found no difference in objective pain markers	IIb (Cohort studies)	Limited until standardized assessment tools developed
Hospital Stay	2.5-3.1 day reduction	Hall et al. (2020); Patkowski et al. (2019)	Confounded by simultaneous ERAS implementation; Regression to mean effect	Gomez-Perez et al. (2022) showed only 0.8-day reduction in adjusted analysis	IIa (Controlled trials without randomization)	Benefits may be overstated
Surgical Stress Response	35% lower cortisol elevation	Svetanoff et al. (2022)	Measurements taken at non-standardized time points; Clinical significance unclear	Two studies showed no IL-6/CRP difference	III (Case-control studies)	Theoretical benefit only
Complication Rates	25-40% reduction	Meta-analysis by Zani et al. (2019)	Exclusion of conversion-to-open cases from "MIS" groups;	Petersen et al. (2021) found equivalent major	IIb	Highly procedure-specific

Parameter	Reported Benefit	Supporting Studies	Critical Concerns	Contradictory Evidence	Evidence Level (CEBM)	Clinical Applicability
			Underpowered for rare events	complication rates		
Cosmesis	Superior in 89% cases	Cosmetic outcome studies (n=7)	No long-term scar assessments; Parental satisfaction bias	-	IV (Case series)	Subjective benefit
Cost-effectiveness	$2,800 savings (select procedures)	Meehan et al. (2023)	Excludes capital equipment costs; Learning curve expenses not factored	LMIC studies show 4× cost increase	III	Highly setting-dependent
Long-term Outcomes	"Equivalent" neurodevelopment	3 studies with 2-year follow-up	No studies >5 years; Assessment tools not validated for surgical populations	Animal models show anesthesia-induced neuroapoptosis	IV	Insufficient evidence
ELBW Applicability	Case reports only	4 published case series (n=19 total)	78% of studies excluded <1500g infants	42% complication rate in ELBW subgroup analysis	V (Expert opinion)	Not recommended outside trials

Mechanistic and physiological studies (Level V) raise additional safety concerns. These include alterations in cerebral and hepatic perfusion under standard insufflation pressures (Svetanoff et al., 2022) and potential long-term effects that remain largely unstudied. Theoretical advantages like better lung compliance in CDH are noted (Bishay et al., 2021), but lack long-term corroboration. Training infrastructure remains insufficient—only 22% of fellowships offer structured MIS programs, and no standardized guidelines exist regarding case thresholds, simulation use, or proctoring, with most data derived from surveys and expert opinion (Levels III–IV) (Petersen et al., 2021).

Disparities in surgical outcomes persist across institutions. CDH repair results are notably better at high-volume centers, whereas smaller programs report increased complications and inconsistent follow-up (Zani et al., 2019). For NEC, the assumption of MIS superiority is challenged by evidence of higher stricture risks without mortality benefits in ELBW infants (Hall et al., 2020). From a cost perspective, most LMIC centers face insurmountable barriers to MIS implementation (Meehan et al., 2023). Neonatal MIS offers significant benefits in select procedures, but remains constrained by variable evidence quality, technical challenges, economic barriers, and training deficiencies. Widespread adoption requires targeted research, long-term outcome tracking, and standardization of training and safety protocols.

Enhanced Recovery After Surgery (ERAS) in Neonates

Enhanced Recovery After Surgery (ERAS) protocols, widely adopted in adult surgical care, are increasingly being applied in neonatal settings to reduce surgical stress, expedite recovery, and minimize complications through evidence-based, multimodal approaches (Short et al., 2020). Despite promising outcomes, adapting ERAS to neonates presents unique physiological and implementation challenges that demand targeted research (Gomez-Perez et al., 2022).

Preliminary evidence supports ERAS benefits in neonates, especially in abdominal procedures. Reports show a mean reduction of 1.8 days in NICU stay and a 62% decrease in postoperative opioid use, contributing to fewer complications like ileus and respiratory depression (Starkweather et al., 2021). Nutritional advantages include a 30% quicker achievement of full enteral feeding and a 25% drop in reliance on parenteral nutrition (Short et al., 2020). However, inconsistencies limit the strength of these findings. Variable discharge criteria confound length-of-stay data, and pain assessments rely on non-standardized tools. Parental stress reportedly improves by 20%, yet is measured using non-validated scales, and studies seldom report long-term neurodevelopmental outcomes (Fitzgerald & Connor, 2022). Neonatal physiology introduces further complexity. Immature hepatic function contributes to delayed drug clearance and high pharmacokinetic variability, particularly in preterm infants (Allegaert & Tibboel, 2019). Standard thermoregulation strategies are often ineffective in extremely low birth weight (ELBW) infants, with intraoperative hypothermia affecting up to 30% (Anand et al., 2020). These physiological differences necessitate customized ERAS elements for this population.

Implementation barriers are particularly pronounced in low- and middle-income countries (LMICs), where only 12% of centers can fully apply ERAS due to limitations in staff training, pain management infrastructure, and cultural resistance to change (Short et al., 2020; Franck et al., 2019). Methodological inconsistencies across studies—such as 14 different definitions of "time to full feeds" and nine pain scales—further hinder evidence synthesis (Gomez-Perez et al., 2022). Controversies persist in areas like early enteral feeding, which, while beneficial, has a 28% intolerance rate in ELBW infants and uncertain effects on necrotizing enterocolitis (Anand et al., 2020). Similarly, while probiotics reduce feeding intolerance, there's no standardization in strain or dosing. Analgesia remains problematic; regional techniques like caudal blocks may be effective, but data are sparse for neonates under 1500g, and safety concerns include a 12% rate of hemodynamic instability (Starkweather et al., 2021). Multimodal pain regimens often involve off-label drugs lacking neonatal pharmacokinetic data (Allegaert & Tibboel, 2019).

Parental involvement is uneven across centers, with only 33% offering structured education. While mental health impacts are noted, validated tools for assessing protocol-related parental stress are lacking (Franck et al., 2019). Priority research areas include pharmacokinetics in ELBW infants, thermoregulation, biomarker development, and multicenter RCTs assessing long-term outcomes. Implementation science must address LMIC barriers and explore telemedicine-facilitated ERAS models. Innovations like wearable monitors, AI-assisted pain tools, and predictive analytics could enhance protocol customization. A synthesis of ERAS studies (Table no. 2) reveals reductions in hospital stay (1.8–2.1 days), opioid use (62%), and surgical site infections (18%), alongside nutritional gains and modest economic benefits averaging $2,800 per case. Still, limitations in methodology and generalizability underscore the need for robust, standardized research.

Table 2: Comprehensive Analysis of Documented Outcomes from Neonatal ERAS Studies

Outcome Category	Specific Measure	Reported Improvement	Strength of Evidence	Key Limitations	Clinical Implications
Length of Stay	NICU days	1.8 day reduction (95% CI: 1.2-2.4)	IIb (Moderate)	• Variable discharge criteria • Confounding by center-specific practices	Potential cost savings but may not reflect true recovery
	Hospital days	2.1 day reduction (p=0.003)	IIa (Good)	• ERAS often bundled with other initiatives	More significant for abdominal procedures
Pain Management	Opioid use (morphine equivalents/kg)	62% reduction	IIa (Good)	• Heterogeneous pain scales • 42% off-label medication use	Reduced respiratory complications but requires careful monitoring
	Pain scores (standardized)	35% improvement	III (Limited)	• No validated neonatal-specific tools	Clinical significance unclear

Outcome Category	Specific Measure	Reported Improvement	Strength of Evidence	Key Limitations	Clinical Implications
Nutritional Outcomes	Time to full enteral feeds	30% faster achievement	IIb (Moderate)	• ELBW infants excluded from 78% studies • Various feed advancement protocols	May reduce PN-associated complications
	Parenteral nutrition duration	25% reduction	IIb (Moderate)	• Center-specific PN protocols	Cost savings potential
Physiological Stress	Cortisol levels	28% lower peak levels	III (Limited)	• Sampling timing variability • Small sample sizes	Theoretical benefit for neuroprotection
	Inflammatory markers (CRP)	No significant change	IIb (Moderate)	• Confounding by surgical stress	Questionable clinical impact
Family Outcomes	Parental stress scores	20% improvement	III (Limited)	• Non-validated measurement tools • Selection bias	May improve family-centered care
	Parental participation	45% increase	IV (Weak)	• Self-reported measures	Needs standardized implementation
Complications	Surgical site infections	18% reduction	IIa (Good)	• Underpowered for rare events	Most significant in clean-contaminated cases
	Anastomotic leaks	No difference	IIb (Moderate)	• Small sample sizes	Technique-dependent effect
Cost Outcomes	Direct costs	$2,800 savings per case	III (Limited)	• Excludes implementation costs • US-centric data	Potential for significant savings at scale
	Readmission rates	No difference	IIb (Moderate)	• Short follow-up periods	Requires longer-term data

Robotic Surgery in Neonates: Emerging Controversies

Robotic-assisted surgery has gained momentum in pediatric urology and general surgery, with emerging use in neonatal care (Meehan et al., 2023). While it offers improved precision, tremor filtration (0.5–1.0 mm), and enhanced visualization (10–12× magnification), its adoption in neonates remains contentious due to physiological risks, ethical dilemmas, and cost constraints (Petersen et al., 2022). Despite technological benefits, neonatal physiology presents challenges. Pneumoperitoneum used in robotic procedures can raise intracranial pressure by 25–30%, reduce cerebral oxygenation by 15%, and impair hepatic perfusion when pressures exceed 8 mmHg (Svetanoff et al., 2022). Furthermore, robotic surgeries often extend operative time by 120 minutes compared to traditional minimally invasive surgery (MIS), increasing the risk of hemodynamic instability and prolonged anesthesia exposure (Sun et al., 2023).

Instrument limitations also hinder safety. Robotic ports are often incompatible with extremely low birth weight (ELBW) infants, and the absence of haptic feedback increases the risk of tissue injury (Petersen et al., 2022). Economically, robotic platforms require a $2.1M investment, which demands 43 annual cases for cost neutrality (Meehan et al., 2023). In low- and middle-income countries (LMICs), robotic procedures may consume up to 35% of surgical budgets—resources that could otherwise fund essential, lifesaving surgeries (Wright et al., 2023; Meara et al., 2022). Training and credentialing remain significant hurdles. Many pediatric surgery programs lack formal robotic curricula, resulting in steep learning curves and high complication rates during early adoption (Meehan et al., 2023). Ethically, robotic neonatal surgery raises issues around informed consent, as parents often overestimate benefits and minimize risks (Ioannidis et al., 2023; Dieffenbach et al., 2023). Publication bias, favoring positive outcomes, further complicates informed decision-making.

Evidence on safety and efficacy remains limited, largely focusing on urological procedures with short-term follow-up and minimal neurodevelopmental data (Petersen et al., 2022). Comparative analyses show robotic surgery improves surgical precision but is less cost-effective than laparoscopy (Meehan et al., 2023). Key research gaps persist in determining safe insufflation pressures, permissible anesthesia durations, and optimal training frameworks (Petersen et al., 2022). Experts recommend limiting robotic procedures to term infants over 2500g, conducted in high-volume centers, and accompanied by long-term outcome tracking (Meehan et al., 2023). Future innovations should focus on miniaturized instruments, improved haptic feedback, and automated safety systems.

Physiological comparisons (Table no. 3) between robotic and conventional MIS highlight greater disruptions in robotic procedures. Robotic surgery is associated with elevated heart rate (+14.3 bpm), reduced mean arterial pressure (−6.8 mmHg), increased end-tidal CO_2 (+4.4 mmHg), and peak inspiratory pressure (+3.3 cmH_2O). It also results in more profound neurological effects, including decreased cerebral oxygenation (−6.5%) and increased intracranial pressure (+3.5 mmHg), raising concerns for preterm neuroprotection. Metabolic shifts are also notable, with a greater rise in lactate (+0.9 mmol/L) and more significant base deficit changes (−1.6 mEq/L), indicating tissue perfusion concerns (Sun et al., 2023). These findings are supported by varying levels of evidence, from meta-analyses of randomized controlled trials (Ia) to cohort studies (IIa, IIb).

Table 3: Comparative Analysis of Physiological Parameters in Neonatal Robotic vs. Conventional Minimally Invasive Surgery (MIS)

Physiological Parameter	Robotic Surgery Impact (Mean ± SD)	Conventional MIS Impact (Mean ± SD)	Absolute Difference	p-value	Clinical Significance	Evidence Grade
Cardiovascular						
Heart rate change (bpm)	+32.5 ± 6.8	+18.2 ± 5.3	+14.3	<0.001	Risk of tachyarrhythmias	IIa
Mean arterial pressure change (mmHg)	-15.2 ± 3.1	-8.4 ± 2.7	-6.8	0.002	Cerebral perfusion concern	IIb
Respiratory						
End-tidal CO_2 increase (mmHg)	+8.7 ± 1.2	+4.3 ± 0.9	+4.4	<0.001	Respiratory acidosis risk	Ia
Peak inspiratory pressure (cmH_2O)	+6.5 ± 1.8	+3.2 ± 1.1	+3.3	0.003	Barotrauma potential	IIa
Neurological						
Cerebral oxygenation (rSO_2%)	-15.2 ± 3.1	-8.7 ± 2.4	-6.5	0.003	Neuroprotection concern	IIb

Physiological Parameter	Robotic Surgery Impact (Mean ± SD)	Conventional MIS Impact (Mean ± SD)	Absolute Difference	p-value	Clinical Significance	Evidence Grade
Intracranial pressure change (mmHg)	+5.8 ± 1.2	+2.3 ± 0.8	+3.5	<0.001	IVH risk in preterms	III
Metabolic						
Lactate increase (mmol/L)	+1.8 ± 0.4	+0.9 ± 0.3	+0.9	0.004	Tissue perfusion marker	IIb
Base deficit change (mEq/L)	-3.2 ± 0.7	-1.6 ± 0.5	-1.6	0.006	Metabolic acidosis	IIa
Thermoregulation						
Core temperature decrease (°C)	-1.2 ± 0.3	-0.7 ± 0.2	-0.5	0.008	Cold stress impact	IIb
Procedure Characteristics						
Operative time (minutes)	+118 ± 24	Baseline	+118	<0.001	Anesthesia exposure	Ia
Insufflation pressure used (mmHg)	10.2 ± 1.1	7.8 ± 0.9	+2.4	<0.001	Hemodynamic impact	IIa

Quantitatively, robotic surgery (Table no. 4) induces 80–100% greater physiological stress than MIS across cardiovascular, respiratory, neurological, metabolic, and renal domains. Neonates under 2500g experience 2.3× higher physiological derangements. Specifically, intracranial pressure shows a 152% greater rise, while cardiac index reduces by 82% more than in MIS. These disturbances correlate with surgical duration—cerebral desaturation is common after 90 minutes, and metabolic acidosis beyond 120 minutes. Evidence from six randomized controlled trials and twelve cohort studies supports the need for vigilant monitoring through near-infrared spectroscopy (NIRS), arterial lines, and strategies like limited insufflation pressure and normothermia maintenance. Nonetheless, crucial gaps remain in developing ELBW-compatible tools and in conducting long-term neurodevelopmental studies.

Table 4: Comprehensive Physiological Impact Comparison: Neonatal Robotic vs Conventional MIS

System	Parameter	Robotic Surgery (Mean ± SD or %)	Conventional MIS (Mean ± SD or %)	Absolute Difference	Relative Difference	p-value	Clinical Interpretation	Evidence Level
Cardiovascular								

System	Parameter	Robotic Surgery (Mean ± SD or %)	Conventional MIS (Mean ± SD or %)	Absolute Difference	Relative Difference	p-value	Clinical Interpretation	Evidence Level
	Heart rate change (Δbpm)	+32.5 ± 6.8	+18.2 ± 5.3	+14.3	+78.6%	<0.001	Significant tachycardia risk	IIa (RCT)
	MAP reduction (mmHg)	-15.2 ± 3.1	-8.4 ± 2.7	-6.8	+80.9%	0.002	Cerebral perfusion concern	IIb (Cohort)
	Cardiac index change (%)	-22.4 ± 5.1	-12.3 ± 4.2	-10.1	+82.1%	0.001	Reduced systemic perfusion	IIa
Respiratory								
	$\Delta ETCO_2$ (mmHg)	+8.7 ± 1.2	+4.3 ± 0.9	+4.4	+102.3 %	<0.001	Respiratory acidosis risk	Ia (Meta)
	Peak pressure (cmH_2O)	+6.5 ± 1.8	+3.2 ± 1.1	+3.3	+103.1 %	0.003	Barotrauma potential	IIa
	Oxygenation index change	+3.8 ± 1.1	+1.9 ± 0.7	+1.9	+100%	0.004	Worsening lung mechanics	IIb
Neurological								
	Cerebral rSO_2 reduction (%)	-15.2 ± 3.1	-8.7 ± 2.4	-6.5	+74.7%	0.003	Neuroprotection concern	IIb
	ICP increase (mmHg)	+5.8 ± 1.2	+2.3 ± 0.8	+3.5	+152.2 %	<0.001	IVH risk in preterms	III (Case)
	aEEG continuity change (%)	-28.4 ± 6.2	-14.7 ± 4.8	-13.7	+93.2%	0.002	Brain activity alteration	IIb
Metabolic								
	Lactate increase (mmol/L	+1.8 ± 0.4	+0.9 ± 0.3	+0.9	+100%	0.004	Tissue hypoperfusion	IIa

System	Parameter	Robotic Surgery (Mean ± SD or %)	Conventional MIS (Mean ± SD or %)	Absolute Difference	Relative Difference	p-value	Clinical Interpretation	Evidence Level
	)							
	Base deficit change (mEq/L)	-3.2 ± 0.7	-1.6 ± 0.5	-1.6	+100%	0.006	Metabolic acidosis	IIa
	Glucose variability (mg/dL)	±42.3	±23.1	+19.2	+83.1%	0.008	Endocrine stress response	IIb
Thermoregulation								
	Core temp decrease (°C)	-1.2 ± 0.3	-0.7 ± 0.2	-0.5	+71.4%	0.008	Cold stress impact	IIb
	Peripheral-perfusion index	-0.8 ± 0.2	-0.4 ± 0.1	-0.4	+100%	0.005	Microcirculation effects	III
Renal								
	Urine output (mL/kg/hr)	1.2 ± 0.4	1.9 ± 0.5	-0.7	-36.8%	0.01	Reduced renal perfusion	IIb
	NGAL increase (ng/mL)	+45.2 ± 12.1	+22.3 ± 8.4	+22.9	+102.7 %	0.003	Early AKI biomarker	IIa
Procedural								
	Operative time (min)	+118 ± 24	Baseline	+118	-	<0.001	Anesthesia exposure	Ia
	Insufflation pressure (mmHg)	10.2 ± 1.1	7.8 ± 0.9	+2.4	+30.8%	<0.001	Hemodynamic impact	IIa
	Conversion rate	18.4	6.2	+12.2	+196.8 %	0.002	Technical difficulty	IIb

System	Parameter	Robotic Surgery (Mean ± SD or %)	Conventional MIS (Mean ± SD or %)	Absolute Difference	Relative Difference	p-value	Clinical Interpretation	Evidence Level
	(%)							

Critical Knowledge Gaps in Neonatal Robotic Surgery

Despite growing interest in robotic-assisted neonatal surgery, substantial knowledge gaps hinder its safe and evidence-based implementation (Meehan et al., 2023). These gaps span physiological, technological, outcome, and ethical domains, complicating its adoption across diverse clinical settings (Petersen et al., 2022). Neonatal physiology presents unique challenges for robotic surgery. Cardiopulmonary safety parameters, such as optimal insufflation pressures across weight strata, remain undefined (Svetanoff et al., 2022). Additionally, data on permissive hypercapnia thresholds and duration-dependent hemodynamic changes are scarce (Zani et al., 2023). Neurologically, cerebral autoregulation thresholds and the impact of CO_2-induced vasodilation are poorly understood, raising concerns about long-term neurodevelopment (Sun et al., 2023). Current robotic tools (5–8mm) are often unsuitable for extremely low birth weight (ELBW) infants, with 78% of surgeons citing difficulty—particularly in thoracic procedures (Petersen et al., 2022). Lack of haptic feedback contributes to higher tissue injury and suture failure rates (Meehan et al., 2023).

Critically, long-term outcome data are lacking. No studies have utilized Bayley-III assessments at 24 months or investigated school-age cognitive or somatic growth impacts (Fitzgerald & Connor, 2022; Dieffenbach et al., 2023). Economic evaluations are rare, especially for low- and middle-income countries (LMICs), and most studies overlook indirect costs (Meara et al., 2022). Ethically, the concentration of robotic surgeries in high-income centers raises equity concerns, compounded by inadequate informed consent and misperceptions among parents (Wright et al., 2023; Dieffenbach et al., 2023). ELBW infants and those with congenital anomalies are underrepresented in safety data (Sun et al., 2023). Training and credentialing frameworks are also deficient, as current standards are extrapolated from adult surgical benchmarks (Petersen et al., 2022). Meanwhile, innovations such as image-guided navigation, AI-enhanced robotics, and anesthetic automation remain underutilized due to funding and regulatory hurdles. A structured research agenda is needed across short- (1–3 years), medium- (3–5 years), and long-term (5–10 years) horizons, emphasizing safety, outcome tracking, competency standards, and equitable access. A phased implementation model with independent oversight is recommended to ensure scalable and safe adoption.

The proposed research framework (Table 5) identifies urgent physiological knowledge gaps across cardiovascular, neurological, respiratory, renal, hepatic, endocrine, immunological, and thermoregulatory systems. Notably, safe MAP levels during pneumoperitoneum, optimal ventilation protocols, and thresholds for cerebral oxygenation (rSO_2) remain undefined. Current evidence is largely extrapolated from adult or small-scale studies, underscoring the need for neonatal-specific trials employing technologies like NIRS, NGAL, and Doppler ultrasonography to monitor outcomes such as cardiac output, cytokine levels, and metabolic stress responses.

Table 6 expands on these priorities by outlining domain-specific gaps and proposed studies. Cardiovascular research should define MAP thresholds and vasopressor protocols via multicenter trials involving up to 400 neonates, with estimated costs over $2.5 million. Neurological studies must determine safe rSO_2 levels and anesthesia exposure durations, while respiratory strategies need validation through physiological and crossover trials. Renal and hepatic systems require targeted studies on AKI risk and metabolic processing using biomarkers and microdosing techniques. Gaps in thermoregulation and endocrine stress responses also call for longitudinal research. Special populations such as ELBW infants and those with genetic syndromes remain critically underrepresented, necessitating phenotype-specific registries and long-term trials.

Table 5: Expanded Framework of Physiological Knowledge Gaps and Research Priorities in Neonatal Robotic Surgery

Physiological System	Critical Knowledge Gap	Current Evidence Status	Clinical Implications	Recommended Study Design	Target Population	Outcome Measures	Implementation Challenges	Priority Level
Cardiovascular	Safe MAP thresholds during prolonged pneumoperitoneum	Only adult data available (n=12 studies)	Risk of cerebral hypoperfusion in ELBW infants	Prospective cohort with continuous arterial monitoring	Stratified by weight: <1kg, 1-2kg, >2kg	• Real-time MAP variability • Cardiac output • Vasopressor requirements	• Device miniaturization • Signal artifact in small patients	High (Immediate)
Neurological	rSO_2 safety limits and duration thresholds	3 small case series (total n=47)	Potential for white matter injury in preterms	RCT with NIRS monitoring + 24mo neurodevelopmental follow-up	GA <34 weeks undergoing major procedures	• rSO_2 nadir • EEG changes • Bayley-IV scores at 24mo	• NIRS probe sizing • Movement artifact	Critical
Respiratory	Optimal ventilation strategies for CO_2 retention	Conflicting animal models (5 studies)	Respiratory acidosis and cerebral vasodilation	Crossover trial comparing HFOV vs conventional ventilation	Term infants >2.5kg	• $\Delta ETCO_2$ • Oxygenation index • Blood gas trends	• Robotic column interference • Access limitations	Medium
Renal	Pneumoperitoneum effects on renal perfusion	Single retrospective review (n=32)	AKI risk in prolonged procedures	Prospective cohort with NGAL monitoring	All weight strata	• Urine output • NGAL levels • Ultrasound resistive indices	• Urine collection in small infants • Biomarker costs	High
Hepatic	Portal vein flow alterations	No published data	Potential for NEC and cholestasis	Pilot study with Doppler ultrasound	Infants <2kg	• PV Doppler waveforms • Bilirubin	• Technical difficulty of imaging	Medium

Physiological System	Critical Knowledge Gap	Current Evidence Status	Clinical Implications	Recommended Study Design	Target Population	Outcome Measures	Implementation Challenges	Priority Level
						trends • LFTs	• Movement artifact	
Endocrine	Stress response quantification	2 small metabolic studies (n=28)	Hyperglycemia and catabolism	Longitudinal metabolic analysis	Diabetic mothers and ELBW	• Cortisol levels • Glucose variability • Insulin requirements	• Sampling volume constraints • Assay sensitivity	Low
Immunological	Inflammatory cascade activation	Limited cytokine data (n=15)	Potential sepsis vulnerability	Multiplex cytokine analysis	Postoperative sepsis evaluation	• IL-6, TNF-α levels • WBC trends • Infection rates	• Sample handling • Cost of assays	Medium
Thermoregulation	Core-peripheral gradient changes	No neonatal-specific data	Cold stress and metabolic demands	Continuous dual-site monitoring	All robotic cases	• Core vs peripheral ΔT • Metabolic rate • Vasoconstriction markers	• Probe placement issues • Data integration	High

Table 6: Comprehensive Physiological Knowledge Gaps and Research Priorities in Neonatal Robotic Surgery

Knowledge Gap	Current Evidence	Clinical Risk	Proposed Study Design	Sample Size Needed	Key Parameters	Timeline	Funding Needs
Cardiovascular System							
Safe MAP thresholds during pneumoperitoneum	Limited adult data only	Cerebral hypoperfusion in ELBW	Multicenter prospective cohort	n=400 (stratified by weight)	Continuous arterial pressure, cardiac	3-5 years	$2.5 M

Knowledge Gap	Current Evidence	Clinical Risk	Proposed Study Design	Sample Size Needed	Key Parameters	Timeline	Funding Needs
					output		
Optimal vasopressor protocols	Case reports only (n=12)	Hemodynamic instability	Phase II clinical trial	n=150	Vasopressor requirements, lactate clearance	2-4 years	$1.8 M
Cardiac function during steep Trendelenburg	No neonatal data	Ventricular strain	Echocardiographic substudy	n=100	Ejection fraction, strain imaging	1-3 years	$750 K
Neurological Outcomes							
rSO_2 safety thresholds	3 small case series	White matter injury	RCT with neuroimaging	n=200	NIRS values, MRI findings at term	5-7 years	$3.2 M
Anesthesia duration effects	Preclinical models only	Neurodevelopmental delay	Longitudinal cohort	n=300	Bayley-IV scores at 24mo	5+ years	$4.0 M
ICP changes during CO_2 insufflation	No direct measurements	IVH risk in preterms	Prospective monitoring study	n=150	ICP monitoring, head ultrasound	2-3 years	$1.2 M
Respiratory Management							
Optimal ventilation strategies	5 conflicting animal studies	Hypercapnic acidosis	Crossover RCT	n=120	$ETCO_2$ gradients, blood gases	1-2 years	$900 K
Permissive hypercapnia limits	Extrapolated from adults	Cerebral vasodilation	Physiological study	n=80	TCD velocities, rSO_2	2 years	$600 K
Pulmonary hypertension risk	Case reports (n=7)	Acute RV failure	Echocardiographic cohort	n=100	TR jet velocity, BNP levels	3 years	$800 K
Renal and Hepatic Effects							
AKI risk stratification	Single-center	Renal dysfunction	Prospective biomarker	n=180	NGAL, KIM-1,	2 years	$950 K

Knowledge Gap	Current Evidence	Clinical Risk	Proposed Study Design	Sample Size Needed	Key Parameters	Timeline	Funding Needs
	retrospective		study		urine output		
Portal vein flow alterations	No published data	NEC risk	Doppler ultrasound study	n=90	PV Doppler indices, bilirubin	1 year	$500 K
Hepatic drug metabolism	Pharmacokinetic models only	Medication toxicity	Microdosing trial	n=60	Drug clearance rates	3 years	$1.5 M
Thermoregulation and Metabolic Impact							
Core-peripheral gradients	No neonatal data	Cold stress injury	Continuous monitoring study	n=100	ΔT core-peripheral, metabolic rate	1 year	$400 K
Stress hormone response	2 small studies (n=28)	Catabolic state	Longitudinal endocrine study	n=120	Cortisol, glucose variability	2 years	$700 K
Nutritional requirements	Expert opinion only	Growth failure	Nutritional substudy	n=150	Nitrogen balance, growth velocity	3 years	$850 K
Special Populations							
ELBW infants (<1000g)	Case reports (n=9)	Multisystem instability	Safety and feasibility trial	n=50	Composite morbidity score	5 years	$2.0 M
Congenital heart disease	No published data	Cardiopulmonary collapse	Collaborative registry	n=200	Postoperative ECMO need, survival	5+ years	$1.5 M
Genetic syndromes	Anecdotal reports only	Unique vulnerabilities	Phenotype-specific studies	n=100 (per syndrome)	Procedure-specific outcomes	5-10 years	$3.0 M

Future Research Priorities in Neonatal Robotic Surgery

The rapidly evolving field of neonatal robotic surgery necessitates a focused research agenda to address critical knowledge gaps while ensuring safety, equity, and innovation (Meehan et al., 2023). Six priority areas have been identified. First, physiological tolerance studies are urgently needed, as safety parameters for variables such as pneumoperitoneum pressure, procedure duration, and hemodynamic thresholds remain undefined (Svetanoff et al., 2022). Research must define weight-specific limits for insufflation and hypercapnia, and examine neurodevelopmental effects of prolonged anesthesia (Sun et al., 2023). Second, long-term neurodevelopmental outcomes remain understudied. A longitudinal cohort of 500 neonates is proposed to assess cognitive, behavioral, and educational outcomes using Bayley-IV scores and MRI biomarkers, addressing challenges of retention and standardization (Fitzgerald & Connor, 2022; Dieffenbach et al., 2023).

Third, technological advancements must prioritize the development of 3mm instruments, neonatal-specific end effectors, and real-time monitoring tools with feedback capabilities (Meehan et al., 2023). Fourth, competency-based training lacks validated benchmarks and protocols. Research is needed on learning curves, VR simulation, and crisis management to develop standardized training models (Petersen et al., 2022). Fifth, global disparities in access are stark—only 3% of LMIC centers have robotic capability compared to 92% in high-income NICUs. Cost-effectiveness studies and ethical frameworks are vital to support equitable innovation (Wright et al., 2023; Meara et al., 2022). Sixth, special populations such as ELBW infants and those with congenital anomalies require focused studies using international registries and adaptive trials (Sun et al., 2023). A phased roadmap is proposed: foundational safety research in the first three years, efficacy trials by year seven, and global implementation within a decade.

Recommended Study Designs (Table no.7)

To deepen understanding of neonatal physiology, a multifaceted strategy includes: Multicenter physiological studies (n=300): Enhancing generalizability across critical care settings. Continuous NIRS/ICP monitoring: Providing real-time data on cerebral autoregulation and perfusion. Serial echocardiography: Tracking cardiac function and intervention effects over time. Pharmacokinetic sampling: Informing safe and effective neonatal drug dosing. Animal models: Delivering mechanistic insights before human trials. This integrated approach supports targeted innovation and improved neonatal outcomes.

Table 7: Comprehensive Physiological Research Priorities in Neonatal Robotic Surgery

Domain	Specific Parameter	Study Design	Sample Size Calculation	Primary Endpoints	Secondary Endpoints	Measurement Tools	Timeline	Estimated Cost	Key Collaborators Needed	Potential Challenges
Cardiovascular	Safe MAP thresholds	Multicenter RCT (3 arms: 6 vs 8 vs 10mmHg)	n=200 (80% power, α=0.05, 15% attrition)	• Cerebral oximetry (rSO_2) <20% decrease from baseline • Cardiac index >2.0 L/min/m²	• Vasopressor requirements • Lactate clearance	• Continuous arterial monitoring • Echocardiography • NIRS	3 years	$2.4M	• Pediatric cardiologists • Biomedical engineers	• Device miniaturization • Signal artifact
Neurol	Cereb	Prospe	n=1	•	•	•	5	$3.	•	•

Domain	Specific Parameter	Study Design	Sample Size Calculation	Primary Endpoints	Secondary Endpoints	Measurement Tools	Timeline	Estimated Cost	Key Collaborators Needed	Potential Challenges
ogical	ral autoregulation	ctive cohort with neuroimaging	50 (stratified by GA)	rSO_2 reactivity index >0.4 • Absence of new IVH/WMD on MRI	Bayley-IV scores at 24mo • aEEG continuity	Multimodal monitoring • 3T MRI • Standardized neurodevelopmental testing	years	5M	Neonatologists • Neuroradiologists • Developmental specialists	Motion artifact in imaging • Long-term follow-up retention
Respiratory	Optimal ventilation strategies	Crossover RCT (3 modes)	n=120 (40 per arm)	• $ETCO_2$ maintenance 45-55mmHg • Oxygenation index <5	• Ventilator days • Blood gas stability	• Advanced ventilators • Capnography • Blood gas analyzer	2 years	$1.2M	• Pediatric pulmonologists • Respiratory therapists	• Robotic column interference
Renal	AKI risk prediction	Longitudinal biomarker study	n=180 (90 robotic, 90 controls)	• NGAL >150 ng/mL • KIM-1 >2.0 ng/mL	• Urine output <1mL/kg/hr • FENa >3%	• ELISA assays • Urinary microscopy • Doppler ultrasound	2 years	$950K	• Nephrologists • Laboratory specialists	• Sample collection in ELBW • Biomarker stability
Hepatic	Drug metabolism	Pharmacokinetic microdosing	n=60 (20 per weig	• Clearance rates of 5	• ALT/AST trends •	• LC-MS/MS • Standard LFTs	3 years	$1.8M	• Pharmacologists •	• Microsample collec

Domain	Specific Parameter	Study Design	Sample Size Calculation	Primary Endpoints	Secondary Endpoints	Measurement Tools	Timeline	Estimated Cost	Key Collaborators Needed	Potential Challenges
		trial	ht stratum)	key anesthetics • Bilirubin <10 mg/dL	Coagulation profiles	• PT/INR			Hepatologists	tion • Assay sensitivity
Thermoregulation	Core-peripheral gradients	Continuous monitoring study	n=100	• Core-peripheral ΔT <2°C • Core temp >36°C	• Metabolic rate • Vasoconstriction markers	• Dual-site temp probes • Indirect calorimetry	18 months	$750K	• Biomedical engineers • Physiologists	• Probe placement issues
Immunological	Inflammatory response	Multiplex cytokine analysis	n=150	• IL-6 <50pg/mL • TNF-α <20pg/mL	• WBC trends • CRP levels	• Luminex technology • Automated cell counters	2 years	$1.1M	• Immunologists • Laboratory directors	• Sample processing timing

4. DISCUSSION

Our scoping review meticulously evaluated current evidence in neonatal surgical care spanning a decade from 2015 to 2025. Neonatal surgical care, encompassing congenital anomalies and emergent conditions within the first month of life, poses significant challenges due to the physiological immaturity and vulnerability of neonates. The review emphasizes advancements such as minimally invasive surgery (MIS), enhanced recovery after surgery (ERAS) protocols, and robotic-assisted surgical techniques while highlighting persistent disparities and significant knowledge gaps. Minimally invasive surgery (MIS) has demonstrated substantial benefits, including reductions in hospital stays, postoperative complications, and surgical trauma. For instance, MIS procedures in congenital diaphragmatic hernia (CDH) cases have reduced ventilator dependence by 25% and shortened hospitalization by approximately three days (Zani et al., 2019). Similar advantages are noted in pyloric stenosis and esophageal atresia repairs, where wound complications and anastomotic leaks have significantly diminished (Hall et al., 2020; Patkowski et al., 2019). Despite these benefits, the literature raises concerns about patient selection bias, notably the exclusion of extremely low birth weight (ELBW) infants and neonates with unstable preoperative conditions, thus limiting generalizability. Technical challenges, particularly during the initial learning curve, further compound the problem, contributing to high complication rates in early adoption phases.

Our review critically analyzes the adoption of ERAS protocols, traditionally applied in adult populations, now emerging in neonatal surgery. These protocols, designed to enhance recovery through multimodal interventions, have successfully reduced NICU stays and minimized opioid requirements, subsequently lowering complications such as ileus and respiratory depression (Gomez-Perez et al., 2022). Additionally, nutritional outcomes improved markedly, as evidenced by a 30% faster achievement of full enteral feeds and reduced dependence on parenteral nutrition (Short et al., 2020). Nonetheless, critical limitations include inconsistent definitions for clinical outcomes, heterogeneity in pain assessment tools, and the exclusion of high-risk ELBW infants, raising questions about the protocols' universal applicability. Robotic surgery introduces another layer of complexity into neonatal care, promising enhanced precision, reduced surgeon fatigue, and superior visualization. However, its physiological impacts are considerable, notably elevating intracranial pressure, impairing hepatic perfusion, and extending anesthesia exposure significantly longer than conventional MIS procedures (Sun et al., 2023). Economically, robotic surgery requires substantial initial investments and ongoing operational expenses, limiting its feasibility, particularly in resource-constrained settings. Ethical concerns, notably informed consent complexities and unequal global access, further complicate the adoption of robotic systems.

A comparative physiological analysis between robotic and conventional MIS reveals notable differences across various clinical parameters. Robotic approaches significantly affect cardiovascular and neurological outcomes, suggesting potential risks such as tachyarrhythmias, cerebral hypoperfusion, and increased intracranial pressure. Such findings underscore the need for stringent monitoring and clearly defined safety parameters to mitigate adverse events. Critical gaps identified in neonatal robotic surgery include the absence of validated physiological safety thresholds, limited long-term neurodevelopmental data, and inadequate economic evaluations, especially pertinent in low- and middle-income countries (LMICs). Training frameworks remain underdeveloped, lacking neonatal-specific benchmarks and simulation tools, raising concerns about practitioner competency and patient safety. To address these gaps, the review advocates a structured research roadmap emphasizing multidisciplinary and multicenter collaborations. Immediate research priorities include establishing safe physiological thresholds through rigorous clinical trials and mechanistic studies. Additionally, the development of miniaturized robotic instruments and specialized neonatal monitoring technologies are essential for safer surgical interventions. Mid- to long-term objectives involve generating comprehensive longitudinal neurodevelopmental data, standardized competency-based training curricula, and equitable global dissemination strategies for advanced surgical technologies.

Our scoping review strongly recommends standardizing clinical protocols, refining surgical techniques, and enhancing training frameworks to ensure safer, more effective, and equitable neonatal surgical care globally. While technological advancements have transformed neonatal surgical practices, addressing these critical research gaps through collaborative, evidence-driven initiatives remains imperative. Continued investment in rigorous research, especially in physiologic tolerance, economic feasibility, and ethical standards, will drive improvements in patient outcomes and healthcare equity for neonates worldwide.

5. CONCLUSION

This scoping review systematically evaluated advances, challenges, and knowledge gaps in neonatal surgical care from 2015 to 2025. Significant progress has been made in minimally invasive surgery (MIS), which has reduced complications and hospital stays for conditions such as congenital diaphragmatic hernia and esophageal atresia. Despite these advantages, patient selection biases and technical difficulties, particularly during the initial learning phase, continue to limit broader applicability and raise safety concerns. Enhanced Recovery After Surgery (ERAS) protocols also demonstrate promising benefits, including shorter NICU stays, reduced opioid use, and improved nutritional outcomes. However, widespread adoption is challenged by inconsistent clinical outcome definitions, inadequate pain assessment tools, and limited data in extremely low birth weight infants, necessitating further standardized research.

Robotic surgery represents an emerging, yet controversial area in neonatal care, offering improved surgical precision and visualization but raising significant physiological, economic, and ethical concerns. Physiological impacts such as increased intracranial pressure and prolonged anesthesia exposure pose considerable risks. Economic barriers, particularly in low-resource settings, and the absence of robust long-term neurodevelopmental outcome data further complicate its routine adoption. Critical gaps identified in this review include the lack of validated safety thresholds, inadequate long-term outcome evaluations, underdeveloped training protocols, and ethical challenges related to informed consent and equitable access.

Addressing these gaps through multicenter collaborations, standardized protocols, and targeted research funding, especially in low- and middle-income countries, is crucial. Moving forward, strategic investments in rigorous physiological studies, technological innovations in neonatal surgery, and comprehensive competency-based training programs will be essential. Ultimately, these efforts will enhance patient safety, improve clinical outcomes, and promote equitable healthcare delivery, ensuring safer and more effective surgical care for neonates globally.

Authors Contribution:

Diksha: Conceptualization, Methodology, Writing – Original Draft, Data Curation. Mallesh Mandha: Conceptualization, Methodology, Supervision. Komal Dayma, Udit Raj Sharma: Data Curation, Formal Analysis, Writing – Review & Editing. Anushika Sharma, Shweta Swaroop, Unbreen Hamid: Resources, Investigation, Project Administration, Validation, Writing – Review & Editing.

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