

A Proposed Framework for the Application of Physiological Monitoring in Fast-Jet Aviation

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INTRODUCTION: The occurrence of physiological episodes in flight has led to an interest in developing pilot physiological monitoring (PhysMon) systems. There is a lack of consensus among engineering, physiology, and aircrew disciplines in the use-cases of highest importance and the sequence of events required to assess these technologies. This paper proposes structured analytical techniques to consider and assess potential PhysMon systems, using tools from across aerospace professions, to create a framework for considering applications of PhysMon. This approach provides a logical structure to critically assess potential systems, consider how a PhysMon system may be positioned within a system-of-systems architecture, identify the challenges in bringing them to the operational setting, and select those concepts with the highest chance of success. By providing a common understanding, this applied framework is intended to improve future development, testing, application, and use of PhysMon systems.

KEYWORDS: logic analysis, wearables, physiological episodes.

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Fast-jet pilots operate in an environment that can place extreme stress on their physiology; however, their physiological effects are not routinely monitored. Recent years have seen growing interest in pilot physiological monitoring (PhysMon), but this has not always been approached in a systematic manner. This communication aims to promote the need for a closer interface between engineering and medicine using an integrated framework to guide a logical, structured, and considered approach to PhysMon.

Physiological Episodes (PhysEps),¹ or Unexplained Physiological Events (UPEs),² have been reported in fast-jet flight and are defined as events during which aircrew physiology is affected from an as-yet unclear source. The mid-2010s saw increased PhysEps reporting, resulting in Congress-mandated investigations in the U.S. and similar probes across NATO nations.³ Investigations into these PhysEps have been inconclusive with multiple issues implicated, e.g., breathing gas pressure variability and aircrew flight equipment restricted breathing.⁴ At that time, investigators lacked physiological data or means to capture these in flight. This reignited interest in PhysMon systems and potential use of “wearables” in the aviation setting.

Efforts to introduce PhysMon technologies have not always followed the process of conceptual/theoretical review, on to laboratory, then to applied analog (centrifuge, hypobaric chamber,

vibration plate), then to flight test. Failure to follow this progressive approach means systems may be flown without adequate characterization of performance in the aviation environment. There has also, at times, been a lack of critical thinking in the approach to consider PhysMon systems even before testing them. **Fig. 1** outlines a structured approach and series of questions to help address this.

An Integrated Approach to Reviewing Potential Physiological Monitoring

PhysMon must be considered in the context of other aircraft systems necessitating the integration of analytical tools used in engineering, medicine, and physiology. To achieve this, we advocate using a framework (Fig. 1) to guide the critique of a proposed PhysMon system, its potential use cases, and

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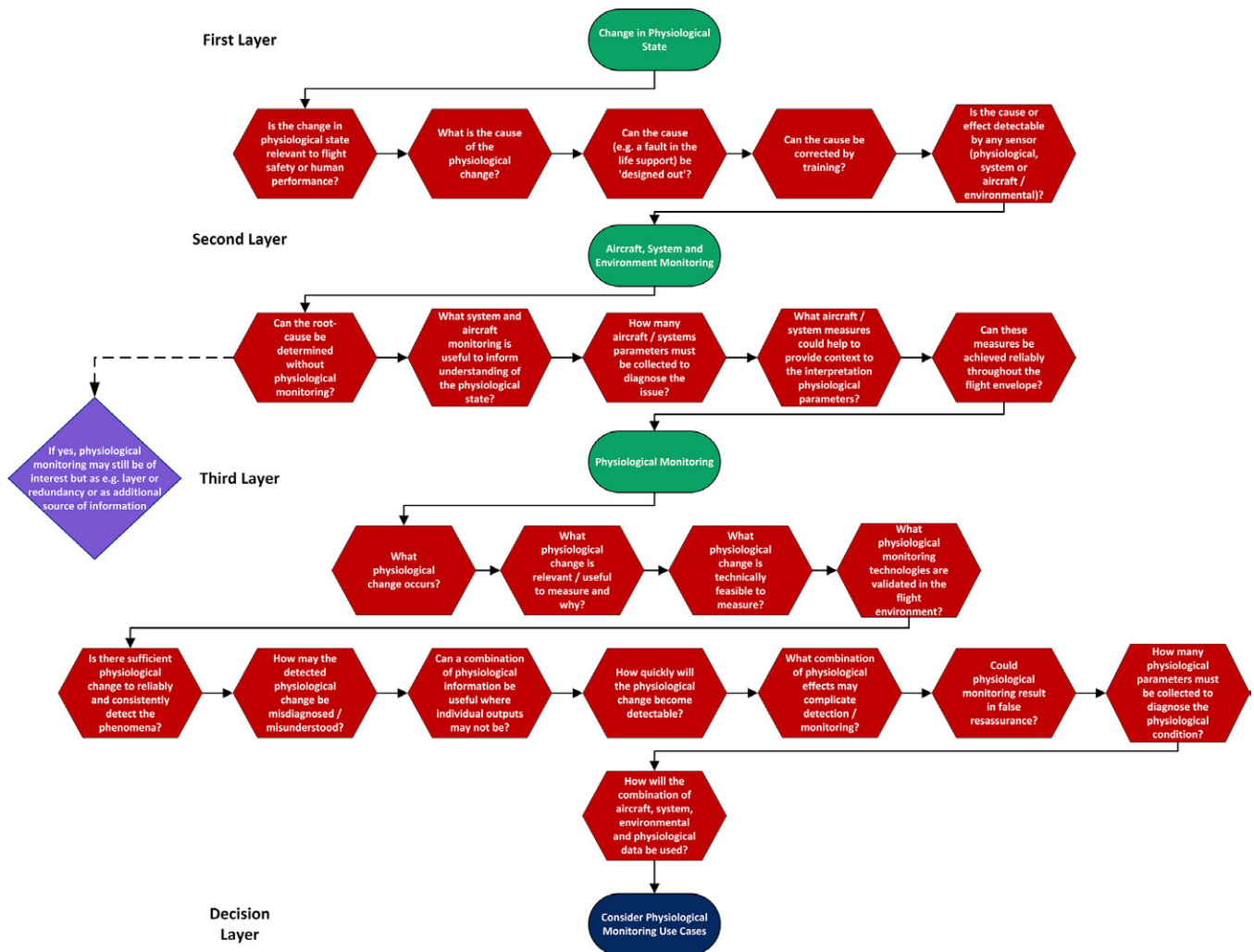


Fig. 1. A framework to guide the critique of a proposed physiological monitoring system, its potential use cases, and the technical assessment and validation for military fast-jet aviation. It details the question set that should be used when assessing the potential physiological monitoring systems and can be used to test the reasoning behind a physiological monitoring concept within the system-of-systems context. It incorporates aspects of both layers of protection analysis (LOPA) and failure tree analysis (FTA) techniques into a single tool, with the answers to each layer assisting the practitioner in determining whether further layers of monitoring are required.

the technical assessment and validation for military fast-jet aviation. The intent is to equip practitioners from across different disciplines with a common toolbox of simple questions to breakdown the problem into different levels of consideration. It proposes a holistic approach that enables consideration around the problem and potential solutions, involving a sequential approach to questioning the physiological change, during which the necessity for different types of mitigations is assessed in a logical sequence. The first two layers provide a series of questions to establish a baseline understanding of the physiological change itself, its relevance to flight safety, and what aircraft, system, and environmental monitoring should be adopted to provide context for the circumstances in which the physiological change occurs. The third builds on this contextual understanding by asking questions that guide a structured analysis of how PhysMon can offer insights beyond those provided by hardware alone.

Traditionally, only the third layer of questions has been applied to PhysMon concepts. The logical flow in Fig. 1 highlights that PhysMon will often not be the first-line mitigation against physiological degradation and must be contextualised by other nonphysiological sources of data. A structured and methodical analysis should be undertaken to assess potential aircraft, environmental, system, and physiological sensing modalities alongside one another, not in isolation. Given the complexity of this task, use of analytical tools such as failure tree analysis (FTA) and bow-tie analysis (BTA) should be applied to understand physiological degradation and risk to flight safety. Detailed question sets can then be formulated to aid in both the critique of PhysMon concepts and the test and validation of proposed systems.

Analytical Tools

Pilot physiology is safety-critical when operating an aircraft, therefore physiological compromise should be analyzed akin to

the failure of any other safety-critical system. One tool that can be used is the FTA. This type of analysis is common in engineering for assessing the root cause of complex system failures, whereby the failure may be the result of a single component failure or a complex interaction of subsystem failures.⁵ These analyses can be very complex, with a recent example being the U.S. Navy's Root Cause and Corrective Action (RCCA) investigation considering 427 branches of a fault tree for their investigations into T-45 PhysEps.³ FTA can be used as a method to identify physiological risks which can be further analyzed for mitigation options in a BTA, a layers of protection analysis (LOPA) that has been used primarily in project management but also adapted for clinical risk management and patient safety.⁶ Fig. 2 shows a simplified example of a BTA which can be used to analyze whether a proposed PhysMon suite, described as a “control,” is effective over and above existing mitigations in one of three ways:

- Preventing the physiological top event (pre-top-event control);
- Reducing the consequences of the top event (post-top-event control);
- Reducing the impact of control degradation factors (degradation factor control).

Physiological Monitoring Use-Cases

The use case of a system will be intimately tied to the requirements for data acquisition accuracy, tolerance for artifacts, and number of physiological parameters to be monitored. Systems can be segregated into categories of in-flight alert/automated action or postflight analysis.

Aircrew currently identify hazardous physiological states through self-identification of symptoms. While an established

method when paired with aeromedical training, it is reliant on subjective experience, liable to error, and potentially flawed when the individual is affected by stressor(s). The ability to identify the physiological status of the pilot objectively through PhysMon could be an improvement over self-identification. However, any novel system should be demonstrated to have fewer false positives/negatives than a trained pilot to be considered an objective improvement. There are also human factors considerations in terms of how such information may be presented to or used by the pilot.

An alternative proposed use case is for PhysMon systems to feed into automated systems, which can be subdivided into continual adjustment or return to safe state. A “safe state” is defined as a state that will not contribute to pilot degradation any further. It is important to note that for any system with a component of in-flight action, how the physiological data would be used to activate or adjust systems is yet to be determined.

Ideally, we want to prevent hazardous physiological states from occurring, which may be achieved more readily through effective monitoring of aircraft and LSS hardware. This is highlighted by the placement order of system, aircraft, and environmental monitoring in Fig. 1. For example, if the LSS is delivering the correct oxygen concentration and pressure at the correct time (in phase with breathing demand) then aircrew should not become hypoxic. Monitoring the system hardware to detect LSS failures will detect issues sooner and, therefore, likely mitigate many PhysEp scenarios earlier than waiting for the human to be affected. PhysMon should instead be used to understand instances where human physiology is altered but the LSS is operating normally, such as during ventilatory hysteresis or hyperventilation.⁷ There are other potential causes of a physiological event in the presence of a functioning LSS which

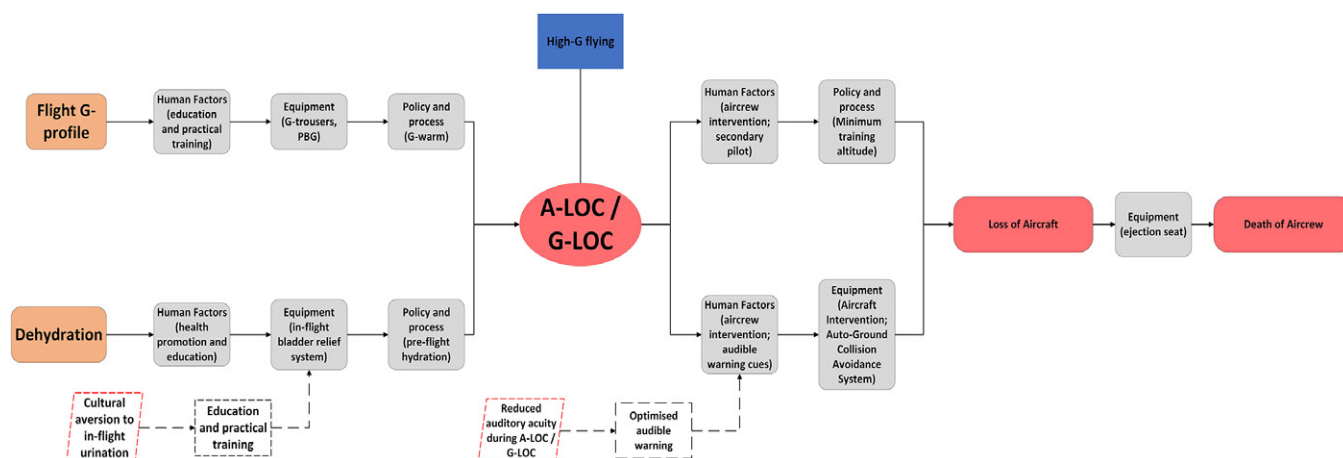


Fig. 2. Example of a simplified bow-tie analysis (BTA) (actual BTA of G-LOC/A-LOC would be substantially larger), split into three sections. The center shows the top event resulting from a hazard (blue). While this shows a single top event, multiple may occur because of a single hazard, or multiple hazards may form a single top event. The left shows threats (orange) which, if unmitigated for, could result in the top event occurring. To prevent this occurring, the opportunity to input control measures (gray) against those threats is shown as a barrier between the threats and the top event. These are usually grouped into thematic controls, with further detail given on examples for each thematic category. On realization of the top event, further control measures to mitigate against the consequence (red) are mapped. Degradation factors (red dashed) interfere with control measures, either pre- or post-top-event, weakening their efficacy or nullifying the control measures. The barrier between these degradation factors and the threat/consequence controls is the degradation factor controls (gray dashed).

complicate the interpretation of PhysMon, but do not indicate an issue with the LSS.

Similarly, we do not necessarily need PhysMon systems to detect G-LOC because the aircraft can be returned to a safe state, and crash can be avoided, through hardware-based monitoring alone, e.g., Auto-Ground Collision Avoidance System (A-GCAS).

Postflight analysis (PFA) encompasses many proposed solutions and can be described as a system which has no active in-flight component, such as aeromedical research, fleet health surveillance, in-flight LSS test, and evaluation or accident investigation. This category of system has a reduced requirement for throughout flight-envelope data capture since failure to measure within more extreme windows may be acceptable given that the system is not safety-critical or capable of in-flight functionality. It must be understood, through test and evaluation, whether there are scenarios that result in inaccurate data so that it can be removed from analysis. PFA concepts which have safety-critical functions, such as those with a role in accident investigation or aeromedical research, may have lower tolerances for perturbations in data output, and requirements for these systems can be better likened to the in-flight alert category.

A concern with PFA data would be in its use. Without additional nonphysiological sensors to capture the cabin environment and cross-referencing with the Flight Data Recorder (FDR), physiological data viewed in isolation, and without context, is of limited use. It would be necessary for any PhysMon suite to be integrated with environmental and systems-monitoring to provide context on causal factors that exposed the aviator to the physiological stressor(s). This emphasizes the importance of the interface between medicine and engineering, a critical concept for PhysMon.

Given that contextual data integration is necessary, PFA systems would require a significant amount of work to process this multimodal data. The assistance of machine-learning (ML) or artificial intelligence (AI) could alleviate some of this burden but adds its own challenges of appropriate training and use of inference. Use of ML and AI in the processing of physiological data has its own considerations,⁸ a review of which is outside of the scope of this communication.

An example of a specific PFA use-case is fleet health surveillance, which is based upon the concept of flight data monitoring (FDM). The Airbus A400M is an example of a modern aircraft equipped with sophisticated FDM of aircraft flight characteristics, maneuvers, and other critical components/flight behaviors. This continuous monitoring of flight behavior enables abnormalities in the fleet to be detected and reported to gatekeepers for analysis and can take place prior to any incident/accident occurring. If the system detects a dangerous flight behavior, for example over-rotation on take-off/landing, the software flags this for further investigation by a gatekeeper. They can then either discard the flagged events or highlight them as requiring intervention, such as supplementary crew training.

PhysMon could be utilized in a similar fashion in which rather than focus on individual physiological responses, the system would instead monitor physiological trends across fleets/

population groups over time. The benefit of this approach over more individualistic monitoring analysis is the anonymisation of personal data, preventing single anomalous data points from grounding pilots unnecessarily and penalising individual aircrew. Utilizing PhysMon in this manner is likely to be more acceptable to aircrew, who are unlikely to wish to be monitored more than necessary. Thorough consideration of privacy and data protection implications is critical for any collection of personally identifiable information, particularly physiological information.

Several PhysMon solutions used in flight are being proposed for use in the training environment. Trainee pilots are exposed to an environment with which they are much less acquainted than their fully trained counterparts, potentially predisposing them to higher levels of stress and resulting in higher rates of PhysEps.⁹ They are also expected to take on vast quantities of information at a rapid pace. They learn of the insidious danger of hypoxia, which can predispose them to overreporting of incidents where they don't feel "quite right" as suspected hypoxia, even if other psychophysiological explanations were more likely.⁹ A robust PhysMon system must be able to contribute to the understanding of whether there was a genuine physiological issue or if the incident was misreported. This would result in significant time and financial savings for the investigating operator.

General Principles for Physiological Monitoring Systems in Aviation

The selection of PhysMon suites in aviation could be aided by a general set of principles to guide assessment of their appropriateness for this setting. These principles will help exclude systems which don't work; however, they are high-level principles and therefore do not detail specifics of testing each technology. While some have considered the topic,² there is yet to be consensus in the literature on these principles, which is what we aim to achieve in this paper, with particular emphasis on the framework and guiding questions in Fig. 1.

Sensors must be accurate throughout the flight-envelope or designed to exclude data collected in situations where accuracy is compromised. This is a key performance parameter of any sensor and must be characterized in the test and evaluation process. This can be achieved through testing of the device from benchtop to laboratory, on to analog environments, and only then in flight tests. This allows the characteristics of the system to be understood when operating under discrete variables before adding the combination of many during a flight test.

One example demonstrating this need is the use of smartwatches with heart rate and peripheral blood oxygen saturation (S_{pO_2}) functions, which rely on reflectance photoplethysmography (rPPG) at the wrist. Devices using this technology have been demonstrated to be insufficient at collecting S_{pO_2} ¹⁰ when there is movement, a limitation which would not be acceptable for fast-jet flight use.

The impact on comfort, thermal burden, bulk, and weight must be considered against the benefit the system delivers. Both pilot acceptance and functional efficacy of the system will depend on integration into the AFE without impacting

operation of the aircraft. Degradation in normal and/or emergency operation of aircraft systems through bulky or poorly integrated PhysMon systems is likely to distract from the aircrew's primary role of operating the aircraft. Poorly integrated sensing technologies may give rise to poor data quality due to motion artifacts or other anomalies from the inconsistency in form, fit, and function between individuals.

Inference of pilot state from sensor readings of common physiological proxies must be carefully considered and validated in laboratory, flight analog (centrifuge/altitude chamber), and in-flight testing. S_pO_2 is a typical example of a parameter which is sometimes extrapolated out to infer conditions for which it is not appropriate. If aircrew become hypoxic and hyperventilate [due to various in-flight causes or hypoxic ventilatory response (HVR)], carbon dioxide (CO_2) is removed from the blood (hypocapnia) and S_pO_2 increases.¹¹ Hypocapnia causes similar symptoms to hypoxia. In this scenario, without another method to identify hypocapnia, the actual physiological state of the aircrew could be misinterpreted from S_pO_2 alone.¹² S_pO_2 is an accurate measure of the percentage oxygen saturation of hemoglobin within the blood being measured, but it is inappropriate to expect a direct extrapolation of this to oxygen delivery to the tissue or to use it as an absolute diagnostic tool for pilot capacity in the hypoxic condition.

Another example would be end-tidal carbon dioxide ($ETCO_2$), an important clinical measure that is used to estimate the partial pressure of arterial CO_2 ($PaCO_2$) in the blood. While in a laboratory setting, $ETCO_2$ is considered the gold standard for the noninvasive measurement (calculation) of $PaCO_2$,¹³ the association between the two is decoupled when breathing high fraction of inspired oxygen ($F_I O_2$).¹⁴ Given that aircrew commonly breathe high $F_I O_2$ when flying at higher altitudes, $ETCO_2$ cannot be expected to maintain the same relationship with $PaCO_2$ throughout the envelope of aircraft operation. This understanding is especially important when considering the need to contextualise S_pO_2 measurements with a method of identifying hypocapnia. This underscores that no one parameter can be relied upon for pilot physiological state, which has been the conclusion of other aeromedical research institutions.¹⁵

Conclusion

The primary aim of this paper is to suggest a structured approach for multidisciplinary practitioners considering PhysMon in fast-jet aviation. This includes a guide to asking appropriate questions about potential PhysMon systems, from concept through development, testing, and in-service deployment. Practitioners should be openminded to their potential and optimistic about the pace of monitoring-technology development, while maintaining a healthy skepticism about whether these novel systems will perform as intended in the aerospace setting. We hope this suggested approach helps to assess the potential role of the PhysMon system within the context of wider aircraft safety systems, how they will contribute to improved flight safety or human performance enhancement, and whether there are better ways to achieve this. Once these

questions are answered, practical test and evaluation can investigate if the technology works throughout the flight-envelope and whether verification and validation of system requirements has taken place in appropriate flight-relevant settings, as well as human-centered integration.

Practical research should then focus on confirming that any system identified for development through the above process has its system performance characterized through appropriate and common-sense escalation in validation test complexity, adding discrete variables one-at-a-time where possible. Only once device performance has been properly characterized with regards to the effects of the major aviation environmental stressors can it then move to full flight testing. It must also be stressed that the concept of "airworthiness validation" will have different thresholds for acceptability depending on the use-case of the monitoring system, thus it is essential not to divorce the use-case from the sensor when discussing if a subsystem is appropriate for in-flight PhysMon.

PhysMon is a promising area of aviation physiology but potentially more complex than its counterparts used in other industries. We suggest managing this added complexity by using the structured, logical process of analyzing the problem being addressed and clearly defining where/when in that failure case PhysMon would interdict. Prior to expensive test and evaluation procedures, breadboard analysis of the role of a PhysMon system in concert with other aircraft systems is needed. Future research should identify and address the gaps in the literature on physiological effects of flight, along with specific methodologies to test and evaluate proposed technologies for use in this setting.

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