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A SYSTEMS-BASED APPROACH TO SAFETY IN PITUITARY SURGERY

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ABSTRACT

Background. Perioperative management of patients with pituitary tumors is challenging, because it involves complex anatomical, physiological, and pathological considerations that require meticulous attention and seamless teamwork across all stages of care.

Objective. This review aims to explore a comprehensive, safety-oriented approach to pituitary surgery by integrating technical precision with system-level safeguards.

Scope and Methods. We present a narrative review of the perioperative continuum of pituitary surgery, with an emphasis on structured safety strategies and teamwork models.

Key Findings and Clinical Implications. Patient safety must be the foundation of every phase of care. Incorporating frameworks such as the WHO Surgical Safety Checklist, Enhanced Recovery After Surgery (ERAS) pathways, Reason's Swiss-cheese model, Non-Technical Skills for Surgeons (NOTSS), Resilience Engineering, and Surgical Coaching, creates defensive layers that reduce risk.

Conclusion. This integrated, team-based application of perioperative frameworks has the potential to reduce complications and move pituitary surgery closer to a model of zero harm.

INTRODUCTION

Pituitary adenomas represent 10–15% of intracranial tumors and exhibit a range of clinical characteristics depending on factors such as size, growth pattern, hormone secretion, and histopathology (1). In recent years, substantial progress has been made in the management of pituitary adenomas; however, surgical intervention remains the cornerstone of treatment in most cases (2). The main objectives of surgery are to relieve compression of the optic chiasm caused by the tumor, and, in cases of functioning adenomas, normalize hormone levels to resolve related endocrine syndromes (3). Furthermore, surgery provides histological material for accurate diagnosis, which is essential for tumor subtyping and guiding subsequent therapy (4, 5). Pharmacological options play a critical role in reducing tumor size, controlling hormone hypersecretion, and offering non-invasive alternatives or adjuncts to surgery (6).

The decision to proceed with surgery depends on multiple factors, including tumor size, location, and invasiveness, as well as the patient's age, comorbidities, and functional status. Preoperative magnetic resonance imaging (MRI) and computed tomography (CT), play crucial roles in surgical planning and offer insights into tumor characteristics and surrounding anatomical structures. The surgeon's expertise and experience are also critical considerations (7, 8), and it is advisable that patients be treated in Pituitary Tumor Centers of Excellence (PTCOE) (7).

The transsphenoidal approach is the most commonly used surgical technique, and endoscopic procedures provide sufficient visualization of the surgical field and allow precise tumor removal, potentially leading to improved outcomes and fewer complications (9). As gross total resection is not always feasible, surgery forms part of a multimodal treatment strategy, in which adjuvant medical therapy or radiotherapy may be employed to manage residual tumors or persistent hormone secretion. Reoperation remains an option for recurrence, although altered anatomy and scar tissue increase technical difficulty and risk of complications. Careful patient selection, refined imaging, and adjunctive technologies can enhance the safety of repeat procedures (10). Pituitary surgery requires the integration of comprehensive anatomical knowledge, microsurgical or endoscopic technical skills, and the implementation of new advanced tools. Despite technological improvements, patient safety remains a concern (11).

Surgical complications may result from insufficient preoperative planning, intraoperative errors, or postoperative mismanagements. However, not all adverse events are attributable to technical errors; many stem from non-technical factors, such as inadequate situational awareness, communication failures, unclear leadership, cognitive overload, fatigue, equipment malfunctions, and institutional cultures that discourage open communication (11-13). These latent conditions undermine safety measures, transform routine procedures into high-risk situations, and intensify minor errors. However, it is worth noting that complications do not always imply a mistake: optimizing processes and training reduces, but never entirely eliminates the risk. Therefore, comprehensive training, adherence to established protocols, and effective communication among surgical teams are essential to reduce human error.

Medical errors are preventable adverse events occurring during medical care. Despite increasing awareness and preventive strategies, surgical errors continue to appear at a notably high rate (14). Such errors substantially contribute to perioperative complications and adverse events, resulting in patient harm. Surgical complications continue despite adequate technical skills, highlighting the importance of redesigning perioperative workflows to proactively prevent errors through planning and integrated safety protocols.

In the following sections, we analyze human error and its role in surgical complications; then we examine the safety frameworks that create defensive layers to reduce risk. Building on this foundation, we applied these frameworks across the perioperative continuum of pituitary surgery —preoperative, intraoperative, and postoperative phases. To strengthen clinical applicability, each section concludes with a concise Table of Key Points, complemented by detailed tables in the Appendix.

HUMAN ERROR

Human error is a complex and multifaceted phenomenon that manifests at various levels of cognitive processing (15). Errors are not random occurrences but often assume predictable forms influenced by similarity and frequency biases. Comprehending these error mechanisms can facilitate the design of systems and procedures that are more resilient to human error. There are three primary categories of human errors: *skill-based slips and lapses, rule-based mistakes, and knowledge-based mistakes* (16, 17).

Skill-based slips and lapses are errors that occur during routine activities in familiar environments and often result from attentional failures. These involve either omitting necessary checks (inattention) or executing checks at inappropriate times (over attention). *Rule-based mistakes* occur when individuals use effective rules incorrectly or rely on rules that do not work well in certain problem-solving situations. Such mistakes frequently occur when individuals encounter exceptions to general rules or rely excessively on familiar problem-solving strategies. *Knowledge-based mistakes* emerge when individuals encounter novel situations in which they lack pre-programmed solutions. Examples of human error during pituitary surgery are presented in Table 1 and Appendix Table 1.

Table 1. Human Error in Pituitary Surgery — Key Points
Skill-based slips: occur during routine tasks (e.g., inadvertent dural tears)
Rule-based mistakes: applying the wrong rule in a complex case (e.g., fluid restriction in early diabetes insipidus).
Knowledge-based mistakes: unfamiliar anatomy misinterpreted as 'normal' variation

Human error is a significant concern across high-risk industries such as aviation and nuclear power. Although these fields have distinct characteristics, they face common challenges in prevention and management, with human error recognized as a major contributor to incidents (18, 19). In contrast, the surgical field has been slower to adopt all-inclusive approaches. However, there is a growing recognition of the need for similar systems in healthcare (20), and applying effective error prevention frameworks from high-risk industries can help surgeons minimize human error.

SAFETY FRAMEWORKS IN PITUITARY SURGERY

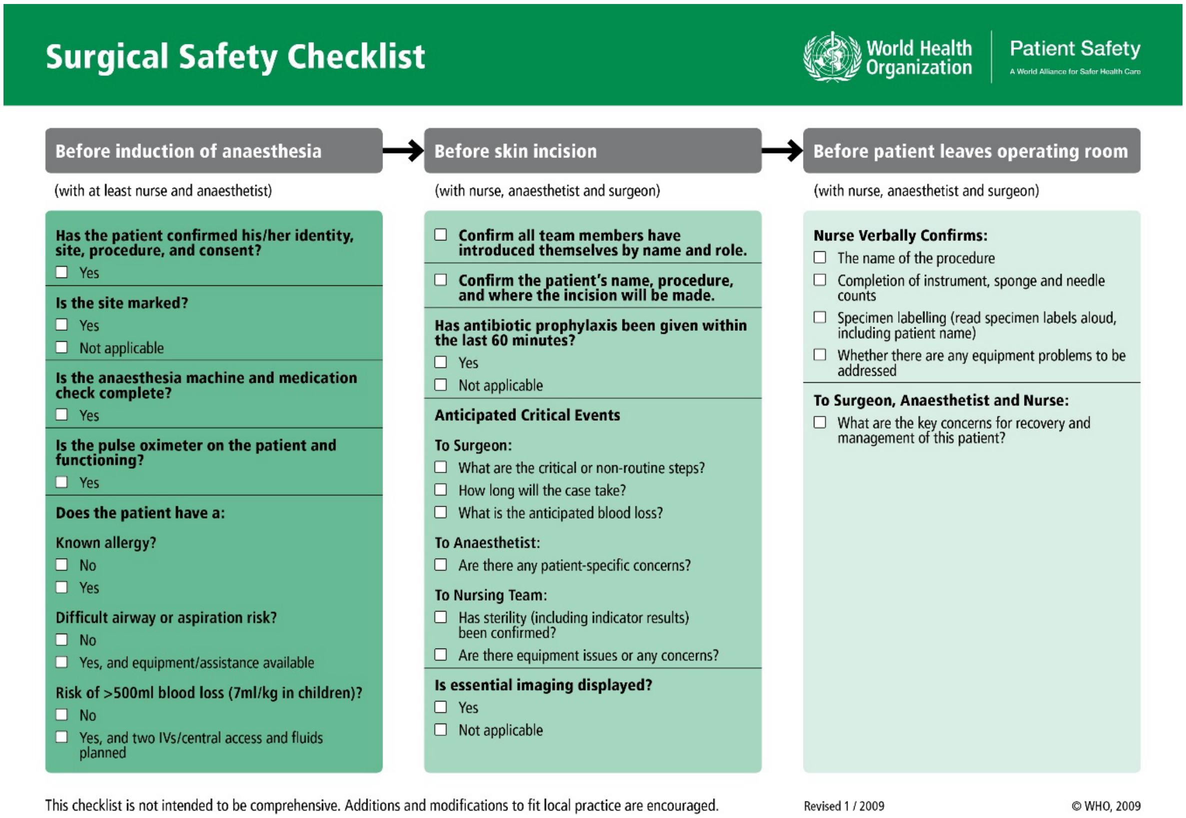
Modern pituitary surgery demands a multi-layered safety strategy that extends beyond the endoscope or microscope. By integrating evidence-based protocols, robust team dynamics, and cognitive aids for high-stakes decision-making, surgeons can anticipate hazards before they materialize, respond swiftly when they do, and learn systematically from every case. As summarized in Table 2, we classified these safety frameworks into three functional categories: *Process Tools*, which provide standardization and outcome metrics; *Human-Factors Frameworks*, which reinforce teamwork, communication, and system resilience; and *Decision-Making Models*, which explain how surgeons manage uncertainty and adapt to intraoperative complexity. Collectively, these elements form an integrated foundation for safer perioperative care. Their application in pituitary surgery is detailed in Table 2 and Appendix Table 2.

Table 2. Core Safety Frameworks for Pituitary Surgery
Process tools WHO Checklist → standardizes safety steps, fosters communication. ERAS Pathways → optimize recovery, shorten stays, improve outcomes. KPI + PROs → combine objective metrics with patient perspectives.
Human-factors Frameworks Swiss-Cheese Model → errors occur when multiple defenses fail. HFACS → traces errors to organizational and supervisory factors. NOTSS → evaluates leadership, teamwork, and situational awareness. Resilience engineering → adapts to unexpected events in the OR. Surgical coaching → peer process using reflection and feedback to improve.
Decision Making Models Decision Models → blend recognition-primed decision-making, critical thinking, and systems thinking.

Process Tools

SAFE SURGERY CHECKLIST

To enhance surgical safety, the World Health Organization (WHO) launched an initiative promoting worldwide adoption of the Surgical Safety Checklist in all healthcare facilities (21). This tool specifies key actions at four critical stages: patient entry to the operating room, before incision, after the procedure, and before transfer to the ward. Implementing the checklist (Figure 1) improves team communication and reduces avoidable errors. Studies have shown that its use decreases the risk of potentially life-threatening adverse events. A version of the WHO checklist has also been adapted for pituitary surgery (22).


Surgical Safety Checklist

World Health Organization | Patient Safety — A World Alliance for Safer Health Care

Before induction of anaesthesia → **Before skin incision** → **Before patient leaves operating room**

Before induction of anaesthesia
(with at least nurse and anaesthetist)

Has the patient confirmed his/her identity, site, procedure, and consent?
☐ Yes

Is the site marked?
☐ Yes
☐ Not applicable

Is the anaesthesia machine and medication check complete?
☐ Yes

Is the pulse oximeter on the patient and functioning?
☐ Yes

Does the patient have a:

Known allergy?
☐ No
☐ Yes

Difficult airway or aspiration risk?
☐ No
☐ Yes, and equipment/assistance available

Risk of >500ml blood loss (7ml/kg in children)?
☐ No
☐ Yes, and two IVs/central access and fluids planned

Before skin incision
(with nurse, anaesthetist and surgeon)

☐ **Confirm all team members have introduced themselves by name and role.**

☐ **Confirm the patient's name, procedure, and where the incision will be made.**

Has antibiotic prophylaxis been given within the last 60 minutes?
☐ Yes
☐ Not applicable

Anticipated Critical Events

To Surgeon:
☐ What are the critical or non-routine steps?
☐ How long will the case take?
☐ What is the anticipated blood loss?

To Anaesthetist:
☐ Are there any patient-specific concerns?

To Nursing Team:
☐ Has sterility (including indicator results) been confirmed?
☐ Are there equipment issues or any concerns?

Is essential imaging displayed?
☐ Yes
☐ Not applicable

Before patient leaves operating room
(with nurse, anaesthetist and surgeon)

Nurse Verbally Confirms:
☐ The name of the procedure
☐ Completion of instrument, sponge and needle counts
☐ Specimen labelling (read specimen labels aloud, including patient name)
☐ Whether there are any equipment problems to be addressed

To Surgeon, Anaesthetist and Nurse:
☐ What are the key concerns for recovery and management of this patient?

This checklist is not intended to be comprehensive. Additions and modifications to fit local practice are encouraged.

Revised 1 / 2009

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Figure 1. Surgical Safety Checklist.

ENHANCED RECOVERY AFTER SURGERY

Enhanced Recovery After Surgery (ERAS) is a comprehensive perioperative care pathway designed to facilitate rapid recovery of patients undergoing major surgical procedures. It was initially developed for colorectal surgery and has shown a significant shift in perioperative care. It re-evaluates traditional methods, replacing them with evidence-based best practices when necessary. ERAS protocols have been applied in pituitary surgery to enhance patient outcomes and reduce hospital stay. These protocols include preoperative, intraoperative, and postoperative phases (23-27) (Table 3 and Appendix Table 3).

Table 3. ERAS Components Adapted for Pituitary Surgery
Preoperative: Patient education, hormonal optimization, counseling on nasal morbidity, transient DI, hydrocortisone for adrenal insufficiency, and frailty screening in the elderly.
Intraoperative: Short-acting anesthesia, normovolemia, temperature, glycemic control, use of remifentanil/propofol, avoidance of overhydration, and maintenance of normothermia.
Postoperative: Early ambulation, sodium monitoring, pain and nausea control — check serum sodium regularly, analgesia, and antiemetics for persistent nausea.

The development of ERAS protocols involves multidisciplinary collaboration, a systematic literature review, and the establishment of institutional guidelines. ERAS should be more than a faster discharge; it must be a structured, surgical-endocrine-aware safety net (24). Prioritizing rapid discharge could compromise postoperative care and possibly increase complications if not managed well. Therefore, achieving a balance between faster recovery and careful patient monitoring is essential when using ERAS protocols for pituitary surgery (28-31).

KEY PERFORMANCE INDICATORS AND PATIENT-REPORTED OUTCOMES

Evaluating outcomes through both Key Performance Indicators (KPIs) and Patient-Reported Outcomes (PROs) offers a complete understanding of success. KPIs are clinician-driven metrics such as surgical complication rates, extent of tumor resection, endocrine normalization, and mortality, which objectively reflect procedural safety and technical efficacy (32). These align with the "surgeon's goals" of removing the tumor, minimizing harm, and preserving pituitary function. However, this perspective may overlook the broader impact of surgery on patient's daily lives.

This is where the PROs are essential. PROs are standardized tools that capture a patient's subjective experiences, including physical symptoms, emotional health, functional abilities, and overall quality of life (33, 34). Importantly, the significance and interpretation of PROs vary across age groups. *Children and adolescents* may be particularly affected by growth delays, hormonal imbalances, school functioning, and social integration, which are often invisible to the standard KPIs. *Young adults* may be concerned about fertility, cognitive performance, and returning to work or study, whereas *older adults* often value vision stability (even if it is already compromised), hormonal balance, and maintaining independence.

Furthermore, balancing surgical risks with age-sensitive PROs is essential. While younger patients may tolerate more aggressive resection in pursuit of long-term functional goals, older patients often benefit more from conservative strategies that prioritize stability, safety, and quality of life. This contrast underscores the gap between "what surgeons aim to achieve" and "what patients hope to recuperate". A technically flawless operation does not guarantee a satisfactory outcome from the patient's perspective. Thus, integrating KPIs with age-sensitive PROs ensures that surgical care is not only clinically effective, but also deeply personalized, respecting the diverse expectations and life goals of each patient. This approach shifts emphasis from technical outcomes to a broader definition of recovery (Table 4 and Appendix Table 4).

Table 4. KPIs and PROs in Transsphenoidal Pituitary Surgery — Summary
Safety & Tumor Control — KPIs: CSF leak, infection, reoperation, extent of resection; PROs: Pain, recovery, reassurance about tumor control.
Endocrine Outcomes — KPIs: Hormone normalization, DI/SIADH, new hypopituitarism; PROs: Fatigue, mood, sexual function.
Vision & Cognition — KPIs: Visual fields/acuity, cognitive deficits; PROs: Reading, independence, attention, memory; Age: School performance in children; return to work in young adults; independence in older adults.
Quality of Life (QoL) — PROs: Physical, emotional, and social functions.
Hospital & Recovery Metrics — KPIs: Length of stay, readmission, nasal morbidity; PROs: Satisfaction, caregiver burden, and autonomy.

Human Factors Frameworks

REASON'S SWISS-CHEESE MODEL

The Swiss Cheese Model, developed by James Reason, is a foundational framework for understanding how errors emerge in complex systems (35). It conceptualizes defenses as a series of barriers represented by Swiss cheese slices. Each slice represents a defensive layer in the system, and the holes in the cheese represent the weaknesses or failures of the defenses. In an ideal scenario, these layers prevent errors. However, in reality, these defenses are imperfect with holes that can align under certain circumstances. When holes line across multiple layers, they create a trajectory for an error or accident to occur, passing through all defensive layers. This model emphasizes that errors are often the result of multiple, small failures rather than a single catastrophic event.

In pituitary surgery, defensive layers may include clinical assessments (clinical presentation, imaging, and hormonal evaluation), procedural safeguards (WHO time-outs and double counts), and team-based strategies (clear communication and role assignments). Each defense represents a slice of cheese, and incorrect diagnosis, fatigue, cognitive load, equipment failure, or ambiguous hand-offs open transient holes. Strengthening the system means widening and varying the slices: double-check radiologic reads, simulation training for vascular catastrophes, mandatory readback of critical data, and allowing any team member to pause the case if concerns arise. Table 5 and Appendix Table 5 illustrate five practical examples of how latent system gaps—often subtle and benign on their own—can align with adverse outcomes if not intercepted.

Table 5. Swiss-Cheese Model in Pituitary Surgery — Key Points
Postoperative Diabetes Insipidus — Failed barriers: poor pre-op risk stratification, stalk injury, delayed Na/urine monitoring.
Intraoperative Visual Deterioration — Failed barriers: incomplete pre-op visual fields, missing risk consent, optic traction during dissection.
Unexpected Residual Tumor — Failed barriers: suboptimal MRI review, no angled endoscope/intra-op imaging, unclear resection goals.
Postoperative CSF Leak / Meningitis — Failed barriers: missed arachnoid defect, inadequate closure, staff missing early leak signs.
Postoperative Hematoma — Failed barriers: inadequate hemostasis, poor BP control, delayed neuro checks

HUMAN FACTORS ANALYSIS AND CLASSIFICATION SYSTEM

Based on Reason's Swiss Cheese Model, the Human Factors Analysis and Classification System (HFACS) offers a framework for analyzing human and organizational contributors to errors (36). Recognizing that adverse events are rarely due to a single mistake, the HFACS categorizes failures across four interconnected levels: *Organizational Influences, Supervisory Factors, Preconditions for Unsafe Acts, and Unsafe Acts*. Each level reveals a point where safety barriers may erode due to human, technical, or systemic issues. In pituitary surgery, HFACS helps teams trace complications not only to technical missteps but also to latent conditions. It complements the Swiss Cheese Model by offering a diagnostic taxonomy for surgical complication analysis and supporting proactive strategies to intercept failures before harm occurs. Table 6 and Appendix Table 6 present an HFACS-informed breakdown of the failure domains in pituitary surgery.

Table 6. HFACS in Pituitary Surgery — Key Points
Organizational Influences — Weak safety culture (no M&M reviews):—Lack of standardized processes (WHO checklist). — Resource limits (inexperienced staff).
Supervisory Factors — Inadequate oversight (residents performing critical steps unsupervised). — Poor case planning (complex tumors scheduled late day). — Failure to correct known problems (equipment defects). — Supervisory violations (skipping time-outs).
Preconditions for Unsafe Acts — Environment (noise OR). — Individual (surgeon fatigue). —Team (miscommunication).
Unsafe Acts — Errors: decision errors (wrong approach), skill errors (optic/carotid injury), perceptual errors (misidentifying the arachnoid boundary). —Violations: routine (skipping imaging workup), exceptional (operating against contraindications).

NON-TECHNICAL SKILLS FOR SURGEONS

Non-technical skills are essential for surgeons to provide safe and effective care, complementing their technical expertise (37). These skills include *situational awareness, decision-making, communication, teamwork, leadership, and stress management* (Table 7 and Appendix Table 7). The Non-Technical Skills for Surgeons (NOTSS) system has been developed to evaluate these competencies (38, 39). Surgeons with strong non-technical skills can effectively share information, manage crises, and improve team performance in the operating room. Research has shown that team training and preoperative briefings can enhance communication and reduce postoperative complications (40, 41). Non-technical skills are the surgeon's invisible instruments. Mastering the scalpel without mastering situational awareness, clear communication, sound decisions, or steady leadership may leave critical defenses full of holes.

Table 7. Core Components of the NOTSS Framework in Pituitary Surgery
Situational Awareness — Anticipate events; *e.g. recognize subtle changes in tumor consistency.*
Decision-Making — Choose the best option, reassess; *e.g. subtotal resection near carotid/optic chiasm.*
Communication — Share plans clearly; *e.g., confirm reconstruction with team.*
Teamwork — Coordinate tasks under pressure; *e.g., with ENT and anesthesia.*
Leadership — Assign roles, build a shared model; *e.g., lead time-out and invite concern.*
Stress Management — Stay composed in crises; *e.g., controlled breathing and delegation during bleed*.

RESILIENCE ENGINEERING

Resilience engineering is an interdisciplinary field that studies how complex systems –*the pituitary team* – can adapt to, absorb, and recover from variability, disturbances, and unexpected events, while continuing to function safely and effectively. Rather than focusing solely on preventing errors, resilience engineering emphasizes how systems succeed under pressure, and how they learn and improve from experience (42). In surgery, resilience engineering shifts the safety paradigm from a reactive model (focused on errors and adverse events) to a proactive model that builds adaptive capacity across the perioperative system. This includes the ability to *anticipate challenges* (e.g., risk of vascular injury or hormonal insufficiency), *monitor* clinical and environmental cues (e.g., changes in anatomy, team fatigue), *respond* flexibly when the surgical plan must be modified, and *learn* from both complications and successful adaptations. This approach recognizes that not all adverse events stem from errors, and many arise when systems are pushed to their limits. Building resilience refers to designing protocols, training, and team structures that can absorb shocks without collapse (Table 8 and Appendix Table 8).

Table 8. Resilience Engineering in Pituitary Surgery — Key Points
Anticipate — *Pre-op*: Predict ICA injury, CSF leak. — *Intra-op*: Expect firm tumors, bleeding, CSF leak risks. — *Post-op*: Anticipate DI, hyponatremia, hematoma.
Monitor — *Pre-op*: Assess hormones, comorbidities, frailty. — *Intra-op*: Track vitals, bleeding, tumor texture, team communication/fatigue. — *Post-op*: Monitor urine, sodium, cortisol, vision, mental status.
Respond — *Pre-op*: Adjust scheduling, administering corticosteroids, postponing optimization. — *Intra-op:* Modify resection (subtotal/staged), use alternate hemostasis. — *Post-op*: Adjust fluids/electrolytes, manage cortisol replacement.
Learn — *Pre-op*: Review prior cases, refine checklists/protocols. — *Intra-op*: Use structured team queries to identify latent safety threats. — *Post-op*: Conduct case reviews, refine early warning protocols.

SURGICAL COACHING

Surgical coaching has emerged as an evidence-based strategy for improving both technical and non-technical performance in the operating room (43). Unlike traditional mentorship, which focuses on long-term professional development, coaching is structured, goal oriented, and performance centered. It uses direct observation, targeted feedback, and facilitates reflection to refine technical and non-technical skills. By reviewing video recordings, engaging in structured debriefings, or conducting real-time intraoperative observations, surgeons can identify blind spots in technique or communication that might otherwise go unrecognized (44, 45). Coaching complements but does not replace mentorship. While mentorship shapes the broader trajectory of a neurosurgeon's career, coaching provides immediate, focused interventions that are necessary to optimize operative performance.

Decision Making Models

Operative judgment and decisions in pituitary surgery are not solely the product of technical skills or anatomical knowledge; they emerge from a dual process: one grounded in cognitive expertise, and the other in relational perception (46). These two pathways work in tandem to guide decision quality in a dynamic operating room environment. (Table 9 and Appendix Table 9)

The first pathway follows the principles of *naturalistic decision-making* (NDM), as articulated in Gary Klein's Recognition-Primed Decision (RPD) model. This model explains how experienced surgeons make effective decisions under pressure, without comparing multiple options. They rely on familiar surgical cues, recall past cases, and mentally project the outcomes of a specific approach. If the simulated result seems acceptable, they proceed. If not, they adapt. In pituitary surgery, this might involve identifying an unusual tumor texture or deviation in the sellar anatomy and quickly deciding on a modified approach based on prior cases, without formal deliberation. The ability to "see and act" in a fluid cognitive loop is the essence of recognition-primed decision-making (47).

Pituitary surgery can present unexpected complexities, because tumor consistency may be variable, anatomical planes may not always be distinct, and bleeding can hinder visibility. In such situations, an additional level of decision-making is required, involving cognitive and collaborative adaptation, a process referred to by Cristancho et al. as *intra-operative reconciliation* (48). This model reveals the ways in which surgeons address ambiguity by reassessing circumstances, redefining challenges, and frequently involving their teams in collaborative decision-making. Rather than clinging to the original plan, the surgeon adjusts in real time by integrating visual, tactile, and verbal feedback until a new, coherent forward path emerges (48). In practical terms, this may mean shifting from suction-based debulking to sharp dissection when faced with a fibrous adenoma, while simultaneously recalibrating the expectations of the team.

The second pathway, layered atop these cognitive processes, is a relational dynamic that operates through "*thin-slice" perception,* a concept introduced by Ambady and Rosenthal (49).*Thin-slicing* refers to the human ability to make surprisingly accurate judgments about others' stress, confidence, or leadership based on mere seconds of observation. In pituitary surgery, *thin-slicing* describes the experienced surgeon's capacity to make swift, intuitive decisions based on minimal but telling cues. Neurosurgeons must often make immediate decisions based on subtle intraoperative signals such as a faint shift in tissue texture, a transient change in bleeding pattern, an unexpected variation in anatomical landmarks, or a fleeting visualization of the arachnoid. These cues, rapidly interpreted through years of procedural experience and tacit knowledge, allow the surgeon to anticipate complications, such as cerebrospinal fluid leaks, or cavernous sinus injury. While *thin-slicing* enhances intraoperative agility, it must be embedded within a robust safety architecture to prevent overreliance on intuition alone. In the OR, team members constantly (and often subconsciously) assess one another's tone, posture, eye contact, and micro-behaviors to gauge trust, cohesion, and competence (50).

Critical and systems thinking further enrich the hybrid model of surgical judgment (51). While recognition-primed decision-making and intraoperative reconciliation focus on the rapid interpretation of intraoperative cues and adaptive problem-solving, *critical thinking* introduces an additional layer of analytical rigor (52-54). It challenges surgeons to question protocol rigidity, assess evidence against patient individuality, and consider the ethical dimensions of care. For example, a *critical thinking* approach might question the suitability of continuing the surgery when unexpected difficulties arise, such as encountering a hard and fibrous tumor, unanticipated bleeding from the tumor, or altered anatomy due to prior interventions or congenital variants. In such moments, rather than proceeding automatically, the surgeon pauses to reassess the risk-benefit balance. This may involve reevaluating the surgical plan, consulting with colleagues intraoperatively, or even deciding to stage the procedure to avoid escalating complications. Such a decision reflects not only technical judgment but also ethical and patient-centered reasoning, prioritizing long-term safety over immediate completion.

Simultaneously, *systems thinking* draws attention to how decisions interact within the broader care continuum (55-57). Decisions made in isolation, such as modifying analgesia or delaying mobilization, can ripple through postoperative workflows, affect interdisciplinary handoffs, and influence overall patient experience. By integrating systems thinking, the surgical team ensures that individual decisions are not only sound in isolation, but also coherent within the team-based, multidisciplinary flow of pituitary care.

Table 9. Decision-Making Models in Pituitary Surgery — Key Points
Recognition-Primed Decision (Klein) — Rapid pattern recognition and mental simulation, e.g. seeing yellow-gray adenoma as in previous cases, and immediately beginning suction debulking.
Intraoperative Reconciliation (Cristancho) — Reframing/adapting plan in uncertainty, e.g. switching from curettage to sharp dissection when the tumor proves fibrous.
Thin-Slice Relational Cues (Ambady & Rosenthal) — Intuitive team responses to subtle stress/trust signals, e.g. assistant surgeon senses rising uncertainty in the lead surgeon's tone.
Critical Thinking — Analytical reasoning that questions assumptions and tailors care, e.g. delaying discharge for borderline sodium despite ERAS norms.
Systems Thinking — Decisions consider the impact on broader surgical/organizational systems, e.g. pausing resection near the cavernous sinus until anesthesia stabilizes blood pressure.

PERIOPERATIVE APPROACH

This section applies these frameworks across the perioperative continuum and translates them into practical strategies. In the preoperative phase, endocrine assessment, imaging workup, and planning, form the basis of safe surgery. The intraoperative phase emphasizes anesthesia, surgical strategies, and teamwork. The postoperative phase focuses on monitoring, early recognition of complications, and recovery pathways.

Preoperative Phase

CLINICAL ASSESMENT

Pituitary adenomas account for approximately 90% of sellar lesions, whereas the remaining 10% comprise a diverse range of other pathologies (58, 59). This underscores the importance of establishing a precise diagnosis to avoid misidentification and ensure appropriate treatment. Therefore, comprehensive clinical evaluation is a cornerstone of the preoperative management of patients with suspected pituitary adenomas. Initial misdiagnosis can result in complications.

The process begins with detailed *history taking*, emphasizing symptoms onset, duration, and progression, with specific attention to manifestations of hormonal excess or deficiency, and neurological symptoms related to tumor mass effect. A critical step is to evaluate whether the reported symptoms are truly attributable to pituitary adenoma. For example, headaches, frequently reported, must be assessed in detail, including their onset, progression, location, and association with other symptoms, such as malaise or low-grade fever. Headaches due to pituitary tumors are often retro-orbital or bifrontal, without any special characteristics. Sudden and intense headaches may indicate pituitary apoplexy. The absence of systemic signs may help to distinguish them from inflammatory or infectious etiologies.

Visual field testing is essential, particularly in cases of suprasellar extension, because it can detect early signs of optic chiasm compression. It is usually complemented by formal ophthalmological evaluation, including visual acuity and fundoscopic examination. Although bitemporal hemianopsia is classically associated with chiasmatic compression, other visual defects, such as altitudinal defects in ischemic optic neuropathy, may represent lesions that are different from pituitary adenomas. Optical coherence tomography (OCT) offers highly detailed information about the health of the optic nerve affected by compression through evaluation of the retinal nerve fiber layer (RNFL) and ganglion cell layer (GCL). It is a valuable tool for early diagnosis, effective monitoring, and accurate prognostication of visual outcomes. In addition, this study provides important insights into the risk of optic nerve damage during surgery. In such cases, subtotal resection may be the optimal strategy to minimize the risk of intraoperative vision loss (60).

Frailty is a physiological vulnerability that increases the risk of adverse perioperative outcomes. Frailty assessment scores, such as the Clinical Frailty Scale (CFS) or the modified Frailty Index (mFI), can be included in the preoperative evaluation (61-63). Incorporating these scores helps to predict surgical risks, potential complications, and overall patient resilience, thus guiding individualized decision making and optimizing surgical outcomes. Frailty assessment helps to tailor surgical planning for individual patient risks.

Finally, preoperative evaluation can include *quality of life* (QoL) assessment using validated instruments, recognizing that pituitary tumors can significantly affect patients beyond their biochemical or anatomical burden. Therefore, QoL evaluation helps to quantify the functional, emotional, and social impact of the disease, identify specific areas of concern, and guide multidisciplinary support before and after surgery (64, 65).

ENDOCRINOLOGICAL WORKUP

Thorough endocrinological evaluation is required to assess pituitary function and tumor secretory status. Baseline hormonal assays include growth hormone (GH), insulin-like growth factor 1 (IGF-1), prolactin, adrenocorticotropic hormone (ACTH), cortisol, thyroid-stimulating hormone (TSH), free thyroxine (FT4), luteinizing hormone (LH), follicle-stimulating hormone (FSH), sex hormones (testosterone or estradiol), and serum sodium and osmolality.

Dynamic hormone testing may be employed to confirm hyperfunctioning tumors (e.g., dexamethasone suppression test for Cushing’s disease, oral glucose tolerance test for acromegaly) or to assess pituitary reserve in cases of suspected hypopituitarism (e.g., ACTH stimulation or insulin tolerance test). The results of this workup guide perioperative hormonal management, including initiation of hormone replacement when indicated .

IMAGING AND DIFFERENTIAL DIAGNOSIS.

High-resolution MRI of the sellar and parasellar regions remains the gold standard for evaluating pituitary adenomas. It provides critical information on tumor size, extent, and anatomical relationships, including cavernous sinus invasion and compression or displacement of the anterior visual pathway, particularly of the optic chiasm. Computed tomography (CT) can be used as an adjunct to assess bony erosion or remodeling of the sella turcica, particularly in reoperative cases or in planning extended surgical approaches.

Simple and Gadolinium-enhanced T1-weighted axial, coronal, and sagittal sequences provide detailed information regarding the lesion. T2-weighted sequences reveal fine anatomical details. Time of flight (TOF) sequences reveal vascular lesions (66). Regarding the differential diagnosis, T1-weighted images without contrast may reveal hyperintense areas within the lesion, suggesting subacute hemorrhage, proteinaceous cystic content, melanin, or fat. Although these findings are not specific, they should prompt consideration of alternative diagnoses, such as pituitary apoplexy, Rathke's cleft cysts, craniopharyngiomas, xanthogranulomas, or melanocytic tumors (58, 67).

Differentiating sellar lesions is crucial for surgical planning. A fundamental yet often overlooked principle of surgical safety is the systematic and timely review of imaging studies. To enhance consistency and foster a culture of accountability, the following guiding maxim is proposed:

"*Check ALL the images, for ALL the patients, EVERY single day.*" This concise yet impactful reminder highlights the importance of routine imaging reviews to discover inadvertent findings that might otherwise go unnoticed. The philosophy behind this practice reflects a broader safety culture; *the small things we miss can become the big things we regret*. Embedding this mindset into daily clinical workflows reinforces team discipline, reduces the risk of omission or misdiagnosis, and aligns with high-reliability strategies designed to minimize preventable harm (Figure 2) (66).

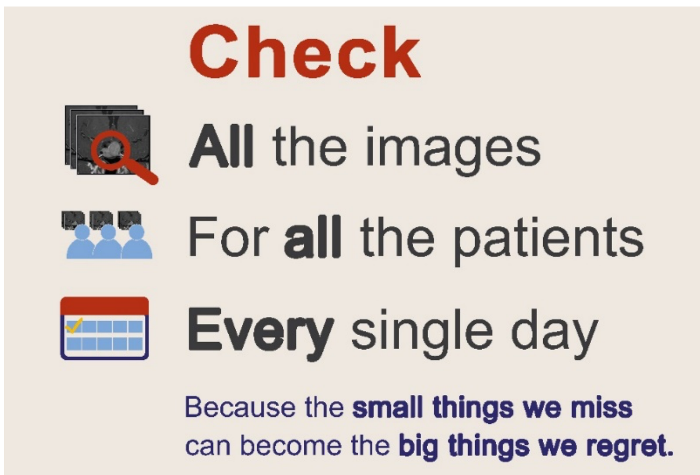

Figure 2.

An integrative approach is important for reducing the risk of misdiagnosis and for supporting effective surgical planning. Surgeons and clinicians should begin by addressing core diagnostic questions: Does clinical presentation align with pituitary adenoma? Are the signs, symptoms, and timing of onset consistent with pituitary tumors? Have the MRI and CT scans been thoroughly reviewed, and are there any clinical or radiological clues suggesting an alternative diagnosis? Longitudinal imaging evaluation may reveal time-based changes that clarify the nature of the lesion. After addressing these questions, a systematic analysis of imaging is recommended to identify the sella turcica and pituitary gland, determine the epicenter of the lesion (sellar, suprasellar, or parasellar), evaluate T1-weighted MRI sequences for hyperintensity, assess CT for calcifications, bone changes, or erosion, and formulate a differential diagnosis. Integrating these clinical and radiologic perspectives into a unified checklist promotes diagnostic accuracy, minimizes oversight, and strengthens multidisciplinary decision making (58) (Table 10 and Appendix Table 10).

Table 10. Diagnostic and Imaging Evaluation of Sellar and Parasellar Lesions
• Review the clinical presentation: consistent with pituitary adenoma ?
• Assess signs, symptoms, onset: compatible with adenoma?
• Perform thorough MRI and CT analysis.
• Look for clinical/radiological clues suggesting alternative diagnosis.
• Compare longitudinal imaging for temporal changes.
• Identify sella turcica and pituitary gland on imaging.
• Determine lesion epicenter: sellar, suprasellar, or parasellar.
• Evaluate T1 hyperintensity on MRI.
• Assess CT for calcifications, bone sclerosis, or erosion.
• Establish differential diagnosis integrating clinical and imaging findings.

RISK STRATIFICATION AND DECISION-MAKING

Risk assessment integrates tumor-specific factors (size, invasiveness, functionality, and proximity to critical structures) with patient-related variables, including age, frailty, comorbidities, and previous treatments. The anatomopathological classification provides further prognostic stratification, especially for reoperations or aggressive tumors. Multidisciplinary case discussions are integral to the formulation of individualized management plans. Decision-making often blends evidence-based protocols with expert clinical judgment, and may rely on naturalistic decision-making models, particularly in complex or ambiguous scenarios.

SURGICAL APPROACH SELECTION

Tumor location, size, extension, and surgeon expertise determine the choice of the surgical approach. The endoscopic endonasal transsphenoidal approach is preferred for most midline pituitary adenomas because of its minimally invasive nature, direct access to the sella, and favorable safety profile. An extended endonasal approach may be required for tumors with a significant lateral or anterior extension.

Although transsphenoidal surgery is the standard treatment for most cases, transcranial (craniotomy) approaches remain indicated in selected scenarios. These include giant adenomas with a prominent suprasellar or retrosellar component not reachable via the sphenoid corridor, or tumors with marked lateral extension into the middle cranial fossa or temporal lobe. Craniotomy may also be considered when prior endonasal approaches have failed or when anatomical constraints, such as sphenoid sinus agenesis or severe septal deformities, preclude safe transsphenoidal access. A tailored operative strategy is established to anticipate potential intraoperative challenges and define the criteria for surgical success.

PREHABILITATION AND PATIENT PREPARATION

Prehabilitation seeks to optimize patients' medical, nutritional, and psychological conditions prior to surgery (68). This proactive approach is particularly important for individuals with complex endocrine and systemic comorbidities. Conditions such as hypertension, diabetes mellitus, and anemia require aggressive management because of their potential to increase intraoperative instability and delay recovery. Hormonal imbalances, including adrenal insufficiency and hypothyroidism, should be promptly corrected to reduce the perioperative risk. Customized exercise regimens may improve cardiopulmonary function and functional reserve, whereas nutritional support is essential for malnourished or catabolic patients. Psychological support plays a dual role in alleviating anxiety and enhancing postoperative resilience, by promoting adherence and strengthening coping strategies. Prehabilitation serves as an important adjunct to Enhanced Recovery After Surgery (ERAS) protocols, facilitating optimal patient outcomes by recognizing that recovery is an active process which commences prior to surgery (68).

Preoperative patient education is crucial for setting expectations regarding the surgical procedure, potential complications (e.g., cerebrospinal fluid leak, diabetes insipidus, and hypopituitarism), and the anticipated course of recovery. This type of education improves patient satisfaction, reduces anxiety, and enhances compliance with medical instructions. Effective methods include verbal counseling, printed materials, and visual aids that explain anatomy, surgical steps, and recovery timelines (34).

PREANESTHETIC ASSESSSMENT

Preanesthetic evaluation involves a thorough examination of laboratory parameters to identify potential concerns, such as infection, anemia, electrolyte imbalances, renal function status, and coagulation profiles. Pregnancy testing is recommended for women of reproductive ages. Airway assessment begins with a review of anthropometric parameters, including weight, height, and body mass index. A detailed medical and surgical history should be followed, specifically noting any previous intubation difficulties, head or neck surgeries, or cervical radiotherapy. Physical examination should include evaluation of the vocal aperture, Mallampati classification, degree of incisor protrusion, cervical spine mobility, and measurement of thyromental and sternomental distances. Additional key features include cervical circumference, condition of the buccal cavity (e.g., macroglossia, dentition), and presence of facial hair, which may affect mask ventilation. When systematically evaluated, these elements help anticipate potential difficulties in airway management and guide appropriate anesthetic planning.

While surgery presents clear benefits, it may also trigger major adverse cardiac events (MACE), including myocardial infarction, acute heart failure, serious arrhythmias, and cardiovascular death (69) . It is essential to determine the risk factors for coronary disease; if any are present, a combination of clinical and surgical risk factors for a major adverse cardiovascular event (MACE) should be established. No additional tests are required if the patient is at low risk (-1%) for MACE. However, if the patient is at a higher risk, functional capacity should be assessed; if it is adequate,(≥4 Metabolic Equivalents of Task (METs)), surgery can be performed. If it is inadequate (<4 METs), pharmacological or exercise-induced stress echocardiography should be considered.

Patients with acromegaly and Cushing’s disease carry a markedly increased burden of cardiovascular and airway comorbidities, elevating perioperative risk and necessitating tailored surgical and anesthetic strategies. In Cushing’s disease, chronic cortisol excess results in a constellation of systemic dysfunctions, including resistant hypertension, accelerated atherosclerosis, hypercoagulability, left ventricular hypertrophy, and impaired glucose tolerance. These conditions collectively increase the risk of myocardial ischemia, arrhythmias, and thromboembolic events during and after surgery. Additional challenges, such as central obesity, cervicofacial fat redistribution, and a high prevalence of obstructive sleep apnea, further complicate ventilation, intubation, and postoperative recovery. (Table 11 and Appendix Table 11).

In acromegaly, prolonged exposure to excess GH and IGF-1 can lead to cardiomyopathy, diastolic dysfunction, valvular disease, systemic hypertension, and insulin resistance. The airway in acromegalic patients poses even greater challenges including macroglossia, prognathism, soft tissue hypertrophy of the pharynx and larynx, and a high incidence of severe obstructive sleep apnea. These structural and functional alterations frequently necessitate meticulous preoperative airway evaluation. It is essential to ensure the availability of difficult airway equipment, such as long-blade laryngoscopes, laryngeal mask airways, bougies, video laryngoscopes, and fiberoptic bronchoscopes. Box 11 and Table 11 (Appendix).

Table 11. Cardiovascular and Airway Burden in Cushing's Disease vs. Acromegaly
• Hypertension — Cushing's: +++ ; Acromegaly: ++
• LV Hypertrophy / Cardiomyopathy — Cushing's: ++ ; Acromegaly: +++.
• Thromboembolism Risk — Cushing's: +++; Acromegaly: +
• Obstructive Sleep Apnea — Cushing's: ++; Acromegaly: +++
• Difficult Airway — Cushing's: ++ ; Acromegaly: +++.
• Arrhythmias / QT Prolongation — Both: ++.

+ mild; ++ moderate; +++ severe burden.

Intraoperative Phase

ANESTHESIA AND PHYSIOLOGICAL MONITORING

Effective anesthetic management in pituitary surgery requires close coordination between neurosurgeons and anesthesiologists, with a shared focus on maintaining airway patency, hemodynamic stability, and metabolic balance. Airway access must be secured early considering the limited facial access imposed by the surgical field. The need for central venous access should be evaluated based on the patient's cardiovascular status and anticipated surgical complexity of the procedure. Long peripheral venous and arterial lines are preferable for remote monitoring.

Therefore, patient positioning is critical. The patient should be placed in the supine position, with the head elevated above the level of the heart to enhance venous drainage and minimize intraoperative bleeding. Gentle neck rotation may be necessary to optimize surgical access. Preventive measures, including ocular protection, pneumatic compression of the lower limbs, and prophylaxis for nausea and vomiting, are standard. Wet pharyngeal tamponade is used to reduce blood aspiration to the stomach and is removed at the end of the procedure. Monitoring includes electrocardiography, noninvasive blood pressure measurement, pulse oximetry, capnography, and blood gas analysis. More invasive monitoring, such as arterial lines or central venous catheters, and urinary catheterization should be evaluated individually for each patient's specific characteristics.

Anesthetic induction typically involves the use of propofol, sevoflurane, and short-acting opioids such as remifentanil. Following intubation, local vasoconstriction is achieved with topical nasal agents, such as epinephrine, oxymetazoline, cocaine, or phenylephrine. Local anesthetic agents, such as lidocaine, levobupivacaine, or tetracaine, may also be used to enhance mucosal anesthesia. The anesthetic goal is to maintain controlled hypotension while preserving adequate cerebral perfusion and normocapnia. Multimodal analgesia is recommended, and intravenous fluids should be limited to avoid obscuring the diagnosis of postoperative diabetes insipidus. Throughout the procedure, intraoperative adjustments in ventilation and CO_2 levels, along with the use of the Valsalva maneuver (involving an intrathoracic pressure of 30–40 mmHg), facilitate the removal of the uppermost portion of the tumor and help assess the integrity of the arachnoid layer and the presence of cerebrospinal fluid (CSF) leaks. After tumor resection, controlled hyperventilation lowers intracranial pressure when the arachnoid protrudes into the surgical field. This pressure reduction helps the arachnoid fall back into place and creates optimal conditions for reconstructing the sellar floor. Before applying sealant, confirm hemostasis under normotension or slight hypertension to expose any hidden bleeding. Emergence from anesthesia should be slow and carefully managed; avoiding coughing and blood-pressure surges reduces the risk of postoperative bleeding, hematoma, and CSF leakage.

SURGICAL CONSIDERATIONS

The endoscopic endonasal approach is the preferred surgical technique for most pituitary adenomas, because it offers excellent visualization, minimal invasiveness, and improved postoperative outcomes. It can be conceptualized as a structured workflow with four phases: nasal, sphenoid, sellar, and closure (9).

Nasal phase: Entry is gained by identifying the choana, septum, and turbinates, followed by lateralization of the middle turbinate and exposure of the sphenoid ostium. Depending on the tumor extension and anticipated reconstruction needs, a unilateral or binostril approach may be employed, with optional harvesting of a vascularized nasoseptal flap.

Sphenoid phase: The anterior sphenoid wall is opened, mucosa is removed, and intersinus septations are drilled to expose the sellar floor. Anatomical variants such as Onodi cells must be recognized to prevent optic nerve or carotid injuries.

Sellar phase: After confirming the midline, the sellar floor is removed and the dura is opened. Tumor removal is typically piecemeal for macroadenomas or extracapsular for microadenomas, using ring curettes, suction, and angled endoscopes for complete resection. Intraoperative strategies include high-definition endoscopes, neuronavigation for real-time orientation, and micro-Doppler or indocyanine green (ICG) angiography for vascular mapping (10). These tools assist in identifying critical neurovascular structures, preserving the normal gland, and reducing complications. Early identification of the arachnoid plane is crucial for minimizing trauma and preventing CSF leakage, which is the most common intraoperative complication.

Closure phase: Hemostasis is achieved with bipolar cautery, hemostatic agents, or packing. Skull base reconstruction is tailored to the presence of a CSF leak, ranging from free mucosal or fat grafts to vascularized nasoseptal flaps. Tissue sealants and, in selected cases, lumbar drainage may be used to reinforce closure and achieve a watertight seal.

While the workflow provides a structured roadmap, its successful execution depends not only on technical proficiency but also on the surgeon’s situational awareness, cognitive workload management, and adaptability to anatomical variations—competencies encompassed within the NOTSS (Non-Technical Skills for Surgeons) framework (41). The interplay between technical and non-technical strategies is summarized in Table 12 and Appendix Table 12.

Table 12. Technical and Non-Technical Strategies in Pituitary Surgery
Technical Strategies
— High-definition endoscopes → enhance visualization.
— Neuronavigation and vascular mapping (ICG/Doppler) → guide anatomy and vascular safety.
— Multilayer reconstruction → reduce postoperative CSF leak risk.
Non-Technical Skills (NOTSS)
— Situational awareness → maintain awareness of anatomy and intraoperative cues.
— Decision-making under pressure → adapt plan to evolving circumstances.
— Team communication and coordination → ensure shared understanding and collaboration.
— Stress and workload management → sustain focus, reduce error in complex cases.

Postoperative Phase

IMMEDIATE RECOVERY AND MONITORING

In some units, patients undergoing routine pituitary surgery do not go to the Intensive care Unit (ICU) or High Dependency Unit (HDU). This is patient dependent. Close observation is necessary because of the potential risk of airway compromise caused by bleeding from the nasal and oropharyngeal areas. Monitor hemodynamics, plasma and urine osmolarity, sodium levels, and polydipsia due to the risk of diabetes insipidus; check serum sodium regularly for the first 24–48 hours.

Early neurological examination, specifically the assessment of visual acuity, visual fields, pupillary reflexes, and extraocular movements, is critical for detecting potential complications. Postoperative headache management is also essential; mild to moderate discomfort is common and is managed with standard analgesics. However, severe or rapidly escalating headaches are uncommon and should promptly raise suspicion of complications, such as intracranial hemorrhage, tension pneumocephalus, or CSF leak.

Structured escalation protocols ensure early detection and prompt intervention of postoperative complications. These include algorithms to manage CSF leaks, hematomas, visual deterioration, and electrolyte abnormalities. We propose the following postoperative early warning scoring system and interdisciplinary rescue protocol to enable timely detection and management of complications (Table 13).

Table 13. Traffic-Light Triggers for Escalation of Care After Pituitary Surgery			
Parameter	**Green** **Routine care**	**Yellow** **Senior review ≤ 30 min**	**Red** **Activate STAT neurosurgery / ICU**
Serum Na^+ (mmol/L)	135 – 145	130 – 134 or 146 – 150	< 130 or > 150 – treat as DI/SIADH crisis; consider hypertonic saline or desmopressin stop
Urine output (2 consecutive h)	50 – 250 mL/h	> 250 mL/h with Na^+ ≤ 145	> 250 mL/h plus rising Na^+ > 145 or osmolality ↑ → probable DI
Vision / Visual fields	Stable or improving	New mild blur or field patch – bedside perimetry	Sudden decrease in acuity, new hemianopsia, or lost light perception → rule-out hematoma, re-image urgently
Headache / retro-orbital pain	≤ 3 /10, controlled with PO analgesia	Escalating to 4–6 /10 despite rescue meds	≥ 7 /10 or explosive onset + nausea → suspect sellar hematoma or CSF tension pneumocephalus
CSF leak / nasal drainage	Nil or scant bloody mucus	Intermittent clear drip when bending forward	Persistent "tap-like" clear drip, salty taste, or halo sign → start acetazolamide, prep OR for repair
Blood pressure (mm Hg)	90 – 160 systolic	161 – 180 or 80 – 89	> 180 or < 80 despite fluids/pressors
Mental status / GCS	Alert & oriented	New confusion or somnolence (GCS 13-14)	GCS ≤ 12, seizures, or focal deficit

ENDOCRINE MANAGEMENT

Endocrine surveillance includes regular hormone panels that assess adrenal, thyroid, and posterior pituitary functions. Particular attention is paid to the ACTH and TSH axes due to their vital role in maintaining homeostasis. Stress-dose corticosteroids are administered perioperatively when indicated, and long-term hormone replacement therapy is initiated based on laboratory and clinical findings. Hypopituitarism, if present, is managed with structured hormone replacement regimens. Regular hormone profiling and replacement adjustments are based on clinical and laboratory data.

COMPLICATIONS

Complications of pituitary surgery can be broadly categorized as endocrinological or anatomical, though additional systemic and intraoperative events may also occur (9, 70). *Endocrinological complications* include diabetes insipidus, syndrome of inappropriate antidiuretic hormone secretion (SIADH), and panhypopituitarism. *Anatomical complications* include hemorrhage, hematomas, internal carotid artery pseudoaneurysms, and CSF fistulas. Complications may also arise during specific surgical stages: *During the operative state*: orbital fractures, nasal deformity, anosmia, and CSF leakage due to cribriform plate injury. *During the sinus phase*: carotid artery injury, bone damage. Other possible complications include meningitis, subarachnoid hemorrhage, vasospasm, ophthalmoplegia, optic nerve disturbances, air embolism, thrombosis, thromboembolism, and pneumocephalus (9, 26). A detailed discussion of these events is beyond the scope of this review.

Table 13 in the Appendix, maps perioperative complications, from CSF leak to pneumocephalus, through multiple safety frameworks. Each entry highlights how the same event can be interpreted differently depending on the lens applied, focusing on system flaws, communication, supervision, protocols, or adaptive responses. This approach underscores the importance of using diverse perspectives to understand and improve surgical safety.

LIMITATIONS AND FUTURE DIRECTIONS

This review proposes a comprehensive, multidimensional framework to enhance the safety and effectiveness of pituitary surgery; however, several limitations should be acknowledged. First, the current work is structured as an integrative narrative review, that lacks the methodological rigor of systematic reviews and meta-analyses. Frameworks and references were selected based on clinical relevance and expert judgment rather than predefined inclusion criteria, which introduces potential for selection bias. Although many of the proposed strategies are supported by the existing literature, quantitative data demonstrating their impact remain limited in the context of pituitary surgery.

Second, the practical feasibility of this approach varies among institutions. Many of the tools discussed, such as intraoperative MRI and neuronavigation, may not be available at all institutions. Similarly, the implementation of frameworks such as HFACS or NOTSS, requires trained personnel, simulation infrastructure, and cultural buy-in, which may not be uniformly present across institutions. The integration of frameworks, although conceptually valuable, can be challenging for clinical teams unfamiliar with human factors terminology or systems thinking. Each institution may choose to adopt one or more of these options, according to its resources.

Third, cultural resistance to change is a major barrier. Despite the growing awareness of human factors in surgery, longstanding hierarchical structures, siloed specialties, and skepticism toward non-technical training can delay adoption. Changing deeply embedded behaviors, such as reluctance to report near misses or hesitancy to engage in debriefings, requires not only training, but also strong leadership, role modeling, and a psychologically safe environment that supports continuous learning.

Fourth, there are limitations related to the adoption and standardization of human factor assessments. Although the NOTSS framework has been recognized, it remains underutilized in structured training programs for pituitary surgeons. Interobserver reliability and real-time scoring remain challenging, and few studies have specifically evaluated how improvements in non-technical skills correlate with postoperative outcomes in pituitary surgery.

Several avenues merit further exploration. Future research should validate this integrated model in high-volume pituitary centers and PTCOE by tracking both clinical outcomes and process indicators to ensure its effectiveness (34, 71). Simulation-based education, combining anatomical drills with cognitive stress and communication challenges, may offer a powerful platform to reinforce non-technical competencies while preserving patient safety. The development of pituitary-specific simulation scenarios and scoring tools tailored to transsphenoidal procedures is a promising research topic.

Digital innovation is an important frontier. Dashboards that integrate KPIs and safety indicators can help teams monitor outcomes in real-time. Artificial intelligence (AI) tools, notably those capable of detecting early warning signs of complications may soon support decision-making and error interception. Future studies should directly involve patients. Incorporating patient and caregiver inputs into ERAS protocols and postoperative recovery metrics will ensure that perioperative strategies align with what matters most to those undergoing surgery , whether it is pain control, cognitive clarity, fertility preservation, or return to independence.

Ultimately, sustainable improvements in pituitary surgery will require not only technical innovation but also a culture of interdisciplinary learning, open communication, and psychological safety. Future studies should examine how organizational structures, team dynamics, and leadership styles shape the adoption and long-term success of safety frameworks. Only through this combined lens of technical precision and human-centered care can we move closer to the goal of zero preventable complications.

CONCLUSIONS

Complications that are traditionally considered inevitable can be reclassified as avoidable when addressed through evidence-based safety practices. These include the implementation of standardized checklists, and robust interdisciplinary communication across the surgical, endocrinological, anesthesiology, and nursing teams. However, technical refinement alone is not enough: sustained progress requires integrating insights from human factors, engineering, and systems science. Fostering a culture of psychological safety, transparency, and shared accountability is essential for improving perioperative outcomes and transforming challenges into learning and growth opportunities. The fusion of technical expertise with system-based approaches and human-centered design does more than prevent harm: it lays the foundation for a safer, more resilient, and more compassionate future for pituitary surgery.

CONFLICT OF INTEREST

The authors declare no commercial or financial ties that could be interpreted as potential conflicts of interest. No external funding influenced the study design, analysis, or conclusions. AI-assisted tools, including ChatGPT (OpenAI), Paperpal, and Grammarly, were used exclusively under the supervision of the authors to support the manuscript preparation and editing. These tools had no role in the generation of the original data or scientific interpretation. All AI-generated or suggested content was critically reviewed, edited, and approved by the authors. The authors have retained their full responsibility for the integrity, accuracy, and originality of the final manuscript.

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APPENDIX

Table 1. Categories of Human Error	
Error Category	**Description / Examples in Pituitary Surgery**
Skill-based slips & lapses (routine task + attention failure)	Unintended burr hole with the high-speed drill: *The surgeon inadvertently taps the drill pedal; the rotating burr nicks the planum sphenoidale, causing an avoidable CSF leak.*
Rule-based mistakes (wrong rule or right rule in the wrong context)	"Standard" transsphenoidal route for lateral cavernous extension: *Following the rule that most macroadenomas can be removed midline, the surgeon avoids the extended endonasal approach. Underestimating the tumor's lateral reach leads to carotid wall injury when angled curettes are pushed too far.* Routine fluid restriction after pituitary surgery: *Applying the general rule that postoperative fluid overload risks SIADH, the ICU limits IV fluids to 50 mL/h. In this patient the real problem is early diabetes insipidus; inadequate replacement drives*

	serum sodium to 160 mmol/L before anyone recognizes.
Knowledge-based mistakes (novel situation + no ready-made script)	Variant carotid anatomy unrecognized: *The carotid bulge appears more medial than expected. Lacking a mental model of dehiscent carotid segments, the surgeon interprets the bleed as cavernous sinus oozing and continues curettage—until torrential arterial hemorrhage forces an emergent packing and aborts the case*. Postoperative visual loss misattributed to "expected swelling": *A patient complains of blurred vision six hours after closure. The surgeon, unfamiliar with the rate of development of a delayed optic-chiasm hematoma, reassures the ward team that edema is common. By the time a CT is ordered, a rapidly expanding sellar hematoma has caused permanent visual field loss.*

Table 2. Perioperative Frameworks by Functional Category

Category	**Framework**	**Definition**	**Role in Pituitary Surgery**
Process Tools	WHO Safe Surgery Checklist	Checklist standardizing key safety steps	Promotes shared mental models, prevents omission of critical steps, and standardizes team communication.
	ERAS (Enhanced Recovery After Surgery)	A multimodal care pathway that improves recovery through evidence-based interventions before, during, and after surgery.	Optimizes patient readiness, shortens recovery time, and reduces complications.
	KPI (Key Performance Indicators)	Quantitative metrics that track surgical safety, efficiency, and outcome quality.	Monitors extent of resection, CSF leak rate, length of stay, and other metrics

			to guide quality improvement.
	PRO (Patient-Reported Outcomes)	Direct patient feedback on symptoms, quality of life, and satisfaction—without clinician interpretation.	Evaluates functional and emotional recovery, guiding personalized follow-up and value-based care.
Human-Factors Frameworks	Swiss Cheese Model (Reason)	Illustrates how errors occur when multiple defensive layers fail simultaneously.	Explains alignment of latent system gaps (e.g., communication, equipment issues) that can lead to CSF leaks or other complications.
	HFACS (Human Factors Analysis and Classification System)	A human-error taxonomy categorizing contributing factors across individual, team, supervisory, and organizational levels.	Used for root-cause analysis of adverse events, informing improvements in training, supervision, and system safeguards.
	NOTSS (Non-Technical Skills for Surgeons)	Evaluates cognitive and interpersonal skills like leadership, teamwork, communication, and stress management.	Enhances coordination and safety in complex or extended transsphenoidal procedures.
	Resilience Engineering	The system's capacity to absorb stress, adapt, and recover while maintaining safe function.	Builds adaptive capacity in the OR to respond to unexpected challenges (e.g., high-risk anatomy, intraoperative bleeding), and to learn from close calls.
	Surgical Coaching	Structured peer-to-peer or expert-facilitated process	Sharpens precision, awareness, and

		using feedback and reflection to improve performance.	teamwork; fosters continuous learning; complements mentorship.
Decision-Making Models	Recognition-Primed Decision (RPD) Model	A cognitive model describing how experts rapidly identify workable courses of action by matching current cues to mental prototypes.	It enables quick planning and mental rehearsal, with real-time adaptation to unexpected anatomy.
	Thin-Slicing	The ability to draw accurate conclusions from very brief observations of behavior or environment.	Informs team dynamics—e.g., spotting early signs of stress, rapport, or leadership breakdown—and prompts timely corrective communication.
	Intraoperative Reconciliation	A process of continually updating a mental model when the surgical field deviates from initial expectations.	Ensures adaptive decision-making when confronted with unexpected anatomy, bleeding, or equipment issues, maintaining patient safety.
	Critical Thinking	The orderly analysis and evaluation of data to make clinical decisions, especially under uncertainty.	Guides preoperative diagnosis, intraoperative judgment adjustments, and real-time plan adaptations based on evolving operative findings.
	Systems Thinking	An all-inclusive approach that views care as an interconnected	Supports proactive design of perioperative pathways,

		system, emphasizing relationships, feedback loops, and patterns	coordination across disciplines, and anticipation of downstream effects

Table 3. ERAS Components Adapted for Pituitary Surgery		
Phase	**ERAS Component**	**Pituitary Surgery Example**
Preoperative	Patient education, hormonal optimization, frailty and nutritional assessment	Counseling about nasal morbidity and transient DI; hydrocortisone replacement in AI; frailty screening in older patients
Intraoperative	Short-acting anesthesia, normovolemia, temperature and glycemic control	Use of remifentanil and propofol; avoiding overhydration; normothermia to reduce infection risk
Postoperative	Early ambulation, structured monitoring of sodium, pain and nausea control	Early ambulation; serum Na every 6 hrs; acetaminophen/tramadol regimen; antiemetics if nausea persists

Table 4. KPIs and PROs in Transsphenoidal Pituitary Surgery by Age Group			
Category	**Key Performance Indicators (KPIs)**	**Patient-Reported Outcomes (PROs)**	**Age-Specific Considerations**
Surgical Safety	CSF leak rate, infection, hemorrhage, reoperation	Pain, nasal discomfort, recovery experience	*Children* need safe anesthesia. *Older adults* value low surgical risk.
Tumor Control	Extent of resection (gross total vs. subtotal), recurrence	Fear of recurrence, desire for reassurance	*All age groups* value tumor control. Parents of *younger patients* may accept

			higher risks for complete resection.
Endocrine Function	Hormone normalization, new hypopituitarism, DI/SIADH	Fatigue, sexual dysfunction, mood changes	*Children*: growth/development. *Young adults*: fertility/libido. *Older adults*: energy, cardiovascular and metabolic balance
Visual Outcomes	Visual field and acuity improvement	Vision clarity, reading ability	*Children* may be impacted academically or socially. *Older* adults prioritize vision for independence.
Quality of Life (QoL)	—	Physical activity, cognitive ability, emotional well-being, social function	*Children*: return to school. *Young adults*: work/career reintegration. *Older adults*: maintaining independence.
Hospital Metrics	Length of stay, ICU admission, readmission	Satisfaction with care, burden on caregivers	Caregiver role crucial in *children* and *frail elderly.* Shorter stays and early discharge

			planning are valued across *all ages.*
Nasal Morbidity	Need for revision surgery, crusting, septal perforation	Nasal breathing, smell/taste disturbances, sinus discomfort, empty nose syndrome	*Young patients* may be more sensitive to aesthetic or sensory changes. *Older adults* may have baseline nasal dryness or septal fragility.
Neurocognitive Function	Postoperative delirium, new-onset cognitive deficit	Attention, memory, processing speed, emotional regulation	Cognitive outcomes particularly relevant for *school-age children* and *older adults*; subtle effects may impair return to work or daily functioning.
Return to Baseline Function	Time to resume activities of daily living, return to school or work, driving clearance	Sense of autonomy, productivity, satisfaction with recovery trajectory	*Pediatric patients*: school participation *Young adults*: occupational and financial independence *Older adults*: driving, personal care, and fall prevention.

Table 5. Swiss Cheese Model in Pituitary Surgery

Adverse Event /Complication	Aligned Holes (Failed Barriers)	Barrier Category	Suggested Defensive Strategies

Postoperative Diabetes Insipidus	Inadequate preoperative risk stratification for DI Incomplete intraoperative preservation of pituitary stalk Delayed postoperative monitoring of urine output and sodium	Clinical Assessment Intraoperative Technique Postoperative Surveillance	Standardized DI risk checklist Intraoperative use of neuronavigation to avoid stalk injury Protocolized early DI monitoring with alerts for polyuria
Intraoperative Visual Deterioration	Incomplete assessment of pre-op visual field deterioration No formal consent on risk of visual worsening Optic nerve traction during tumor dissection	Preoperative Evaluation Informed Consent Surgical Technique	Mandatory preoperative visual field documentation Checklist item confirming optic risk discussed. Gentle decompression sequence under direct visualization
Unexpected Residual Tumor	Suboptimal MRI interpretation pre-op No intraoperative imaging or endoscopic angled view Ambiguous documentation of extent of resection	Radiological Assessment Surgical Technique Team Communication	Dual radiological read pre-op Routine use of angled endoscope or intraoperative MRI Real-time debrief with scrub nurse and assistant surgeon on resection goals.

Postoperative CSF Leak and meningitis	Unrecognized minor intraoperative arachnoid defects Incomplete reconstruction or fat graft displacement Lack of early recognition by floor staff	Surgical Technique Operative Field Management Postoperative Vigilance	Valsalva maneuver before closure Use of multilayered closure with fascia & sealant Nurse training to detect early rhinorrhea and escalate immediately
Postoperative Hematoma	Inadequate hemostasis in tumor cavity Omission of blood pressure control post-op Delayed recognition of neurological deterioration	Surgical Technique Postoperative Medical Management Team Monitoring	Intraoperative checklist for hemostasis before closure Protocolized BP control in recovery room Frequent neuro checks with escalation criteria for re-imaging.

Table 6. Human Factors Analysis and Classification System for Pituitary Surgery

Category	**Description / Examples**
Organizational Influences	• Organizational culture: Absence of structured safety culture — irregular mortality and morbidity reviews, missing team briefings, and weak prioritization of complications — leads to normalization of deviance and unaddressed risks • Operational process: Failure to standardize WHO checklists, imaging review, and endocrine follow-up introduces variability. • Resource management: Limited access to experienced staff, neuronavigation, intraoperative imaging, specialized nursing, and ICU beds increases perioperative risk and reduces response capacity.

Supervisory Factors	• Inadequate supervision: Junior residents are allowed to manage critical steps (e.g., sella opening, hemostasis) without direct oversight. • Planned inappropriate operations: Scheduling complex tumors (e.g., giant adenomas with cavernous sinus invasion) at end of day without backup or assigning underprepared teams for high-risk patients. • Failed to correct known problems: Equipment issues (such as a faulty endoscope light source) or recurring complications (like delayed DI recognition) remain unresolved despite multiple incidents • Supervisory violations: Skipping surgical time-outs or bypassing CSF leak tests despite high-risk anatomy.
Preconditions for Unsafe Acts	• Environmental Factors: - Tools/technology: Obsolete drill systems, missing angled endoscopes, malfunctioning suction, or poorly designed OR ergonomics that contribute to poor visualization or delayed responses - Physical environment: Inadequate lighting in the operating room, uncomfortable temperature conditions, or distraction from noise can impact concentration during precise tumor dissection. - Task factors: Reoperations, anatomy near optic nerves or cavernous sinus, instances of intraoperative hemorrhage can involve high cognitive • Individual Factors: - Mental state: Surgeon's stress due to fatigue, personal issues, or high case load. Emotional pressure to complete case rapidly. - Physiological state: Surgeon fatigue from overnight calls, dehydration, skipped meals, or illness • Team Factors: - Communication: Failure to verbally share surgical plan or miscommunication regarding hemostasis status during closure. Insufficient handover between surgical and recovery personnel. - Coordination: Inadequate planning for intraoperative sampling, or lack of coordination among multiple teams regarding post-operative instructions.

	- Leadership: Lead surgeon fails to delegate roles clearly, neglects to lead safety briefing, or undermines team input during complication management.
Unsafe Acts	• Errors: - Decision errors: Incorrectly assuming that a tumor can be fully resected using a standard approach when extended exposure is required - Skill- based errors: Inadvertent injury to optic nerve or carotid artery during dissection due to momentary lapses in attention or hand control. - Perceptual errors: The arachnoid boundary may be incorrectly identified as a result of bleeding, limited endoscopic visibility, or visual misperception within a two-dimensional field. • Violations: - Routine violations; Skipping pre-op imaging review meeting or proceeding without finalizing hormonal workup because 'the case looks straightforward' - Exceptional violations*:* Proceeding with surgery despite clear contraindications or without obtaining full patient consent during emergency situations represents rare but high-risk deviations from standard practice norms.

Table 7. Core Components of the NOTSS (Non-Technical Skills for Surgeons) Framework		
Skill Domain	**Description**	**Example in Pituitary Surgery**
Situational Awareness	Gathering and understanding information to anticipate future events.	Recognizing subtle changes in tumor consistency
Decision-Making	Formulating options, choosing the best course, and reassessing as needed.	Opting for subtotal resection upon encountering fibrous tumor texture near the carotid or the optic chiasm.
Communication	Exchanging information clearly and effectively with the team.	Confirming reconstruction plan with assistant and scrub nurse before closure.
Teamwork	Working collaboratively and supporting others under time pressure.	Coordinating intraoperative tasks with ENT and anesthesia.
Leadership	Guiding the team, assigning roles, and ensuring a shared mental model.	Leading a preoperative time-out, clarifying roles, and inviting concerns.

Stress Management	Maintaining composure and task focus on high-pressure situations.	Using controlled breathing and task delegation during sudden arterial bleed.

Table 8. Resilience Engineering in Pituitary Surgery			
Capability	**Preoperative**	**Intraoperative**	**Postoperative**
Anticipate	Predict complications: ICA injury, apoplexy, CSF leak, hormonal crises. Plan imaging review, multidisciplinary input, surgical complexity.	Anticipate difficult anatomy, firm tumors, bleeding sites, CSF leak risks. Prepare alternative tools and approaches.	Anticipate DI, hyponatremia, adrenal insufficiency, CSF leaks, hematoma. Schedule labs and follow-up based on individual risk.
Monitor	Evaluate clinical signs, hormonal status, MRI findings (e.g., Knosp grade), comorbidities, frailty.	Continuously assess vital signs, bleeding, tumor texture, endoscopic visuals, communication flow, and team fatigue.	Monitor urine output, sodium, cortisol, fluid balance, visual recovery, early signs of CSF leak or mental status changes.
Respond	Modify scheduling, initiate corticosteroids in hypocortisolism, or postpone for optimization. Previous treatment in patients with Cushing´s disease	Change resection plan; convert to subtotal or staged approach; use alternate hemostasis or closure methods.	Adjust fluid/electrolyte therapy, manage cortisol replacement, escalate care or imaging, initiate lumbar drain or repair if leak suspected.
Learn	Review prior similar cases; refine protocols and checklists.	Conduct structured intraoperative questions to identify latent safety threats.	Conduct case reviews and M&M discussions; refine early warning protocols.

Table 9. Decision Making Models in Pituitary Surgery		
Decision-Making Mechanism	**Description**	**Pituitary Surgery Example**
Recognition-Primed Decision (Klein)	Rapid pattern recognition and mental simulation based on prior experience.	Surgeon sees yellow-gray soft tumor consistent with previous adenoma cases, immediately begins suction debulking without need for alternate plan comparisons.
Intra-operative Reconciliation (Cristancho)	Reframing and adapting the surgical plan in response to unexpected findings or evolving uncertainty.	Initial plan for curettage is revised when tumor proves fibrous and resistant; surgeon switches to sharp dissection and modifies team plan in real time.
Thin-Slice Relational Cues (Ambady & Rosenthal)	Team members form immediate, intuitive impressions of stress, trust, or leadership based on brief behavior.	Assistant surgeon senses rising uncertainty in the lead surgeon's tone during a sudden bleed and instinctively irrigates the field without needing to be asked.
Critical Thinking	Analytical reasoning that questions assumptions, evaluates risks, and tailors decisions to specific clinical contexts.	Surgeon re-evaluates early discharge plan for a patient with borderline sodium levels and Cushing's history, opting for extended monitoring despite ERAS norms.
Systems Thinking	Understanding how individual actions influence the broader surgical and organizational system	Surgeon delays tumor resection near cavernous sinus to allow anesthesiologist to stabilize blood pressure, avoiding potential cascade of complications.

Table 10. Diagnostic and Imaging Evaluation of Sellar and Parasellar Lesions	
Checklist Step	**(Yes/No)**
Review the clinical presentation: Is it consistent with a pituitary adenoma?	

Evaluate signs, symptoms, and onset: Are they compatible with an adenoma?	
Ensure thorough analysis of MRI and CT scans	
Identify any clinical or radiological clues that suggest an alternative diagnosis	
Review longitudinal imaging studies for temporal changes	
Identify the sella turcica and pituitary gland on imaging	
Determine the epicenter of the lesion: sellar, suprasellar, or parasellar	
Evaluate hyperintensity on T1-weighted MRI sequences	
Assess CT for calcifications, bone sclerosis, or erosion	
Establish a differential diagnosis based on integrated findings	

Table 11. Cardiovascular and Airway Burden in Cushing's Disease and Acromegaly

Comorbidities	**Cushing's Disease**	**Acromegaly**
Hypertension	+++ (often severe)	++ (common, less volatile)
Left ventricular hypertrophy / cardiomyopathy	++	+++
Thromboembolism risk	+++ (hypercoagulable)	+ (mild–moderate)
Obstructive sleep apnea	++ (central fat deposition)	+++ (macroglossia, craniofacial changes)
Difficult airway	++	+++
Arrhythmias / QT prolongation	++	++
Legend: + = mild burden; ++ = moderate; +++ = severe burden		

Table 12. Pituitary Surgery: Technical vs Non-Technical Strategies		
Category	**Component**	**Purpose/Function**
Technical Strategies	High-definition endoscopes	Enhance visualization of the surgical field
	Neuronavigation and vascular mapping (ICG/Doppler)	Guide anatomical orientation and identify vascular structures
	Multilayer reconstruction to prevent CSF leaks	Reduce risk of postoperative CSF leaks
Non-Technical Skills (NOTSS)	Situational awareness	Maintain awareness of anatomical changes and intraoperative cues
	Decision-making under pressure	Adapt surgical plan to evolving circumstances
	Team communication and coordination	Ensure shared understanding and timely collaboration
	Stress and cognitive workload management	Sustain focus and prevent errors during complex tasks

Table 13. Case Map: CSF Leak and Pneumocephalus in Pituitary Surgery			
Complication	**Framework**	**Contributing Factor**	**Interpretation / Example**
CSF Leak	Swiss Cheese Model	Minor arachnoid defect overlooked during closure	Latent technical error combined with inattention creates a trajectory for CSF leak
	NOTSS	No verbal confirmation of complete reconstruction	Team communication failure; safety check omitted during closure
	HFACS	Endoscope light malfunction ignored for multiple cases	Supervisory failure and normalization of deviance
	ERAS	Inadequate early postoperative monitoring protocol	Failure to include nasal drainage alert in nursing checklist
	Resilience Engineering	Late recognition by night shift nurse prompts urgent call	Team adapts successfully under stress, prevents meningitis
Pneumocephalus	Swiss Cheese Model	Unsealed skull base defect allows air entry	Multiple barriers failed: poor closure, lack of

			Valsalva test, missed signs of pneumocephalus
	NOTSS	Severe headache misattributed to normal recovery pain	Lack of situational awareness and weak escalation protocol delay CT imaging
	HFACS	No flag in Medical Record for severe headache	Latent precondition for unsafe acts; communication failure between teams
	ERAS	Post-op care bundle lacked neuro check for escalating pain	Protocol gap in postoperative monitoring fails to detect pneumocephalus early
	Resilience Engineering	On-call resident rapidly scan after nurse insistence	Adaptation under pressure; event contained through timely escalation