World J Surg (2013) 37:1185–1192
DOI 10.1007/s00268-013-1971-3

World Journal of Surgery

ORIGINAL SCIENTIFIC REPORTS AND REVIEWS

Lessons for Surgeons in the Final Moments of Air France Flight 447

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Published online: 6 March 2013

Abstract

Background All surgeons make mistakes, and learning from critical incidents may help improve performance. The present study aimed to highlight lessons for surgeons from analysis of the final moments of Air France Flight 447. All of the authors work in teams and situations where safety, technical performance, and non-technical skills are critical. This review was born out of discussions regarding the events of Flight 447; specifically, whether the airline disaster was relevant to their work, and whether they could learn anything from it.

Methods The study is based on review of the crash reports of Flight 447, which lost flight speed indication after formation of ice prevented air from entering flight speed indicators during a storm. Following a subsequent stall, the aircraft fell at a rate of >10,000 feet/min until it crashed into the Atlantic Ocean, killing 228 passengers and crew.

Results There were errors in decision making, reasoning, communication, and teamwork. Such non-technical skills failures have been recognized previously and can be addressed by existing non-technical skills training. A reliance on autopilot meant that the pilots were unfamiliar with high-altitude flying when the autopilot is disengaged. They were unprepared for and affected by such a sudden and serious problem; an event called "surprise and startle" by the accident investigation. The absence of the senior pilot (who was on a scheduled break) in the critical final minutes slowed error recognition and recovery.

Conclusions Unintended consequences of modern safety strategies may be under-recognized and can lead to adverse events. Both simulation-based and non-simulation–based training should include "surprise and startle" events beyond the scenarios trainees might expect. Likewise, in the face of increasing reliance on modern technology, surgeons should ensure that they would be able to perform procedures in the absence of such technologies. Specific training may improve surgeons' non-technical skills, and recognition of such skills could also be used to help select future surgeons.

Introduction

Aviation and surgery are both professions where errors can have serious consequences. Despite the many advances in aviation safety, one of the world's most modern aircraft crashed on 1 June 2009, killing all 228 passengers and crew. Healthcare has already drawn on many lessons from aviation, including crew resource management (CRM), risk management, human factors training, teamwork, and communication [1–3]. There will always be times when surgeons are forced to function under stress, where the

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chances of error increase and decision-making skills will be tested. Human factors have been implicated in errors across all specialities [3–7]. Although no single factor can prevent mistakes, a culture of safety with multiple layers of checks minimizes errors [8–10]. This review was intended to analyze the key events from the final few minutes of a doomed flight, to see if any lessons for surgeons can be learned.

Methods

Source of information

The present study was based on the findings of the third interim report (July 2011) and the final report (July 2012) of the crash of Air France flight 447, published by the French Bureau of Investigation and Analysis (Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile; BEA) [11]. It was released following retrieval and analysis of the flight data recorder (FDR) and cockpit voice recorder, followed by technical and human factors analysis. Permission to use the publicly available details and images from the reports was granted by BEA. A list of the key principles and definitions used within this article is included in the accompanying display (Box 1).

Box 1 Key principles and definitions

Angle of attack: Angle between the wing and the airflow. Too great an angle of attack and the wing no longer produces lift

Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA): The French authority responsible for safety investigations into accidents or incidents in civil aviation

Crew Resource Management (CRM): Introduced by NASA, these principles involve the most effective use of people, technology, and protocols to maximize efficiency and safety

Dual input: Most aircraft have two yokes that are connected in such a way that both pilots can feel the inputs of the other pilot at all times. In Airbus aircraft, the inputs are independent, and then are averaged by the flight computer

PF/PNF (Pilot Flying/Pilot Not Flying) The active roles of the two pilots on the flight deck. The PNF is commonly called the Pilot Monitoring, to stress that while this crew member is not using control inputs he/she still has an active role

Pitot tubes: Probes on the exterior of the aircraft used to measure the aircraft's airspeed

Stall: When the aerodynamic surfaces lose their effectiveness because of an excessive angle of attack, the wings stop producing lift

Task fixation: When an individual concentrates on a single aspect of a case or task to the detriment of other more relevant aspects

TO/GA (Take Off/Go-Around): A calculated maximum thrust setting to increase both altitude and speed with optimum efficiency at low altitudes

Recovery of information

The crash occurred east of the Mid-Atlantic Ridge, where the seabed is characterized by peaks at 700 m depth and troughs at over 4 km depth. The crash site was discovered to be 15 km wide of the scheduled flight path, on a plateau at 3,980 m depth. The recovery of bodies, wreckage, and FDR involved an initial surface search for debris followed by a search for underwater locator beacons, which was unsuccessful. A detailed sonar and autonomous underwater vehicle search revealed the crash site and allowed for recovery of bodies, FDR, and selected pieces of aircraft by a remotely operated vehicle. This recovery was completed two years after the crash.

Results

Flight details

Air France flight 447 was an Airbus A330-200 aircraft, with 3 flight crew, 9 cabin crew, and 216 passengers. The flight crew included an experienced captain and two first officers, the least experienced of whom had 800 hours flying time on the Airbus A330-200. The scheduled flight from Rio de Janeiro to Paris has been broken down into three key phases (see accompanying outline (Box 2)).

Phase 1: take-off to loss of reliable airspeed indication [00:00:00 (hours, minutes, seconds) to 02:10:05]

The pilots of Flight 447 elected to fly directly through a heavy area of storms, whereas four other flights on similar paths diverted around the worst storm areas (Fig. 1). Flying to a higher altitude to avoid the bad weather became a preoccupation for the crew. Once the Captain decided to leave for a scheduled rest, the more inexperienced of the two first officers became the pilot flying (PF). Prior to leaving the cockpit, the Captain asked him if he held a commercial flying license, which suggests that his competencies had not been addressed during the pre-flight briefing. The specific roles and command structure for the two first officers had also not been set in place, which is likely to have contributed to the lack of synergy during later events.

Flight 447 lost reliable flight speed indication after ice crystals prevented air from entering the three external pitot tubes (which supply information to the air speed indicators) during the storm (Fig. 2). Although these first steps of the error chain may have been avoided by flying around the storm, this was not the cause of the crash.

Box 2 Selected key speech and events from phases 2 and 3 of Flight 447

Time	Event	Altitude (feet)
0:00	Autopilot disengages 2 h, 10 min, 5 s into the flight.	35,024
0:01	The flight control law changes from “normal” to “alternate.”	
0:28	Pilot 2 (PNF): “You’re going up so go back down.”	37,124
0:37	Pilot 1 (PF): “We are in—yeah, we are in climb.”	
0:46	Continuous stall alarm begins	37,500
0:58	Pilot 1: “I’m in TOGA.”	
1:27	Pilot 1: “I don’t have control of the airplane at all.”	
1:38	Captain enters cockpit.	
1:40	End of continuous stall alarm.	35,372
2:25	Pilot 1: “Am I going down?”	
	Pilot 2: “Go down.”	
	Captain: “No climb there.”	
	Pilot 1: “I’m climbing ok so we’re going down.”	
2:34	Pilot 1: “Ok we are in TOGA.”	
2:39	Captain: “It’s impossible.”	20,028
3:20	Pilot 1: “What is … how come we’re continuing to go right down now?”	
3:31	Pilot 1: “Nine thousand feet.”	9,332
3:34	Pilot 2: “Climb climb climb climb.”	
	Pilot 1: “But I’ve been at maxi nose-up for a while.”	
	Captain: “No no no, don’t climb.”	
	Pilot 2: “So go down.”	
4:00	Captain: “Watch out you’re pitching up there.”	4,024
	Pilot 2: “I’m pitching up?”	
	Pilot 1: “Well we need to … we are at four thousand feet.”	
4:23	End of recordings at 2:14:28	

PF pilot flying, *PNF* pilot not flying, *CPT* captain, *TOGA* Take Off/Go-Around

Phase 2: aircraft loses reliable airspeed indication (02:10:05 to 02:10:51)

Once the air speed indication became invalid, the autopilot and autothrust systems automatically disengaged. Within 10 s, the aircraft had rolled right to a bank angle of 8 degrees, and the nose pitched to 11 degrees up. The PF announced “I have the controls” and made a rapid left nose-up input almost to the mechanical stops of the side stick. The nose pitched further up, and at 02:10:10 the stall warning activated. While both first officers recognized the loss of airspeed indications, neither of them called for the “unreliable airspeed procedures.” Comparing the three airspeed indications, the Pilot not Flying (PNF) urged the PF multiple times to lower the nose. However, the aircraft was already climbing through 37,000 feet and continued to climb.

Phase 3: aircraft goes out of control (02:10:51 to 02:14:28)

At 02:10:51, the stall warning activated again as the angle of attack (the angle between the wing and the oncoming airflow) increased to 6 degrees. As result of subsequent PF inputs, the pitch angle increased from 6 to 13 degrees and the angle of attack increased to 10 degrees. Approximately 5 s later, the thrust levers were placed into the TO/GA (take off/go-around) thrust settings. TO/GA is an autothrust setting, usually used in low-level flying, which gives a calculated maximum thrust setting to increase both altitude and speed with optimum efficiency. However, at higher altitudes in less dense air, a go-around maneuver would have to be performed differently compared to at ground level, and the manner in which it was executed did not recover the aircraft from the stall; in fact, the pitch up commands worsened it. This appears to be about the point where the aircraft went out of control. The stall led to a rapid descent at a rate of over 10,000 feet per minute that lasted 3 min 30 s. During this time, the angle of attack increased and the aircraft remained stalled for the rest of the incident (Fig. 3).

The PNF initially suggested descending, but this was not followed up with confirmation, shout-outs of pitch/speed discrepancies, or suggested strategies. The absence of task sharing and communication led to a lack of synergy. The PF did not directly ask the PNF for his assessment. There were moments when the flight crew discussed whether they were in fact ascending or descending. Dual-input commands were recorded, where the two pilots were performing conflicting maneuvers. The unreliable airspeed indication checklist was not referred to at any point.

The Airbus A330-200 routinely functions in “normal law,” where the flight computer prevents actions that will lead to a stall. However, as air speed indication was lost, the avionics computer moved to “alternate law.” This mode of flying has far fewer restrictions and allowed the nose-up inputs to continue despite the stall. Neither pilot made reference to alternate law or to the continuous 54 s stall alarm. Nor, it was later found, had they received any high-altitude training for the “manual airplane handling of approach to stall and stall recovery at high altitude” procedure.

At 02:11:42, the Captain returned to the flight deck (1 min and 30 s after being called). The stall alarm ceased moments after his return, although a stall was still occurring. He was given inadequate information from the

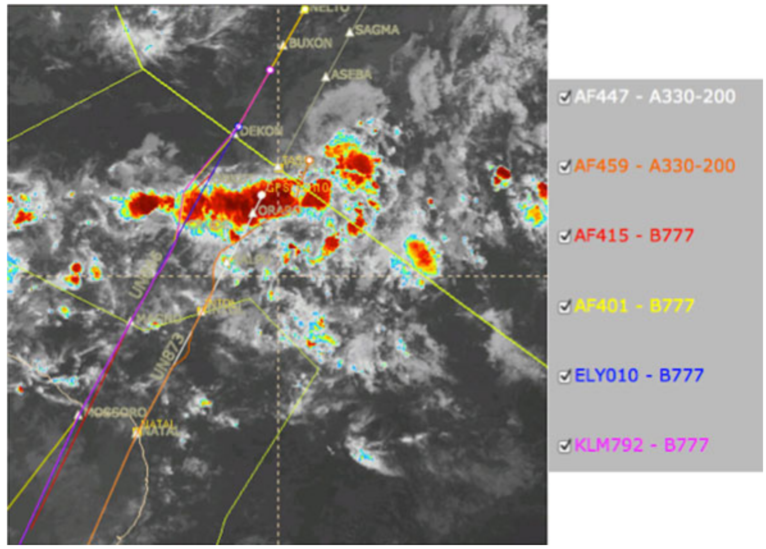

Fig. 1 The flight-path of Flight 447 (*white line*) and five other aircraft in the area at the time, in relation to storm activity (*red*) over the Atlantic Ocean. The coast of Brazil is in the *bottom left corner*. The full animation is available at: http://www.bea.aero/en/enquetes/flight.af.447/trajectoires/trajectoires010609.html

obviously confused and stressed co-pilots in an "aurally saturated" environment. The Captain chose to sit behind the two co-pilots. This approach allowed an overall assessment of the situation and for the Captain to issue commands. However, had he had taken the controls, it is likely he would have relieved the constant nose-up inputs by the PF that were contributing to the stall.

At 02:12:04 the PF remarked that he believed they were overspeeding (i.e., that the aircraft was traveling beyond its permitted maximum speed). The information displayed, the aerodynamic noises being transmitted from the wing, the possibility of overspeeding, and the stall alarm led to confusion in the cockpit. This caused the PF to perform antagonistic actions: he responded to the potential overspeeding by reducing thrust and applying nose-up inputs, while responding to the potential stall situation by intermittently applying maximum thrust. The fruitless action of his TO/GA settings led to more confusion and possibly mistrust in the flight warnings, perpetuating task fixation on potential overspeeding as well as gaining height.

From this point until impact, the stall warning activated when the nose was lowered and went silent when the nose was pulled up. Angle of attack is the parameter that enables the stall warning to be triggered, but it was rendered useless in this situation. When the angle of attack values became invalid, the warning stopped, even though the aircraft was still stalled. By design, when the [forward] airspeed measurements are lower than 60 knots, the three angle of attack values become invalid. Although the pilots were aware that altitude was declining rapidly, they appear to have been unable to determine which instruments to trust; it may have appeared to them that all values were incoherent. The continued chaotic control between the PF and the PNF illustrated confusion, de-structuring of task-sharing, and loss of cognitive control.

Discussion

Recommendations made

Several specific technical and human performance recommendations were made after the reports were issued. The most relevant to surgeons include the following:

1. Pilots must learn how to avoid situations that lead to loss of control, and they must know how to recognize and escape from them if they do occur.
2. The design of training must be such that it generates surprise and startle to teach pilots how to react and work in stressful situations.

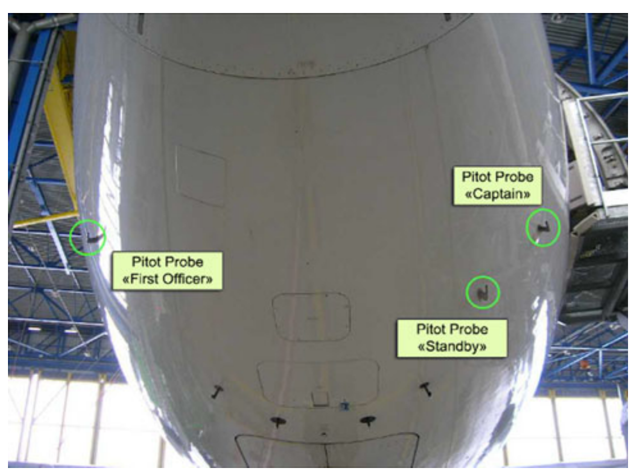

Fig. 2 Position of pitot probes on Airbus A330

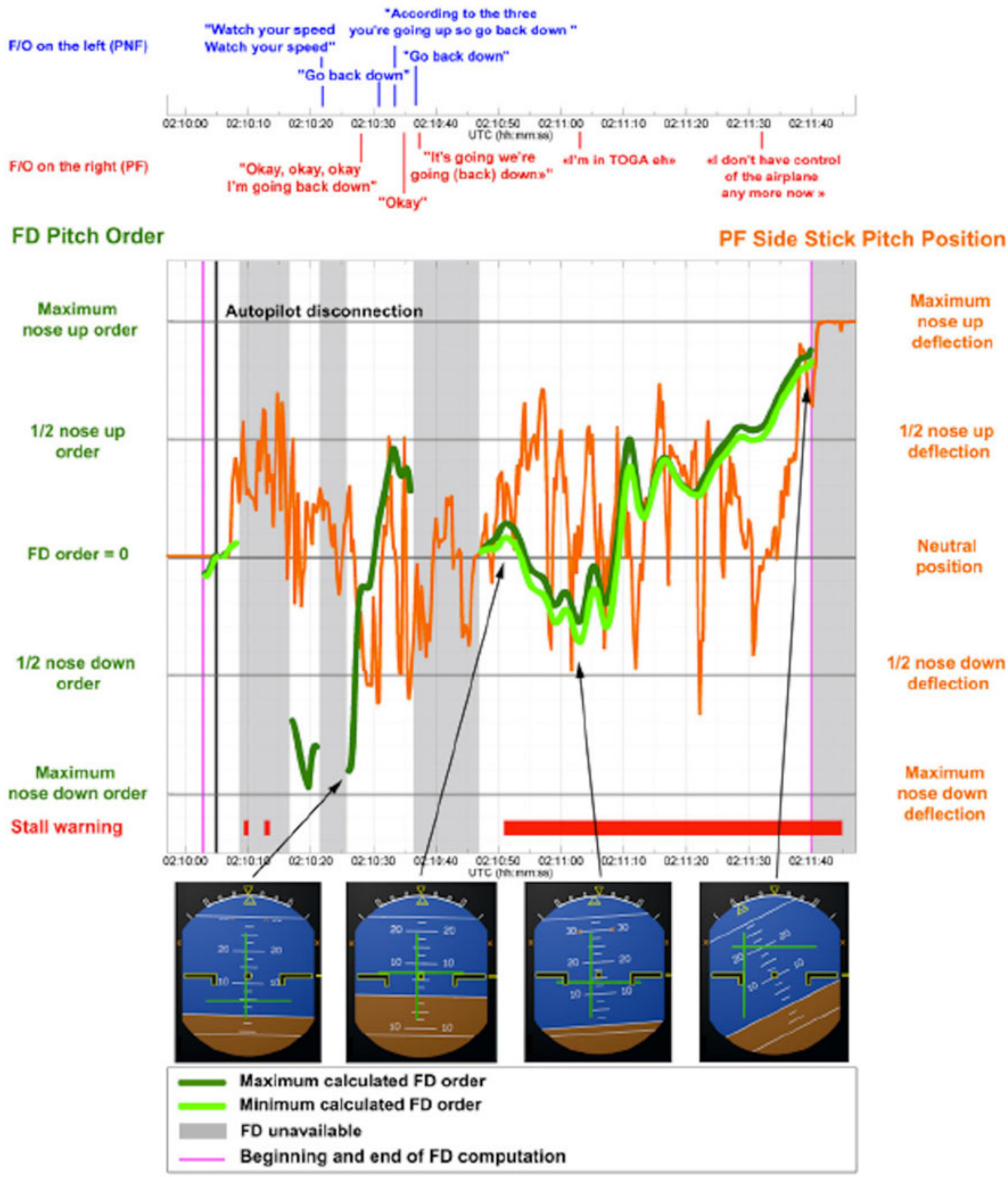

Fig. 3 Flight director (FD) *crossbar* positions from the time of autopilot disconnection, illustrating the pitch up inputs

3. Implementation of a new decision-making method: the copilot expresses his or her opinion first, prior to the final decision being made by the Captain.
4. Simulator fidelity should be improved to avoid the risks of "negative training." Such improvements occur when shortfalls in simulators are overcome by training people how to "use the simulator" and not the actual technique or scenario being simulated. Negative training can prompt inappropriate responses during actual tasks through unrealistic or incorrect simulations.

Even in the era of randomized trials, investigation of single critical incidents remains an important learning tool for both pilots and surgeons [7, 12]. The crash of Flight 447 occurred in circumstances that were outside of normal conditions, bringing stress and confusion that affected critical decision making. The members of the flight crew was unsure of one another's roles, and they communicated suboptimally. The first officers did not share tasks effectively and did not communicate their thoughts or strategies to each other or to the returning Captain. The Captain had not provided them with the framework to do so prior to leaving the flight deck. The pilots did not read out the available data (vertical velocity, altitude, etc.) and did not comment on the stall warnings; the PF apparently did not realize that the aircraft was stalled.

Similar communication breakdowns, lack of synergistic teamwork, and poor application of non-technical skills have been implicated in errors across virtually all medical specialties [2, 3, 5, 6, 13, 14]. From this viewpoint, the error chain, which started with the decision to fly through the weather storm, is in keeping with Reason's Swiss cheese model of error [10]. Parallels between this and the well-known Bromiley case [7] outlined in the accompanying display (Box 3) can be made in terms of error recognition and recovery.

Are there any novel lessons to be learned?

Novel lessons may be learned from this incident by analyzing the error chain in light of modern safety features of the flight that were designed to specifically prevent this very event. Despite the most modern available technology, fifteen minutes after the Captain took a scheduled rest break the airplane crashed. There is evidence relating fatigue to errors and, as a result, shift work, working hours restrictions, and scheduled rests have been introduced for medical staff [15, 16]. The downside of these safety strategies is a discontinuity in practice and reduced senior coverage during shifts. Had the senior pilot been present during the critical moments of the autopilot disengagement, it is reasonable to suggest that his experience would have prevented the final moments of the error chain, in particular reactions relating to continued nose-up inputs.

Alongside protocol-driven procedures, autopilot systems were developed to further reduce errors by removing the human element factor. Integration of such systems into surgical practice remains at an early stage, although with increased protocolization and technological presence in healthcare, their increased use is likely [17]. Although the co-pilots were adequately trained in manual handling for take-off and landing situations, their reliance on autopilot during the routine high-altitude phase of flying and their inexperience with manual flight with minimal computer input contributed to the disaster. Their reliance on the aircraft's computer systems may have led to a false belief that a stall would not be permitted by the avionics systems. However, as the aircraft was flying in alternate law (because of the loss of air speed indicators), stall occurred as a result of the continued nose-up inputs from the PF.

It is reasonable to suggest that doctors are becoming increasingly reliant on technology for decision making and performance, not always for the best. For example, in a prospective study of computed tomography scans in the diagnosis of patients undergoing emergency laparotomy, the initial diagnostic accuracy was only 78 % [18]. Surgeons are also using computer-aided visualization and navigation, electronic prescribing that predicts and corrects dosages, and artificial neural networks that are used for diagnosis [19–21]. Under these circumstances, doctors should be trained to perform to an equal standard without such technology to prepare for cases of failure or unexpected deviation.

Box 3 A patient's story: the Bromiley case

In 2008, Martin Bromiley described the death of his wife following a "can't intubate, can't ventilate" situation during elective general anesthesia for laryngeal surgery [7]. Despite several attempts at tracheal intubation, three senior consultants did not follow established alternative protocols that they knew about. Although the members of the team involved in the care were competent and capable of dealing with this emergency situation, they failed to respond correctly. The Bromiley case demonstrates failures related to task fixation, situational awareness, teamwork, and hierarchy. Important lessons for anesthetists and beyond were learned from that case and the openness with which it was analyzed. The complete case can be found at: The case of Elaine Bromiley—an anonymous version of an Independent Report on the death of Elaine Bromiley

www.chfg.org/wp-content/uploads/ElaineBromileyAnonymousReport.pdf

Error recovery

Cognitive analysis of error management has identified dual processing theories as key during error recognition [22]. Under this model, System 1 is non-analytical thinking, where rapid decisions are made based on prior experiences, without deep thought. System 2 is analytical thinking, which is deeper, more critical, more analytical but also slower. Stress research confirms the accuracy of this model, showing that as stress increases, thought processes and breadth of attention decrease [3, 23]. The PF selecting TO/GA settings, followed by continued nose-up inputs, suggests System 1 thinking based on prior experiences of manual handling at low altitudes. Task fixation worsened the situation, further increasing stress on the pilots and reducing their capacity for analytical thought. Individuals may favor one of the dual processing theory decision making styles over the other [24]. More effective error recognition and recovery may be afforded by equipping individuals with the ability to think with both systems. Anecdotally, some pilots use a DODAR acronym (Diagnose, Options, Decide, Assign roles, and Review), although its use is unproven in healthcare settings.

Decision making under pressure

Hierarchical constructs still exist in medicine; only 55 % of consultant surgeons are willing to reject steep hierarchies

[3]. Whereas a steep hierarchy has been found to be the major fault in other critical incidents (including the Bromiley case), in the case of Flight 447 the absence of this hierarchy worsened synergy. In the operating room, establishing clear team roles and hierarchies is particularly important during this era of working hours restriction, where the make-up of surgical teams frequently changes. A simple but potentially effective lesson to be learned from Flight 447 may be modification of the medical decision-making model: junior opinion is routinely expressed prior to the senior decision. When coupled with "crew resource management" (CRM) and decision-making skills, this may allow for better decision making, especially when working with unfamiliar teams. Whether all doctors will benefit from CRM training or just those working in high-risk specialties is yet to be determined [25].

Simulation training and non-technical skills

Training for every possible technical malfunction may be impractical, but improving generic decision-making and error management skills would be applicable across many situations. Whereas simulation training has become firmly established in medicine, its evolution has focused largely on training for technical skills [26]. Only in recent years has its use for non-technical skills training been explored [1, 2, 27]. Current research into simulation, especially in surgical disciplines, has focused on reproducibility and validity [28]. In these simulated situations, trainees may expect to be exposed to common adverse events, but these situations lack the stress of the less common but more serious occurrences. Adding "surprise and startle" to simulator and non-simulator training packages may improve exposure and response to stress; such surprises should be above and beyond factors that are pre-programmed or expected within simulator modules. Such exposure may also allow likely non-analytical [reflex] actions to be better appreciated; the immediate nose-up inputs by a pilot after unexpected disengagement of autopilot were likely to have been reflex, but unfortunately they were the incorrect response. Because CRM can rapidly degrade in situations of stress, this type of training may equip individuals and teams with additional error-recognition skills and decision-making experience when faced with a sudden surprise.

Flight 447 suggests that decision-making and CRM skills, when under changing and challenging conditions, should form a part of non-technical skills training for surgeons.

Various tools have been developed to assess such responses, including non-technical skills for surgeons (see the accompanying description of NOTSS) (Box 4), Observational Teamwork Assessment for Surgery (OTAS), and Anaesthetists' Non-Technical Skills (ANTS) [13, 29, 30]. Proving that non-technical skills training in the absence of "real-world" pressure provides any additional benefit requires further assessment and validation [2]. It is likely, however, that with increasing sophistication of technology, surgical error may increasingly come from non-technical skills failures. Thus non-technical skills ability could be used to help select doctors for specialist training in surgery, as it is already employed to help select future pilots in aviation [3].

Box 4 Non-technical skills for surgeons (NTSS)–key domains [29]

Category	Element
Situation awareness	Gathering information
	Understanding information
	Projecting and anticipating future state
Decision making	Considering options
	Implementing and reviewing decisions
Communication and teamwork	Exchanging information
	Establishing a shared understanding
	Co-ordinating team
Leadership	Setting and maintaining standards
	Supporting others
	Coping with pressure

Can surgeons learn from the ways the flight incident was investigated?

The aviation industry analyzes critical events within a no-blame culture, allowing for any valuable lessons to be readily identified from rare or tragic events. An example is the Aviation Safety Reporting System, which grants automatic immunity for reports filed within 10 days. This has led to a database of over 975,000 reports, which has undoubtedly improved airline safety [31]. Critical incident reporting and analysis in surgery remains suboptimal; it is unlikely that all critical incidents are recognized or reported [32]. This is to the detriment of surgeons, and valuable lessons are being lost until a time at which the profession is more open about mistakes. More routine use of systems such as the United Kingdoms' Confidential Reporting System in Surgery [CORESS] should therefore be encouraged [33].

Conclusions

All humans make mistakes. The human factors errors that contributed to the crash of Flight 447 have been described before as elements of human error. However, in the Flight 447 incident, that these errors occurred in the setting of modern and robust safety systems is of novel interest. It also highlights the importance of introducing "surprise and startle” events into modern simulation training, rather than focusing solely on reproducibility. This analysis is not meant to undermine the safety of established measures that have already made flying one of the safest modes of travel in the world. However, it is clear that there are limitations to widely accepted safety strategies. Like airline pilots, in the face of modern technology, surgeons must ensure that they can perform in the absence of such technologies. Likewise, surgeons should also recognize the importance of good decision making within a framework of effective non-technical skills and routine training in CRM. Ability in these non-technical skills could be used to help select future surgeons.

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