National Aeronautics and Space Administration “threat and error” model applied to pediatric cardiac surgery: Error cycles precede ~85% of patient deaths

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ABSTRACT

Background: We hypothesized that the National Aeronautics and Space Administration “threat and error” model (which is derived from analyzing >30,000 commercial flights, and explains >90% of crashes) is directly applicable to pediatric cardiac surgery.

Methods: We implemented a unit-wide performance initiative, whereby every surgical admission constitutes a “flight” and is tracked in real time, with the aim of identifying errors. The first 500 consecutive patients (524 flights) were analyzed, with an emphasis on the relationship between error cycles and permanent harmful outcomes.

Results: Among 524 patient flights (risk adjustment for congenital heart surgery category: 1-6; median: 2) 68 (13%) involved residual hemodynamic lesions, 13 (2.5%) permanent end-organ injuries, and 7 deaths (1.3%). Preoperatively, 763 threats were identified in 379 (72%) flights. Only 51% of patient flights (267) were error free. In the remaining 257 flights, 430 errors occurred, most commonly related to proficiency (280; 65%) or judgment (69, 16%). In most flights with errors (173 of 257; 67%), an unintended clinical state resulted, ie, the error was *consequential*. In 60% of consequential errors (n = 110; 21% of total), subsequent *cycles* of additional error/unintended states occurred. Cycles, particularly those containing multiple errors, were very significantly associated with permanent harmful end-states, including residual hemodynamic lesions ($P < .0001$), end-organ injury ($P < .0001$), and death ($P < .0001$). Deaths were almost always preceded by cycles (6 of 7; $P < .0001$).

Conclusions: Human error, if not mitigated, often leads to cycles of error and unintended patient states, which are dangerous and precede the majority of harmful outcomes. Efforts to manage threats and error cycles (through crew resource management techniques) are likely to yield large increases in patient safety. (J Thorac Cardiovasc Surg 2015;149:496-507)

Schematic of threat and error cycle.

Central Message

In pediatric cardiac surgery, cycles of error and rescue may precede adverse outcomes. Managing threat and error cycles may improve patient safety.

Clinical Relevance

This evaluation confirms that error was common and two thirds of these errors are consequential. The message derived from this experience is that when errors lead to an unintended deviation from the expected clinical course, extreme vigilance and optimal use of all available resources are required to prevent or break the threat and error cycle.

Supplemental material is available online.

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In June 2009, a fully functional Airbus A330 stalled at 38,000 feet and disintegrated after colliding belly first with the Atlantic Ocean with a forward velocity of only 107 knots.¹ Both engines were fully powered, and all instruments were functioning correctly. A few minutes before the collision, when the plane was in a completely unremarkable cruising configuration, temporary icing of a pitot tube led to a brief and transient loss of airspeed data, and autopilot disengagement. The pilots responded with some inappropriate, manual flight-control inputs, which led to

Abbreviations and Acronyms

CRM	= crew resource management
ECMO	= extracorporeal membrane oxygenation
FAA	= Federal Aviation Administration
LOSA	= line operation safety audits
NASA	= National Aeronautics and Space Administration
OR	= odds ratio
RACHS	= risk adjustment for congenital heart surgery

an escalation of unintended states, errors, and increasingly unstable flying configurations. The crew became evermore confused and disbelieving of their instruments. Task-sharing and coordination of roles was poor, and even at the point of impact, the 2 pilots were attempting to make opposite maneuvers with the control sticks.¹

Such incidents, though dramatic, are extremely rare: The aviation industry currently functions beyond the 6- σ safety level* (approximately 3.2 incidents per million sorties²).

This high performance level in aviation has evolved over 4 decades of technologic advances, paralleled by a crucial realization that humans are the least-reliable resource in a cockpit—and our fallibility needs to be understood and managed.^{3,4} Behavioral science researchers, as part of joint National Aeronautics and Space Administration (NASA) and Federal Aviation Administration (FAA) initiatives, have now scrutinized more than 30,000 simulator and live flights since the 1970s.⁵ These investigations have demonstrated that: (1) error is ubiquitous and inevitable, (2) error rates are highly linked to ambient “threats” and crew workload, and (3) errors need to be actively managed.^{6–8} A “threat and error” model has since emerged that is utilized by the FAA, NASA, commercial airlines, and air accident investigators.^{7,9–11}

We applied the FAA threat-and-error model to our pediatric cardiac surgery program. A unit-wide performance initiative was implemented, whereby every surgical admission constituted a “flight” and was tracked in real time. We sought to determine whether cycles of errors, and unintended patient states, are associated with permanent postdischarge outcomes. This threat and error initiative is the result of a progressive series of error and

mortality investigations that we have undertaken, including an in-depth exploration of all patient deaths over a 10-year period,¹² and the prevalence and impact of error in management of hypoplastic left heart syndrome.¹³

METHODS**Threat and Error Model and Line Operation Safety Audits**

The FAA uses a threat and error model that was developed by the NASA/FAA-funded Human Factor Project^{9,14} and was derived from observation and analysis of aircrew functioning in simulators and live commercial flight. In the latter (known as Line Operation Safety Audits [LOSAs]¹⁰), pilots trained in threat-and-error assessment observe from the jumpseat and provide confidential and deidentified accounts of the flight. They specifically describe threats, errors, unintended aircraft states, and resulting outcomes (see [Appendix E1](#), for FAA LOSA templates⁹). LOSA observers do not evaluate performance, but instead observe and record it. LOSAs are very common, and every commercial airline performs them periodically.

In the model,^{10,15} external threats act on the cockpit crew and increase the likelihood that they will make an error. Errors may then give rise to an unintended situation or circumstance, a deviation from the original intended flight plan. Such unintended states may or may not give rise to cycles of additional errors or unintended states. These cycles are believed to amplify the situation, reduce safety margins, and occasionally lead to a permanent harmful outcome (such as a crash).

A “threat” is defined as an external influence that increases the operational complexity of the intended flight.^{9,10} Loosely stated, a threat is anything out of the ordinary that takes a situation away from the “ideal.” Threats are typically beyond the control of the cockpit crew, but rather come *at* the crew. In aviation, threats have been found to fall into 5 general categories ([Table 1](#)).

An “error” in this context is defined as a human action, or inaction, that leads to a deviation from the intended or expected circumstance that then leads to a reduction in safety margin and an increased probability of an adverse event.^{9,10} Errors therefore come *from* the crew, and also have been found to fall into 5 general categories: protocol violations, procedural, communication, proficiency, and decision errors ([Table 1](#)).

An “unintended state” refers to a circumstance or configuration that was not expected as part of the original flight plan, and therefore represents a deviation from the expected ideal journey.^{9,10} An unintended state is part of the flight, and not a permanent result, which is instead an “outcome.” For example, a stall is an unintended state; a resulting crash is an outcome.

Clinical Correlate

We studied 524 consecutive and complete patient flights, involving 500 children admitted for pediatric cardiac surgery at our institution (reflecting approximately 80% of our annual case volume). Institutional ethics board approval was obtained, and a waiver of consent was granted. The patient flight was considered to be the period from patient arrival in the operating room until the point of discharge or death, and was considered complete if a preoperative “flightplan” had been generated. The “cockpit crew” was considered to be the clinical team directly administering patient care: the anesthesia, surgical, perfusion, and nursing teams in the operating room, and the intensive care, surgical, and cardiology teams during the postoperative period.

A detailed synopsis of each patient’s history and investigations was generated preoperatively, which included stated flight intentions (the flightplan) and was reviewed for every flight at an open presurgical

*For confusing reasons that relate to long-term process iteration models, 6 σ actually correlates statistically to 4.5 standard deviations, and hence 3.4 events per million, or an event rate of 0.00034%. Commercial aviation exceeds this quality metric. The top pediatric heart surgery centers currently function at $\sim 3.5\sigma$ in terms of patient mortality.

TABLE 1. The main subcategories of threats, errors, and unintended states in aviation, with medical corollaries and examples

Measure	Aviation	Cardiac surgery	Examples
Threats	Terrain	Morphology	
		Atypical morphology for diagnosis	d-TGA with 1L, 2RCx coronary arrangement
		Complex cardiac topology	Dextrocardia
		Morphology affecting cannulation	Left SVC and no bridging innominate vein
		Composite or multiple lesions	Coarctation with coexisting ALCAPA
		Lesion causing marked hemodynamic instability	Large pericardial effusion
	Weather	Comorbidities	
		Small for the repair type	1.8 kg coarctation
		Large or obese for repair type	100 kg, BMI 39 adolescent for PVR
		Failure of one or more systems	Elevated creatinine or lactic acidosis
		Septic or SIRS	Febrile and elevated inflammatory markers
Errors	Aircraft malfunctions	Noncardiac congenital lesion	DiGeorge syndrome, or trisomy 21
		Other	
		Equipment	
		Malfunction	Bair-hugger not working
		Not available	Echo probe not available
	External errors	External factors	
		Nonstandard care/protocol deviation	Errors types (see below) made by personnel external to immediate “cockpit” team
		Procedural error	
		Communication	
		Proficiency	
Unintended states	Operational pressures	Decision strategy	
		Diagnostics and imaging	
		Latent and other threats	
		Operational stressors	Not enough staff members
		Violation of SOP	
	Procedural	Nonstandard practice	
		Deviation or nonadherence (intentional or unintentional) to a standard practice, departmental protocol or care pathway	Patient (identification) checks not adhered to (leading to the unintended state of the wrong patient arriving in the operating room)
		Procedural	
		“Mistake,” lapse, or inattention during the execution of a task, akin to a “typo” when entering coordinates	Heparin given inadvertently
		Incorrect suture count	
Unintended states	Communication	PPM inadvertently programmed incorrectly	
		Poor communication (and timing) during organ procurement	
	Proficiency	Proficiency error	
		Execution of a procedure that is suboptimal, even if considered “difficult”	SVC stenosis at cannulation site
		For proficiency errors that were inferred with a high index of suspicion, a separate category of “inferred proficiency error” was considered.	Hemorrhage during ductus ligation
		These were almost all very long cardiopulmonary bypass runs that were excessive for the procedure.	Phrenic injury
	Decision error	Decision or judgment error	Long anesthetic induction/line insertion*
			Residual moderate valve regurgitation†
			Surgical heart block
			Inadequate endotracheal tube fixation
			Residual VSD patch leak‡
Unintended states	Aircraft handling		Acid-base mismanagement
			Failed attempt at sternal closure
			Error in diagnosis
			Error in timing of surgical repair
			Failed extubation
	Cardiopulmonary instability		MPA band too loose
			Unexpected level of inotropy or vasopressors
			Unplanned additional CPB run
			Urgent sternal opening
			Cardiac arrest
Unintended states			JET

(Continued)

TABLE 1. Continued

Measure	Aviation	Cardiac surgery	Examples
	Navigation	Residual lesions (in-hospital)	Excessive hemorrhage Hemodynamic (regurgitation, stenosis, etc)† Ventricular dysfunction§
	Configuration	Noncardiac end-organ dysfunction (in-hospital)	Neurologic—cerebral bleeding, seizures Respiratory—pneumonia, pulmonary hemorrhage Renal—acute renal impairment Gastrointestinal—NEC, gastrointestinal bleeding Chylothorax Sepsis Thrombo-embolic complications Wound complications Failure to progress Change in flight strategy Revision of original intended flight
		Decision-strategizing	Unintended mechanical support Unintended transcatheter intervention Unintended surgical intervention
		Interventions	Brain (clinical stroke, persisting seizures) Chronic renal impairment/dialysis Chronic respiratory compromise Chronic gastrointestinal dysfunction Persisting limb injury Chronic wound issues
Outcome	Incident or crash	Persisting end-organ decrement (after discharge)	Hemodynamic (regurgitation, stenosis, etc)† Ventricular function§ Persisting arrhythmia/pacemaker
		Residual lesions (persisting)	
		Death	

d-TGA, Dextro-transposition of the great arteries; *L*, left; *R*, right; *Cx*, cumflex; *SVC*, superior vena cava; *ALCAPA*, anomalous left coronary artery from the pulmonary artery; *BMI*, body mass index; *PVR*, pulmonary vascular resistance; *SIRS*, systemic inflammatory response syndrome; *SOP*, standard operating procedures; *PPM*, permanent pacemaker; *VSD*, ventricular septal defect; *MPA*, main pulmonary artery; *CPB*, cardiopulmonary bypass; *JET*, junctional ectopic tachycardia; *NEC*, necrotizing enterocolitis. *Anesthesia department agreed that induction and line insertion >1 hr reflected proficiency error. †Significant valve regurgitation was considered moderate or worse. ‡Significant patch leak was considered visible by both color and 2-dimensional echo. Tiny color jets at suture line with no visible defect not considered. §Ventricular dysfunction was considered moderate or worse.

conference. When this threat-and-error initiative was introduced, preoperative flightplans were not generated for neonatal patent ductus arteriosus ligations or for primary extracorporeal membrane oxygenation (ECMO) cannulations; therefore, patients who underwent these procedures are not part of the cohort. At the beginning and end of the surgical procedure, the operating room team conducted a formal debriefing of all system, equipment, and external factors that influenced the expected and actual progress of the case.

A 1.0 full-time equivalent Heart Center performance coordinator was dedicated solely to tracking patient progress through the threat and error model initiative in real time, via clinician interviews and clinical chart review. The coordinator was experienced in clinical cardiovascular research, but was tasked with recording data rather than adjudicating it. The role involved continually verifying the clinical progress of inpatients, from charts and clinical team member interviews. Staff physicians from all disciplines were interviewed at least weekly for additional aspects of clinical care that might constitute threats, errors, unintended states, or outcomes.

An infographic (Figure 1) depicting the flight was generated for every patient; we have found these to be a powerful visual aid to convey complex patient journeys. Time is represented on the x-axis, and crude risk level is represented on the y-axis. Cardiopulmonary bypass durations and number of runs are depicted graphically, and postoperative recovery is heralded by a number of stepwise reductions in risk level from chest closure, through

extubation, transfer from intensive care, and home. Unexpected escalations in therapy (reintubation, extracorporeal support, reoperations) can be easily depicted in a time-related fashion. Pertinent clinical events, adverse incidents, and other comments from debriefings are shown, as are echo results or other investigations for residual lesions. The graphics are generated manually by the performance coordinator, at present, but automated software is in the final stages of testing.

Infographics showing inpatient flights were openly discussed at weekly Heart Center rounds for clarification and consensus (by majority opinion). Inpatients and their infographics were discussed repeatedly each week until the end of flight (discharge or death). Finalized data for each flight were then recorded in a database, and clinical events were classified as a threat, error, unintended patient state, or permanent outcome, according to guidelines for conducting LOSAs as described by the FAA.⁹ If links between such events were recognized, they were recorded.

Threat and error types (Table 1) are generally self-explanatory, but some need brief explanation. A violation error represents noncompliance (intentional or otherwise) with a standard departmental clinical practice or treatment paradigm. These errors are very easy to define (and common) in aviation because of the high prevalence of checklists and standard operating procedures. Although less easily defined in medicine, violations were nevertheless evident because our Heart Center has care pathways for most diagnoses and procedures.

TABLE 2. Total numbers of threats, errors, unintended states, and outcomes, among the 524 patient flights

Category	n	%	n	%	n	%	n	%
Threats	763	—	Errors	428	—	Unintended patient states	1313	—
Morphology	230	30	Violation	10	2	Cardiorespiratory instability	371	28
Atypical	84	11						
Arrangement	23	3	Procedural/lapse	14	3	Excessive bleeding	28	2
Perfusion	18	2						
Composite	56	7	Communication	18	4	Thrombosis/embolus	25	2
Co-morbidities	424	56	Proficiency	280	65	Residual cardiovascular lesion	376	29
Unusually small	57	7						
Unusually large	8	1	Inferred proficiency	32	7	Noncardiac end-organ dysfunction	303	23
Unusually critical support	7	1						
Emergent	6	1	Judgment	69	16	Unplanned intervention	116	9
End-organ dysfunction	152	20						
Sepsis	16	2				Failure to progress	72	5
Noncardiac congenital defect	144	19						
						Revision of intended strategy	1	0
Equipment	26	3						
Malfunction	18	2				Change in intended strategy	18	1
Not available	8	1						
External threat	79	10						
Operational or latent threat	1	<1						

A procedural error is best thought of as a simple mistake or lapse: a pilot entering the wrong coordinates in a cockpit, or a doctor administering the wrong drug. The term proficiency error is intrinsically unsettling to surgeons (in itself a good reason to draw attention to it, and thereby better understand surgical error), but these errors reflect a suboptimal execution of a technical procedure, even one that is considered difficult. It is analogous to “rudder and stick skills” in aviation. A valve-repair leading to moderate regurgitation[†] would be considered a proficiency error, even if the child were premature and syndromic with highly dysplastic valves (indeed, these are threats that prompted the proficiency error). Judgment errors reflect clinical decisions (where clear choices existed) that are subsequently considered to be erroneous during open discussion.

Categorization of events was subjectively made according to the general clinical standard expected by the Heart Center team for the particular procedure, patient, or diagnosis. We, therefore, might consider 3.1 kg to be unusually small for an elective tetralogy of Fallot repair (ie, a threat), whereas other centers that routinely repair this lesion during the neonatal window may not consider this to be a threat. Adjudication is therefore the qualitative and subjective opinion of clinicians (exactly as LOSA assessment is the qualitative and subjective opinion of pilots trained in threat and error assessment), and consensus was achieved through majority opinion.

Using definitions from the FAA model, a threat that is linked to an error is a mismanaged threat and an error linked to an unintended state is a consequential error.⁶ From the latter, the unintended state may lead to a cycle, defined as additional errors or unintended states. Unintended states are part of the flight (inpatient journey); detrimental consequences that persist

at or beyond the point of discharge are instead outcomes (akin to the resulting accident in an aviation incident).[‡]

Statistical analysis explored the relationship between cycles and outcomes. Data were analyzed using SAS statistical software (Cary, NC) using parametric statistics. Comparisons between means and proportions were determined using the Student *t* test and Fisher exact test, respectively. Multivariable models for predicting binary outcomes were analyzed using logistic regression. Values of *P* < .05 were considered statistically significant.

RESULTS

The 524 patient flights represented consecutive surgical cases in our tertiary-level center, with a catchment-area population of approximately 11 million, covering most of eastern Canada. Therefore, case mix and complexity were highly variable, as indicated in Table E1. Most cases involved cardiopulmonary bypass (85%), and only 6% (*n* = 31) were for acquired, rather than congenital, disease. Univentricular or borderline physiology was present in 73 (14%). The intended flightplan was a primary corrective procedure in 358 (68%), a planned staged procedure in

[†]Hemodynamically “significant” valvular stenosis or regurgitation was considered to be moderate or worse (unless there was no intention to improve it according to the flightplan). Hemodynamically significant ventricular dysfunction was considered to be moderate or worse. If ventricular function was moderate preoperatively, then severe postoperative dysfunction would be considered significant.

[‡]This differentiation between unintended states and outcomes represents an important departure from conventional surgical thinking, which considers both to be “complications.” Acute postoperative renal failure is a significant unintended deviation from the intended flight plan—perhaps akin to single-engine failure in an aircraft. However, if complete recovery occurs, and the child is discharged with no long-term sequelae, then that unintended state did not lead to an *outcome*—ie, we landed at the planned destination in one piece despite the unintended engine problem.

FIGURE 1. Patient infographic. The patient’s in-hospital journey is tracked schematically, with time on the x-axis and crude “risk” on the y-axis. Once preoperative assessments have been made, decision-strategizing leads to publication of a presurgical “flightplan” detailing clinical information (some of which indicates threats). The duration and number of bypass runs are illustrated, at the end of which the intraoperative echo details are indicated. From arrival in intensive care, the expectation is a stepwise reduction in risk levels, before returning to the ward and then home. All pertinent clinical events are detailed on the graphic, including unexpected escalations in risk, cardiac arrests, runs of mechanical support, and reoperations. All the events on slides were subsequently coded as threats, errors, or unintended states, according to the threat and error model described herein. In this example, 2 threats are linked (without an error) to postcardiopulmonary bypass pulmonary hypertension (unintended state). However a proficiency error results in a significant residual VSD, leading to the unintended state of a 2nd cardiopulmonary bypass run. Nevertheless, the child made a reasonable recovery with de-escalation in risk levels through intensive care and to the ward. A wound infection also occurred, but was not deemed to have been related to an identifiable upstream error. ICU, Intensive care unit; VSD, ventricular septal defect; ex-prem, ex-premature; T, threat; U, unintended state; ECMO, extracorporeal membrane oxygenation; CPB, cardiopulmonary bypass; E, proficiency error.

105 (20%), and an unintended revision of an earlier procedure in 49 (9%).

Only 7% (n = 41) of the 524 flights reflected the metaphorical ideal, with no threat, no error, no unintended state, and no harmful outcome. Instead, in the vast majority of flights, at least one threat (n = 379; 72%), and/or one error (n = 257; 49%), and/or one unintended state (n = 387; 74%) occurred. For the entire cohort, 18% had undesirable postflight outcomes (Table 2): 7 children died (1.4%[§]); 13 had permanent end-organ injuries (all cerebral, 2.5%); and 68 had residual hemodynamic lesions (13%), of which 13 required readmission for surgical revision during the follow-up period (2%).

Threats

A total of 763 threats were identified in 379 patient flights. Threat prevalence in the 5 main categories is shown in Table 2. Coexisting morbidities and nonideal morphologic features comprised >85% of threats. The

most-common specific subtypes of threats were end-organ dysfunction (20%), noncardiac congenital lesions (19%), and unusual or complex variants of a particular lesion type (11%). Almost all (97%) threats were apparent before the flight had begun, ie, by the end of preoperative work-up and before arrival in the operating room. The 16 threats that occurred during or after surgery all related to equipment that was found to be either malfunctioning or unavailable.

The large majority of threats were managed effectively, in that they did not trigger an error (657 of 763; 86%). However, 106 threats in 75 patients were “mismanaged,” ie, linked to subsequent errors (Figure 2). Threats relating to coexisting morbidities and nonideal morphologic features were much more likely to be mismanaged (P = .0027 and .0084, respectively), especially small patient size (P < .0001). Other types of threat, such as equipment, scheduling, external factors, or system issues (latent threats¹⁶) seemed to be more effectively managed.

Errors

A total of 428 errors were identified in 257 patient flights. Therefore, 51% of all patient flights were error free. The spectrum of error types and their prevalence are shown in

[§] Although 1.4% mortality may seem low, it is not significantly different from any other recent year; the study cohort is from 2012, during which the annual mortality was 1.8% (not including primary ECMO or neonatal patent ductus arteriosus ligations). The very fact that our unit’s mortality has been static for ~10 years was one of the factors prompting this error initiative.

FIGURE 2. Schematic representation of the prevalence of threats, errors, consequential threats, and cycles of errors/unintended patient states.

Table 2. Proficiency errors and judgment errors were the most prevalent. The majority (58%) of identified errors occurred during the surgical window, but 30% occurred in the operating room before skin incision, and 12% occurred postoperatively. Patients who were in a higher risk adjustment for congenital heart surgery (RACHS) category had a high risk for experiencing an error ($P = .0001$). Operations using cardiopulmonary bypass were more likely to be associated with an error ($P = .02$), versus off-pump, and the lowest error rate was observed in operations involving thoracotomy ($P = .004$). Patient weight, specific diagnoses, or bi- or uni-ventricular physiology were not strong independent determinants of whether a patient would experience an error, over and above RACHS risk status. Overall, the 257 patient flights with errors had a significantly higher rate of residual hemodynamic lesions (Table 3).

In 67% of the 257 patient flights that contained error, the error led to an unintended state and was therefore classified as consequential (Figure 2); the remaining 33% of errors presumably either were genuinely inconsequential or were effectively overcome such that no unintended patient state occurred. Whether an error was consequential did not relate to RACHS complexity, weight, diagnosis, or morbidity. Similarly, errors arising from mismanaged threats and de novo unprompted errors both had a similar likelihood of being consequential ($P = .80$). However, the type of error was important: Judgment errors were especially likely to be consequential (odds ratio (OR) 3.8; $P < .0001$), versus other error types, including proficiency errors. Overall, consequential errors were strongly associated with residual hemodynamic lesions, end-organ injury, and death (Table 3).

The unintended state arising from a consequential error may itself lead to a cycle of further unintended states or errors. Such error cycles occurred after almost two thirds of consequential errors (Figure 2). Overall, error cycles occurred in 21% of all patient flights, and in 3 flights, 2 distinct error cycles occurred. Multivariate preflight predictors of whether error cycles might occur included a high RACHS category for the patient ($P < .0001$) and the

presence of baseline threats, irrespective of type ($P = .02$). Patient weight, previous sternotomy, specific lesion type or operation type, and specific threat type, all seemed to be poor indicators of whether error cycles might occur. However, once the flight was in progress, certain intraoperative events were strong determinants of error-cycle occurrence: necessary revision of part of the primary planned procedure (OR 10, $P < .0001$), aborting the primary plan (OR 9, $P = .011$), undertaking an additional unplanned procedure (OR 17, $P < .0001$), having to leave the chest open (OR 5, $P < .0001$), and patient return to intensive care while still intubated (OR 2.3, $P = .011$).

Error cycles were strong determinants of harmful outcomes (Figure 2, Table 3). The prevalence of residual, hemodynamically important, cardiovascular lesions was significantly higher after flights containing cycles (28%) versus those without (9%; $P < .0001$). Permanent end-organ injury was evident for 13 flights, and all were neurologic (12 with confirmed brain injury, 1 with recurrent seizures). Nine of these injuries occurred after flights containing error cycles (9%), whereas 4 occurred in the 414 flights without error cycles (prevalence 1%; $P < .0001$). Six of the total of 7 deaths occurred after error cycles (86%, $P < .0001$). The OR of dying during a flight containing error cycles, versus during flights with no error cycles, was +23. The total number of errors in each cycle ranged from 1 to 8; the occurrence of multiple errors within cycles was highly associated with a greater risk of residual hemodynamic lesions ($P < .0001$), end-organ injury ($P = .002$), and death ($P = .01$).

DISCUSSION

The medical profession has been obstinate in its approach to human error.⁸ Instead of adopting a *systems approach* to error, which is characteristic of high-stakes industries with impeccable 6- σ safety records (aviation, air traffic control, nuclear energy⁸), the medical profession epitomizes the *personal approach* to error. Accordingly, error is considered to be a result of the shortcomings of a person or small group of individuals, on whom responsibility for the error is therefore deemed to rest. The personal approach acts as a

TABLE 3. Prevalences of outcomes for specific patterns of threat, error, and unintended state

Threat/error pattern	Example	Residual hemodynamic lesion (n = 68, 13%)	End-organ injury (n = 13, 2%)	Death (n = 7, 1.3%)
Any threat	T	57 (15)	12 (3)	7 (1.8)
379 (72)		.03	.13	.20
Any error	E	49 (19)	10 (4)	6 (2.3)
257 (49)		<.0001	.05	.06
Consequential error	E ~ U	45 (26)	10 (6)	6 (3.4)
173 (33)		<.0001	.001	.006
Error “cycles”	E ~ U ~ E ~ U	31 (28)	9 (9)	6 (5.4)
110 (21)		<.0001	<.0001	<.0001
Cycles containing single error	E ~ U ~ U ~ U	13 (19)	4 (6)	3 (4.4)
66 (13)		.11	.07	.05
Cycles containing multiple errors	E ~ U ~ E ~ U	18 (41)	5 (11)	3 (6.8)
44 (8)		<.0001	.002	.01
Cycle not triggered by threat	E ~ U ~ U ~ U	18 (23)	3 (4)	3 (4)
77 (15)		.006	.42	.07
Cycle triggered by threat	T ~ E ~ U ~ U ~ U	14 (39)	6 (17)	3 (8)
36 (7)		<.0001	<.0001	.009

Values are the number (proportion) of outcomes in each threat/error pattern. *P* values, shown after number (proportion) represent Fisher exact test of comparisons of these proportions versus children not harboring the stated error pattern. Children who experience error cycles exhibit a high prevalence of outcomes. This is especially so in the subset of children with cycles containing multiple errors (vs single error with multiple, downstream, unintended states), and in the subset of children with cycles that are associated with an upstream mismanaged threat (vs error cycles initiated by a de novo error not triggered by a threat).

disincentive to report errors and inhibits the search for systemic conditions or triggers for error occurrence.

Using the personal approach, aviation commentators concluded that the junior copilot at the controls of Air France flight 447 was responsible for the loss of 228 lives, as a result of inappropriately attempting to climb steeply from 35,000 ft under full throttle and consequently breaching the flight envelope of the aircraft.¹⁷ The events as deciphered by air accident investigators using their systems approach, rather than the personal approach, are depicted in Figure E1 and provide crucial insight into why safety margins progressively degraded.¹ As an example, the investigation revealed that airline simulator training sessions for stall warnings are frequently undertaken only at low altitudes,¹ in which case the full-throttle and climb approach (“take-off and go-around” [TOGA] configuration) is in fact the correct pilot response. Furthermore, the cockpit voice recorder provided insight into the chaos and confusion in the cockpit during the few minutes of the emergency. The pilots did not coordinate well, or make full use of all their available resources¹; they rapidly lost situational awareness and never took rationale steps to recover it.

We believe that direct corollaries to a plane flight exist in cardiac surgery. Deviations from the ideal expected journey, through human error—perhaps triggered by a patient- or system-related threat—lead to unintended clinical states. These can rapidly be amplified into additional errors or further unintended deviations, leading to progressive reductions in safety margins. Extreme vigilance and excellent resource utilization may allow successful recovery. However, if the team does not

coordinate well, or fails to utilize all available resources, the resulting chain of events leads to a high likelihood of patient injury or death.

Major differences between cardiac surgery and aviation are evident. One crucial difference is the role of the patient: Aviation involves a human-machine interface, with environmental/system modifiers, whereas medicine involves a human-patient interface, with many modifiers, including machinery, system factors, etc. Consequently, surgery is more complex, perhaps evidenced by the <10% of all patient journeys that proceed as the metaphorical ideal with no patient threats, errors, or unintended states. It may be that patient factors (comorbidities/morphology) are difficult or impossible to control well; system threats were in fact more often better managed than patient-related threats such as comorbidities and morphology.

Errors were common, and they related poorly to specific operation types (although the broad spectrum of procedures hampers statistical discrimination) and specific threat types. Instead, technical complexity (cardiopulmonary bypass and RACHS) was the main driver of errors, which is entirely consistent with results of studies of flight simulations in high-workload situations.^{11,18,19} Even seemingly inconsequential errors had an impact on residual hemodynamic lesions, but especially important were consequential errors (occurring in one third of all flights) and error cycles (in one fifth of all flights), which were both highly linked to poor outcomes such as residual lesions, brain injury, and death.

Certain surgical occurrences were very strongly linked to subsequent cycles of errors and unintended states. Having

to revise part of an operation, aborting a primary plan, or performing an additional unplanned procedure were all strongly linked to error cycles. Possibly, such occurrences should trigger declaration of a heightened level of vigilance, focused operating-room communication, and acquisition of additional personnel or experience, to prevent or break such cycles. Effective recognition and management of error and risk through effective utilization of all available resources is the central focus of what is termed crew resource management (CRM).²⁰ Since its inception at a NASA/aviation industry workshop¹⁸ in 1979, CRM has become a mandatory and core component of commercial cockpit training. Application of aviation CRM training to benefit surgical team performance has long been suggested^{21,22} and was recently confirmed in a large Veterans Affairs study, in which a 50% reduction in patient mortality was observed.²³

The aim of CRM is to train people to perform effectively in degraded situations,^{1,21} to avert the sort of disintegration of team coordination and resource utilization that occurred in the cockpit of flight 447. In CRM, the first priority is to maximize safety margins. Only after this has been achieved does attention turn to problem solving as the next step. During training, emphasis is placed on 4 behavioral indicators: ability to cooperate, management and leadership, situational awareness, and decision making.¹ Crews develop effective cross-checking and support capabilities that reduce confusion and enhance task allocation. Analysis of recent near-catastrophes has demonstrated exemplary CRM skills by the cockpit crew and serves as anecdotal support of CRM's merit.¹¹ Comparable training has been developed for medical and surgical teams in pediatric cardiac surgery and critical care in an effort to learn to help them function with maximal effectiveness.²⁴

The aeronautical industry has pursued its understanding of threat and error management through various data sources; we have progressively attempted to pursue comparable data within the cardiac surgery field. In the same way that air accident investigations of incidents have proven to be invaluable for aviation safety, as a first step, we conducted an exhaustive review of error prevalence and impact relating to all 261 patient deaths in our program over a 10-year period.¹² In the majority of cases, error was linked to the deaths, and such errors were most common in high-complexity patients (eg, single-ventricle), and during high-workload clinical windows.

As a second iteration, we focused on all high-risk single-ventricle patients and learned that ~80% experienced errors, and these errors led to survival decrements¹³ of ~15%. This current initiative represents an

attempt to track patients for evidence of error, as they pass through our program. Although the concept is based on LOSAs, the tracking process is not a LOSA in practice. LOSAs involve continuous observation for granular detail, small errors, and particularly important, ambient distractions. The long duration of each patient flight precluded this LOSA approach in our study, so the detail is more subjective and less granular. An important consequence of our less-granular approach is that fidelity is lost, an important limitation that we fully acknowledge. Without continuous observation, errors are occasionally identified because of an unintended state or outcome. We see no easy way to circumvent this problem using a unit-wide, inpatient journey-tracking approach.

The concept and definitions employed in our methodology, however, are based on LOSA models, and our strategy is also more "real world" and practical; the methodology described herein has now been implemented across our unit as routine practice. Other teams researching this field have pursued more accurate and granular LOSA models, most notably the great Ormond Street team during their studies of error in arterial switch operations,²⁵ but they focused solely on intraoperative events. We now intend to move closer to the true LOSA model, by implementing routine operating-room audiovisual recordings and combining these data with our current protocol. This approach will allow for greater error detection, and assessment of ambient distractions, and provide crucial assessment for nontechnical CRM skills.

In summary, high-stakes industries all have a philosophy about human error akin to that in aviation: (1) All have developed a preoccupation with failure and have engrained a culture of systemic vigilance; (2) All have endorsed and promoted mechanisms for blame-free error assessment and analysis; and (3) All accept that human error is both ubiquitous and inevitable. Assessment of error within our program confirms that error is common, and two thirds of these errors are consequential. One fifth of all patients experience error cycles, which are highly associated with residual lesions, end-organ injury, and death. When error leads to an unintended deviation from the expected clinical course, extreme vigilance and optimal use of resources is essential to prevent or break error cycles.

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¹¹For example, US Airways flight 1549 successfully landed in the Hudson River after a double bird strike shortly after take-off. British Airways flight 38 lost thrust on both engines at an altitude of 720 ft during the final approach to Heathrow and crash-landed 890 ft short of the runway. There was no loss of life in either accident, and both crews were praised for their CRM skills during the crises.

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Key words: threat, error, resource management, aviation

Discussion

Dr Martin Elliott (London, UK). Thank you very much. I have no disclosure. First of all, I would like to congratulate Dr Hickey and the team from the Hospital for Sick Kids for such an open,

honest, and transparent review of error in their practice. It demonstrates again to me the importance of human factors research in complex teamwork.

I think, before my comments, it is important to set some context about the Hospital for Sick Kids, because there aren't many places that could do this work. First, there is a strong local tradition of self-awareness and self-criticism; second, they have standard operating procedures per diagnosis and procedure, which many centers do not. Third, there has been a strong tradition of collegiality and a relentless pursuit of excellence. Those are the core foundations required to build your work.

I have 3 questions. The first one is based on the role, described in your article, of Line Operation Safety Audit (LOSA) pilots sitting in the jumpseat, where, incidentally, at my stage in my career, I would love to sit. If you are doing 500 cases, as you have reported here, and you have only one primary person who is collecting all the information, this is a different observational model than the LOSA model that you describe in the NASA "threat and error" practice. So, how do you deal with observer error, and the fact that when you do your multiple analyses retrospectively each week, you might have hindsight bias as well?

Dr Edward Hickey (Toronto, Canada). Thank you very much. In relation to your opening comments, we are lucky in Sick Kids to have already a very corporate and open culture; that has come from a 10-year plan that is really attributable to Dr Van Arsdel and Dr Redington. I would suggest that, yes, we are lucky here, but actually, that type of environment is directly applicable and could be instituted in almost any hospital. So, rather than Sick Kids hampering other institutions in doing that, it really should encourage them to have that sort of open accountability culture.

With regard to the LOSAs, you are absolutely right. Our methodology stemmed from LOSAs, which, for the wider audience, have been mandatory for all airlines since the 1980's, and they have trained pilots who sit in the jumpseat and observe the flight crew. They are not judging errors; they are just recording them. It is totally anonymous, and they are so ubiquitous that pilots really don't mind or behave any differently whether there is somebody there or not, and many tens of thousands of LOSAs have been done.

We were trying to mimic that type of model. It is totally impractical to have somebody following every minute of a patient's journey, and it becomes very time consuming. Now, you at Great Ormond Street Hospital, 10 years ago, managed to do that with the arterial switch operation, and that was a huge exercise. But to try and do that over the whole timeframe of a patient's stay is very difficult. So, yes, there are great practical limitations in having someone track all those data.

That is why we use the open forums both preoperatively and postoperatively, which are completely open for all members of the Heart Centre, to voice their concerns about any particular aspect of a patient's journey, and then we try to get consensus. So it isn't just that one person who is judging anything. The observer is simply recording everything to be brought to the open forum.

Dr Elliott. My second question relates to the fact that you did not include distractions and interruptions during surgery or diagnostic procedures, which both Ken Catchpole and Jane

Carthey identified as really important threats, indeed some of the biggest threats, to safety. I wondered whether that, and perhaps the complexity of the team size, and the number of interactions between individuals, should have been considered as threats.

Dr Hickey. I fully agree with you. A major problem with our approach, as I said, owing to limited resources, is that we are just seeing the tip of the iceberg. We are missing a large number of threats; we are missing a large number of errors, particularly error types; we are probably missing certain communication errors; and we are certainly missing many system-type threats and external errors. This is a limitation that we would love to be able to address, whether through video recording or sound recording, in the operating room. I think it would be extremely valuable. But certainly, we are missing many of these errors that your more-granular approach 10 years ago was able to capture better.

Dr Elliott. I share your view about the need for a black box in all these environments, by the way.

You've talked about the complex patients, particularly those who have multiple additional procedures or reoperations that trigger error cycles. I wondered whether you have considered that as a latent threat; in other words, the flight plan might have been wrong in the first place, and then you are actually compensating for it in an inappropriate way because the flight plan was wrong.

The second part of that, of course, is that although Crew Resource Management (CRM) training has been shown by Julia Neily's group to work at the VA by reducing surgical mortality, how do you expect that to be changed quickly enough to deal with the publicity that is going to come after your paper is published?

Dr Hickey. In relation to the latent threats, I think you may be right, for certain situations. By having an open forum and discussing things retrospectively, we were trying to identify upstream judgment or decision errors, and we hope we captured those as best as we could.

CRM is going to be a generational thing; it is going to happen over 10 or 15 years, and I hope the younger generation will be able to take these models of threat and error and implement them in due course.

Dr David Sugarbaker (*Baylor, Tex*). In terms of a systems approach, versus the maybe more traditional responsibility by the individual, if you make the analogy to a football team, the way in which the team functions would be somewhat analogous to a systems approach in terms of preventing team error, but the individual, let's say the quarterback or the pulling guard, could still fumble, which is an individual issue, or there could be an interception thrown.

So in studying this issue a little bit, it appears that a lack of skill in an individual or a lack of attention, if you will, or focus, can lead to significant error that may not be addressed by a systems approach. Could you comment on that?

Dr Hickey. Yes. Doctors don't like systems models. We like to embrace the personal approach.

Dr Sugarbaker. I am not talking about what we like or don't like. Can you address the focus on individual performance versus team performance?

Dr Hickey. Yes. A systems approach is not mutually exclusive to a personal approach. Within a systems approach, you have personal accountability, and you can still assess individuals on a personal level, and highlight them and then implement measures to bring them up to a level. It doesn't also hamper people from excelling, like doctors; we like individuals to excel. It doesn't hamper that at all.

But what it does draw away from is the naming, blaming, and shaming, which tends to just limit the insight into error and threats. It contains it around a certain individual.

Dr Sugarbaker. Right, but I am not talking about naming, blaming, and shaming. I know that's all terrible. But the point I was just trying to make, and I think you have addressed it, is that I have seen situations in which individual error was the issue, but a systems approach was applied because it is the popular thing to do. The only point I'm trying to make, and I think you have made it nicely, is that there are situations where individual inattention is the problem, and where a systems approach is applied to that, and it is ineffectual, as opposed to additional coaching of the individual.

Dr Craig Smith (*New York, NY*). Dave has largely made one of my points. I have a comment and a question. Dave's comment is partly what I was saying, but we do need both personal and system responsibility, if only because in this very popular aviation analogy, the pilot always goes down with the plane, which is not what happens in the operating room, and we need to teach people personal responsibility.

The question has to do with the role of factors like morphology and risk adjustment for congenital heart surgery (RACHS) scores and so forth. It went by pretty fast. I wasn't sure how you really take that into account as the source of error. That also is different from the aviation analogy, because you can't go back and re-engineer that plane. That is a state that is given, not something that can be re-engineered.

Dr Hickey. So what you are alluding to, really, is that in medicine there is a key third interface, and that is the role of the patients, and that is not there in aviation, and there are certain patient factors that we cannot control.

Now, we looked in our analysis for patient factors that stood out, but because we had such a broad, all-inclusive cohort with such a broad spectrum of procedures and diagnoses, the discriminatory power is very difficult to achieve.

Yes, RACHS score is important, but interestingly, small patient size wasn't, and we do lots of neonatal operations with very few errors and excellent outcomes. Similarly, you can operate on older adolescents with multiple reoperations who have the opposite outcome. Our next stage, and now we have more than 1000 in our database, is to focus on key index operations like tetralogy of Fallot and ventricular septal defects, etc, to see if we can tease out more discriminatory power.

To emphasize your first comment, and Dr Sugarbaker's, it is absolutely key to point out that personal accountability is part of a systems approach, and I can't emphasize that enough.

Dr Pedro del Nido (*Boston, Mass*). I also echo what David Sugarbaker said. I think there is a balance between the process measures, which we focus on, and which you are trying to highlight, versus individual responsibility in these teams. A great part of it has to do with the medical case where the patients differ and

applying analogies from the air flight industry or NASA where they're either starting off roughly in the same place or dealing with the same problem. We don't face that in medicine. Every patient is different with respect to their anatomic variables and also their risk categories, and I think it is dangerous to apply that kind of methodology to what we do.

Having said that, my question to you is that we also have a lot of new technology that is being introduced, and we have the choice of applying it. For example, intraoperative echocardiography in congenital heart disease, I think, has had a huge impact on outcomes in patients, yet we don't study its impact on medical errors because it is a technology advance that will have a significant role to play in not only understanding the disease but also recognizing when we have incomplete correction of a lesion. Where does that fit into your analysis?

Dr Hickey. Intraoperative echo, and indeed, every single echo that the patient has had during their inpatient journey were all part of our assessment of whether errors were made and whether unintended deviations were made. So, for example, if we came off with moderate regurgitation after a valve repair, that is an unintended state, we did not want that, and in fact it is the result of an upstream technical error in repairing the valve, which may then be upstream, having been prompted by the threat of a terribly dysplastic abnormal morphology.

So all of this is incorporated in our methodology, which, as we fully acknowledge, is inherently nonscientific. It is qualitative; it is real life. It is what the Heart Center physicians themselves interpreted for that patient's journey.

Dr del Nido. My point is quite different. My point is that the fact that the echocardiogram detected that you have a residual atrioventricular (AV) valve regurgitation is actually a good thing, because what happened was that the surgeon went back and got it fixed, whereas in the past when that technology wasn't available, that patient would have been discovered long after the surgery or would have struggled for days because of a hemodynamically incomplete repair.

Our view of the incorporation of technology has to be looked at in that light, rather than simply checking off the number of errors that we commit during the patient's hospitalization.

Dr Hickey. Yes, absolutely, and we are not just checking off the number of errors. We are using all the new technology to judge whether we have achieved satisfactory results or not. And you are absolutely right. In the days before echo, yes, all these errors and unintended states would have been missed and gone by the wayside.

Dr Asif Hasan (*Newcastle, UK*). Is this the death knell for people like Donald Ross and Magdi Yacoub, who with their flamboy-

ance could change the course of the operation, sometimes for the better?

Dr Hickey. Maybe. I can't really comment on that.

Dr Sugarbaker. I want to make one other point relating to Dr del Nido's comments regarding new technology. I think that in situations, from my standpoint, and maybe you could comment very briefly, where there is technology that assists or extends our diagnostic ability (for instance, intraoperative echo would extend our ability to assess the heart), there is other technology, sort of like the navigator in your car, which replaced your ability to read a map, and I think at times there is technology which actually is detrimental to our overall clinical approach, certainly to that of our trainees, because it is a replacement technology, as opposed to an extending technology.

I wonder if you could comment on that. Do you get the point?

Dr Hickey. I do, but I am not sure whether your example of a technology that you are alluding to in this is replacing the surgeon's accountability or responsibility.

Dr Sugarbaker. No, I am not suggesting it is, but I wondered if you could comment on sort of the difference, in the effect on potential error rates, of a technology that extends your ability to assess the situation, like an echocardiogram or, when I was training, the interoperative arteriogram for a distal revascularization—those surgeons who did it had a better idea as to what the anastomosis looked like; there was a lower stenosis rate and thrombosis rate—as opposed to technologies such as the GPS (global positioning system) or the navigator, where one's ability to assess the situation from a clinical standpoint is actually somewhat impeded in terms of the knowledge base. Do you see what I mean?

Dr Hickey. Yes. Our knowledge base is only finite, so as technology advances, yes, some skills will be taken away from the surgeon, just like medical school now is filled with genetics and things that didn't exist 30 years ago, and so some of their other knowledge base is going to be distilled down and diluted down. That's just a natural result of this progression. I don't think the introduction of these technologies is necessarily a bad thing, either in the cockpit or in the surgical arena.

Dr Sugarbaker. I am not suggesting that they are bad, but there are certain times when it would be essential to call on a potential skill, and my only point is that as technology comes along, we have to be mindful as to which clinical skill, ability, or diagnostic ability is being replaced, and ask whether that is an essential component. At some point, we won't be feeling the pulse, because of the overall monitoring and so forth.

I just wanted to make that point, and I think you have done a great job with the paper. Thank you.

APPENDIX E1.

Threat Management Worksheet

Threat ID	Threat Description			Threat Management	
	Describe the threat	Threat Type	Phase of Flight 1 Predepart / Taxi 2 Takeoff/Climb 3 Cruise 4 Des/Appro/Land 5 Taxi-in	Linked to flight crew error? (Yes / No)	How did the crew manage or mismanage the threat?
T1	Runway and taxiway construction on their departing runway (final 2000)	103	1	No	Threat mismanaged - CA failed to include the construction and closures in his brief. No plans were made in the event of a rejected takeoff, which is required by airline SOP.
T2	Late ATC runway change - changed runway to 24R from 25L due to a slow moving aircraft on 25L	101	4	Yes	Threat managed - CA reprogrammed the FMC, handled the radios, and placed emphasis on the FO to fly the aircraft.
T3	After a late runway change, ATC called back and told the crew that it was at their discretion to land on 24R or 25L	101	4	Yes	Threat managed - CA asked for the FO's preference. They mutually decided to continue the approach into 24R because it was already in the FMC.
T4	On taxi-in, there were no wing walkers meeting the aircraft in a congested ramp area in LAX	204	5	Yes	Threat managed - The crew called ground ops and wing walkers were dispatched to the airplane
T5					
T6					
Threat Codes					
Environmental Threats			Airline Threats		
100 Adverse Weather 101 ATC 102 Terrain			200 Airline Operational Pressure 201 Cabin 202 Aircraft Malfunctions / MEL Items 203 Ground Maintenance		
103 Airport Conditions 104 Heavy traffic (air or ground) 199 Other Environmental Threats			204 Ground / Ramp 205 Dispatch / Paperwork 206 Manuals / Charts 299 Other Airline Threats		

Error Management Worksheet

Error ID	Error Description			Error Response / Outcome		Error Management	
	Describe the crew error	Phase of flight 1 Predepart / Taxi 2 Takeoff/Climb 3 Cruise 4 Des/App/Land 5 Taxi-in	Linked to threat? (If Yes, enter the Threat ID)	Error Type	Crew Error Response 1 Detected 2 No response	Error Outcome 1 Inconsequential 2 Undesired state 3 Additional error	How did the crew manage or mismanage the error?
E1	CA failed to brief a rejected takeoff for shortened departing runway due to construction	1	T1	403	2	1	No error management.
E2	FO failed to set his airspeed bugs.	1		304	2	3	Linked to error #3
E3	In running the Before Takeoff Checklist, the FO skipped the takeoff data item.	1		401	2	2	Linked to UAS #1
E4	At FL200, the crew was cleared to FL270. They accepted and the FO dialed 230 instead of 270 in the Mode Control Panel.	2		302	1	1	Error managed - Captain caught the error on cross-verification.
E5	FO, hand flying, let the airplane slip a little to the left during the final approach	4		300	2	2	Linked to UAS #2
Error Type Codes							
Aircraft Handling		Procedural			Communication		
300 Manual Flying 301 Flight Control 302 Automation 303 Ground Handling 304 Systems / Instruments / Radios 399 Other Aircraft Handling		400 SOP Cross-verification 401 Checklist 402 Callout 403 Briefing 404 Documentation 499 Other Procedural			500 Crew to External Communication 501 Crew to Crew Communication 599 Other Communication		

Examples of LOSA score sheets published by the FAA for use by threat and error observers. Guidelines on the implementation of LOSAs are available elsewhere.⁹ Des/App, Descend/approach; CA, captain; SOP, standard operating procedure; ATC, air traffic control; FMC, flight management computer; FO, flight officer; LAX, Los Angeles International Airport; MEL, minimum equipment list; A/C, aircraft; G, glide slope; FM, flight management system; TDZ, touchdown zone. Reproduced from the Federal Aviation Administration.⁹

Undesired Aircraft State (UAS) Management Worksheet

UAS ID	UAS Description		UAS Response / Outcome			UAS Management
	Linking Error? (Enter the Error ID)	Undesired aircraft state description	UAS Code	Crew UAS Response 1 Detected 2 No response	UAS Outcome 1 Inconsequential 2 Additional error	How did the crew manage or mismanage the undesired aircraft state?
UAS 1	E2	Wrong airspeed bugs on takeoff roll	1	1	1	Errors mismanaged - The bug error should have been caught with the Before Takeoff Checklist, but the FO missed the item. The FO detected and corrected the error on the roll.
UAS 2		FO landed left of the centerline.	86	1	1	Error mismanaged - FO tried to correct but still landed left of the centerline. Approach was stable and made the first high-speed taxiway.
UAS 3						

Undesired Aircraft State Type Codes		
Configuration States 1 Incorrect A/C configuration - flight controls, brakes, thrust reversers, landing gear 2 Incorrect A/C configuration - systems (fuel, electrical, hydraulics, pneumatics, air-conditioning, pressurization, instrumentation) 3 Incorrect A/C configuration - automation 4 Incorrect A/C configuration - engines Ground States 20 Proceeding towards wrong runway 21 Runway incursion 22 Proceeding towards wrong taxiway / ramp 23 Taxiway / ramp incursion 24 Wrong gate 25 Wrong hold spot 26 Abrupt aircraft control - taxi	Aircraft Handling States - All Phases 40 Vertical deviation 41 Lateral deviation 42 Unnecessary WX penetration 43 Unauthorized airspace penetration 44 Speed too high 45 Speed too low 46 Abrupt aircraft control (altitude) 47 Excessive banking 48 Operation outside aircraft limitations	Approach / Landing States 80 Crew induced deviation above G/S or FMS path 81 Crew induced deviation below G/S or FMS path 82 Unstable approach 83 Continued landing - unstable approach 84 Firm landing 85 Floated landing 86 Landing off CL 87 Long landing outside TDZ 88 Landing short of TDZ 99 Other Undesired States

APPENDIX E1. (Continued)

FIGURE E1. Threat and error model summarizing the last 4 minutes of Air France flight 447, as described in the official accident report.¹ The flight was proceeding as planned: cruising at 35,000 ft at 540 kt under autopilot control. Poor weather and high cumulonimbus clouds (T₁) contributed to icing of a pitot tube with loss of airspeed data, and therefore autopilot disengagement: the major threat (T₂). A latent threat¹⁶ was a design fault, which predisposed the plane to pitot tube icing. Loud, rare, and distressing stall warnings sounded in the cockpit because of the erroneous airspeed data. The junior copilot in the right-hand seat took manual control and made a major proficiency error (E_{2P}) by inappropriately pulling back on the stick and climbing. This important error may have been prompted by limited simulator training sessions of low-altitude stalls, during which an appropriate response is to pull the nose up under full throttle (LT₂). The 2 copilots did not carry out or follow "loss of airspeed checklists" (E_{3V}): if they had, they would not have climbed in altitude. The preceding errors all contributed to unintended loss of speed and excessively high altitude (U₁). At one point, the PF becomes concerned about *over-speed* and reduces throttle (E_{4J}), probably because training sessions disproportionately focus on the risks of high-altitude over-speed, which tend not to apply to the modern Airbus A330 (LT₃). The progressive climbing and loss of airspeed (U₁) gradually lead to a breach in aircraft flight ceiling (U₂). The senior PNF recognizes this, but a lack of communication and cross-checking (E_{5C}) leads to his requests to descend never actually materializing. This latter error in communication was likely exacerbated by perhaps the earliest protocol violation in the flight: the captain not clearly debriefing and allocating roles prior to his retiring for rest (E_{1V}). The pitot tube de-ices and provides accurate airspeed—only 27 seconds after it initially malfunctioned. At this moment in time, all instruments are entirely functional, the aircraft is airborne, and the pilots are—briefly—in control. From this point on, therefore, the events are entirely manmade (shaded area). Because of the falling airspeed, the stall warnings restart (and continue until the end of the flight). The junior copilot (having started to put the nose down and gain speed) immediately responds inappropriately again by pulling the nose up sharply and applying full-throttle (TOGA) (E_{6P}). The resulting gradual increasing angle of attack led to gradual loss of kinetic energy despite 100% engine thrust. The usual maximum angle of attack prior to stall is typically ~20°; however, soon the angle of attack exceeded 40°, with a velocity of ~100 kt. The flight envelope had been breached, and the aircraft was in a nose-up flat stall (U₃). Throughout these final minutes, there was complete loss of situational awareness. Air accident investigators have suggested that lack of horizons, owing to nighttime flight, may have contributed to disorientation (T₃). Crew resource management techniques were poor (E_{7C}), and perhaps were exacerbated by the number of extremely rare and stressful aural stall alarms (T₄). Behavioral science experiments have demonstrated that in highly stressful situations, humans tend to act on aural stimuli preferentially over visual stimuli (perhaps explaining the TOGA response to stall warnings, compared with digesting the information on visual displays).²⁶ The aircraft was plummeting at >10,000 ft/minute. A distressing point is that, when passing through 10,000 ft, both PF and PNF were fighting with the controls, the more senior copilot trying to push the nose down and gain speed. A design flaw in the A330 meant that neither man could feel the other's maneuvers, and they "cancelled out" (LT₄). As they passed through 2000 ft, the terrifying GPW sounded (an automated voice repeating "...pull up...pull up...," and the PF declared in despair "...but I've been pulling up all the time!") At this moment, the PNF

TABLE E1. Selected primary operations (“flights”) to illustrate the breadth and diversity of clinical practice represented by these 524 surgical procedures on 500 children

Clinical details	n	%
Primary operation (not exclusive)		
Isolated VSD	51	10
Tetralogy of Fallot	48	9
Fontan	38	7
Atrioventricular septal defect	31	6
Isolated coarctation	25	5
Isolated secundum ASD	23	4
Isolated primum ASD/partial AVSD	20	4
Subaortic stenosis	20	4
Bidirectional cavopulmonary connection	18	3
VSD + RV muscle bundles	16	3
Arterial switch for d-TGA	13	2
Permanent pacemaker implantation	13	2
Arterial switch and VSD	12	2
Ross operation	12	2
Mitral valve repair	11	2
Sinus venosus ASD/PAPVC	11	2
RV-PA conduit replacement	10	2
PA band	9	2
RVOT augmentation	8	2
Norwood operation	7	1
Systemic-pulmonary shunt	7	1
Aortic valve repair	6	1
Heart transplant	5	1
PDA ligation	5	1
Rastelli	5	1
Supra-cardiac TAPVC	5	1
Supra-valvular aortic stenosis	5	1
“Pulmonary”	4	1
Arch augmentation	4	1
Unifocalization	4	1
ALCAPA repair	3	1
Coarctation and VSD	3	1
Interrupted aortic arch repair	3	1
Kawashima	3	1
Truncus arteriosus repair	3	1
Vascular ring	3	1
Infra-cardiac TAPVC	2	<1
Pulmonary artery plasty	2	<1
Yasui operation	2	<1
Bentall operation	1	<1
Berlin heart LVAD	1	<1
Hybrid stage 1	1	<1

VSD, Ventricular septal defect; ASD, atrial septal defect; AVSD, atrioventricular septal defect; RV, right ventricular; dTGA, dextro-transposition of the great arteries; PAPVC, partial anomalous pulmonary venous connection; PA, pulmonary artery; RVOT, right ventricular outflow tract; PDA, patent ductus arteriosus; TAPVC, total anomalous pulmonary venous connection; ALCAPA, anomalous left coronary artery arising from the pulmonary artery; LVAD, left ventricular assist device.

suddenly realized that this major error had transcended the entire emergency, and that they were in a steep nose-up stall. It was too late to regain control, however, and impact followed 4 seconds later. Cockpit voice recorder transcripts are available at <http://www.planecrashinfo.com/cvr090601.htm> (warning: distressing content). *Ft*, Feet; *kt*, knots; *TOGA*, “take-off, go-around” configuration; *GPW*, ground proximity warning; *PF (R)*, pilot-flying (31-year-old copilot Bonin, in right-hand seat); *PNF (L)*, pilot-not flying (38-year-old Roberts in left-hand seat); *A/P*, autopilot; *LT*, latent threat; *T*, threat; *E_A*, error (proficiency); *E_V*, error (protocol violation); *E_J*, error (judgment); *E_C*, error (communication); *U*, unintended state.