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The Flush Model

A Novel Framework to Manage Surgeons' Mental Fatigue and Cognitive Load

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Background: Mental fatigue significantly impairs surgeons' cognitive performance, compromising patient safety. However, surgical practice lacks an integrated framework to understand and mitigate this cognitive strain effectively.

Conceptual Model: We propose adapting the Flush model, initially developed for endurance sports, to surgical settings. This model conceptualizes mental fatigue through a dynamic analogy of a water tank composed of 4 main components: perceived fatigue (ballcock), fatigue accumulation (filling rate), fatigue recovery (drain rate), and a safety margin (security reserve). We detail how intrinsic cognitive load, extraneous stressors, physiological and psychological factors, and circadian influences collectively drive mental fatigue accumulation.

Clinical Implications: The Flush model clarifies how mental fatigue fluctuates during surgical procedures and highlights practical recovery methods such as brief mindfulness interventions, microbreaks, cognitive offloading, and ergonomics adjustments. It emphasizes maintaining a cognitive safety reserve to safeguard against errors during critical surgical phases, providing surgeons with actionable strategies to manage fatigue in real time.

Future Directions: We recommend empirical validation through real-time monitoring using physiological measures (eg, heart-rate variability, pupillometry) coupled with subjective assessments (eg, NASA Task Load Index, Surgery Task Load Index). Integrating Flush principles into surgical training, simulation programs, and institutional policies could foster a culture prioritizing cognitive performance and patient safety.

Conclusions: The Flush model provides a comprehensive, intuitive framework for understanding and addressing surgeons' mental fatigue. Its implementation promises to enhance cognitive resilience, reduce surgical errors, and improve both patient outcomes and surgeon well-being.

Keywords: cognitive load, Flush model, mental fatigue, patient safety, surgeon performance

INTRODUCTION

Surgeons routinely face long hours, complex procedures, and high-stakes decisions that test the limits of their mental endurance.[1] Mental fatigue, that is, a psychobiological state caused by prolonged periods of demanding cognitive activity, manifests through specific subjective (eg, increased feelings of tiredness, lack of energy), behavioral (eg, decline in cognitive performance), and physiological (eg, alterations in brain activity) changes.[2] One of the most critical cognitive functions affected by mental fatigue is situation awareness, that is, the perception of environmental elements, the comprehension of their meaning, and the projection of their future status.[3] Studies have demonstrated that mental fatigue significantly impairs surgeons' situation awareness by degrading their ability to detect relevant cues in the operating environment, understand their implications, and anticipate potential complications.[4] This deterioration in attentional abilities and other associated cognitive functions (eg, planning[5] and performance monitoring[6]) creates significant risks in the operating room.[7,8] In a systematic review of the literature concerning 134 studies, a deterioration in surgical outcome (eg, patient mortality, patient length of stay, complications) when fatigue was present was shown in 46% of the simulator studies, while 35.5% of real-life studies showed a deterioration.[9] In addition, a comprehensive study of American surgeons showed that each incremental increase in emotional exhaustion measured on a scale from 0 to 54 was associated with a 5% higher likelihood of reporting major medical errors.[10] Despite the critical nature of this issue, guidance on how to conceptualize and manage prolonged cognitive strain in surgery remains limited.[11]

A central factor associated with mental fatigue is cognitive load, broadly defined as the total mental effort required to

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complete a task.[12] In surgery, the demands on a surgeon's cognitive resources are multifaceted: they must interpret complex visual information, integrate multiple sensory inputs, perform highly coordinated motor tasks, and make time-critical decisions under uncertainty.[13] Additionally, extraneous stressors such as equipment malfunctions, communication breakdowns, and environmental distractions can significantly elevate the surgeon's cognitive load.[14,15] Mental fatigue and cognitive load are interrelated but not identical. A surgeon may start a case with a manageable cognitive load, but as hours pass, the sustained load can cumulate into mental fatigue, diminishing the surgeon's effective working memory capacity and executive function. High perceptual demands (eg, monitoring many visual details[16]) or continuous multitasking elevate mental load and, if prolonged, lead to fatigue. Conversely, a fatigued surgeon's capacity to handle load is reduced, meaning even moderate tasks can overwhelm them. This interplay is highly relevant in surgery: for instance, performing a routine procedure at the end of a 12-hour shift can feel as challenging as a complex case when one is rested, due to accumulated fatigue.[17] In summary, mental fatigue is the consequence of enduring heavy cognitive load without sufficient recovery, and in turn, it impairs the ability to manage new loads. Understanding these concepts in tandem is the first step toward developing strategies that safeguard surgeons' cognitive performance.

To bridge this gap, we propose applying the Flush model, a holistic framework originally devised in endurance sports,[18] to the surgical domain.

THE FLUSH MODEL: A HOLISTIC FRAMEWORK FOR FATIGUE ACCUMULATION AND RECOVERY

The Flush model provides a dynamic representation of how fatigue builds up and dissipates, accounting for both physical and mental stressors. The name references a complete hydraulic system (specifically a flush tank mechanism) rather than just the flushing action itself. This provides a practical metaphor where mental fatigue gradually accumulates like water filling a tank, while recovery mechanisms function as a variable drain valve that allows controlled release to prevent overflow. Unlike the common perception of a toilet flush as an all-or-nothing action, this model emphasizes the entire regulated system with its continuous filling process and adjustable drainage capabilities. This article highlights the Flush model's value in understanding surgeon mental fatigue and cognitive load, with implications for training, fatigue mitigation, and patient safety. Furthermore, we explore how this model could guide future research directions and institutional policies, including potential adaptations from other high-reliability fields such as aviation.

The Ballcock (Buoy)—Perceived Fatigue Sensor

The Flush model consists of 4 key components (Fig. 1). The first component, the ballcock (or buoy), functions as a floating valve in a tank that rises and falls with the water level. In the model, it represents the surgeon's perceived level of mental fatigue at any given moment. In contrast to physical fatigue, which stems from repetitive muscle use,[12] mental fatigue is characterized by subjective feelings of tiredness and lack of energy due to sustained mental effort.[19] Surgeons are intimately familiar with this phenomenon: after hours of continuous operative planning, decision-making, and focused attention, their cognitive resources become depleted. In a clinical evaluation, 85% of surgeons reported experiencing moderate to high mental fatigue by the end of a workday.[19] A recent study by McCormick et al[20] revealed even more concerning data among orthopedic residents: they were cognitively fatigued during 48% of their waking hours and experienced impairment equivalent to a blood alcohol level of 0.08% for 27% of their time awake.

As fatigue accumulates (water level rises), the surgeon feels more tired and mentally taxed. If fatigue decreases (water level falls), the perceived fatigue decreases. Conceptualizing mental fatigue as a "rising water level" aligns with resource-based models that view cognitive capacity as a limited reservoir that can be depleted or replenished over time.[21] In practical terms, this corresponds to the surgeon's self-awareness of how exhausted they feel. A high "ballcock" means the surgeon recognizes they are approaching their limit. This subjective sensation is crucial because it often drives behavior: for example, a surgeon who feels extremely fatigued might consciously slow their operating pace or seek a short pause to recover. The Flush model's inclusion of a perceptual sensor emphasizes that fatigue is not just physiological; it is also about the brain's interpretation of one's state.[18] Notably, the model allows that certain factors can modulate the perception of fatigue: research shows that caffeine modulates adenosine receptors in the central nervous system, reducing perceived exertion[22]; adrenaline surges during acute stress can momentarily mask feelings of tiredness[23]; and willpower (or self-control) can override subjective fatigue signals, although this capacity is itself finite and can become depleted over time.[24] In surgery, this means that during an adrenaline-fueled trauma case, a surgeon might perceive less fatigue than they would in a calmer elective case, even at the same level of objective stress, effectively "turning down" the sensitivity of the fatigue alarm in the moment.

Filling Rate – Fatigue Accumulation

The filling rate corresponds to how quickly water (fatigue) flows into the tank. Multiple factors steadily add to a surgeon's workload, aligning with cognitive load theory's components: intrinsic load (task complexity), extraneous load (environmental distractions), and germane load (learning and adaptation efforts).[25] When the total load remains high without relief, it depletes working memory capacity, eroding situational awareness and decision-making.[26] In the following section, we outline how task-related demands, environmental/organizational stressors, physiological/psychological factors, and chronobiological timing each contribute to fatigue accumulation.

Task-Related Factors (Cognitive Demands, Complexity, Duration)—Intrinsic Load

Surgical tasks themselves impose significant cognitive demands. High case complexity and prolonged duration inherently generate heavy intrinsic cognitive load, requiring intense concentration and problem-solving.[27] More complex or novel procedures demand greater mental effort, especially for less-experienced surgeons who must devote additional resources to learning and adapting (germane load) in real time.[11] As operative time lengthens, fatigue mounts: studies show that surgeons experience mounting mental exhaustion, irritability, and impaired judgment as a procedure approaches 4 hours.[28] Even before such long durations, the continuous cognitive strain from managing surgical steps, making decisions, and avoiding errors gradually fills the fatigue "reservoir." This accumulation of intrinsic load over time diminishes fine motor precision and can slow a surgeon's reactions,[29] underscoring how task demands translate into fatigue.

Environmental and Organizational Factors (Interruptions, Communication, Workload, Conditions)—Extraneous Load

The operating room environment and workflow can introduce extraneous cognitive load, that is, distractions and pressures unrelated to the surgical task itself. Frequent interruptions are a prime example: one observational study found nearly

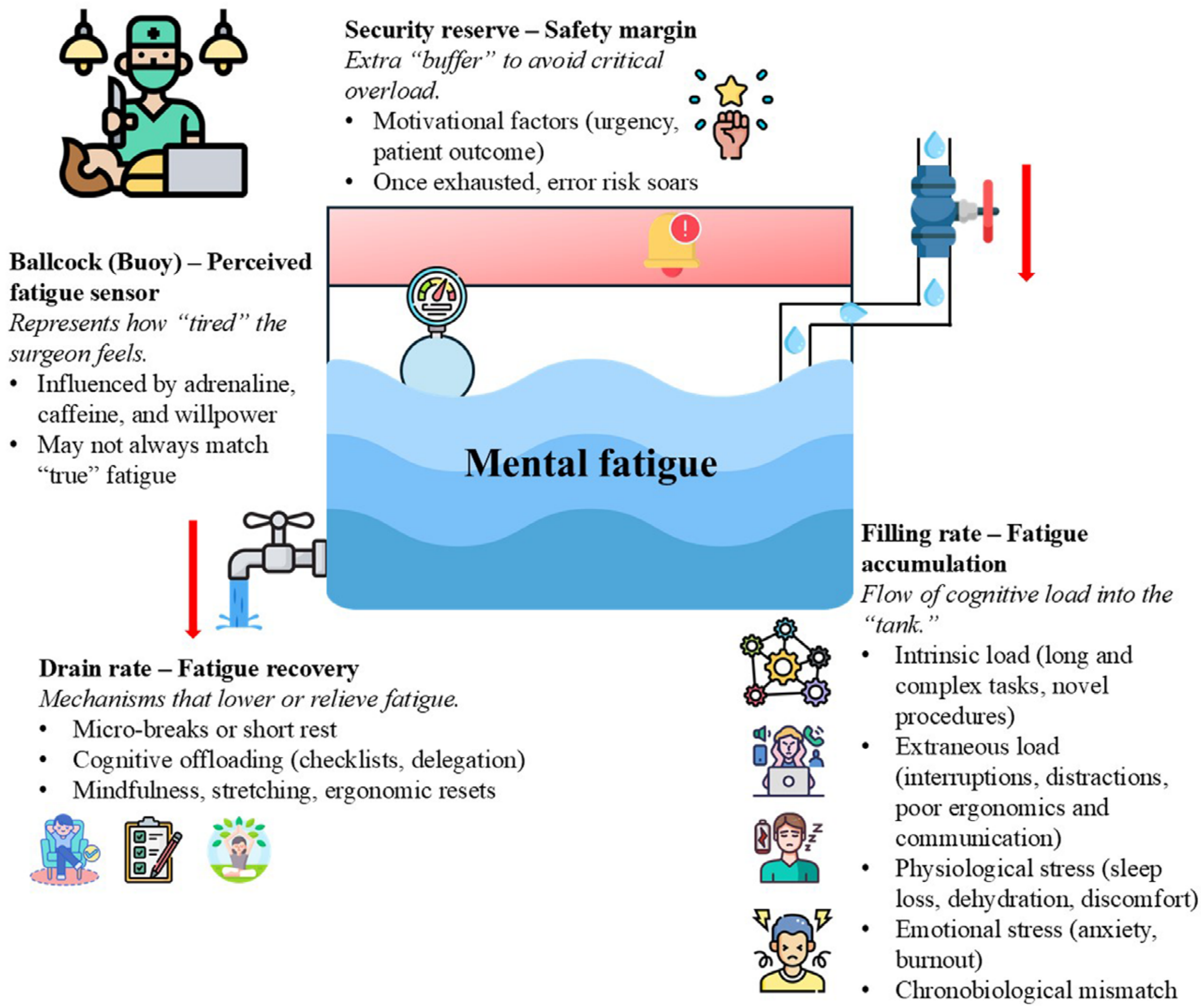

FIGURE 1. Flush model for mental fatigue in surgery. (Adapted from Millet,[18] originally devised for endurance sports. Created by the authors.) The Flush model illustrates how mental fatigue accumulates (filling rate) and dissipates (drain rate) in a "tank." The "ballcock" reflects the surgeon's perceived fatigue, which can be momentarily reduced by adrenaline, caffeine, or willpower. Filling rate encompasses factors such as intrinsic load (complex procedures, high cognitive demands), extraneous load (interruptions, poor ergonomics and communication), and physiological/psychological stress (sleep deprivation, anxiety). Drain rate depicts recovery strategies (short microbreaks, cognitive offloading, and mindfulness) that lower fatigue. At the top, the security reserve (buffer zone) provides a temporary margin before catastrophic overload (burnout, significant errors). Once this margin is exceeded, performance declines sharply.

10 interruptions per hour during surgery (eg, people entering/exiting and pager calls), with equipment issues and operating room environment problems causing the greatest disruption to team function,[15,30] particularly when distractions are auditory.[31] McMullan et al[32] conducted a comprehensive systematic review and meta-analysis of operating room workflow disruptions. They categorized these disruptions into 3 types: distractions (eg, noise and conversations nearby), interruptions (eg, answering questions and responding to pagers), and disruptions (eg, equipment failures and protocol deviations). Their analysis revealed these events occupied 22.0% of total operative time. Such disruptions were significantly associated with extended operative duration, impaired team performance, surgical errors, and increased risk of surgical site infections.

Communication breakdowns or teamwork lapses present another hazard; poor communication is a known extraneous load that requires surgeons to expend additional effort to maintain situational awareness,[33,34] which can be exacerbated if the surgeon lacks confidence in his/her team.[35] Notably, an analysis of surgical error incidents found that communication failures contributed to 43% of errors and fatigue or excessive workload contributed to 33%,[8] highlighting how teamwork and workload pressures directly feed into fatigue and mistakes. High workload pressure, such as multiple back-to-back cases or time pressure to speed up, further amplifies cognitive strain. Surgeons under time stress often must multitask and rush, which has been linked to higher error rates when cognitive load is exceeded.[36] Similarly, suboptimal conditions (eg, poor lighting, noise, or missing equipment) create frustrating extra hurdles that tax the surgeon's concentration. All of these factors add layers of extraneous load, accelerating fatigue accumulation by forcing the surgeon's brain to manage nonoperative problems alongside the surgical task. Over time, this constant juggling act erodes focus and can jeopardize performance.[15]

Physiological and Psychological Factors (Sleep, Hydration, Stress, Discomfort)

A surgeon's physical and mental state critically influences fatigue buildup. Sleep deprivation is a well-documented cause of cognitive fatigue: extended wakefulness can degrade performance as severely as alcohol intoxication.[37] Fatigued surgeons coming off overnight call show measurably poorer nontechnical skills, with reduced situational awareness and impaired decision-making noted after nights of short sleep (ie, <5 hours).[38] Although experienced surgeons may compensate by working more slowly, their alertness and communication still suffer when sleep deprived. Inadequate hydration and nutrition during long surgeries also contribute to fatigue: even mild dehydration (~2% body weight) can impair attention, short-term memory, and psychomotor speed,[39] while low blood sugar from missing meals saps concentration. Physical discomfort and pain (eg, musculoskeletal strain from standing in awkward positions for hours) create constant background distractions and stress. Surgeons in physical discomfort must devote mental resources to pushing through pain or numbness, leaving less capacity for the task at hand.[40] Likewise, emotional stress and mental strain (eg, anxiety about a complication or general burnout) can accelerate fatigue by consuming mental energy.[41] However, the relationship between stress and surgical performance is complex and multifaceted. While acute stress responses can initially enhance performance through increased alertness and focus,[13] prolonged elevation of stress hormones like cortisol and adrenaline during long procedures ultimately leads to cognitive depletion and decreased performance.[42] Recent empirical evidence has identified key factors modulating this relationship: surgical experience and stress management abilities significantly influence outcomes, particularly during crisis situations where the combination of high experience and low stress levels produces optimal technical and nontechnical performance.[43] Notably, specific surgical contexts generate varying stress levels (eg, complex or rarely performed procedures or inadequate surgical assistance), with 40% of surgeons reporting direct links between stress and intraoperative complications (Anton et al)[44]. Although moderate levels of anticipatory stress may enhance performance in certain conditions,[45] mounting evidence emphasizes how acute stress significantly impacts both technical and nontechnical skills.[46]

Chronobiological Considerations (Circadian Rhythms and Time-of-Day Effects)

Human performance is tightly linked to the circadian rhythm,[47] controlled through a complex network of cellular clocks synchronized by environmental cues such as light, meals, and physical activity.[48] Time of day, therefore, plays a role in fatigue accumulation. Most people experience a natural dip in alertness in the late night to early morning hours (eg, around 3–5 AM), coinciding with peak melatonin levels and preceding the daily minimum in core body temperature.[49,50] Surgical procedures conducted during these circadian "troughs" tend to face greater fatigue-related challenges. Evidence shows that elective surgeries performed in the evening or at night have higher risks of adverse outcomes compared with those done in daytime,[51] though interestingly, some studies have shown better outcomes for afternoon cardiac surgeries due to circadian variation in ischemia-reperfusion tolerance.[52] Even within normal working hours, individual chronobiology matters (some surgeons may be morning-oriented or evening-oriented, affecting when they function optimally). Circadian misalignment, such as an out-of-sync schedule or rapid shift rotations, exacerbates fatigue.[53] Surgeons who frequently rotate between day shifts and night shifts cannot fully adjust their body clocks, leading to chronic sleep loss and circadian disruption.[20] In practice, an early-morning start after an overnight call or a long case that extends into the night will see the surgeon fighting against their biological clock as well as the task itself. Chronobiological lows thus accelerate fatigue accumulation and can undermine concentration, making errors more likely when performing at suboptimal times.

Waste Pipe (Drain Rate)—Fatigue Recovery

In the Flush model tank analogy, water can leave the tank through a drain, lowering the level. Applied to the surgical setting, the waste pipe represents opportunities for recovery or relief that reduce accumulated fatigue.[54] Techniques such as mindfulness have been shown to reduce mental fatigue and enhance emotional well-being.[55] Mindfulness-based practices typically involve brief, structured exercises (eg, guided breathing, body scans, or focused attention) that help individuals maintain a nonjudgmental awareness of their thoughts and emotions.[56] In the surgical context, such techniques can be integrated during short breaks or before and after procedures to reduce mental fatigue and emotional distress. For instance, studies have shown that healthcare providers who engage in mindfulness sessions report lower perceived stress and anxiety.[57] Furthermore, even while on the job, surgeons can drain some mental and physical fatigue from their "tank" through deliberate rest and recovery strategies. Short microbreaks are a prime example: brief pauses of even a few minutes to relax muscles, stretch, and reset mentally have been shown to significantly reduce fatigue and improve vigor without compromising performance.[58] A systematic review found that taking microbreaks during operative tasks produced small but significant reductions in surgeons' reported fatigue (effect size $d \approx 0.35$).[59] In the Flush model, such pauses open the drain and let the water level drop slightly, preventing an overflow of exhaustion. Other drain mechanisms in surgery include cognitive offloading, that is, using checklists or aides-mémoire so that some information does not have to be actively held in working memory, effectively lightening the immediate load.[60] Beyond these surgical-specific strategies, Proost et al[61] highlight additional countermeasures from sports that hold promise for the operating room: moderate caffeine use (blocking adenosine to sustain alertness), pleasant odors (eg, peppermint) to boost arousal, music to reduce perceived effort and enhance mood, and extrinsic motivators (eg, small rewards or positive feedback) to sustain engagement. Each likely acts via dopaminergic mechanisms, offering a mental "lift" when fatigue looms. Short, feasible adaptations, such as a quick sip of coffee before a prolonged case, a subtle scented inhaler, or soft background music, can thus complement existing interventions without disrupting surgical flow.

Security Reserve—Safety Margin

The security (or emergency) reserve is an extra space at the top of the tank that prevents overflow. It symbolizes a buffer capacity that allows the individual to avoid catastrophic failure even when fatigue is extreme. In endurance sports, this reserve is what keeps an athlete from literally collapsing by forcing a pace reduction or stopping at a critical threshold.[18] In a surgical context, the security reserve can be thought of as the surgeon's innate or learned ability to press on despite fatigue up to a point, and the intrinsic protective mechanisms that enforce a stop if absolutely necessary. For example, a surgeon might feel utterly exhausted (water level at the brim) yet still summon the energy to finish the critical last steps of a procedure, tapping into their reserve. This reserve is partly physiological and partly motivational. The Flush model posits that the size of the reserve is determined mainly by motivation.[18] A highly motivated surgeon (due to personal determination or the knowledge that a patient's life is on the line) may effectively have a larger reserve: they are willing to tolerate a higher level of fatigue and keep functioning near their limits. However, once the reserve is exhausted or if it is very small, the risk of errors skyrockets because the individual has no remaining buffer; any additional strain could "overflow" into a serious lapse (analogous to water spilling over). In practical terms, the security reserve reminds us that there is a hard limit to human cognitive endurance. Pushing beyond it can lead to burnout[62] or mistakes like a lapse in sterility or a slip of the hand.[63] While individual awareness of these limits is important, institutional safeguards are essential to provide reliable protection. Institutions might ensure a buffer by implementing policies such as a maximum duration for continuous operating (eg, recommending a second surgeon take over after X hours).[64] These system-level protections are particularly important for early-career surgeons who may not yet accurately gauge their personal limits under extreme fatigue. Individually, surgeons must be attuned to their personal limits, that is, recognizing the signs when their reserve is running low (eg, inability to focus eyes, nodding off microsleeps, or marked irritability and loss of situational awareness). The Flush model's concept of a reserve for safety aligns with the idea of "fatigue-proofing" critical moments: ensuring that during the most crucial parts of a surgery, the surgeon has enough cognitive margin left to perform safely. If earlier parts of the process drained too much, that reserve may not be there when needed most, regardless of motivation level.

In summary, the Flush model provides a comprehensive mental model for how fatigue is generated and managed: the perceived effort (ballcock) reflects the balance between fatigue inflow and cognitive load (filling rate) and recovery outflow (drain rate), all moderated by a safety buffer (reserve) to prevent total system failure. Rather than seeing fatigue as a binary (fresh vs tired) or a vague feeling, we can conceptualize it as a continuously varying level that results from a balance of demands and recuperation at any moment. This model encourages surgeons and educators to actively manage that balance, that is, to pace mental fatigue and cognitive load like an endurance runner pacing speed, avoiding surges that lead to premature exhaustion and incorporating "breaks" to keep overall fatigue in check.

PRACTICAL IMPLICATIONS AND FUTURE DIRECTIONS

Translating the Flush model[18] into routine surgical practice promises to enhance both surgeon well-being and patient safety. By framing mental fatigue within a dynamic, easy-to-visualize structure, the model helps practitioners recognize how physical exertion, cognitive load, and motivational reserves collectively govern operative performance. As a corollary, microinterventions such as brief breaks, cognitive offloading, or task rotation become more than ad hoc solutions; they are essential "drain" mechanisms that protect against error and burnout.[58,60,65] Notably, current evidence suggests that short intraoperative pauses and mindfulness-based strategies can be implemented without compromising operative efficiency, underscoring the feasibility of the Flush model-driven interventions in real-world settings.[57,59]

Looking ahead, several research and implementation priorities emerge:

1. Prospective validation and technology-enhanced monitoring: While the components of the Flush model are grounded in known fatigue[21] and cognitive load theories,[25] future studies should empirically track surgeons' "filling rate," "drain rate," and "reserve" in different procedures. Subjective workload measures (eg, NASA Task Load Index, a validated multidimensional rating scale measuring mental demands, physical demands, temporal demands, performance, effort, and frustration[66]; Surgery Task Load Index, a surgery-specific workload assessment scale that evaluates mental demands, physical demands, temporal demands, task complexity, situational stress, and distractions[67]) and physiological metrics (pupillometry, heart-rate variability), potentially processed through machine learning algorithms and artificial intelligence-powered analytics platforms capable of real-time data integration and pattern detection,[68] could validate the model's predictive value for error rates or case outcomes.[14] In aviation, for instance, electrocardiography and eye-metric analyses have been used in real time to detect early signs of fatigue,[69] and emerging tools such as speech-pattern monitoring or photoplethysmogram sensors in headsets are showing promise for unobtrusive fatigue detection.[70,71] Adapting such technologies to the operating room could help surgeons, teams, and institutions identify elevated "filling rates" or dwindling "reserves" before performance is critically compromised.

A key challenge remains determining each surgeon's individual threshold—how "high" their tank might fill before performance could potentially deteriorate. Biomathematical fatigue models like SAFTE (Sleep, Activity, Fatigue, and Task Effectiveness; ie, a model that predicts performance based on sleep history, circadian rhythms, and work schedules), while offering value for group scheduling, appear to face limitations when accounting for interindividual variability.[72] Ingre et al[73] demonstrated that even with identical input data, these models can produce predictions that vary considerably from observed individual performance. One possible approach to address this limitation could be personalized profiling through longitudinal studies in high-fidelity simulation environments, where surgeons might perform standardized tasks under gradually increasing cognitive load.[74] Such a multidimensional strategy could potentially combine the same real-time physiological metrics mentioned earlier, surgical-specific subjective evaluations, and technical performance metrics to identify precisely when errors begin to emerge for each surgeon.

2. Integrative training programs: Flush model principles should be integrated into surgical education as a fundamental component of professional development, equal in importance to technical skill acquisition.[75] The model's intuitive tank analogy provides an effective pedagogical framework for understanding fatigue's complex dynamics in surgery. Through this lens, residents and experienced surgeons can better conceptualize how cognitive resources deplete and replenish during clinical practice. The visual nature of the model facilitates meaningful discussions about personal experiences with fatigue, promoting both self-reflection and peer learning. Simulation-based curricula can leverage this framework to create targeted scenarios that challenge surgeons to recognize and respond to fatigue-related performance decrements.[43] Beyond skill development, simulation environments provide a safe, controlled setting to evaluate the feasibility and effectiveness of various fatigue mitigation strategies. For instance, studies could assess how mindfulness exercises or strategic caffeine use affect technical performance and decision-making under extended operative conditions.
3. Institutional policy development: Hospitals can operationalize the Flush model via supportive scheduling, "2-surgeon" approaches for lengthy cases, mandatory break protocols, and nonpunitive fatigue reporting systems. While these policies draw inspiration from aviation safety frameworks, where Fatigue Risk Management Systems mandate rest periods, limit flight-duty times, and encourage strategic napping and crew rotations,[76] the direct transposition of aviation protocols to healthcare requires careful consideration. Unlike standardized flight operations, surgical procedures involve higher variability in task complexity, duration, and unpredictable emergencies. Nevertheless, certain aviation safety principles can be effectively adapted: Crew Resource Management modules emphasizing teamwork, communication, and shared vigilance have successfully transferred to healthcare settings, demonstrating reduced error rates and improved team performance.[77] While aviation's use of pharmacological interventions (eg, short-acting hypnotics for improved sleep or mild stimulants) remains under strict oversight, such measures require more extensive evaluation in surgical contexts. Healthcare institutions can

implement evidence-based adaptations such as scheduling high-complexity procedures at times of peak alertness, establishing clear handover protocols for extended operations, and developing reporting systems that acknowledge the unique challenges of surgical fatigue. Additionally, emerging evidence supports the integration of mindfulness practices into healthcare settings: brief mindfulness interventions have shown promise in reducing stress and improving attention among healthcare providers,[57] while enhanced psychological flexibility through mindfulness practices predicts better individual outcomes for hospital workers.[78] However, the implementation of mindfulness programs requires careful consideration of organizational context and work demands to avoid it becoming another source of pressure rather than support.

In sum, the Flush model provides a theoretically grounded yet pragmatically adaptable framework for understanding and mitigating mental fatigue in surgery. Rather than replacing established safety protocols, it integrates and reinforces them, offering surgeons and institutions a shared language to identify, measure, and address the complex interplay of physical strain, cognitive workload, and motivational limits.[18] By systematically applying Flush model insights, the field can move toward a culture that normalizes strategic breaks, mutual support, and situational awareness, thereby safeguarding both the performance of surgical teams and the well-being of the patients they serve.

REFERENCES

1. Bagrodia A, Rachakonda V, Delafuente K, et al. Surgeon fatigue: impact of case order on perioperative parameters and patient outcomes. *J Urol*. 2012;188:1291–1296.
2. Van Cutsem J, Marcora S, De Pauw K, et al. The effects of mental fatigue on physical performance: a systematic review. *Sports Med*. 2017;47:1569–1588.
3. Endsley MR. Toward a theory of situation awareness in dynamic systems. *Hum Factors*. 1995;37:32–64.
4. Feller S, Feller L, Bhayat A, et al. Situational awareness in the context of clinical practice. *Healthcare (Basel)*. 2023;11:3098.
5. van der Linden D, Frese M, Meijman TF. Mental fatigue and the control of cognitive processes: effects on perseveration and planning. *Acta Psychol (Amst)*. 2003;113:45–65.
6. Lorist MM, Boksem MAS, Ridderinkhof KR. Impaired cognitive control and reduced cingulate activity during mental fatigue. *Brain Res Cogn Brain Res*. 2005;24:199–205.
7. Bourne SK, Walcott BP, Sheth SA, et al. Neurological surgery: the influence of physical and mental demands on humans performing complex operations. *J Clin Neurosci*. 2013;20:342–348.
8. Gawande AA, Zinner MJ, Studdert DM, et al. Analysis of errors reported by surgeons at three teaching hospitals. *Surgery*. 2003;133:614–621.
9. Reijmerink IM, van der Laan MJ, Wietasch JKG, et al. Impact of fatigue in surgeons on performance and patient outcome: systematic review. *Br J Surg*. 2024;111:znad397.
10. Shanafelt TD, Balch CM, Bechamps G, et al. Burnout and medical errors among American surgeons. *Ann Surg*. 2010;251:995–1000.
11. Tokuno J, Carver TE, Fried GM. Measurement and management of cognitive load in surgical education: a narrative review. *J Surg Educ*. 2023;80:208–215.
12. Mizuno K, Tanaka M, Yamaguti K, et al. Mental fatigue caused by prolonged cognitive load associated with sympathetic hyperactivity. *Behav Brain Funct*. 2011;7:17.
13. Arora S, Sevdalis N, Nestel D, et al. The impact of stress on surgical performance: a systematic review of the literature. *Surgery*. 2010;147:318–30, 330.e1.
14. Dias RD, Ngo-Howard MC, Boskovski MT, et al. Systematic review of measurement tools to assess surgeons' intraoperative cognitive workload. *Br J Surg*. 2018;105:491–501.
15. Weigl M, Antoniadis S, Chiapponi C, et al. The impact of intra-operative interruptions on surgeons' perceived workload: an observational study in elective general and orthopedic surgery. *Surg Endosc*. 2015;29:145–153.
16. Lavie N, Beck DM, Konstantinou N. Blinded by the load: attention, awareness and the role of perceptual load. *Philos Trans R Soc Lond B Biol Sci*. 2014;369:20130205.
17. Sugden C, Athanasiou T, Darzi A. What are the effects of sleep deprivation and fatigue in surgical practice? *Semin Thorac Cardiovasc Surg*. 2012;24:166–175.
18. Millet GY. Can neuromuscular fatigue explain running strategies and performance in ultra-marathons?: the Flush model. *Sports Med*. 2011;41:489–506.
19. Maffiuletti N, Lepers R. Muscular and mental fatigue in surgeons. *Ann R Coll Surg Engl*. 2012;94:67–67.
20. McCormick F, Kadzielski J, Landrigan CP, et al. Surgeon fatigue: a prospective analysis of the incidence, risk, and intervals of predicted fatigue-related impairment in residents. *Arch Surg*. 2012;147:430–435.
21. Marcora S. Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs. *J Appl Physiol (1985)*. 2009;106:2060–2062.
22. Meeusen R, Duclos M, Foster C, et al; European College of Sport Science. Prevention, diagnosis, and treatment of the overtraining syndrome: joint consensus statement of the European College of Sport Science and the American College of Sports Medicine. *Med Sci Sports Exerc*. 2013;45:186–205.
23. McMorris T, Swain J, Smith M, et al. Heat stress, plasma concentrations of adrenaline, noradrenaline, 5-hydroxytryptamine and cortisol, mood state and cognitive performance. *Int J Psychophysiol*. 2006;61:204–215.
24. Ackerman PL, Kanfer R. Test length and cognitive fatigue: an empirical examination of effects on performance and test-taker reactions. *J Exp Psychol Appl*. 2009;15:163–181.
25. Paas FGWC, Van Merriënboer JJG. Instructional control of cognitive load in the training of complex cognitive tasks. *Educ Psychol Rev*. 1994;6:351–371.
26. Howie EE, Dharanikota H, Gunn E, et al. Cognitive load management: an invaluable tool for safe and effective surgical training. *J Surg Educ*. 2023;80:311–322.
27. Cheng H, Clymer JW, Po-Han Chen B, et al. Prolonged operative duration is associated with complications: a systematic review and meta-analysis. *J Surg Res*. 2018;229:134–144.
28. Reyes DA, Tang B, Cuschieri A. Minimal access surgery (MAS)-related surgeon morbidity syndromes. *Surg Endosc*. 2006;20:1–13.
29. Slack PS, Coulson CJ, Ma X, et al. The effect of operating time on surgeons' muscular fatigue. *Ann R Coll Surg Engl*. 2008;90:651–657.
30. Göras C, Olin K, Unbeck M, et al. Tasks, multitasking and interruptions among the surgical team in an operating room: a prospective observational study. *BMJ Open*. 2019;9:e026410.
31. Nasri BN, Mitchell JD, Jackson C, et al. Distractions in the operating room: a survey of the healthcare team. *Surg Endosc*. 2023;37:2316–2325.
32. Mcmullan RD, Urwin R, Gates P, et al. Are operating room distractions, interruptions and disruptions associated with performance and patient safety? A systematic review and meta-analysis. *Int J Qual Health Care*. 2021;33:mzab068.
33. Akasaka H, Hakamada K, Morohashi H, et al. Impact of the suboptimal communication network environment on telerobotic surgery performance and surgeon fatigue. *PLoS One*. 2022;17:e0270039.
34. Tiwary A, Rimal A, Paudyal B, et al. Poor communication by health care professionals may lead to life-threatening complications: examples from two case reports. *Wellcome Open Res*. 2019;4:7.
35. de Leval MR, Carthey J, Wright DJ, et al. Human factors and cardiac surgery: a multicenter study. *J Thorac Cardiovasc Surg*. 2000;119:661–672.
36. Westbrook JI, Raban MZ, Walter SR, et al. Task errors by emergency physicians are associated with interruptions, multitasking, fatigue and working memory capacity: a prospective, direct observation study. *BMJ Qual Saf*. 2018;27:655–663.
37. Williamson AM, Feyer AM. Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. *Occup Environ Med*. 2000;57:649–655.
38. Quan SF, Landrigan CP, Barger LK, et al. Impact of sleep deficiency on surgical performance: a prospective assessment. *J Clin Sleep Med*. 2023;19:673–683.
39. Adan A. Cognitive performance and dehydration. *J Am Coll Nutr*. 2012;31:71–78.
40. Haneda M, Wargocki P, Dalewski M, et al. The effects of thermal discomfort on task performance, fatigue and mental work load examined in a subjective experiment. In: *Proceedings of Healthy Buildings 2009 — 9th International Conference & Exhibition, Syracuse (NY), September 13–17 2009*. Vol 1. International Society of Indoor Air Quality and Climate; 2009:1097–1100.
41. Zhang H, Wang J, Geng X, et al. Objective assessments of mental fatigue during a continuous long-term stress condition. *Front Hum Neurosci*. 2021;15:733426.

42. Ellenbogen MA, Schwartzman AE, Stewart J, et al. Stress and selective attention: the interplay of mood, cortisol levels, and emotional information processing. *Psychophysiology*. 2002;39:723–732.
43. Wetzel CM, Black SA, Hanna GB, et al. The effects of stress and coping on surgical performance during simulations. *Ann Surg*. 2010;251:171–176.
44. Anton NE, Montero PN, Howley LD, et al. What stress coping strategies are surgeons relying upon during surgery? *Am J Surg*. 2015;210:846–851.
45. Awtry J, Skinner S, Polazzi S, et al. Association between surgeon stress and major surgical complications. *JAMA Surg*. 2025;160:332.
46. Tam A, Bateman S, Buckingham G, et al. The effects of stress on surgical performance: a systematic review. *Surg Endosc*. 2025;39:77–98.
47. Bellicoso D, Trudeau M, Fitch MI, et al. Chronobiological factors for compassion satisfaction and fatigue among ambulatory oncology caregivers. *Chronobiol Int*. 2017;34:808–818.
48. Martin D, McKenna H, Galley H. Rhythm and cues: role of chronobiology in perioperative medicine. *Br J Anaesth*. 2018;121:344–349.
49. Caldwell JA, Caldwell JL, Schmidt RM. Alertness management strategies for operational contexts. *Sleep Med Rev*. 2008;12:257–273.
50. Rosekind MR, Gander PH, Gregory KB, et al. Managing fatigue in operational settings 1: physiological considerations and counter-measures. *Hosp Top*. 1997;75:23–30.
51. Meewisse AJG, Gribnau A, Thiessen SE, et al. Effect of time of day on outcomes in elective surgery: a systematic review. *Anaesthesia*. 2024;79:1325–1334.
52. Montaigne D, Marechal X, Modine T, et al. Daytime variation of perioperative myocardial injury in cardiac surgery and its prevention by Rev-Erbα antagonism: a single-centre propensity-matched cohort study and a randomised study. *Lancet*. 2018;391:59–69.
53. Yang N, Elmatite WM, Elgallad A, et al. Patient outcomes related to the daytime versus after-hours surgery: a meta-analysis. *J Clin Anesth*. 2019;54:13–18.
54. Janhofer DE, Lakhiani C, Song DH. Addressing surgeon fatigue: current understanding and strategies for mitigation. *Plast Reconstr Surg*. 2019;144:693e–699e.
55. Johansson B, Bjuhr H, Rönnbäck L. Mindfulness-based stress reduction (MBSR) improves long-term mental fatigue after stroke or traumatic brain injury. *Brain Inj*. 2012;26:1621–1628.
56. Creswell JD. Mindfulness interventions. *Annu Rev Psychol*. 2017;68:491–516.
57. Gilmartin H, Goyal A, Hamati MC, et al. Brief mindfulness practices for healthcare providers – a systematic literature review. *Am J Med*. 2017;130:1219.e1–1219.e17.
58. Park AE, Zahiri HR, Hallbeck MS, et al. Intraoperative "micro breaks" with targeted stretching enhance surgeon physical function and mental focus: a multicenter cohort study. *Ann Surg*. 2017;265:340–346.
59. Albulescu P, Macsinga I, Rusu A, et al. "Give me a break!" a systematic review and meta-analysis on the efficacy of micro-breaks for increasing well-being and performance. *PLoS One*. 2022;17:e0272460.
60. Gillespie BM, Chaboyer W, Thalib L, et al. Effect of using a safety checklist on patient complications after surgery: a systematic review and meta-analysis. *Anesthesiology*. 2014;58:298.
61. Proost M, Habay J, De Wachter J, et al. How to tackle mental fatigue: a systematic review of potential countermeasures and their underlying mechanisms. *Sports Med*. 2022;52:2129–2158.
62. Dimou FM, Eckelbarger D, Riall TS. Surgeon burnout: a systematic review. *J Am Coll Surg*. 2016;222:1230–1239.
63. West CP, Tan AD, Habermann TM, et al. Association of resident fatigue and distress with perceived medical errors. *JAMA*. 2009;302:1294–1300.
64. Weissman JS, Rothschild JM, Bendavid E, et al. Hospital workload and adverse events. *Med Care*. 2007;45:448–455.
65. Treadwell JR, Lucas S, Tsou AY. Surgical checklists: a systematic review of impacts and implementation. *BMJ Qual Saf*. 2014;23:299–318.
66. Hart SG, Staveland LE. Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock PA, Meshkati N, editors. *Human mental workload*. Amsterdam: Elsevier; 1988. p. 139–83.
67. Wilson MR, Poolton JM, Malhotra N, et al. Development and validation of a surgical workload measure: the surgery task load index (SURG-TLX). *World J Surg*. 2011;35:1961–1969.
68. Rafaih AB, Ari K. Artificial intelligence-driven approaches to managing surgeon fatigue and improving performance. *Cureus*. 2024;16:e75717.
69. Hu X, Lodewijks G. Detecting fatigue in car drivers and aircraft pilots by using non-invasive measures: the value of differentiation of sleepiness and mental fatigue. *J Safety Res*. 2020;72:173–187.
70. de Vasconcelos CA, Vieira MN, Kecklund G, et al. Speech analysis for fatigue and sleepiness detection of a pilot. *Aerosp Med Hum Perform*. 2019;90:415–418.
71. Wilson N, Guragain B, Verma A, et al. Blending human and machine: feasibility of measuring fatigue through the aviation headset. *Hum Factors*. 2020;62:553–564.
72. Hursh SR, Redmond DP, Johnson ML, Thorne DR, Belenky G, Balkin TJ, et al. Fatigue models for applied research in warfighting. *Aviat Space Environ Med*. 2004;75(3 Suppl):A44–53.
73. Ingre M, Van Leeuwen W, Klemets T, et al. Validating and extending the three process model of alertness in airline operations. *PLoS One*. 2014;9:e108679.
74. Stefanidis D, Anton NE, Howley LD, et al. Effectiveness of a comprehensive mental skills curriculum in enhancing surgical performance: results of a randomized controlled trial. *Am J Surg*. 2017;213:318–324.
75. Yule S, Parker SH, Wilkinson J, et al. Coaching non-technical skills improves surgical residents' performance in a simulated operating room. *J Surg Educ*. 2015;72:1124–1130.
76. Wingelaar-Jagt YQ, Wingelaar TT, Riedel WJ, et al. Fatigue in aviation: safety risks, preventive strategies and pharmacological interventions. *Front Physiol*. 2021;12:712628.
77. Buljac-Samardžić M, Dekker-van Doorn CM, Maynard MT. What do we really know about crew resource management in healthcare?: an umbrella review on crew resource management and its effectiveness. *J Patient Saf*. 2021;17:e929–e958.
78. Ramaci T, Bellini D, Presti G, et al. Psychological flexibility and mindfulness as predictors of individual outcomes in hospital health workers. *Front Psychol*. 2019;10:1302.