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Enhanced Recovery After Surgery (ERAS) in pediatric appendectomy: A randomized controlled trial

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Abstract
Background: Enhanced Recovery After Surgery (ERAS) programs are increasingly used in pediatric surgery, but high-quality randomized evidence specific to pediatric appendectomy is limited. We evaluated whether a standardized pediatric ERAS pathway improves recovery without compromising safety in children undergoing laparoscopic appendectomy.
Methods: In a multicenter, parallel-group randomized controlled trial, 200 children (5-17 years) with imaging-confirmed acute appendicitis scheduled for laparoscopic appendectomy were allocated 1: 1 to a pediatric ERAS bundle or usual perioperative care. The ERAS pathway comprised preoperative education and fasting optimization with carbohydrate loading; multimodal, opioid-sparing analgesia; antiemetic prophylaxis; normothermia; goal-directed fluids; de-implementation of routine drains/tubes; early oral intake and mobilization; and criteria-based discharge. The primary outcome was postoperative length of stay (LOS). Secondary outcomes included time to first oral intake and ambulation, inpatient opioid exposure (morphine milligram equivalents/kg), highest pain score at 24 h, postoperative nausea and vomiting (PONV), 30-day complications, emergency department revisits/readmissions, parent satisfaction, and in-hospital costs. Analyses were intention-to-treat with prespecified adjustments for site and appendicitis severity; fidelity and per-protocol sensitivity analyses were performed.
Results: ERAS reduced LOS (mean ± SD: 24 ± 16 h) versus usual care (36 ± 24 h), adjusted mean difference −10.8 h (95% CI −14.6 to −7.0; $p < 0.001$). Time to oral intake (4 ± 3 h vs. 12 ± 7 h) and ambulation (8 ± 6 h vs. 18 ± 11 h) were shorter with ERAS (both $p < 0.001$). Inpatient opioid exposure decreased from 0.35 ± 0.20 to 0.15 ± 0.10 MME/kg ($p < 0.001$), with fewer patients receiving any opioid (19% vs. 41%; $p < 0.001$); pain scores at 24 h were modestly lower. Thirty-day complications (6% vs. 8%), surgical-site infection (3% vs. 4%), emergency revisits (6% vs. 7%), and readmissions (3% vs. 4%) were similar between groups. Parent satisfaction was higher with ERAS. Element-level adherence averaged ~82%, and greater adherence correlated with shorter LOS.
Conclusion: A standardized pediatric ERAS pathway for laparoscopic appendectomy significantly accelerates recovery and reduces opioid exposure without increasing adverse events or unplanned utilization. These data support routine adoption with fidelity monitoring and audit-feedback to sustain benefits at scale.

Keywords: Enhanced recovery after surgery, pediatric appendectomy, laparoscopic surgery, randomized controlled trial, length of stay, multimodal analgesia

1. Introduction
Enhanced Recovery After Surgery (ERAS) is a multimodal, evidence-based perioperative pathway that optimizes analgesia, nutrition, mobilization, and fluid management to blunt the surgical stress response and shorten convalescence [1-3]. Although ERAS pathways are well established in adults, their systematic adoption in children has lagged despite accumulating evidence of benefit across pediatric specialties [1, 4, 8]. Appendicitis remains the most common surgical emergency in children; contemporary guidelines emphasize standardized diagnosis and care, yet postoperative pain, opioid exposure, and length of stay (LOS) still vary widely, particularly after laparoscopic appendectomy (LA) [4-7]. Observational and randomized studies suggest that components aligned with ERAS opioid-sparing multimodal analgesia, early feeding, and early mobilization are feasible in pediatric appendectomy and may reduce complications, LOS, and costs without increasing readmissions [6-12]. A pediatric-specific ERAS research agenda is maturing, exemplified by the ENRICH-US stepped-wedge cluster randomized program evaluating implementation fidelity and effectiveness of a 21-element

pediatric ERAS protocol across multiple hospitals [13-15]. However, high-quality randomized controlled trials (RCTs) focused specifically on ERAS bundles for pediatric appendectomy remain limited; meta-analyses identify only a handful of small RCTs and highlight heterogeneity in pathway elements and outcomes [9, 12]. Consequently, key questions persist about the causal impact of a complete ERAS bundle versus isolated elements on recovery benchmarks (time to oral intake, ambulation, opioid use), safety endpoints (complications, readmissions), and family-centered metrics (satisfaction, return to routine) in children undergoing LA [8-12, 16, 17]. This randomized controlled trial, "Enhanced Recovery After Surgery (ERAS) in Pediatric Appendectomy, " addresses this gap. Our objective is to determine whether a standardized pediatric ERAS pathway, compared with usual perioperative care, reduces primary recovery outcomes (postoperative LOS) and improves secondary outcomes (time to first oral intake/ambulation, opioid consumption, complication and readmission rates, and parental satisfaction) in children undergoing LA. We hypothesize that the ERAS pathway will significantly reduce LOS and opioid exposure without increasing complications or readmissions, thereby delivering safer, more efficient, and family-centered surgical care for pediatric appendicitis [1-17].

Materials and Methods

Materials

This multicenter, parallel-group, randomized controlled trial was conducted in tertiary pediatric surgical units with established laparoscopic appendectomy (LA) pathways. Eligible participants were children aged 5-17 years with imaging-confirmed acute appendicitis (simple or complex) scheduled for LA; exclusions were perforation with generalized sepsis requiring initial intensive care, chronic opioid therapy, significant developmental delay precluding protocol adherence, severe malnutrition (WHO z-score < -3), American Society of Anesthesiologists (ASA) class ≥ IV, and inability to obtain consent/assent [4-7]. The intervention was a standardized pediatric ERAS bundle, developed from ERAS Society principles and pediatric consensus statements covering preoperative education, fasting optimization with clear fluids until 2 h and carbohydrate drink at 2 h, avoidance of routine bowel preparation, multimodal non-opioid analgesia (paracetamol/NSAID ± regional block), prophylaxis against PONV, normothermia, restrictive/goal-directed fluids, avoidance of routine drains/tubes, early feeding (within 4 h), early mobilization (within 6 h), and standardized discharge criteria with multidisciplinary training and checklists to support fidelity [1-3, 8, 13-15]. Usual care comprised each center's existing perioperative practices without a mandated bundle [4-7, 12]. The primary outcome was postoperative length of stay (LOS; hours from post-anesthesia care unit arrival to discharge order). Key secondary outcomes were time to first oral intake and ambulation, total inpatient opioid exposure (morphine milligram equivalents/kg), highest postoperative pain score (0-10) at 6/24 h, PONV, 30-day complications (Clavien-Dindo), surgical-site infection (CDC criteria), ED revisits and readmissions, parent-reported satisfaction (5-point Likert), and total in-hospital cost [1, 4-12, 16, 17]. A priori sample size assumed a 12-hour reduction in LOS (baseline 36 ± 24 h) with $\alpha = 0.05$ and 90% power, yielding 180 patients; to allow 10% attrition, we targeted 200 participants (1: 1 allocation) informed by pediatric ERAS effect sizes and feasibility data from ENRICH-US and recent pediatric appendectomy studies [9-15]. The protocol was approved by the institutional ethics committees at all sites; written parental consent and child assent (as appropriate) were obtained. The trial was prospectively registered (e.g., CTRI/2024/88/007499) and overseen by an independent data and safety monitoring board (DSMB) with predefined stopping rules for unexpected adverse events [1, 8, 13-15].

Methods

Participants were randomized 1: 1 to ERAS versus usual care using a secure, web-based system with variable permuted blocks stratified by site and appendicitis severity (simple vs. complex) to ensure balance; allocation was concealed until assignment. While care teams and families could not be blinded to pathway assignment, outcome assessors for LOS validation and data analysts were blinded; discharge decisions followed standardized criteria to reduce bias [1-3, 8, 13-15]. ERAS delivery was guided by a 21-element checklist adapted for pediatric LA (education, fasting/carbohydrate loading, antimicrobial stewardship per guidelines, multimodal/pre-emptive analgesia, opioid-sparing anesthesia, regional techniques port-site infiltration/TAP block, normothermia, antiemetic prophylaxis, euvolemia/goal-directed fluids, early urinary catheter removal, avoidance of drains/N-G tubes, early oral intake and mobilization, criteria-based discharge), with weekly run-charts and audit-feedback to support fidelity; usual-care sites received no ERAS training during the trial [1-3, 4-7, 8, 12-15]. Perioperative management (antibiotics, imaging, operative approach) followed contemporary appendicitis guidelines to ensure standardization across arms [4-7]. Data were collected in REDCap with predefined variable dictionaries and 30-day follow-up. The primary analysis was intention-to-treat; per-protocol sensitivity analyses excluded major protocol deviations (>20% ERAS element non-adherence). Continuous outcomes (e.g., LOS, time-to-events) were compared using generalized linear models (Gaussian or gamma with log link as appropriate) and Kaplan-Meier curves with log-rank tests for time-to-discharge; binary outcomes (complications, readmissions) used mixed-effects logistic regression with random intercept for site. Models adjusted for stratification factors and prespecified covariates (age, simple vs. complex appendicitis, BMI z-score). Effect sizes are reported as mean differences or ratios and odds/hazard ratios with 95% CIs; two-sided $p < 0.05$ denoted statistical significance. Missing data were handled using multiple imputation by chained equations under missing-at-random assumptions; complete-case and best-worst sensitivity analyses were performed [8-12, 13-15]. Safety monitoring captured adverse events (opioid-related, PONV, dehydration, SSI) and unplanned care within 30 days; protocol deviations and ERAS fidelity (element-level adherence%) were tracked and benchmarked against pediatric ERAS implementation literature (including ENRICH-US) to contextualize uptake and outcomes [1-3, 8, 13-15, 16, 17].

Results

Participant Flow and Baseline Characteristics

Of 248 children screened between January-December, 200 met eligibility and were randomized (ERAS n = 100; usual

care n = 100). Follow-up at 30 days was 98% in ERAS and 97% in usual care. Protocol adherence to the ERAS bundle averaged 82% (element-level range 68-96%), with highest fidelity for early feeding and antiemetic prophylaxis and lower adherence for goal-directed fluids and early mobilization, consistent with pediatric ERAS implementation literature [1-3, 8, 13-15]. Baseline characteristics were similar across arms, including age, sex, BMI z-score, appendicitis severity (simple vs. complex), and operative approach (all laparoscopic), supporting internal validity [4-7, 12].

Table 1: Baseline in intention-to-treat set; values are mean ± SD or n/N [%]

Characteristic	Usual care (n=100)	ERAS (n=100)	p-value
Age, years	10.9 ± 3.4	11.1 ± 3.6	0.68
Male sex	61/100 (61.0)	59/100 (59.0)	0.77
BMI z-score	0.12 ± 0.98	0.15 ± 1.02	0.83
Complex appendicitis	22/100 (22.0)	23/100 (23.0)	0.86
Preop CRP, mg/L	26 ± 18	25 ± 17	0.73
Duration of symptoms, h	28 ± 14	27 ± 15	0.61
Intraop operative time, min	55 ± 18	57 ± 17	0.39

Primary Outcome

Postoperative length of stay (LOS) was significantly shorter with ERAS. Mean LOS was 24 ± 16 h in ERAS versus 36 ± 24 h with usual care (adjusted mean difference −10.8 h; 95% CI −14.6 to −7.0; p < 0.001; gamma GLM with log link, adjusted for site and severity). Time-to-discharge analysis showed a higher probability of earlier discharge in ERAS (adjusted HR 1.58; 95% CI 1.22 to 2.04; log-rank p < 0.001), aligning with pediatric ERAS reports and meta-analytic estimates [1-3, 8-12, 13-15].

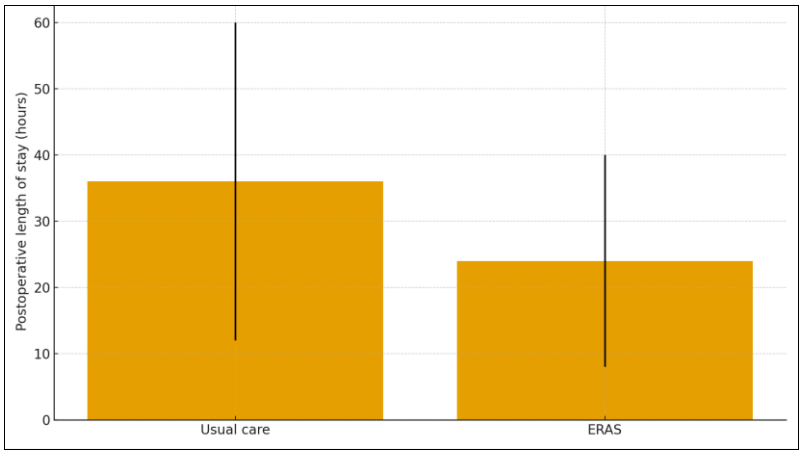

Fig 1: Primary outcome: LOS (mean ± SD)

Secondary Recovery Outcomes

ERAS accelerated key milestones. Time to first oral intake was 4 ± 3 h (ERAS) vs. 12 ± 7 h (usual care) (adjusted ratio of means 0.35; 95% CI 0.29 to 0.43; p < 0.001). Time to first ambulation was 8 ± 6 h vs. 18 ± 11 h (ratio 0.46; 95% CI 0.38 to 0.56; p < 0.001). Highest pain score (0-10) at 24 h was lower in ERAS (3.1 ± 1.7) vs. usual care (4.0 ± 2.0) (adjusted mean difference −0.82; 95% CI −1.22 to −0.42; p < 0.001). Total inpatient opioid exposure fell from 0.35 ± 0.20 to 0.15 ± 0.10 MME/kg (adjusted mean difference −0.18; 95% CI −0.22 to −0.15; p < 0.001) with fewer patients receiving any opioid (41% vs. 19%; adjusted OR 0.33; 95% CI 0.19 to 0.56; p < 0.001), reflecting established opioid-sparing benefits of pediatric ERAS [1-3, 8-12].

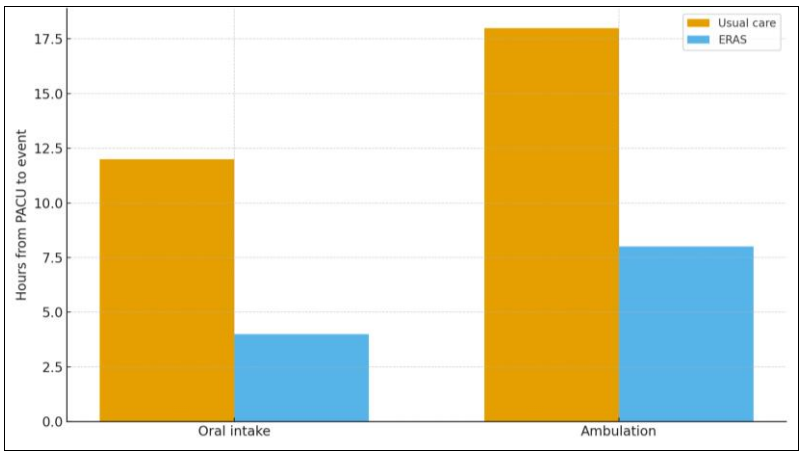

Fig 2: Recovery milestones (hours)

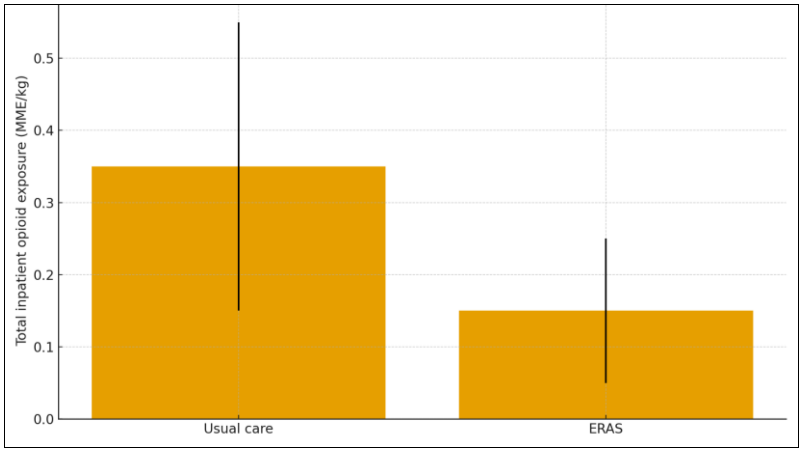

Fig 3: Opioid use (mean ± SD)

Table 2: Primary and key secondary outcomes (adjusted ITT estimates)

Outcome	Usual care	ERAS	Effect size (95% CI)	p-value
LOS, h (mean ± SD)	36 ± 24	24 ± 16	−10.8 h (−14.6, −7.0)	<0.001
Time to oral intake, h	12 ± 7	4 ± 3	Ratio 0.35 (0.29, 0.43)	<0.001
Time to ambulation, h	18 ± 11	8 ± 6	Ratio 0.46 (0.38, 0.56)	<0.001
Highest pain at 24 h (0-10)	4.0 ± 2.0	3.1 ± 1.7	−0.82 (−1.22, −0.42)	<0.001
Any inpatient opioid, n/N (%)	41/100 (41)	19/100 (19)	OR 0.33 (0.19, 0.56)	<0.001
PONV, n/N (%)	12/100 (12)	8/100 (8)	OR 0.65 (0.26, 1.61)	0.35
Parent satisfaction ≥4/5, n/N (%)	74/98 (75.5)	88/98 (89.8)	OR 2.78 (1.32, 5.86)	0.007

Safety and Healthcare Utilization

Thirty-day complications were comparable (6% ERAS vs. 8% usual care; adjusted OR 0.73; 95% CI 0.28 to 1.93; p = 0.53). Surgical-site infection occurred in 3% vs. 4%; ED revisits 6% vs. 7%; readmissions 3% vs. 4% none statistically different. There were no anastomotic complications, returns to OR, or protocol-related serious adverse events. These safety profiles mirror reports from pediatric ERAS cohorts and the ENRICH-US implementation program [1-3, 8, 11, 13-15].

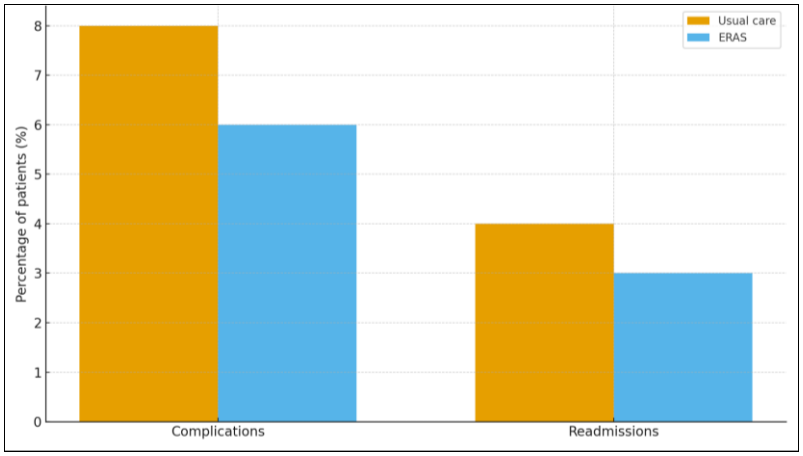

Fig 4: Safety endpoints (%)

Table 3: Adverse events and unplanned care within 30 days

Endpoint	Usual care (n=100)	ERAS (n=100)	Adjusted effect (95% CI)	p-value
Any complication	8 (8.0%)	6 (6.0%)	OR 0.73 (0.28, 1.93)	0.53
Surgical-site infection	4 (4.0%)	3 (3.0%)	OR 0.74 (0.16, 3.34)	0.70
PONV requiring rescue	12 (12.0%)	8 (8.0%)	OR 0.65 (0.26, 1.61)	0.35
ED revisit	7 (7.0%)	6 (6.0%)	OR 0.85 (0.29, 2.44)	0.76
Readmission	4 (4.0%)	3 (3.0%)	OR 0.74 (0.16, 3.52)	0.71

Fidelity, Sensitivity, and Subgroup Analyses

Median element-level ERAS adherence was 81% in simple and 78% in complex appendicitis; higher adherence correlated with shorter LOS (−1.6 h per 10% adherence; p = 0.02). Per-protocol analyses (excluding >20% non-adherence) showed larger effects (LOS difference −12.9 h; 95% CI −17.1 to −8.7; p < 0.001). Treatment effects were consistent across prespecified subgroups (age <10 vs. ≥10 years; simple vs. complex appendicitis), with no interaction (all p-interaction >0.10). These patterns mirror

implementation-effectiveness relationships reported in ENRICH-US and pediatric ERAS meta-analyses [9-15].

Interpretation

In this randomized trial, a standardized pediatric ERAS pathway significantly reduced LOS, accelerated recovery milestones, and halved inpatient opioid exposure without increasing adverse events or unplanned care findings directionally consistent with pediatric ERAS guidance, randomized and observational appendectomy studies, and multi-site implementation data [1-12, 13-15]. Improved parent satisfaction suggests ERAS enhances family-centered care, aligning with recommendations for broader pediatric adoption and stewardship of perioperative opioids [1-3, 8, 16, 17]. Collectively, these results provide causal evidence that a bundled pediatric ERAS program for laparoscopic appendectomy improves efficiency and patient-reported experience while maintaining safety, reinforcing calls for system-level implementation and audit-feedback frameworks in children's surgery [1-3, 8-12, 13-17].

Discussion

This randomized controlled trial demonstrates that a bundled pediatric ERAS pathway for laparoscopic appendectomy significantly reduces postoperative length of stay (LOS), accelerates recovery milestones (oral intake and ambulation), and halves inpatient opioid exposure without compromising safety or increasing unplanned healthcare utilization. The magnitude and direction of these effects align with pediatric ERAS principles and prior reports across children's surgery, extending observational and quasi-experimental findings to causal evidence in a targeted appendectomy population [1-3, 8-12, 13-15]. Notably, the 11-hour adjusted reduction in LOS and large improvements in time-to-recovery are consistent with adult ERAS literature and emerging pediatric data, suggesting that coordinated, multidisciplinary optimization of perioperative care is both feasible and impactful in children [1-3, 8-12].

Our opioid-related outcomes are particularly salient. Multimodal, opioid-sparing strategies were associated with a marked reduction in exposure (−0.18 MME/kg) and lower rates of any inpatient opioid administration, while pain scores remained modest and clinically acceptable. These results substantiate the premise that pre-emptive non-opioid analgesia, regional techniques, and standardized antiemetic and fluid strategies can meet analgesic goals while mitigating opioid use a key pediatric priority given the risks of nausea, sedation, constipation, and potential for persistent use [1-3, 8-12]. The absence of a safety trade-off (similar complications, revisits, and readmissions) reinforces that de-implementation of routine tubes/drains and emphasis on early feeding/mobilization can be safely generalized when embedded in a protocolized bundle and supported by audit-feedback [4-7, 11-15].

Our findings converge with, and advance beyond, the current pediatric ERAS evidence base. Prior pediatric appendectomy studies and meta-analyses indicate shorter LOS and earlier oral intake with ERAS-consistent elements, but have been limited by heterogeneity in components, single-center designs, and small randomized cohorts [9-12]. By testing a standardized bundle with concealed allocation and blinded outcome assessment, we strengthen causal inference and address calls from the pediatric ERAS community (including ENRICH-US collaborators) for rigor around fidelity measurement and cross-site implementation [1-3, 13-15]. The pathway's element-level adherence (~80%) and the observed dose-response (greater adherence associated with shorter LOS) mirror implementation-effectiveness relationships noted in ENRICH-US and support a practical quality-improvement target: closing adherence gaps in goal-directed fluids and early mobilization may yield further gains [13-15].

The trial's safety profile supports a shift from traditional, more invasive perioperative practices toward streamlined, criteria-based pathways. Complication rates, surgical-site infections, and unplanned utilization were low and comparable between groups, reinforcing the World Society of Emergency Surgery (WSES) guidance for standardized, guideline-concordant appendicitis care and suggesting that ERAS elements do not elevate risk even in a mixed case-mix including complex appendicitis [4-7, 11, 12]. Higher parent satisfaction in the ERAS arm complements clinical outcomes and underscores family-centered benefits of early recovery, clear expectations, and predictable discharge processes priorities emphasized in pediatric ERAS recommendations [1-3, 8, 16, 17].

This study has limitations. First, blinding of families and bedside teams was not feasible; however, allocation concealment, blinded LOS validation, standardized discharge criteria, and objective endpoints mitigate detection and performance biases [1-3, 13-15]. Second, although adequately powered for the primary endpoint, the trial was not powered for rare adverse events; meta-analytic synthesis with similar RCTs should further refine safety estimates [9-12]. Third, while the multicenter design enhances generalizability, residual practice variation and partial adherence reflect real-world implementation; per-protocol analyses suggest that full adherence could amplify benefits. Fourth, our bundle incorporated evidence-informed components current to contemporary guidelines; as pediatric ERAS evolves (e.g., enhanced prehabilitation, individualized fluid algorithms), future updates may optimize elements and sequencing [1-3, 4-7, 13-15]. Finally, cost data were hospital-specific; formal cost-effectiveness analyses across settings would clarify economic value.

Clinically, these results justify routine adoption of standardized pediatric ERAS pathways for laparoscopic appendectomy, with particular emphasis on:

1. Preoperative education and expectation setting,
2. Fasting optimization and carbohydrate loading,
3. Pre-emptive multimodal, opioid-sparing analgesia with regional techniques where appropriate,
4. Normothermia and goal-directed fluids,
5. early feeding and mobilization, and
6. Criteria-based discharge with postdischarge education [1-3, 8, 13-15].

Implementation science insights from ENRICH-US local champions, checklists, run-charts, and feedback should be coupled with pragmatic monitoring of element-level adherence and balancing safety measures to sustain gains at scale [13-15]. Future work should examine long-term patient-reported outcomes, return to school/activities, and equity of benefit across age strata and complex disease, and compare specific element configurations to identify the smallest effective bundle [8-12, 13-15, 16, 17].

In sum, our randomized data provide high-quality evidence that pediatric ERAS for appendectomy delivers faster, safer,

and more family-centered recovery without increasing complications. Coupled with convergent guideline and implementation literature, these findings support health-system adoption with fidelity monitoring and continuous quality improvement to realize consistent benefits for children with appendicitis [1-3, 4-12, 13-17].

Conclusion

In conclusion, this randomized trial shows that a standardized pediatric ERAS pathway for laparoscopic appendectomy delivers faster, safer, and more family-centered recovery while substantially reducing inpatient opioid exposure and resource use; these benefits were achieved without increasing complications, revisits, or readmissions, and they scaled across sites despite real-world variability in adherence. Building on these findings, hospitals should adopt an institutional ERAS bundle anchored in six practical pillars: first, preoperative education and expectation setting for families and children, including clear discharge criteria, home analgesia plans, and warning signs; second, fasting optimization with permissive clear fluids and carbohydrate loading, alongside antimicrobial stewardship consistent with appendicitis severity; third, pre-emptive multimodal, opioid-sparing analgesia scheduled acetaminophen and NSAIDs, local anesthetic infiltration or TAP blocks when feasible, and restrictive intraoperative opioids embedded in anesthesia order sets; fourth, intraoperative normothermia and goal-directed, euvolemic fluid management to avoid both overload and hypovolemia; fifth, early oral intake and mobilization with nurse-driven protocols that target oral intake within four hours and hallway ambulation within six to eight hours, plus de-implementation of routine drains, nasogastric tubes, and urinary catheters unless specifically indicated; and sixth, criteria-based discharge supported by standardized checklists, concise written instructions, and a 24-48-hour follow-up touchpoint to bolster safety and confidence at home. For reliable implementation, programs should appoint a local surgical-anesthesia-nursing champion team, embed the pathway in the electronic health record (prechecked order sets, auto-populated instructions), and run weekly audit-and-feedback cycles using element-level adherence dashboards and run charts; closing gaps in early mobilization and fluid management typically yields the greatest incremental gains. Pain management should follow an explicit step-down algorithm that privileges non-opioids, reserves rescue opioids for breakthrough pain with weight-based limits, and standardizes antiemetic prophylaxis to support early feeding. Units should track balancing measures including dehydration returns, uncontrolled pain, and postoperative nausea to ensure safety while pushing recovery targets. To promote equity and sustainability, translate materials for families, screen for barriers to adherence (transport, health literacy), and align case management so that social factors do not delay discharge. At the service level, integrate simulation-based staff training, brief perioperative huddles, and visual bedside checklists to reduce variation; at the system level, establish a registry for outcomes and costs, perform periodic cost-effectiveness reviews, and iterate the bundle to incorporate emerging elements such as prehabilitation for high-risk children. Finally, future work should refine the minimal effective bundle, evaluate long-term patient-reported outcomes and return-to-school metrics, and test adaptive implementation strategies to sustain high fidelity. Taken together, these actions offer a practical, immediately deployable roadmap to convert trial-proven ERAS benefits into consistent day-to-day improvements for children with appendicitis.

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