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SPECIAL ARTICLE

Lessons from the sky: an aviation-based framework for maximizing the delivery of quality anesthetic care

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Abstract
Though aviation is practiced in airplanes and anesthesiology in operating rooms, the two professions have substantial parallels. Both require readiness to manage a crisis situation, where lives are at stake, at a moment's notice and with incomplete information. The determinants of quality performance in both professions extend far beyond knowledge base and formal training. The science of human factors, a prominent cornerstone of the aviation industry, has not yet found the same place in medicine, but it could change the understanding and execution of medical decision-making in profound ways. This article reviews specific components of crisis management and root cause analysis in aviation that can serve as models for improving those same aspects within anesthesiology.

Keywords Aviation · Crisis management · Human factors · Root cause analysis · Error

Introduction

While one profession is practiced in airplanes and the other in operating rooms, aviation and anesthesiology possess striking parallels. Both require readiness to manage a crisis situation, where lives are at stake, at a moment's notice and with incomplete information. The stress and fast pace of a crisis situation can make executing even simple, routine actions feel arduous. Professionals in both fields must work well under stress but also, in calm moments, possess meticulous, unwavering attention to detail to ensure that all components of their system are functioning properly and errors are avoided to the greatest extent possible.

The determinants of the delivery of quality care by anesthesiologists extend far beyond medical knowledge. The science of human factors, a prominent cornerstone of the aviation industry, has not yet found the same place in medicine—but it could change the understanding and execution of medical decision-making in profound ways. If a new video laryngoscope or central venous cannulation kit were associated with superior clinical outcomes and fewer complications, then anesthesiologists would flock to the product with great interest. The new piece of equipment may not prove to be an exact fit for each physician's practice, but an investigation would at least occur, because potentially omitting a tool in one's armamentarium that could possibly result in better performance or saving lives seems imprudent. The same can be said for the lessons available to be learned from the aviation industry, in terms of both accident reporting and simulation-based human factors studies.

Part I: accident reporting

In the United States, civil aviation accident investigation is conducted primarily by a federal agency known as the NTSB (National Transportation Safety Board). This agency is comprised of a variety of professionals with graduate degrees in aerospace engineering, aeronautical science, psychology, law, information technology, meteorology, and business. The NTSB publishes a report following each civil aviation accident. A case study of one NTSB report presents multiple tools that anesthesiologists can utilize for quality improvement following patient morbidity and mortality events.

Eastern Airlines Flight 401 crashed into the Florida Everglades on December 29, 1972, killing 99 individuals on board. The subsequent 50-page accident report produced by the NTSB [1] included an extensive root cause analysis, expert testimonies, and recommendations for improved

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safety measures. When the NTSB analyzed the unexpected descent and crash of Eastern Airlines Flight 401, four hypothesized contributing factors were clearly listed and explored: the pilot's physical status, the equipment–user interface, pilot training, and the presence of distractions [1]. The applicability of this investigative framework to anesthesiology can be demonstrated by considering a case of anesthetic recall during an emergent early-morning laparoscopic appendectomy at a teaching hospital (Fig. 1). Suppose an otherwise healthy 25-year-old female with acute appendicitis undergoes a laparoscopic appendectomy under general anesthesia and subsequently reports intraoperative recall. An anesthesiology resident, who had been working in the operating room for the entirety of his 24-h shift aside from several small breaks, failed to notice the transient "vaporizer empty" alert produced by the anesthesia machine ventilating the patient, distracted by a brief episode of hypotension and a malfunctioning computer. The hospital takes great interest in conducting a root cause analysis to determine how this incident occurred and what policy changes may be indicated to minimize the risk of future recall events. If the same four categories of factors listed in the NTSB investigation of Eastern Airlines Flight 401 are addressed in systematic fashion, then significant headway could be made in understanding the etiology of the recall incident and identifying actionable steps to mitigate future risk. First, "subtle incapacitation of the pilot" in the NTSB report would become "subtle incapacitation of the anesthesiology resident due to sleep deprivation" in the hospital report. Second, the factor "autoflight system operation" cited by the NTSB would be paralleled by "limitations of the warning system on the anesthesia machine" in the hospital report. Finally, where the NTSB considers flight crew training and distractions as factors, the hospital report would consider its anesthesiology resident training program and the presence of distractors to which the resident in this case was susceptible.

Specific elements of the NTSB investigation style that can be applied to anesthesiology include:

1. Careful attention to individual physical and psychological factors that may have contributed to error (Fig. 1). Autopsy of the Eastern Airlines 401 captain revealed a meningioma displacing and effacing the right occipital lobe of his brain, which may have compromised peripheral vision (though numerous individuals who had interacted with the captain both personally and professionally attested to the absence of any obvious peripheral visual compromise) [1]. Just as this condition is addressed in the NTSB accident report, sleep deprivation identified after reviewing an anesthesiology resident's call shift should be included in the investigation of an awareness case. While research on incapacitation produced by sleep deprivation or substance abuse is abundant in medicine, anesthesiologists should also consider other physical and psychological limitations. Studies of differences among pilots with respect to temperament and degrees of risk aversion and aggression [2] and the association with likelihood of accident involvement [3], the frequency of ST-segment depression and nuclear cardiac ischemia after exposure to aviation mental stress [4], and vestibular function as related to risk for spatial disorientation during flight [5] may possess parallels in anesthesiologist performance.
2. Review of detailed data records surrounding the incident to facilitate maximum understanding and avoid oversight of key contributory details (Fig. 1). The NTSB report on Eastern Airlines Flight 401 [1] presented specific data obtained from the cockpit voice recorder and flight data recorder and integrated it into its analysis—for instance, "some 288 s prior to impact, the DFDR readout indicates a vertical acceleration transient of 0.04 g causing a 200-f.p.m. rate of descent" [1]. In anesthesiology, the equivalents of these recorders are found in the vital sign monitors, anesthesia machine, and electronic anesthesia recordkeeping system. Optimal analysis of adverse anesthesiology events would be facilitated by a system where patient data from all of these sources, in addition to surgical records kept by the circulating operating room nurse, are integrated into one cohesive database.
3. Application of science of human factors in determining the root cause (Fig. 1). Human factors is the study of human behavior in relation to certain environments, technology, or services [6], which can be applied to optimize performance and safety [7]. Well-utilized in the aviation industry, its principles are equally applicable to anesthesiology. In the case of Eastern Airlines Flight 401, when the crew prepared to land, the green indicator light that should illuminate upon full extension of the landing gear was noted to have malfunctioned. The crew members became fixated upon restoring the expected illumination of that light, to the extent that they ignored working flight instruments and failed to detect an unexpected descent in time to avoid crashing into the ground (Fig. 1). This fixation error occurred despite the captain's 30,000 h of flying experience [8]. Similar errors may occur when an anesthetist becomes fixated upon restoring the computer documenting the anesthetic record (Fig. 1) or silencing a persistent but unimportant alarm. The human factors analysis and classification system (HFACS) [9], a broad human error framework originally used by the United States Armed Forces, provides a systematic method of conducting root cause analysis and considering the organizational and individual factors that ultimately culminate in error. It categorizes human error at four different levels: actions taken by operators, existing preconditions for unsafe acts, inadequate super-

NTSB: Eastern Airlines Flight 401 Crash

1. Subtle incapacitation of the pilot.

Subtle incapacitation had to be considered in view of the finding of a tumor in the cranial cavity of the captain. The medical examiner suggested that the space-occupying lesion could have affected the captain's vision particularly where peripheral vision was concerned.

It was hypothesized that if the captain's peripheral vision was severely impaired, he might not have detected movements in the altimeter and vertical speed indicators while he watched the first officer remove and replace the nose gear light lens. However, the captain's family, close friends, and fellow pilots advised that he showed no signs of visual difficulties in the performance of his duties and in other activities requiring peripheral vision.

2. The autoflight system operation.

the mismatch between computers "A" and "B" would become a significant factor in this analysis. Because of this mismatch and the system design, a force exerted on the captain's control wheel in excess of 15 pounds, but less than 20 pounds, could result in disengagement of the altitude hold function without the occurrence of a corresponding indication of the first officer's annunciator panel. This would lead to a situation in which the first officer, unaware that altitude hold had been disengaged, would not be alerted to the aircraft altitude deviation.

3. Flightcrew training.

The throttle reductions and control column force inputs which were made by the crew, and which caused the aircraft to descend, suggest that crewmembers were not aware of the low force gradient input required to effect a change in aircraft attitude while in CWS. The Board learned that this lack of knowledge about the capabilities of the new autopilot was not limited to the flightcrew of Flight 401. Pilot training and autopilot operational policies were studied extensively during the field phase of the investigation, and were discussed, at great length, in the public hearing connected with this accident. Although formal training provided adequate opportunity to become familiar with this new concept of aircraft control, operational experience with the autopilot was limited by company policy.

4. Flightcrew distractions.

3. The nose gear position light lens assembly was removed and incorrectly reinstalled.
4. The first officer became preoccupied with his attempts to remove the jammed light assembly.
5. The captain divided his attention between attempts to help the first officer and orders to other crewmembers to try other approaches to the problem.
6. The flightcrew devoted approximately 4 minutes to the distraction, with minimal regard for other flight requirements.

Anesthesiology: Recall During a Laparoscopic Appendectomy

1. Subtle incapacitation of the anesthesiology resident due to sleep deprivation.

The incident occurred during the 23rd hour of a 24-hour call for the anesthesiology resident involved. Chart review indicates that he had been continuously responsible for cases during the entire call period, with only a ½ hour break each for lunch and dinner and three other 15-minute breaks at various time points. Thus, no opportunity had existed for strategic napping.

2. Limitations of the warning system on the anesthesia machine.

Review of the anesthesia machine's alarm log indicates that a "CHECK VAPORIZER" alarm appeared in both audio and visual format at 0518. The alarm was not silenced by the anesthesiology resident in the room at the time, but the alarm tone sounded only once, and the visual message disappeared within 30 seconds even without being dismissed. Records indicate that a second alarm also sounded at 0518 due to a low non-invasive blood pressure (NIBP) reading on the vital sign monitor. This alarm consisted of a highlighted, flashing NIBP value and a loud tone, louder than the one on the anesthesia machine, that repeated every three seconds until manually silenced.

3. Anesthesiology resident training.

The training program for CA-1 (Clinical Anesthesia, Year 1) residents at this hospital was studied extensively during the investigation. While residents were instructed on how to read vaporizer levels and refill them, neither the written manual presented at the start of their training, nor the simulation-based educational program that comprised their first week of training, alerted residents to the fact that the alarm for an empty vaporizer was very inconspicuous and transient on their particular model of anesthesia machine.

4. Anesthesiology resident distractions.

Review of the anesthetic record indicates that, from 0518-0520, the resident treated hypotension. This resolved by 0522 according to the vital sign monitor's record, but from 0520-0534, no data entries are made into the computerized record keeping system, and from 0530-0534, the system rebooted. The period from 0535-0538 includes a large number of data entries into the electronic anesthesia record, indicating that the resident may have been distracted from administration of the anesthetic due to a computer malfunction that required rebooting and the subsequent need to catch up on charting.

Figure 1. Applicability of an NTSB aviation accident report to anesthesiology. The four potential root causes of the Eastern Airlines Flight 401 crash may closely parallel those implicated in a case of recall during an early-morning laparoscopic appendectomy at a teaching hospital. 1) The NTSB analyzes the flight captain's intracranial tumor as a potential physical limitation; anesthesiology resident sleep deprivation may represent another such limitation. 2) Failures of the human-machine interface may include lack of warning of pilots about altitude deviation or anesthesiology residents of an empty gas vaporizer. 3) Inadequate operational experience with a new autopilot system may hamper pilot performance, and anesthesiology resident training may fail to highlight the limitations of the notification system for empty vaporizers on an anesthesia machine. 4) Either a jammed nose gear position light assembly, or a computer software failure couple with transient patient hemodynamic instability, may produce distraction serious enough to contribute to error. *Reprinted with permission from the National Transportation Safety Board, File No. 1-0016: Aircraft Accident Report. 14 June 1973*

Fig. 1 Applicability of an NTSB aviation accident report to anesthesiology. The four potential root causes of the Eastern Airlines Flight 401 crash may closely parallel those implicated in a case of recall during an early-morning laparoscopic appendectomy at a teaching hospital. (1) The NTSB analyzes the flight captain's intracranial tumor as a potential physical limitation; anesthesiology resident's sleep deprivation may represent another such limitation. (2) Failures of the human–machine interface may include lack of warning of pilots about altitude deviation or anesthesiology residents of an empty gas vaporizer. (3) Inadequate operational experience with a new autopilot system may hamper pilot performance, and anesthesiology resident's training may fail to highlight the limitations of the notification system for empty vaporizers on an anesthesia machine. (4) Either a jammed nose gear position light assembly, or a computer software failure coupled with transient patient hemodynamic instability, may produce distraction serious enough to contribute to error [1]

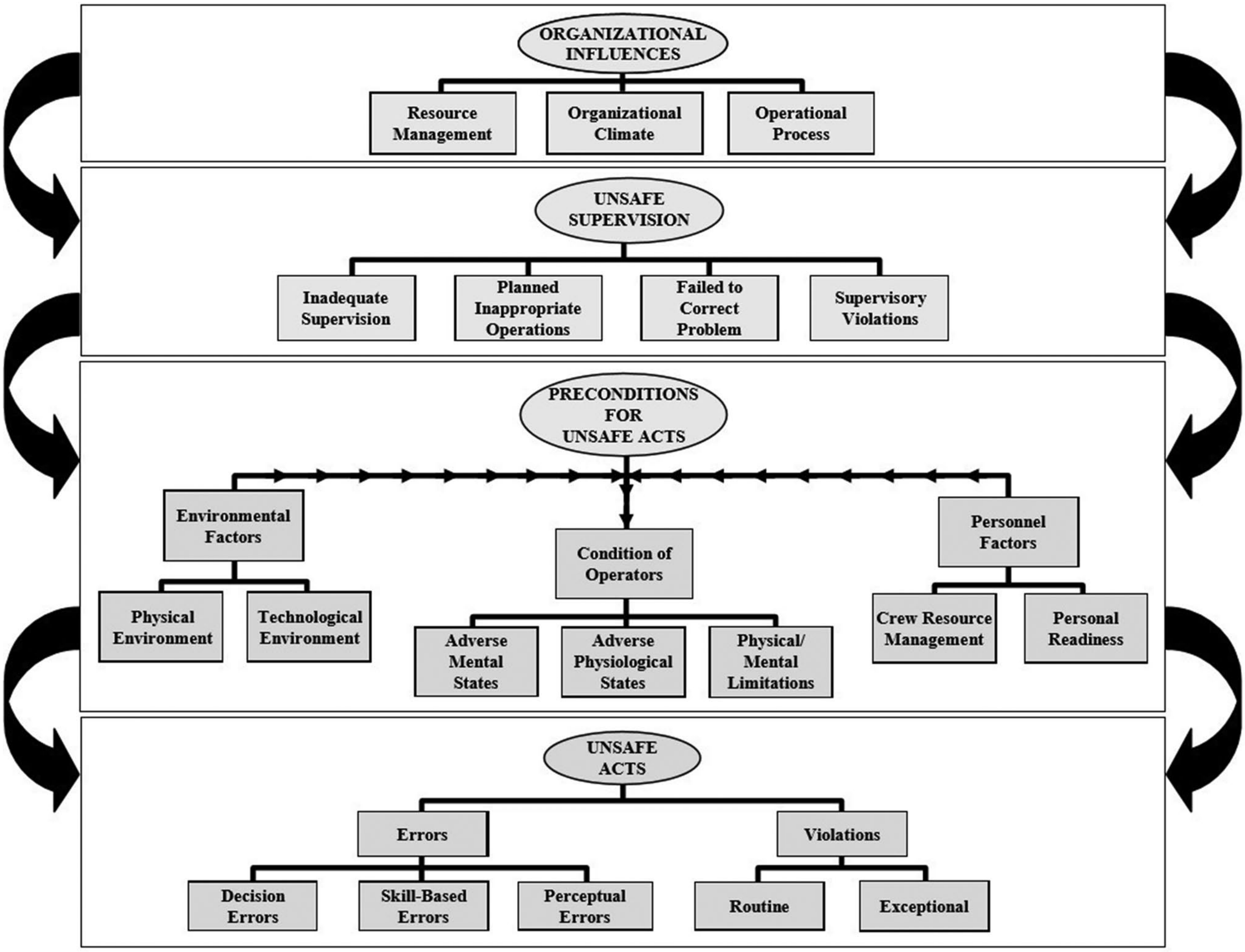

Fig. 2 The human factors analysis and classification system (HFACS). Widely utilized in aviation, this framework can also guide the analysis of adverse events within anesthesiology

vision, and influences at the level of the organization (Fig. 2). This framework is equally applicable to errors in anesthesiology.

4. Recommending changes to existing educational and training programs following adverse event analysis. In its report on Eastern Airlines Flight 401 [1], the NTSB noted that the new autopilot system in place on this aircraft was poorly understood by many pilots because "operational experience with the autopilot was limited by company policy" and recommended that the Eastern Air Lines training program add "more frequent quality control progress checks of the student during the ground school phase of the training and an early operational proficiency followup check in the flight simulator after the pilot has flown the L-1011 in scheduled passenger service." A second example is found in a German accident investigation of a midair collision between a passenger and cargo jet [10]. In a violation of air traffic control regulations, one controller had gone to rest and left his partner to man two different workstations. The increased cognitive workload resulted in the controller's delayed detection of the two aircraft in unacceptably close proximity to one another. When the controller finally realized the danger, he contacted the crew of the passenger jet and instructed them to descend one thousand feet. His instructions were in direct opposition to those given by an automated system on the aircraft, known as the traffic collision avoidance system (TCAS), which urged the crew to ascend instead. The crew decided to follow the air traffic controller's instructions. Meanwhile, the cargo jet was also descending as instructed by its TCAS, and the two planes crashed into one another. TCAS was a relatively new technology at that time, and following this tragedy, investigators recommended [11] to the International Civil Aviation Organization that a clear policy be implemented whereby pilots must favor TCAS over air

traffic controller instructions if the two conflict. These incidents can be extrapolated to anesthesiology, where the most benefit is accrued from morbidity and mortality analyzes when findings are promptly translated into direct quality improvement recommendations.

Part II: simulation-based error analysis

A substantial proportion of the literature on pilot error consists of simulation-based studies, where prospective interventions can be conducted without the obvious ethical and logistical challenges associated with executing such studies in real flying environments. Simulation has found an increasingly prominent role in anesthesiology education in the recent years, but it can also be utilized to study error mechanisms and identify effective quality improvement strategies.

The effect of sleep deprivation upon pilot performance has been safely studied in a simulator [11], using observers who were blinded to the sleep deprivation status and duty history of the pilot subjects. Sleep-deprived crews were shown to utilize similar decision-making processes as their rested counterparts, but implementation of these processes took longer. In relation to the anesthesia awareness case detailed above, simulation-based studies could explore the threshold at which sleep deprivation meaningfully impacts performance on various clinical tasks, and whether it differs for anesthetists at various levels of training. The information could be used to improve anesthesiology departmental policies regarding mandatory breaks or educate residents to recognize the initial heralding signs of impaired performance and be on high alert for specific areas that tend to show compromise first.

Simulation is also a valuable vehicle for studying policy-level interventions to improve professional performance, as it allows for manipulation of only one variable—the condition impacted by the policy—at a time, freeing researchers of the confounders that inevitably surface in real-life work environments. An excessively high cognitive task load can certainly increase the chance of mistakes and compromise outcomes in aviation and anesthesiology alike, and through simulation, the impact of specific interventions to decrease this load can be systematically evaluated. For instance, in a simulation-based study of forty-five cockpit crews [5], a scenario containing a high task load resulted in significantly worse crisis resource management performance than a moderate task load scenario. Only in the moderate task load scenario were performance advantages gained by extensive situation orientation (awareness) and allowing time to plan. Studying the thresholds for various levels of cognitive load in anesthesiology may pave the way for optimization of operating room design, crisis resource manuals and checklists, and other resources; determination of varying thresholds for anesthesiologists of different levels of experience may impact the training and supervisory guidelines used for residents in teaching hospitals. The simulation platform allows for a much higher-quality study design than retrospective reviews of adverse events or prospective observational studies of interventions whose impacts may be confounded by a variety of individual patient, provider, and situational factors.

Conclusion

Literature published within the aviation and human factors industries presents a unique lens through which anesthesiologists can view their own errors, challenges, and quests for improved performance. Systematic error review and reporting, along with simulation-based studies of error mechanisms and quality improvement interventions, represent two major vehicles for advancement within anesthesiology that are already successfully demonstrated by the aviation industry. The fundamental similarities between the two professions present unique opportunities for interdisciplinary learning and progress.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. National Transportation Safety Board. File no. 1-0016: aircraft accident report. Reprinted with permission from https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR7314.pdf. Accessed 14 June 1973.
2. Makarowski R, Piotrowski A. The psychological profile of pilots of passenger planes: analysis of temperamental traits, aggression and risk. Med Pr. 2017;68(5):639–51.
3. Lubner ME. Aviation accidents, incidents, and violations: psychological predictors among United States pilots. Diss Abstr Int. 1992;53(6-B):3003–4.
4. Doorey A, Denenberg B, Sagar V, Hanna T, Newman J, Stone PH. Comparison of myocardial ischemia during intense mental stress using flight simulation in airline pilots with coronary artery disease to that produced with conventional mental and treadmill exercise stress testing. Am J Cardiol. 2011;108(5):651–7.
5. Gradwell D, Rainford DJ. Ernsting's aviation and space medicine. 5th ed. Boca Raton: CRC Press; 2016. p. 314.
6. Rouse M (2005) "DEFINITION: human factors (ergonomics)." TechTarget. http://searchmicroservices.techtarget.com/definition/human-factors-ergonomics.
7. International Air Transport Association. "Human factors in aviation". http://www.iata.org/training/courses/Pages/aviation-human-factors-tcvt05.aspx. Accessed 3 Dec 2017.

8. Job M. Air disaster, vol. 1. Minneapolis: Motorbooks International; 1995.
9. Shappell S, Detwiler C, Holcomb K, Hackworth C, Boquet A, Wiegmann D. Human error and commercial aviation accidents: a comprehensive, Fine-Grained Analysis Using HFACS. Washington DC: Federal Aviation Administration; 2006.
10. German Federal Bureau of Aircraft Accidents Investigation. Investigation report AX001-1-2 (English) 2004.
11. Anca JM. Multimodal safety management and human factors: crossing the borders of medical, aviation, road, and rail industries, vol. 23. Boca Raton: CRC Press; 2017.