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# Tubeless technique with artificial intelligence empowerment: advancing from "enhanced recovery" toward "immediate recovery" in surgery

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## INTRODUCTION

Since Kehlet introduced Enhanced Recovery After Surgery (ERAS) in the late 1990s, multimodal, evidence-based perioperative care has substantially reshaped surgical practice[1]. Through preoperative optimization, minimally invasive surgery, and early mobilization and feeding, ERAS shortens hospital stay by ~1.9 days and reduces complications by ~29%[2,3]. Yet recovery is still deemed to begin within 24 h after surgery - by which time hypothalamic-pituitary-adrenal (HPA)-axis activation, disturbed cerebral perfusion pressure (CPP), systemic inflammation, and transient immunosuppression are already underway[4].

In thoracic surgery, the tubeless technique developed by Professor Jianxing He's team has advanced the field[5]: by avoiding invasive tubes and combining precision sedation with regional blocks, carefully selected patients undergo Video-Assisted Thoracoscopic Surgery (VATS) while breathing spontaneously[6,7], which avoids or attenuates stressors such as mechanical ventilation and deep sedation rather than removing surgical stress itself. Building on these modifications, we propose using "Immediate Recovery Surgery (IRS)". This ERAS-based framework brings recovery milestones forward, enabling suitable patients to resume oral intake, mobilize, and communicate on the day of surgery. IRS is offered as a domain-specific refinement within ERAS and as a hypothesis for evaluation, not as a validated replacement, since its application is predominantly thoracic (pulmonary nodules and early-stage lung cancer).

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In parallel, machine-learning-based perioperative decision-support tools are gradually moving from retrospective model development toward evaluation in clinical settings. Relevant studies include radiomics- and deep-learning-based approaches that integrate clinical, imaging, and molecular features to support pulmonary nodule risk stratification and individualized pathway planning, as illustrated by the DECIPHER-NODL model[8]; hypotension warning systems designed to reduce the risk of intraoperative hypotension[9]; and prospective assessments of machine learning (ML)-generated postoperative risk estimates as adjuncts to clinician judgment[10]. In China, "Nan-Fang-Zhi-Ma" anesthesia mode and the "Shen-Gong-Shen-Shu" operating-room platform have been publicly reported as emerging implementation examples[11,12]. Such tools may help refine thoracic perioperative care, though their added value remains to be demonstrated[13].

## FROM ENHANCED RECOVERY TO IMMEDIATE RECOVERY: A SCIENTIFIC LEAP

### ERAS achievements and internal limitations

ERAS's rationale is acceleration: shortening the time to return to baseline function through coordinated perioperative measures. However, in clinical practice, several potent iatrogenic stressors - mechanical trauma from intubation and positive-pressure ventilation, and the immunomodulatory effects of deep sedation and neuromuscular blockade - may arise during the intraoperative phase[14], leaving a window in which neuroendocrine, inflammatory, and immune cascades can amplify before selected postoperative ERAS interventions can take effect. ERAS addresses these consequences through coordinated perioperative optimization[1,2], whereas IRS aims to narrow this window from within ERAS, not to depart from it, by reducing selected iatrogenic triggers in carefully selected patients.

### Immediate recovery surgery as a proposed extension of ERAS

Operationally, we define IRS as an ERAS-based perioperative pathway with tubeless intraoperative implementation, in which carefully selected patients maintain spontaneous breathing; avoid routine tracheal intubation, urinary catheterization, and postoperative chest drainage when clinically appropriate; receive precision regional anesthesia and opioid-sparing analgesia; and reach predefined recovery milestones during emergence from anesthesia or on the day of surgery. IRS is therefore best understood not as a replacement for ERAS but as a domain-specific refinement within it, in which the intraoperative technical package is chosen specifically to reduce iatrogenic perturbation and advance the point at which recovery can begin.

Framed this way, the IRS's contribution is primarily conceptual and organizational rather than a new biological mechanism: its elements - non-intubated/awake anesthesia and ERAS - already exist. What IRS adds is threefold: (i) it designates a specific tubeless intraoperative package as the means of attenuating surgical stress upstream within an ERAS pathway; (ii) it shifts the start of recovery toward emergence and the day of surgery; and (iii) it attaches predefined, measurable milestones and explicit safety boundaries to that timepoint, so that "immediate" recovery becomes an auditable endpoint rather than a rhetorical claim [Table 1]. This milestone-and-safety specification is what distinguishes IRS from simply combining non-intubated VATS with a standard ERAS pathway.

Because this evidence derives almost entirely from thoracic surgery - non-intubated and tubeless VATS for pulmonary nodules and early-stage lung cancer - the IRS framework is presented here primarily in a thoracic context. Whether it extends to abdominal, orthopedic, cardiac, esophageal, or other procedures remains an open question that would benefit from further cross-specialty study.

**Table 1. Operational definition and measurable endpoints distinguishing ERAS from the proposed IRS framework**

| Dimension | ERAS | IRS | Measurable endpoint/operational criterion | Assessment domain |
|---|---|---|---|---|
| Framework orientation | General enhanced-recovery framework emphasizing full-chain perioperative management[2] | ERAS-based pathway with tubeless intraoperative implementation; "ERAS outside + tubeless inside" | Protocol specifies eligibility, tubeless components, rescue criteria, and same-day recovery milestones | Process/organizational |
| Recovery activation time | Recovery activities usually begin several hours to 24 h after surgery[3] | IRS hypothesizes earlier recovery activation during emergence from anesthesia or on the day of surgery in selected patients | Time from the end of surgery or arrival in the post-anesthesia care unit to awake verbal communication, oral intake, and ambulation; very early activation within the first postoperative hour may be explored when feasible | Clinical recovery |
| Tube and airway pathway | Conventional tracheal intubation, urinary catheterization, and drainage may be used as part of routine practice | Avoids routine tracheal intubation, urinary catheterization, and postoperative chest drainage when clinically appropriate; preserves spontaneous breathing[24] | No routine tube placement; record conversion to intubation, catheter reinsertion, chest-tube reinsertion, or rescue drainage | Safety |
| Intervention level | Coordinated perioperative multimodal optimization, including early feeding, early mobilization, and complication prevention | Hypothesized upstream reduction of selected iatrogenic physiological disturbances through precision anesthesia, regional nerve block, and opioid-sparing analgesia[17] | Anesthetic dose, opioid and muscle-relaxant exposure, oxygenation, hemodynamics, and conversion/rescue events | Process (exposure)/Safety |
| Core functional target | Shorter length of stay and lower complication rates[2] | Proposed focus on earlier restoration of basic life and social functions, including speaking, oral intake, and walking, potentially on the day of surgery in selected patients | Time to speaking, drinking/eating, standing/walking, discharge readiness, length of stay, and patient-reported recovery | Clinical recovery |
| Immune and inflammatory protection | Partial optimization through reduced surgical stress and perioperative care bundles | May help preserve cellular immune status and attenuate inflammatory activation by reducing avoidable tubes, deep sedation, and mechanical ventilation[5,15,16,19] | NK-cell activity changes and inflammatory markers such as IL-6, CRP, and TNF-alpha | Biological/Mechanistic biomarkers |
| Pain prevention | Routine multimodal analgesia and postoperative pain control | Precision regional nerve block combined with a low-stress tubeless strategy, hypothesized to reduce nociceptive input and central sensitization[3] | Acute pain score, opioid consumption, and chronic post-surgical pain incidence during follow-up | Clinical recovery (pain) |
| Safety boundary | Applicable across broad ERAS populations with procedure-specific adaptation | Restricted to carefully selected patients with predefined conversion and rescue pathways[24] | Conversion to intubation, respiratory failure, major complications, readmission, reintervention, and mortality | Safety |

Endpoints are grouped by dimension in the table above. Endpoints are further classified into three assessment domains to support future validations: clinical-recovery endpoints (e.g., time to oral intake, ambulation, verbal communication, discharge readiness, and length of stay), biological/mechanistic markers (e.g., NK-cell activity, IL-6, CRP, and TNF-α), and safety outcomes (e.g., conversion to intubation, respiratory failure, reintubation, reintervention, readmission, and mortality). Rows addressing the framework orientation and intraoperative intervention also carry process/exposure measures, which are not outcome endpoints and are labelled accordingly. ERAS: Enhanced Recovery After Surgery; IRS: Immediate Recovery Surgery; NK: natural killer; IL-6: interleukin-6; CRP: C-reactive protein; TNF-α: tumor necrosis factor-alpha.

The proposed IRS framework involves five dimensions:

(1) Earlier initiation of recovery - during emergence or within the first postoperative hour, measured from the end of surgery or arrival in the post-anesthesia care unit rather than several hours later - to intervene before stress, inflammatory, and catabolic cascades are fully amplified; the extent of benefit against the Table 1 endpoints remains to be shown.

(2) Reduction of upstream iatrogenic perturbation - chiefly by avoiding mechanical ventilation, deep sedation, and unnecessary tubes in selected patients.

(3) Potential immune preservation (preliminary): surgical trauma can activate systemic inflammatory and stress responses and transiently perturb antitumor immune status. A study preliminarily suggested that, compared with tracheal intubation, supraglottic airway management may be more favorable for postoperative recovery of (natural killer) NK cell maturation and activation status in patients undergoing surgery[5]. Another randomized controlled trial reported significantly lower early postoperative interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α) levels after non-intubated thoracic surgery than after intubated surgery[15,16].

(4) Possible attenuation of chronic-pain pathways: precision regional blockade may reduce the central sensitization implicated in chronic post-surgical pain (CPSP), consistent with emerging evidence[17]. Limited non-intubated thoracic surgery data suggest a possible, non-significant trend toward lower long-term analgesic use[18]. The specific contribution of this component within an IRS pathway has not been prospectively quantified.

(5) A shift in patient experience - toward earlier comfort, oral intake, mobilization, and communication in selected patients.

## CORE SCIENTIFIC MECHANISM: A MULTI-LEVEL PHYSIOLOGICAL CASCADE

We frame the tubeless rationale as a nonlinear, multi-level cascade in which a small reduction in iatrogenic input - avoiding intubation, positive-pressure ventilation, deep neuromuscular blockade, and chest-tube nociception - may attenuate downstream stress, inflammatory, and immune responses. We invoke the "butterfly effect" only as an illustrative heuristic, not a literal description: the surgical stress response is multifactorial, only partly modifiable by any single intervention, and the contribution of each avoided stressor is unquantified. The levels below are therefore a mechanistic hypothesis rather than an established causal chain.

(1) HPA-axis/sympathoadrenal attenuation and cerebral perfusion: nociception and tissue injury drive the HPA axis [corticotropin-releasing hormone (CRH)→adrenocorticotropic hormone (ACTH)→cortisol] and catecholamine release, while intubation, positive-pressure ventilation, and deep sedation impose additional stimuli. Avoiding them may attenuate - not abolish - stress-hormone release; meanwhile, spontaneous negative-pressure ventilation avoids the raised intrathoracic pressure that impedes cerebral venous drainage, helping preserve cerebral perfusion. These effects are plausible but unquantified in tubeless cohorts.

(2) Systemic inflammation: tissue trauma releases damage-associated molecular patterns that activate innate signaling [e.g., nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB)] and drive cytokine release; IL-6 stimulates hepatic C-reactive protein (CRP) production, and mechanical/one-lung ventilation adds ventilator-induced biotrauma. Preliminary thoracic surgery studies suggest a trend toward lower early postoperative IL-6, CRP, and TNF-α levels after non-intubated approaches compared with intubated approaches[5,15,16,19]. But these data derive from only two thoracic (lung-resection) cohorts and vary with procedure, resection extent, and patient factors; they should therefore be read as preliminary and setting-specific, pending broader validation.

(3) Pharmacological "subtraction": reducing opioids and neuromuscular blockers lowers the cumulative drug load. Opioids and volatile agents are immunomodulatory, and high opioid exposure has been linked to impaired NK function; an opioid- and relaxant-sparing strategy may attenuate these side effects, though the beneficial effect in tubeless surgery remains unmeasured and likely modest.

(4) Cellular immunity and central sensitization: one high-dimensional single-cell study linked tubeless management with relative NK-cell preservation[5]. Given the role of NK cells in immunosurveillance, this is a plausible advantage for cancer patients. Still, it rests on a single preliminary dataset, and translation to long-term oncological outcomes remains unproven. For pain, combining regional blockade with reduced upstream drive could act on two contributors to central sensitization - a hypothesized, not demonstrated, dual mechanism.

## ARTIFICIAL INTELLIGENCE PERIOPERATIVE EMPOWERMENT: FROM TECHNICAL ASSISTANCE TOWARD INTELLIGENT DECISION SUPPORT

Whereas the tubeless approach minimizes intraoperative iatrogenic perturbation, artificial intelligence (AI) can shift perioperative management from experience-driven to data-informed. Within the IRS, AI is best viewed not as an autonomous decision-maker but as a decision-support layer spanning the perioperative chain - patient selection, intraoperative control of the narrow margins that spontaneous-breathing anesthesia demands, and earlier detection of deterioration during recovery. Because the IRS depends on well-selected patients tolerating surgery without an artificial airway, catheter, or chest drain, the quality of stratification and vigilance matters more than in conventional pathways. As a concept-proposing Perspective, this article does not present original AI data; the applications below illustrate how AI could support the IRS and are still being developed and prospectively validated.

(1) Preoperative - selection and risk stratification. Previous studies have developed risk scores to stratify postoperative complication risk in patients undergoing non-intubated VATS[20]. More recently, machine-learning models have also been explored for perioperative risk prediction; for example, one machine-learning analysis of uniportal anatomical segmentectomy reported an accuracy of approximately 70% for predicting prolonged air leak (PAL)[21]. Air leak is a key safety boundary for omitting chest drainage, such PAL prediction models may help stratify patients and inform selection for non-intubated or tubeless pathways. However, these should be read as illustrative rather than definitive, since they derive from a single-center cohort and performance varies with case mix; any such figure is hypothesis-generating until validated in thoracic tubeless populations. Such tools should support, not replace, judgment - e.g., a high predicted risk could move a borderline candidate toward a conventional intubated approach - with thresholds defined and validated prospectively.

(2) Intraoperative - closed-loop control. Sustaining sedation and analgesia while preserving spontaneous breathing under artificial pneumothorax leaves a narrow margin - inadequate depth risks patient movement and airway compromise, while excessive depth may suppress respiratory drive - making precise anesthetic control essential. AI-based closed-loop systems that optimize the sedation-analgesia balance bear directly on stable spontaneous ventilation and may reinforce opioid/relaxant-sparing goals[22], though the incremental benefit under non-intubated conditions remains unquantified.

(3) Postoperative - complication prediction. Because the IRS compresses the interval to recovery, early recognition of deterioration is essential as patients mobilize and resume oral intake. Institutional systems such as "Shen-Gong-Shen-Shu" have been described as predicting common postoperative complications (e.g., respiratory or cardiac failure) in real time.

(4) Validation and implementation. The named systems are best regarded as developmental or single-institution prototypes lacking external prospective validation; performance in one specialty or cohort does not automatically transfer to the thoracic tubeless setting. Implementation imposes a learning curve distinct from the surgical/anesthetic one - staff must interpret outputs, recognize unreliable predictions, and avoid automation complacency and alert fatigue - and tools validated at high-volume centers may require recalibration elsewhere. Until externally validated, AI is best positioned as an adjunct that supports rather than replaces clinical judgment.

## INTEGRATION PATH AND FUTURE OUTLOOK

### ERAS + tubeless + AI

The three components are complementary, not competing: ERAS provides the full-chain perioperative framework, the tubeless approach refines its intraoperative phase, and AI adds data-driven support spanning selection and risk stratification, intraoperative management, and complication surveillance. Rather than replacing ERAS, IRS is an ERAS-based extension that combines reduced intraoperative iatrogenic perturbation with AI-assisted decision support, aiming to move selected patients further along the recovery curve - toward milestones reached during emergence or on the day of surgery - while acknowledging that the magnitude and consistency of any such shift remain to be established in prospective comparative studies.

### Challenges

Whether and how the tubeless approach is adopted depends on patient selection, team experience, and safety infrastructure.

First, maintaining gas exchange during spontaneous ventilation under an open or artificial pneumothorax is anesthetically demanding, and the team must be prepared to convert to intubated general anesthesia should instability arise rapidly[23,24]. During the early learning curve and in higher-risk or complex cases, this favors initial adoption at high-volume tertiary centers with experienced teams, structured training, and credentialing - a higher-volume-centers-first model.

Second, and without contradiction, tubeless protocols avoid the placement of double-lumen tubes and single-lung ventilation. This eliminates one specific, skill-intensive step but does not reduce overall anesthetic complexity; readiness for emergent airway control and lung isolation must be maintained. For carefully selected low-risk patients, and as team experience accumulates, the absence of this step may gradually lower one barrier to broader adoption, supported by emerging consensus statements and technical standards[3,25]. This should not, however, be read as a claim that the technique is already broadly suited to lower-resource settings: safe dissemination beyond experienced centers still depends on adequate training and on maintained capacity for rapid conversion and airway rescue. The apparent tension between "requiring an expert team" and "spreading more widely" is therefore one of sequence and patient selection - broader use should follow accumulated experience and safeguards, not precede them.

Third, the AI components require external, prospective validation before routine reliance and raise concerns about data governance, transparency, and explainability. Because performance varies across centers, learning curve and training considerations also apply to digital tools.

### Future directions

Research should prioritize multicenter randomized trials comparing IRS with conventional ERAS; standardized, measurable definitions of "immediate" recovery with prespecified endpoints and safety indicators; prospective validation of the proposed immunological advantages and their link to long-term oncological outcomes; and quantification of the contribution of tubeless protocols to CPSP reduction.

Because the evidence is almost entirely thoracic, extension to other specialties - and to more complex cardiac and esophageal procedures - should be tested rather than assumed[26].

## CONCLUSION

Perioperative care continues to evolve toward earlier, better-defined recovery. Within an ERAS-based framework, the tubeless approach may reduce intraoperative iatrogenic stress, while AI can support more precise, individualized decisions. For appropriately selected patients - at present principally those undergoing thoracic procedures - this combination offers a plausible route to recovery that is not only faster but also anchored to explicit, measurable milestones. Whether it confers consistent benefit over conventional ERAS and generalizes beyond thoracic surgery remains to be tested in prospective, multicenter studies.

## DECLARATIONS

### Authors' contributions

Made substantial contributions to the conception of the work: Zhang M, Liu H, Xu X, Thiery JP, Zhong N, He J

Performed clinical observations and provided practical feedback: Peng G, Yang C, Liu X, Wang W (Wenjun Wang), Li S, Xie S, Liang M

Provided important administrative and technical support: Wang W (Wenxi Wang), Wang W (Wenjun Wang)

Drafted the initial manuscript: Zhang M, Shi J, Wang R, Wang W (Wenxi Wang)

Revised the manuscript critically for important intellectual content: Zhang M, Thiery JP, He J

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He J is an Editorial Board Member of *Artificial Intelligence Surgery*. He J was not involved in any steps of editorial processing, notably including reviewer selection, manuscript handling, and decision-making. The other authors declare no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

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