Systems Safety Risk Analysis of Fatal Night Helicopter Emergency Medical Service Accidents

Bryan B. Aherne; Chrystal Zhang; Won Sun Chen; David G. Newman

INTRODUCTION: In the United States, the proportion of Helicopter Emergency Medical Service (HEMS) fatal accidents remained unchanged despite an overall decreasing accident rate. Previous research showed night HEMS operations influenced fatal outcomes. Pilots with <6 yr of HEMS domain task experience (low-DTE) had a higher likelihood of a night operational accident in conditions associated with adverse weather. This study sought to determine whether a difference existed between day and night fatal accident rates and identify influences contributing to night fatal HEMS accidents. Any risk factors identified will be used for a risk analysis to inform future operational safety of the night visual flight rule (VFR) HEMS transport system.

METHODS: Historical accident data and industry hours were obtained. Both pilot DTE groups (low and high) and mission VFR and instrument flight rule (IFR) capability were identified using data from 32 night VFR operational fatal HEMS accidents. Accidents were stratified by loss of control and controlled flight into terrain, pilot DTE, and flight rule capability. The effectiveness of both DTE groups and both flight rule capabilities were measured using system safety risk analysis techniques.

RESULTS: Night fatal accident rates were statistically different from daytime. Low-DTE pilots and the VFR capability combination had the highest likelihood of night operational nonsurvivable accident.

CONCLUSION: Low-DTE pilots and the VFR capability were the least effective mission combination to avoid hazardous conditions at night and maintain spatial orientation, respectively. The analysis identified measures to reduce likelihood of night fatal operational accidents.

KEYWORDS: operational safety, Systems Theoretic Accident Modeling and Processes, risk, rotary-wing, Helicopter Emergency Medical Services, night.

Aherne BB, Zhang C, Chen WS, Newman DG. *Systems safety risk analysis of fatal night Helicopter Emergency Medical Service accidents*. Aerosp Med Hum Perform. 2019; 90(4):396–404.

Adverse weather increases the fatal accident risk associated with Helicopter Emergency Medical Service (HEMS) operations at night under visual flight rules (VFR).[1] In 1988, the U.S. HEMS industry fatal accident rate was higher than that of other commercial helicopter operations,[21] and from 1997 to 2001 exceeded that of all other aviation operations.[8] Between 1978 and 1998, almost half (49%) of all HEMS accidents occurred at night, despite most (62%) missions being flown during the day.[8]

Since 2014, the Federal Aviation Administration (FAA) has mandated that formal risk assessments are required before each mission.[9,24] However, since that time, night HEMS fatal accidents have continued. Several studies have shown that fatal accidents involving HEMS operations are more likely at night compared to day.[5,13] Adverse weather presents the highest risk to safety for VFR missions at night.[1,2,5] In addition, pilots with less than 6 yr HEMS domain task experience (low-DTE) is also a risk factor. Previous research has demonstrated a higher risk

From the Department of Aviation, Faculty of Science, Engineering and Technology, and the Department of Statistics, Data Science and Epidemiology, Faculty of Health, Arts and Design, Swinburne University, Melbourne, Australia; and the Aviation Medicine Unit, School of Public Health & Preventive Medicine, Monash University, Melbourne, Australia.

This manuscript was received for review in May 2018. It was accepted for publication in January 2019.

Address correspondence to: Associate Professor David G. Newman, M.B., B.S., D.Av. Med., MBA, Ph.D., FRAeS, FACAsM, FAICD, Head, Aviation Medicine Unit, School of Public Health & Preventive Medicine, Faculty of Medicine, Nursing and Health Sciences, Monash University, 553 St. Kilda Rd, Melbourne, Victoria 3004, Australia; david.newman@monash.edu.

DOI: https://doi.org/10.3357/AMHP.5180.2019

of fatal accident in situations where low-DTE pilots encounter an atmosphere significantly associated with nonvisual meteorological conditions (non-VMC).[1,2] Adverse weather can merge with a dark night environment, making it difficult for accurate in-flight evaluation of VFR conditions.[1,2,14] If the pilots' preflight weather evaluation is poor and visual external features essential for VFR operations are lost, spatial orientation must be maintained by reference to aircraft instruments.[1,2,9] However, orientation by reference to instruments is a flying skill that degrades, requiring regular use and practice.[22] The majority (84%) of pilots in previous studies of night HEMS fatal accidents had not recorded any instrument flying in the previous 3 mo and were noninstrument proficient.[1,2] This increased their likelihood of disorientation.[12,21,22] Only four pilots in those accidents[1,2] maintained instrument-pilot proficiency and operated an instrument flight rules (IFR) certified helicopter, but conducted operations in accordance with night VFR. An IFR capability offers the best chance of maintaining spatial orientation by reference solely to aircraft instruments.[1,21]

Despite the total HEMS accident rate generally decreasing from 1983 to 2015, the proportion of these accidents that were fatal remained the same.[9,13] Some authors have argued that HEMS operators should acquire aircraft with more stringent airworthiness standards and full IFR certification.[9] Others have called for a systems safety approach to be used so as to understand the multifactorial nature of night fatal accidents.[13] Such a systemic analysis would provide a focus to identify measures to prevent further night HEMS accidents. A systems safety approach has previously been used in an organizational study of three night VFR weather-related HEMS accidents in Europe.[15]

Therefore, this study used a system safety approach to night HEMS accident data to answer three research questions. Firstly, is there a difference between day and night fatal accident rates? Secondly, what risk factors (alone or in combination) are driving this night HEMS fatal accident rate? Thirdly, what steps could be taken by the industry to reduce this fatal accident rate?

METHODS

Study Population

Retrospective accident data were used in this study and no experiments involving human participants were conducted. The data source was 32 single-pilot night VFR HEMS fatal accidents between 1995 and 2013 caused by loss of control (LCTRL) or controlled flight into terrain (CFIT).[1,2] To determine the 1995–2013 day and night fatal accident rate, accident frequency per 100,000 flying hours was identified and extrapolated from previous research.[7–9,20] The total HEMS fatal accident rate was determined from the total of day and night fatal accidents. Daytime fatal accidents were used only for fatal accident rate analysis. The night HEMS fatal accident rate for all accidents and for the 32 LCTRL/CFIT accidents specific to this study were identified. Night HEMS hours were estimated at 38% and day hours 62%, of industry total flight hours (**Table I**).[8]

Factors to be considered were DTE (low & high) and VFR and IFR capability. IFR capability refers to a pilot who is instrument-rated, maintains instrument-pilot proficiency, and operates an instrument equipped and certified helicopter capable of operating under IFR procedures.[1,2] VFR capability refers to a pilot who does not maintain instrument-pilot proficiency and/or an aircraft not equipped or certified for IFR procedures. IFR capability permits night operations under IFR or VFR. VFR capability operations are exclusive within VFR.

In this study, two systems safety approaches were used. The first one was the Systems Theoretic Accident Modeling and Processes (STAMP),[17] which was used in the European HEMS study.[15] This approach has been applied to other complex transport system investigations in aviation[3] and rail.[26] STAMP focuses on each level within a socio-technical system.[18] It proposes that problems in the control of complex systems are primarily due to 'control flaws', such as inadequate design or enforcement of constraints at lower levels.[15] Accidents result from flawed processes involving interaction among people, organizational structures, engineering activities, and physical system components.[15] Within STAMP, safety-related constraints specify relationships among system variables that broadly defines a nonhazardous or safe system state.[17] Models such as this were originally designed for wide application in systems accidents and, as such, often use terms that do not readily lend themselves to the aviation environment. As an example, the STAMP term "constraint violation" is used to indicate when that systems safety state is jeopardized. In contrast, "violation" in the aerospace human factors context implies a deliberate decision by a human operator to disregard procedures. In the European HEMS study, pilot weather-related decisions and lack of experience in night instrument flying were identified as inadequate decisions and control actions, as control flaws in the system.[15] Aviation regulations like VFR and IFR, as well as safety requirements set for HEMS operators and pilots, were identified as constraints.[15]

The second approach used in this study was a systems safety risk analysis technique developed by Marais to complement the STAMP model.[18] It incorporates risk considerations into decision making at system design.[18] The impact on future risk over the system's lifetime can be evaluated using historical control flaw and constraint data using probability algorithms.[18] In terms of risk analysis for ongoing night VFR HEMS operations, control flaws and constraints defined by the European HEMS study can be applied to the pilot weather-related decisions and instrument flying capability from the night U.S. HEMS accident data using the risk analysis technique. The output of that analysis will assess the likelihood of an adverse event over the system's lifetime.[18] The risk analysis categorizes a system's risk controls as 'design options'.[18] Their impact on risk and ability to enforce constraints are analyzed to evaluate the future effectiveness of the system.[18] Effectiveness is mediated by the relationship between the control flaw and the hazard the design option seeks to prevent or minimize.[18]

An atmospheric marker used by pilots to determine likelihood of cloud ceiling and reduced visibility is air temperature

Table I. The 1995–2013 Helicopter Emergency Medical Service (HEMS) Day and Night Fatal Accident Rate (FAR), HEMS Industry FAR, HEMS Night Loss of Control (LCTRL), and Controlled Flight into Terrain (CFIT) FAR.

YEAR	ALL DAY HEMS FATAL ACCIDENTS	ALL NIGHT HEMS FATAL ACCIDENTS	TOTAL FLIGHT HRS (TFH)	ALL DAY HEMS FAR (62% OF TFH)	ALL NIGHT HEMS FAR (38% OF TFH)	TOTAL HEMS FAR	(*N* = 32) NIGHT HEMS FATAL LCTRL & CFIT	(*N* = 32) NIGHT HEMS FATAL LCTRL & CFIT FAR
1995	0	1	171,670	0	1.53	0.58	1	1.53
1996	0	1	185,239	0	1.42	0.53	1	1.42
1997	0	2	190,497	0	2.76	1.04	1	1.38
1998	1	3	187,216	0.86	4.21	2.13	2	2.81
1999	1	2	207,327	0.77	2.53	1.44	1	1.26
2000	1	3	194,271	0.83	4.06	2.05	2	2.70
2001	2	2	217,584	1.48	2.41	1.83	0	0
2002	2	3	230,000	1.40	3.43	2.17	1	1.14
2003	2	2	255,000	1.26	2.06	1.56	2	2.06
2004	1	5	290,000	0.55	4.53	2.06	5	4.53
2005	4	2	340,000	1.89	1.54	1.76	2	1.54
2006	2	1	370,000	0.87	0.71	0.81	1	0.71
2007	1	1	372,000	0.43	0.70	0.53	1	0.70
2008	2	5	369,000	0.87	3.56	1.89	4	2.85
2009	0	2	345,000	0	1.52	0.57	2	1.52
2010	2	4	352,000	0.91	2.99	1.70	2	1.49
2011	0	1	375,000	0	0.70	0.22	0	0
2012	0	1	380,000	0	0.69	0.26	1	0.69
2013	0	5	400,000	0	3.28	1.25	3	1.97
Total	22	46					32	
Average				0.64	2.35	1.28		1.59

Result 1. Mann-Whitney U-Test HEMS Day FAR and HEMS Night FAR, $U = 316$, $z = 3.968$, $P < 0.001$; Kolmogorov-Smirnov test $T = 2.109$, $P < 0.001$.
Result 2. Mann-Whitney U-Test HEMS Day FAR and ($N = 32$) HEMS Night LCTRL & CFIT FAR, $U = 284$, $z = 3.042$, $P = 0.002$; Kolmogorov-Smirnov Test $T = 1.622$, $P = 0.010$.

and the temperature at which air reduces to its dew point.[11] Dew point is where air is completely saturated and it is highly likely moisture will condense out in the form of low cloud, fog, and rain.[11] The difference between air temperature and its dew point is known as temperature dew point spread (TDPS).[11] Each 1°C decrease in TDPS highly likely lowers the cloud ceiling by approximately 400 ft above ground level.[11] Previous research identified the night fatal HEMS operational accidents significantly encountered non-VMC in the 0–4°C TDPS range.[1]

From the 32 night accidents, 27 associated with non-VMC in the 0–4°C TDPS range[1] were stratified by accident frequency and fatalities, by low DTE and pilots ≥6 yr HEMS experience (high DTE), encountering hazardous operational conditions (HOC), i.e., flight over featureless terrain devoid of man-made lighting and/or the presence of cloud or fog,[2] and by VFR and IFR capability for LCTRL and CFIT causes. Fatal injuries ($N = 100$) represented 93% of occupant injury outcomes for the 32 accidents. In the 27 non-VMC associated accidents, 86 fatalities (86%) occurred.[1,2] This data will be used for the statistical tests of independence.

Procedures

Two design options and their control flaw data will be used in this study:

1. Low-DTE and high-DTE are pilot HEMS experience design options. DTE enforces the night VFR, evaluates mission operational conditions, including external orientation features and nighttime weather cues obtained from multiple sources without the redundancy of daytime visual cues to discern VMC.[1,2]
2. VFR capability and IFR capability are instrument flying design options. Either capability is required under night VFR to enforce spatial orientation by reference to the helicopter instruments. An instrument proficient pilot in an IFR certified helicopter (IFR Capability) has a greater chance of spatial orientation[22,27] compared to VFR Capability.

To avoid HOC under night VFR, pilot DTE evaluation decisions are a preventative control.[1,2] If HOC is encountered, the VFR/IFR capability is a recovery control.[1,2]

Fig. 1 shows design option, constraint, control flaw, hazardous state, and accident constraint terms used within the risk analysis technique.[18] The row below shows those terms as they apply to the night VFR HEMS operational system. Both design options and their application were described in the two previous paragraphs. The night VFR regulations and operator procedures are a constraint enforced by pilot DTE evaluation. The loss of visual cues following entry into HOC, i.e., a hazardous system state, indicates where the STAMP term "constraint violation" applies to a night VFR HEMS operation. Spatial orientation is the accident constraint enforced by the pilot's instrument flying scan. Sustained spatial disorientation is a system control flaw resulting from a pilot's inadequate instrument flying scan. The bottom of each column shows a night VFR HEMS mission which encounters HOC on a flight to a patient. The sequence at position 1 shows each flight rule capability approved and available for night VFR operations. At position 2 the pilot receives a task request and makes an inadequate evaluation of the environment, including weather-related feature event objects, e.g., TDPS,[1] and accepts the flight. At position 3, while enroute, the visual external features deteriorate. At position 4, the pilot loses

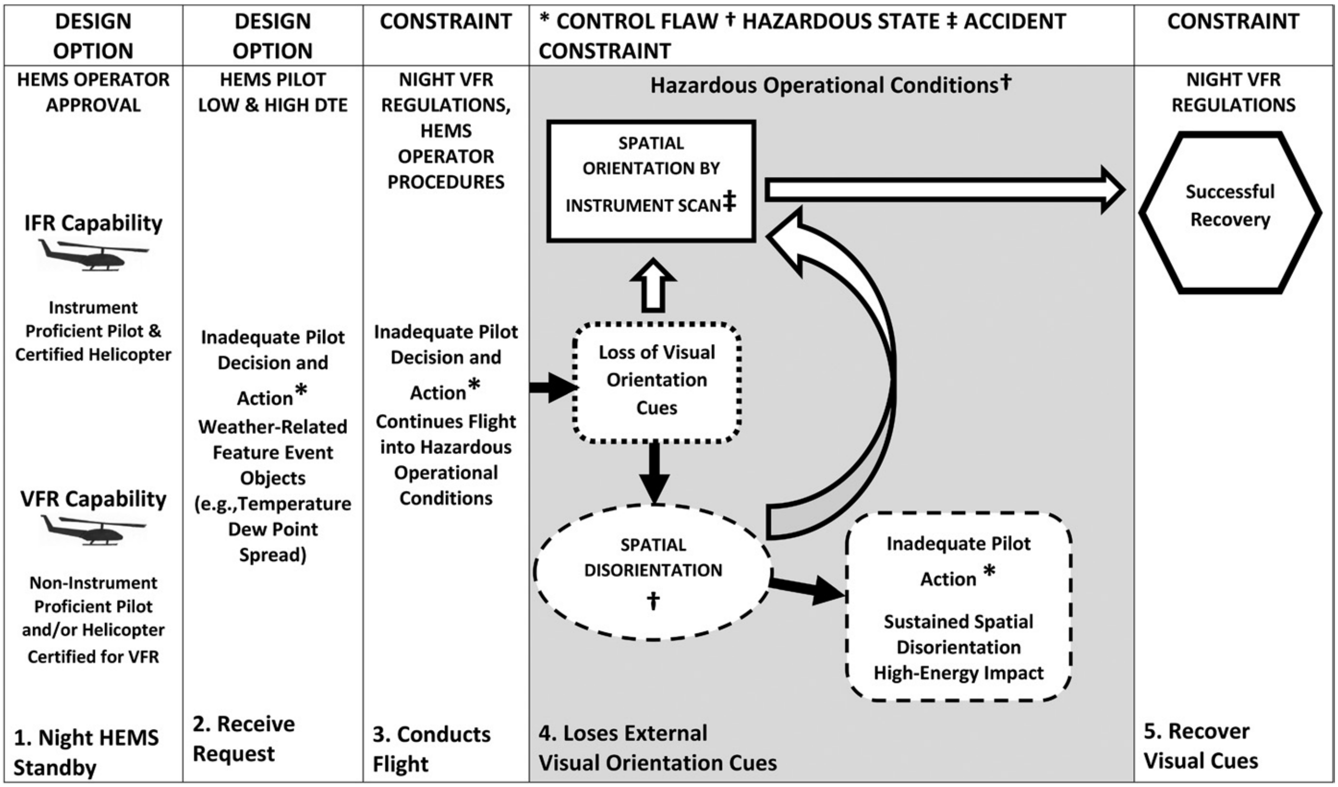

Fig. 1. Safety systems risk analysis terms applied to night visual flight rule (VFR) Helicopter Emergency Medical Service (HEMS) VFR and instrument flight rule (IFR) capability, pilot low and high domain task experience (DTE), preventative and recovery controls, and night operational accident sequence.

visual orientation cues and must switch to an instrument scan.[1,2] The white arrows indicate spatial orientation by reference to the helicopter's instruments leading to a successful recovery sequence to visual conditions at position 5. Tracing the solid black arrow from position 4 shows if the effects of spatial disorientation are experienced, risk treatment by the correct instrument scan, indicated by the white arrow, returns the pilot to spatial orientation. The white arrows represent the expected recovery process used by the night VFR HEMS system. Inadequate pilot action, i.e., failing to adapt to an instrument scan, leads to sustained spatial disorientation and a high-energy impact with terrain. From inadequate pilot decision at position 2 through to position 4, tracing the black arrows to terrain impact represents the historical night VFR HEMS system's operational accident sequence.[1]

The risk analysis technique was used to evaluate pilot DTE and flight rule capability for night VFR HEMS as a high-risk system[5,9] and produce a residual risk assessment. The pilots' decision and night spatial disorientation were scoped[18] as HEMS crew inadequate decisions and control actions leading to control flaws by the European HEMS study.[15] Design option effectiveness is the reduction in probability obtained at that particular scope and type of effort.[18] Design option stability indicates, where applicable, how rapidly effectiveness declines over a system's lifetime, the degree of continued vigilance required for it to remain effective, and potential issues where risk may increase over time. Design option observability indicates how easy it is to determine correct implementation, effectiveness at hazard mitigation, and potential areas where it may be difficult to observe increasing risk over time.[18] The effectiveness results can be used to estimate residual risk for the overall system given the design options.[18]

This study considers only one control flaw under each constraint.[18] The constraint violation expression result ranks each control flaw under the analysis.[18] Those with the highest probability of constraint violation have the largest effect and are ranked higher, thereby directing where to focus risk reduction interventions.[18] As all accidents entered HOC,[1,2] the pilot group with the highest probability of encountering non-VMC will have a higher weather-related decision control flaw ranking. Sustained spatial disorientation identified by both and each cause (LCTRL or CFIT) will rank the VFR and IFR capability.

The effectiveness of design option combinations can be determined by propagating the probabilities from control flaws through constraints to hazards and accidents.[18] Risk is estimated by applying the expressions to the selected set of design options.[18] Fatalities and accident frequency by low and high-DTE and VFR and IFR capability combinations were determined.

The probability of an accident related to a specific hazard is given by:

$$P(\text{Accident}) = P(\text{Accident} \mid \text{Specific Hazard}) \times P(\text{Hazardous State}).$$

The P (Accident) in this study uses pilot sustained spatial disorientation and high-energy impact. The P (Accident|Specific Hazard) can be determined by analysts' use of context-specific factors.[18] For the risk analysis, the conditional probability of spatial disorientation from both causes[1] given the VFR or IFR capability uses *P* (SD VFR) and *P* (SD IFR) obtained from **Table II**. The *P* (Hazardous State) uses HOC encountered by Pilot DTE, i.e., *P* (Low-DTE) and *P* (High-DTE) from Table II.

The accident expression in the analysis is therefore:

$$P(\text{Sustained spatial disorientation and high-energy impact})$$
$$= P(\text{Spatial disorientation given the VFR or IFR capability in HOC})$$
$$\times P(\text{HOC by Pilot DTE})$$

The four design option combination probabilities will be determined. Fatal accident rates for the highest combination probability result, for low and high-DTE, and for VFR and IFR capability will be determined.

Statistical Analysis

Accident frequency, fatalities, pilot-DTE, TDPS, VFR/IFR capability, non-VMC/VMC, and LCTRL/CFIT variables were collated using a PC-based spreadsheet program (Microsoft® Excel 2007). Statistical analysis was conducted using a statistical software tool (SPSS Statistics, version 24, IBM Corp, New York, NY).

The Kolmogorov-Smirnov test was used for the assumption that fatal accident rate data were nonparametric. The Mann-Whitney *U*-test determined whether a statistical difference existed between rates. Fisher's exact test of independence was chosen to analyze the association between variables. A *P*-value of less than 0.05 (two-tailed) was deemed statistically significant. Due to small sample size, bootstrapping was performed with 10,000 iterations using the bias-corrected and accelerated method for computing more reliable 95% confidence intervals (CI). Relative risk (using percent relative effect) and odds ratios[6] (OR) were calculated to assess likelihood and risk. The design option combination with the highest probability was chosen to test if occupant fatalities were statistically different from other combinations.

RESULTS

A significant difference between day and night HEMS fatal accident rates was seen (result 1, Table I). The 32 HEMS nighttime LCTRL/CFIT[1,2] fatal accident rate was also significantly different from daytime (result 2, Table I).

In the 0–4°C TDPS range, 20 low-DTE and 7 high-DTE pilots attempted flights (for FARs, see **Fig. 2**). Of the low-DTE pilots, 14 had ≤2 yr DTE (novices).[1] In the 27 0–4°C TDPS range accidents, 90 occupants averaged 3.33 (SD ± 0.68) per accident [low-DTE 3.35 (SD ± 0.59), high-DTE 3.28 (SD ± 0.95)].

Low-DTE ranked the highest probability for non-VMC (Table II). VFR capability was ranked the highest probability for spatial disorientation (Table II; **Fig. 3**). In the 0–4°C TDPS range, 20 flights (74%) encountered non-VMC. The low-DTE & VFR capability combination had the highest probability of sustained spatial disorientation (Table II; **Fig. 4**).

Of the fatalities ($N = 86$) in the 0–4°C TDPS range, 70% occurred within the low-DTE pilot and VFR capability and were statistically different from other combinations (outcome 4, **Table III**). Similar results were seen when analyzed for occupants ($N = 90$) in those flights where 68% were with the same combination ($P < 0.05$, OR 5.42, 95% CI 1.54–25.12). Low-DTE pilots were significantly associated with nonsurvivable accidents in the 0–4°C TDPS range compared to high-DTE (outcome 1, Table III). VFR capability showed no association with a nonsurvivable accident in the 0–4°C TDPS range, or across all TDPS (outcomes 2 and 3, Table III).

Table IV shows the low-DTE fatal accident rate was over three times greater than high-DTE. The VFR fatal accident rate was over six times greater than IFR capability. Of the night HEMS LCTRL/CFIT fatal accident rate, 18 low-DTE and VFR capability combination flights in 0–4°C TDPS conditions accounted for 56%.

DISCUSSION

This study found the 32 night operational fatal accidents made a statistically greater contribution to the overall HEMS fatal accident rate, compared to daytime fatal accidents, during 1995 to 2013. The analysis identified low-DTE pilots with VFR capability had a consistent and steady fatal accident rate in atmospheric conditions associated with non-VMC. Their 56% contribution to the operational accidents in this study resulted in the highest proportional influence for the night and total HEMS industry fatal accident rate during the period. Low-DTE pilots and VFR capability were the least effective mission combination in avoiding hazardous conditions at night and maintaining spatial orientation, respectively.

The low-DTE pilots higher non-VMC probability ranking (Table II) was expected given they flew most missions and 74%

Table II. Accident Flights in 0–4°C Temperature Dew Point Spread (TDPS) by Fatalities and Accident Frequency, Probability (*P*) of Spatial Disorientation (SD) by Loss of Control (LCTRL) and Controlled Flight into Terrain (CFIT) by Visual and Instrument Flight Rule Capability (VFR & IFR), and Probability (*P*) of Pilot Domain Task Experience (DTE) in 0–4°C TDPS Flights and Non-Visual Meteorological Conditions (Non-VMC).

ACCIDENT CAUSE	FREQUENCY	RANKING
SD Both Causes	VFR: 0.85 = 1*0.85 [0.85 = 1*0.85]	VFR ranked higher 0.70 [0.70]
	IFR: 0.15 = 1*0.15 [0.15 = 1*0.15]	
SD LCTRL	VFR: 0.53 = 0.62*0.85 [0.55 = 0.65*0.85]	VFR ranked higher 0.50 [0.51]
	IFR: 0.03 = 0.23*0.15 [0.04 = 0.25*0.15]	
SD CFIT	VFR: 0.32 = 0.38*0.85 [0.30 = 0.35*0.85]	VFR ranked higher 0.20 [0.19]
	IFR: 0.12 = 0.77*0.15 [0.11 = 0.75*0.15]	
Low-DTE	0.55 = 0.71* 0.77 [0.52 = 0.70*0.74]	Low-DTE ranked higher 0.35 [0.30]
High-DTE	0.20 = 0.85* 0.23 [0.22 = 0.86*0.26]	
Low-DTE & VFR	0.65 [0.63]	
High-DTE & VFR	0.20 [0.22]	
Low-DTE & IFR	0.12 [0.11]	
High-DTE & IFR	0.03 [0.04]	

[Accident Frequency].

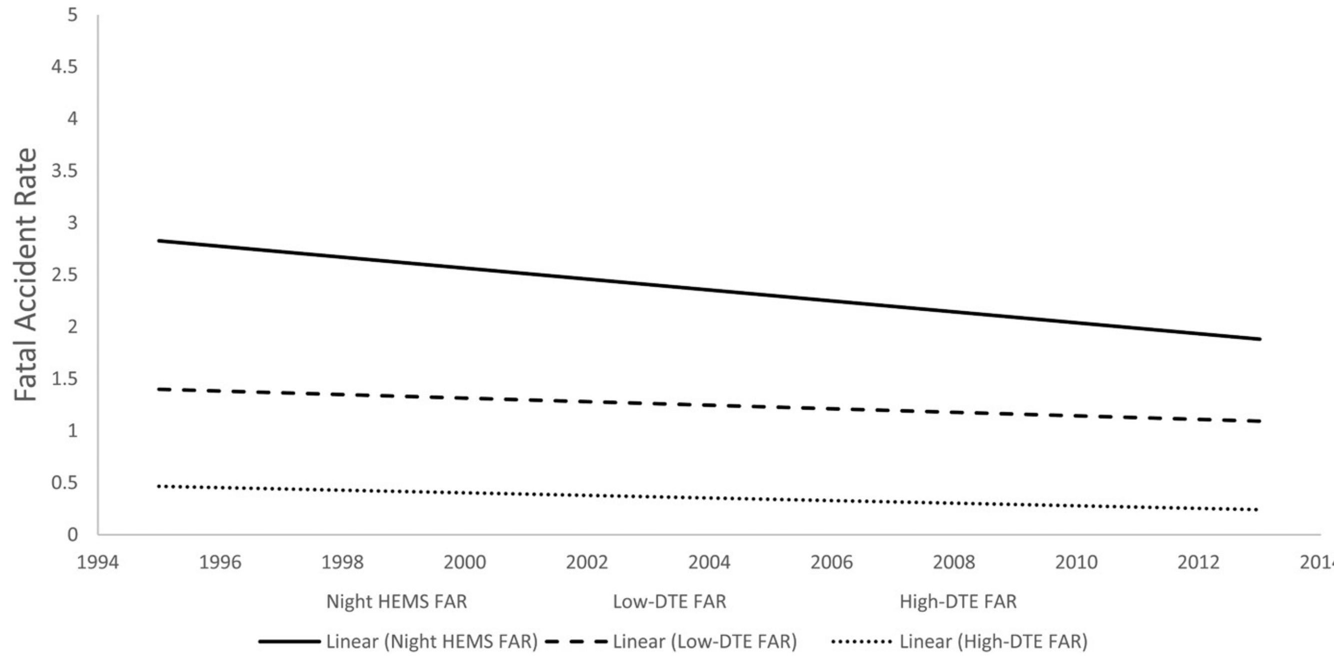

Fig. 2. 1995–2013 Helicopter Emergency Medical Service (HEMS) low domain task experience (DTE) and high domain task experience (DTE) fatal accident rate (FAR) trendlines and night HEMS FAR trendline.

of accidents encountered non-VMC. The higher sustained spatial disorientation ranking (Table II) for VFR capability was expected and consistent with the literature.[22,25,27] The rankings with the highest result identifies where to direct risk interventions to reduce the probability of future control flaws.[18] Those results indicate the low-DTE pilots were most likely to encounter adverse weather and those with VFR capability were more likely to be disoriented. This is consistent with the interrelationship between effectiveness of controls and likelihood.[16] The similar odds ratio results for fatalities compared to occupants in that combination demonstrate the small survival chance people have in an environment that the night VFR HEMS retrieval system was not designed for.

Since most accidents encountered non-VMC, it was expected VFR capability might influence a nonsurvivable accident given the majority of fatalities occurred in those flights. However, this was not seen. The low-DTE pilots' association with nonsurvivable accidents (outcome 1, Table III) suggests

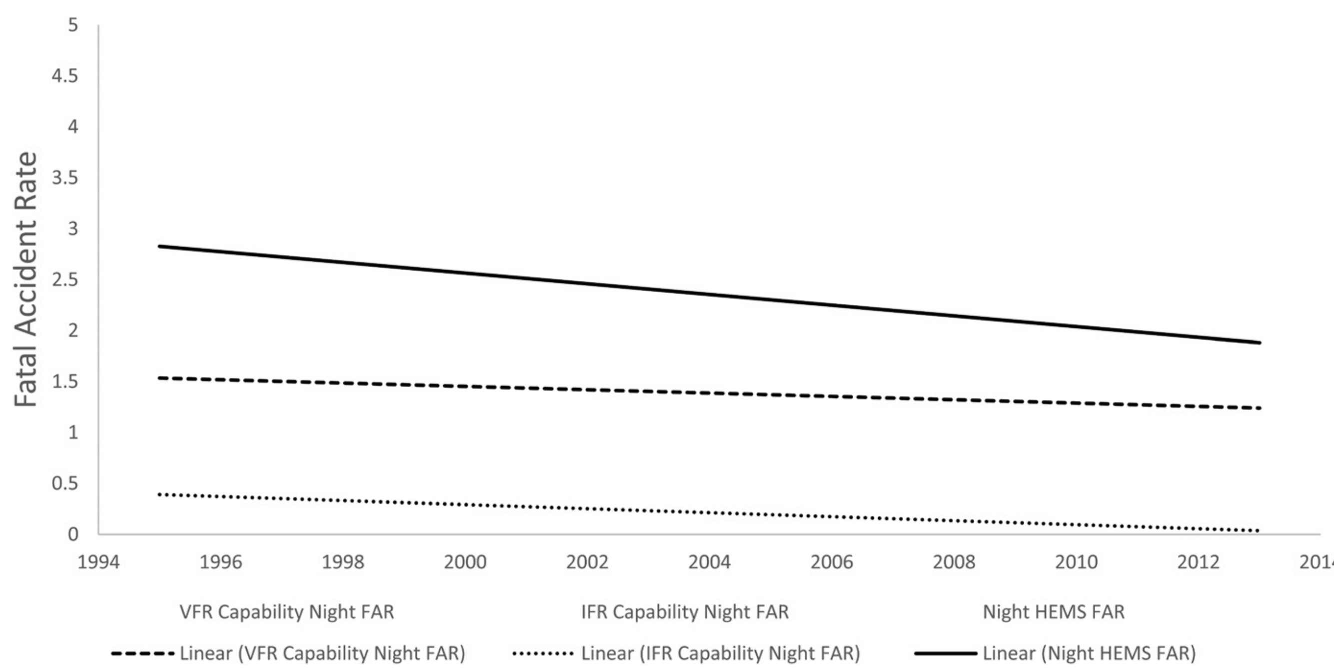

Fig. 3. 1995–2013 Helicopter Emergency Medical Service (HEMS) visual flight rules (VFR) and instrument flight rules (IFR) capability fatal accident rate (FAR) trendlines and night HEMS FAR trendline.

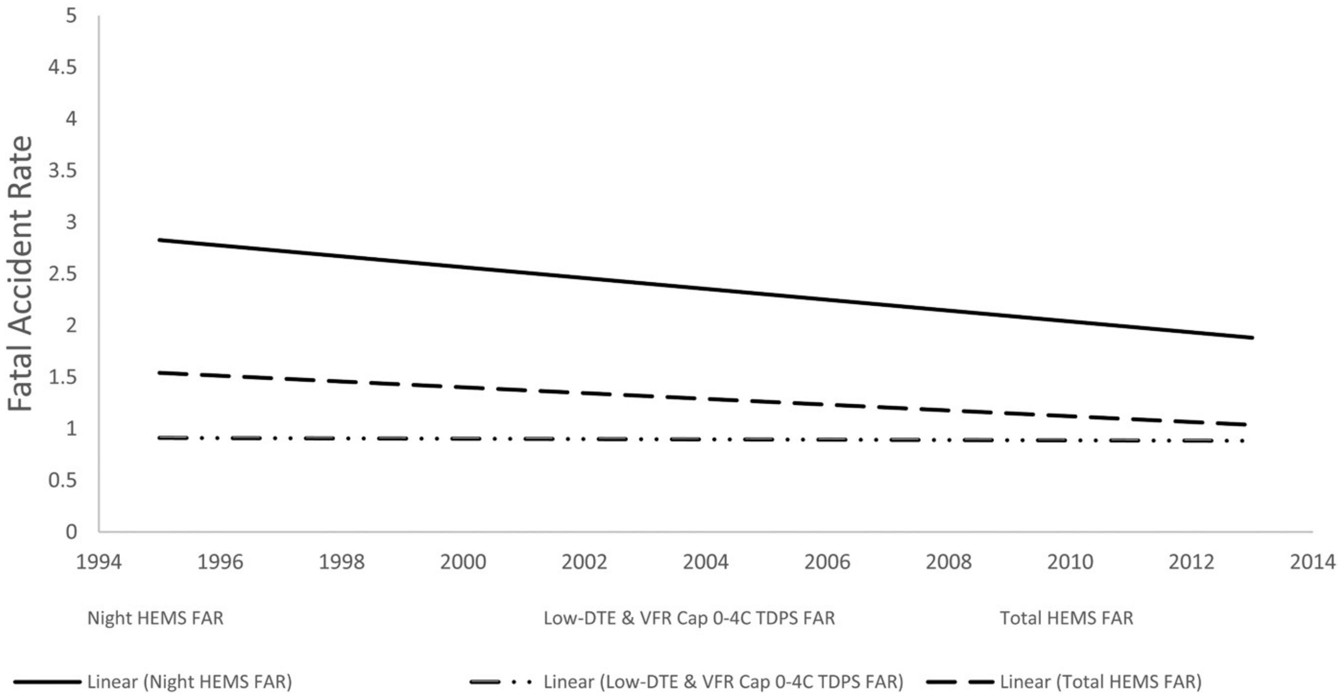

Fig. 4. 1995–2013 Helicopter Emergency Medical Service (HEMS) low domain task experience (DTE) and visual flight rules (VFR) capability combination fatal accident rate (FAR) trendline in 0–4°C temperature dew point spread (TDPS) and night HEMS fatal accident rate trendline and total HEMS fatal accident rate trendline.

their decisions and subsequent entry into HOC significantly contributed most to the likelihood of a nonsurvivable accident.

Night operations influence of HEMS accident severity is consistent with offshore helicopter fatal accident rate analysis.[19] If visual orientation cues are lost and cannot be rapidly regained, the effects of sustained spatial disorientation at night and the deceleration forces imposed by high-energy horizontal and/or vertical impact speeds[9] are mostly nonsurvivable.[4,9,22] The inability to reacquire visual orientation cues to see obstacles and take avoiding action or mitigate accident consequences[5] is central in explaining why the statistical difference was found between day and night operational fatal accident rate (result 2, Table I).

The low-DTE pilots' ranking (Table II) indicate interventions[18] for those pilots are required to reduce risk. The average occupant exposure between high- and low-DTE pilots were similar, and the high-DTE overall reduced likelihood result (outcome 1, Table III) appear to demonstrate the protective effect[2] of peer high-DTE pilots rejecting mission requests or discontinuing flights in similar conditions.[1] The low-DTE non-VMC ranking (Table II) and their 10% increase in inadvertent IMC findings previously reported[1] are consistent with that.

The low-DTE pilots' effect on the overall night HEMS fatal accident rate was to proportionally increase it over time. These results suggest that their effectiveness in avoiding HOC declined during that period. Of the 14 ≤2-yr pilots (novices)[1] who made

Table III. Non-Survivable Accident Frequency in 0–4°C Temperature Dew Point Spread (TDPS) Exposed to Pilot Domain Task Experience (DTE) and Visual Flight Rules (VFR) Capability, Low-DTE Mission Fatalities in 0–4°C TDPS Exposed to VFR Capability, and Non-Survivable Accident Frequency in 0–2, 0–3°C TDPS Exposed to Low-DTE & VFR Capability Combination.

OUTCOME VARIABLE	EXPOSURE	ODDS RATIO (BCA 95% CI)	RELATIVE RISK (BCA 95% CI)	*P*-VALUE*
1. Non-Survivable Accident ($N = 27$) in 0–4°C TDPS	High-DTE (reference)	8.00‡ (1.25–48.00)	1.64 (1.01–4.23)	$P = 0.042$
	Low-DTE			
2. Non- Survivable Accident ($N = 27$) in 0–4°C TDPS	IFR Capability (reference)	2.22 (0.67–24.00)-	-	$P = 0.495$
	VFR Capability			
3. Non- Survivable Accident ($N = 32$) all TDPS	IFR Capability (reference)	1.53 (0.543–17.60)	-	$P = 1.0$
	VFR Capability			
4. Low-DTE Mission Fatalities in 0–4°C TDPS	IFR Capability (reference)	5.38‡ (1.40–25.14)	1.78 (1.09–4.36)	$P = 0.010$
	VFR Capability			
5. Non-Survivable Accident in 0–3°C TDPS	All Other Combinations (reference)	†	1.50 (1.125–3.00)	$P = 0.037$
	Low-DTE & VFR Capability Combination			
6. Non-Survivable Accident in 0–2°C TDPS	All Other Combinations (reference)	†	1.50 (1.125–3.00)	$P = 0.047$
	Low-DTE & VFR Capability Combination			

* $P < 0.05$; †unable to calculate OR due to no survivors and non-integer decimal values unable to be used in the bootstrapping software; ‡large effect size.

Table IV. The 1995–2013 Helicopter Emergency Medical Service (HEMS) Night Operational Fatal Accident Rate (FAR), Low and High-Domain Task Experience (DTE) FAR, and Instrument Flight Rule (IFR) and Visual Flight Rule (VFR) Capability FAR in the 0–4°C Temperature Dew Point Spread (TDPS) Range.

YEAR	(*N* = 27) LOW-DTE FAR	(*N* = 7) HIGH-DTE FAR	(*N* = 28) VFR CAPABILITY FAR	(*N* = 4) IFR CAPABILITY FAR	(*N* = 18) LOW-DTE & VFR CAPABILITY 0–4°C TDPS FAR
1995	1.53	0	0	1.53	0
1996	1.42	0	1.42	0	1.42
1997	0	1.38	1.38	0	0
1998	1.40	1.40	2.81	0	1.40
1999	1.26	0	1.26	0	1.27
2000	2.70	0	2.71	0	2.71
2001	0	0	0	0	0
2002	1.14	0	1.14	0	1.14
2003	1.03	1.03	1.03	1.03	0
2004	4.53	0	4.54	0	2.72
2005	0.77	0.77	1.55	0.77	0
2006	0.71	0	0.71	0	0
2007	0.71	0	0.71	0	0.71
2008	1.43	1.43	2.14	0.71	1.43
2009	1.52	0	1.52	0	0.76
2010	1.49	0	0.75	0	1.49
2011	0	0	0	0	0
2012	0	0.69	0.69	0	0
2013	1.97	0	1.97	0	1.97
Average	1.24	0.35	1.39	0.21	0.89

up 70% of the low-DTE group, their opportunities to accumulate HEMS domain task experience by deliberate practice was limited; some had only months of DTE.[2] The results here and in earlier research[1,2] likely reflect the multifactorial effects of incorrect weather evaluation,[1] implicit mission stress and pressures,[2,24] or a combination of the (preceding) two.[1,10] Learners, like novice pilots, are expected to make mistakes during the skill acquisition period.[1,2,23]

In considering the observability parameter for DTE, if safety procedures are not regularly assessed for compliance, shortcuts[18] or work-arounds[15] could go unnoticed, increasing risk through complacency.[18] Work-arounds could also lead to misconceptions of a pilots' operational agility, which may obscure established safety boundaries.[15] Without intervention strategies and continued vigilance, low-DTE pilots, particularly novices, would be more likely to encounter HOC. Since 2014, a further seven night fatal HEMS accidents have occurred; four remain under investigation. Three final reports confirmed LCTRL/CFIT was causal: all were low-DTE pilots, including two novices. Two encountered non-VMC in the 0–4°C TDPS range, with the third encountering non-VMC in 5°C TDPS.

When considering the stability parameter, the higher contribution of VFR capability to the night HEMS fatal accident rate suggests a decline in its effectiveness for preventing spatial disorientation during the period. The LCTRL conditional probability results for VFR compared to IFR capability (0.62 vs. 0.23, Table II) are consistent with HEMS noninstrument proficient pilot results in earlier experimental research (0.67 vs. 0.15).[27]

When considering the flight rules observability parameter, if the quality of maintenance or inspection of design options decrease, they become less effective over time.[18] If a night VFR HEMS operation encounters HOC, pilots are expected to maintain spatial orientation by sole reference to the helicopters instruments.[9] However, without the pilot regularly using and concertedly maintaining instrument flying skills, they deteriorate[22] and, in poor weather, provide limited value.[21] An additional layer of stability above frequent instrument flying skill retention is afforded by a regular quality inspection process[18] known as the instrument-proficiency check.[2] A flight examiner assesses an instrument-pilot's ability and competency to correctly interpret aircraft attitude and navigation instruments at defined intervals over 1 yr.[22,27] Both maintenance and inspection of instrument-pilot skills provide stability to maximize spatial orientation using the aircraft instruments. Moreover, the helicopter's maintenance and ongoing inspection to the IFR certification standard provides the instrument and navigation suite[2] which underpins that stability. Therefore, without interventions such as regular instrument flying, instrument-pilot proficiency checks, and ongoing IFR aircraft certification standards, VFR capability will more likely increase the chance of sustained disorientation episodes in the future. The three post-2013 night accidents were VFR-capable flights.

The low-DTE and VFR capability 0–4°C TDPS range trendline remained steady while the total (day and night) and night HEMS fatal accident rate trendlines declined. This combination's steady rate suggests a sustaining effect, resulting in the unchanging proportion of fatal accidents previously reported.[9,13] Nonsurvivable accidents were significantly greater for the low-DTE and VFR combination in the 0–3 and 0–2°C TDPS range (outcomes 5 and 6, Table III), where 84% of accidents, 79% of fatalities, and 86% of non-VMC findings occurred.[1]

The HEMS weather-related risk assessment process is not straightforward or simple.[24] Implicit pressures exist for all HEMS pilots conducting risk assessments,[1,10,24] and inexperienced HEMS pilots have reported regularly seeking input from experienced peers to gain confidence in the risk assessment process.[24] Those pressures[1,10,24] have the potential to avoidably inflate the expected mistakes learners make[23] in a specialized domain.[2] FAA-mandated risk assessment procedures[9,24] were identified in the three post-2013 accidents. Only one report was able to specify the level of weather-related risk that was assessed by the pilot; weather conditions of 'yellow' indicated that 'commencing a flight may not be possible.' Perceived mission pressures[1,10,24] were reported by the NTSB as 'self-induced' by the pilot in the 'yellow' risk accident.

Risk is a function of likelihood and consequence.[16,18] The accidents in this study all had catastrophic outcomes. Likelihood remains the only dimension available to reduce night operational accident risk. If close supervision[1,2] and other interventions[18] for low-DTE pilots are absent, those pilots would be more likely to encounter HOC in the future, with VFR capability leading to a greater chance of spatial disorientation in those conditions. The fatalities involved in those design option combinations consisted mostly of paramedics and flight nurses. Because these accident types are predominantly nonsurvivable,[9] a shared fate for each occupant means they share, in part, the decision making process for each flight.[24] Their informed decisions play an equally critical function in the operational safety of the HEMS retrieval system.

A limitation of this study is the retrospective nature of accident analysis. However, its purpose was to identify risk factors to a specific group of two night-VFR fatal operational accident types, not all HEMS accidents. HEMS accident rate data were not consistently reported until 2002[8] and anomalies may exist between sources.

The analysis determined that HEMS DTE and 0–4°C TDPS[1] were two simultaneous interacting phenomena that contributed to the unchanging proportion of fatal accidents during the period. The results and findings here identify risk factors which appear, albeit with the limited post-2013 data, as precursors in other night operational accidents. This design option combination was identified as having the highest likelihood of night operational accident. The results of this study represent a strong safety case for implementing interventions for low-DTE pilots and for retaining or upgrading to an IFR capability in order to reduce the likelihood of night fatal operational accidents.

ACKNOWLEDGMENTS

Authors and affiliations: Bryan B. Aherne, Grad. Dip. Tech., M.Tech.Mgt., and Chrystal Zhang, MBA, Ph.D., Department of Aviation, Faculty of Science, Engineering and Technology, and Won Sun Chen, M.Sc., Ph.D., Department of Statistics, Data Science and Epidemiology, Faculty of Health, Arts and Design, Swinburne University, Hawthorn, Victoria, Australia, and David G. Newman, MBA, Ph.D., A/Professor and Head, Aviation Medicine Unit, School of Public Health & Preventive Medicine, Monash University, Melbourne, Victoria, Australia.

REFERENCES

1. Aherne BB, Zhang C, Chen WS, Newman DG. Pilot decision making in weather-related night fatal helicopter emergency medical service accidents. Aerosp Med Hum Perform. 2018; 89(9):830–836.
2. Aherne BB, Zhang C, Newman DG. Pilot domain task experience in night fatal helicopter emergency medical service accidents. Aerosp Med Hum Perform. 2016; 87(6):550–556.
3. Allison C, Revell K, Stanton N, Sears R. Systems theoretic accident model and process (STAMP) safety modelling applied to an aircraft rapid decompression event. Saf Sci. 2017; 98:159–166.
4. Australian Transport Safety Bureau. Reports AO-2010-076, AO-2011-102. [Accessed 14 Oct 2017]. Available from www.atsb.gov.au.
5. Baker SP, Grabowski JG, Dodd RS, Shannahan DF, Lamb MW, Li G. EMS helicopter crashes: what influences fatal outcomes. Ann Emerg Med. 2006; 47(4):351–356.
6. Bland JM, Altman DG. Statistics notes. The odds ratio. BMJ. 2000; 320(7247):1468.
7. Blumen I. Opportunities for safety improvement in helicopter EMS. 2015 Industry data. [Accessed 22nd January 2016]. Available from http://www.aeromedsocaustralasia.org/img.ashx?f=f&p=darwin_2015%2fPICKERING_Tim+Mick+Wilson+Oration.pdf. Source data confirmed with author Dr. Ira Blumen, private correspondence; April 5, 2016.
8. Blumen IJ, Coto J, Maddow CL, Casner M, Felty C, et al. A safety review and risk assessment in air medical transport. Air medical physician handbook. Salt Lake City (UT): Air Medical Physician Association; 2002.
9. Boyd DD, Macchiarella ND. Occupant injury severity and accident causes in helicopter emergency medical services (1983–2014). Aerosp Med Hum Perform. 2016; 87(1):26–31.
10. Connell LJ, Reynard WD. Incident reports highlight hazards in EMS helicopter operations. Alexandria (VA): Flight Safety Foundation; 1995; 21(4).
11. Federal Aviation Administration, United States Government. Pilots handbook of aeronautical knowledge. Washington (DC): FAA; 2008.
12. Holmes SR, Bunting A, Brown DL, Hiatt KL, Braithwaite MG, Harrigan MJ. Survey of spatial disorientation in military pilots and navigators. Aviat Space Environ Med. 2003; 74(9):957–965.
13. Hon HH, Wojda TR, Barry N, MacBean U, Anagnostakos JP, et al. Injury and fatality risks in aeromedical transport: focus on prevention. J Surg Res. 2016; 204(2):297–303.
14. Johnson CW. The role of night vision equipment in military incidents and accidents. In: Johnson CW, Palanque P, editors. Human error, safety and systems development. IFIP International Federation for Information Processing, vol. 152. Boston (MA): Springer; 2004.
15. Kontogiannis T, Malakis S. A systemic analysis of patterns of organizational breakdowns in accidents: a case from Helicopter Emergency Medical Service (HEMS) operations. Reliab Eng Sys Safe 2012; 99:193–208.
16. Lawson S. Establishing a safety-based risk control effectiveness score as an alternative to conventional acceptable risk analysis and evaluation methods. Unpublished doctoral dissertation. Brisbane, Queensland, Australia: University of Queensland; 2010.
17. Leveson NG, Dulac N. Safety and risk-driven design in complex systems-of-systems. Proceedings of the 1st NASA/AIAA Space Exploration Conference; Orlando, FL; February 2005. Reston (VA): AIAA; 2005.
18. Marais K. A new approach to risk analysis with a focus on organizational risk factors. Unpublished doctoral dissertation. Cambridge (MA): Massachusetts Institute of Technology; 2005.
19. Nascimento FAC, Majumdara A, Jarvis S, Ochieng WY. Safety hazards in nighttime offshore helicopter operations. 37th European rotorcraft forum; 2011; Ticino Park, Italy. Red Hook (NY): Curran Associates, Inc.; 2011.
20. National Transport Safety Board, United States Government. Review of U.S. civil aviation accidents calendar year 2011. [accessed 27 May 2017]. Available from https://www.ntsb.gov.
21. National Transport Safety Board, United States Government. Safety study-commercial emergency medical service helicopter operations. Washington (DC): NTSB; 1988. Report No.: SS-88-01.
22. Newman DG. An overview of spatial disorientation as a factor in aviation accidents and incidents. Canberra, Australia: Australian Transport Safety Bureau; 2007. Transport Safety Investigation Report.
23. O'Hare D, Wiggins M, Batt R, Morrison D. Cognitive failure analysis for aircraft accident investigation. Ergonomics. 1994; 37(11):1855–1869.
24. Rodi J. A generic qualitative exploration of the process and experience of helicopter emergency medical services pilots assessing risk prior to flight. Unpublished doctoral dissertation. Minneapolis (MN): Capella University; 2014.
25. Stott JRS. Orientation and disorientation in aviation. Extrem Physiol Med. 2013; 2(1):2.
26. Underwood PE, Waterson PE, Braithwaite G. Accident investigation in the wild—a small-scale, field-based evaluation of the STAMP method for accident analysis. Saf Sci. 2016; 82:129–143.
27. Wuerz RC, O'Neal R. Role of instrument proficiency in the safety of helicopter emergency medical services. Acad Emerg Med. 1997; 4(10):972–975.