"Fatigue: Where Biology Meets Technology"

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June 17, 2008: Keynote Session

Abstract
Modern humans have created technologies that challenge the limitations placed on all species by time and space. Commercial aviation technologies are some of the more remarkable achievements that have accelerated human contact and figuratively shrunk the planet. But the brain structures that made the technologies capable of routinely transporting tens of millions of people through Earth's atmosphere are not the only brain structures relevant to the safe operations of modern aircraft. In all human brains are the ancient biological imperatives of sleep and circadian timing that have ubiquitous and profound influences over human alertness, cognitive performance and related goal-directed behaviors. These endogenous neurobiological drives in humans contribute to fatigue and its risks to performance in personnel involved in commercial aviation -- especially in transmeridian and long-haul aviation.

Although there have been considerable efforts to use scheduling and human redundancy (e.g., crew relief/rotation) to manage fatigue risks in commercial aviation, there remains untapped potential for fatigue management based on new scientific data on fatigue causes and mitigation, and on novel technologies to management fatigue risks. The integration and validation of such information and technologies could form the basis for a dynamic fatigue risk management system that can be adapted to changing operational needs and idiosyncratic factors that contribute to risk. Fatigue occurs in the brain (e.g., when sleep pressure is elevated) and is manifest in behavior (e.g., reduced vigilance) that can increase risk of an adverse event. A system approach based on integrated components that are scientifically valid and operationally practical might emphasize prevention, prediction, detection and intervention to dynamically manage fatigue and risk. Prevention refers to behaviors and technologies that reduce risks in advance.

Related to prevention is prediction of risks (e.g., via operational databases to identify higher risk scenarios; technologies that can model human vulnerability to fatigue or to risk, and potentially indicate where to mitigate the causal link between fatigue and risk). Detection of fatigue (or risk) refers to behaviors and technologies in the work environment that can reliably indicate the presence of fatigue (or risk). Finally, intervention refers to countermeasures used operationally to mitigate fatigue, or performance deficits, or risks. For all four of the components of a putative fatigue risk management system, there are likely to be three levels of discovery and development:

(1) what may be useful immediately; (2) what is knowable in the near-term; (3) and what may be achievable in the far-term. The empirical development and validation of system components requires both sound evidence of positive benefits that exceed current practices, and evidence that there are no unwanted consequences to safety, costs or personnel. It should include the best available information on the biology of fatigue and its risk mitigation with novel technologies. Identifying these components will require standards of evidence, creativity, and a willingness to be decisive. The flexibility that may be achievable in such an evidenced-based system has the potential to accommodate more frequent changes in commercial aviation while managing risk.

Major points

- The integration and validation of new scientific information on human fatigue and its mitigation, and on technologies mitigating fatigue could form the basis for a dynamic fatigue risk management system that can be adapted to changing operational needs and idiosyncratic factors that contribute to risk.

- A system approach based on integrated components that are scientifically valid and operationally practical might emphasize prevention, prediction, detection and intervention to dynamically manage fatigue and risk.

- The empirical development and validation of system components requires both sound evidence of positive benefits that exceed current practices, and evidence that there are no unwanted consequences to safety, costs or personnel. It should include the best available information on the biology of fatigue and its risk mitigation with novel technologies.

Biography

David F. Dinges is a Professor and Chief of the Division of Sleep and Chronobiology, and Director of the Unit for Experimental Psychiatry in the Department of Psychiatry, and Associate Director of the Center for Sleep and Respiratory Neurobiology at the University of Pennsylvania School of Medicine. He is also Adjunct Professor in the School of Biomedical Engineering, Science and Health Systems, Drexel University.

During the past three decades his research has been supported by NIH, NASA, NSBRI, DOD (AFOSR, ONR), DOT (FAA, FMCSA, NHTSA), DHS (TSA), foundations and some private companies. He has advised both federal and private entities in the U.S. and abroad on scientific evidence for regulatory policies regarding duty hours and fatigue management. As a behavioral neuroscientist, his research focuses on physiological, neurobehavioral, and cognitive effects of fatigue from work schedules, sleep loss, disturbances of circadian biology, and stress, and the implications of these unmitigated effects on health and safety. He has conducted extensive scientific work on development and validation of behavioral, technological, and biological interventions for these effects. Examples of his contributions to behavioral understanding human sleep need and sleep deprivation include his work on the cumulative effects of chronic sleep restriction, on differential vulnerability to the cognitive effects of sleep loss, on the benefits of prophylactic/power napping, on the impact of split-sleep schedules, and on circadian contributions to restricted sleep schedules. Examples of his contributions to technological prediction and detection of sleepiness and fatigue include his work with others to advance and improve mathematical models of performance risk from fatigue, development and validation of the psychomotor vigilance test (PVT), and laboratory, simulator and field studies of the validity (or lack of validity) of various fatigue monitoring technologies. Examples of his contributions to biological mitigation of fatigue include his studies of caffeine and wake-promoting medications.

In addition to his extensive laboratory research—which includes some of the largest laboratory controlled studies ever conducted on sleep loss effects in healthy humans—he has conducted research in commercial cockpit simulators and aircraft, in truck cab simulators and over the road, and in space analog environments under the ocean and in space flight. Dr. Dinges currently leads the Neurobehavioral and Psychosocial Factors Team for the NASA funded National Space Biomedical Research Institute (NSBRI). He is a member of the NIH NINR Council. He has been President of the U.S. Sleep Research Society and of the World Federation of Sleep Research and Sleep Medicine Societies, and served on the Board of Directors of the American Academy of Sleep Medicine and the National Sleep Foundation. He is currently Editor-in-Chief of SLEEP, the leading scientific journal on sleep research and sleep medicine in the world. He has received numerous awards, including the 2004 Decade of Behavior Research Award from the American Psychological Association, and the 2007 NASA Distinguished Public Service Medal.

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Text of Presentation

DR. DAVID DINGES: Let me begin by thanking Mr. Sumwalt and the organizers, Drs. Steven Hursh and Melissa Mallis, for asking me to speak. I appreciate the significance of this meeting and the very important work you are going to do for the next few days and throughout this Fatigue Symposium, by discussing issues that have been at times intractable and mired in adversarial relationships. But I would urge you to do what the symposium organizers asked and rise above the disagreements to focus on novel solutions.

The previous presenter spoke of Charles Lindbergh's historic solo nonstop crossing of the Atlantic in May of 1927. I would add that from the perspective of fatigue, Lindbergh's flight was paradoxical. He reported extensively in his flight logs of that auspicious journey that he struggled for many hours to remain awake as he flew, that he had difficulty attending to the compass and holding the plane on course due to loss of alertness, and his fatigue worsened to the point that he became disoriented and believed he could land on the ocean (as published in the *Spirit of St. Louis,* Charles A. Lindbergh, NY: Scribners, 1953). Yet reports of the flight — including those of such renowned scientific journals as *Science* and *Scientific American*, made no mention of Lindbergh's incredible struggles with sleepiness and fatigue during the historic crossing. The extent of Lindbergh's fatigue during the flight and the risks it posed to his survival only became clear when he published the *Spirit of St. Louis* more than 25 years after the event. The world remembers him for his heroic act, but his fatigue nearly brought a premature end to his achievement. The risks posed by fatigue continue to this day to be important concerns in commercial aviation.

The brains of all pilots and all professionals involved in ensuring safe commercial aviation contain the genetically programmed neurobiology that put all humans to sleep each day and that time our 24-hour cycles of sleep and waking. There is extensive scientific evidence on the brain mechanisms that control our vigilance states across a day, and on the nature of performance changes and unreliability when we attempt to override our need for sleep and its biological timing. The high-tech, high-mobility, high-consumption lifestyles we create put us in conflict with our biological heritage.

Despite the challenges of fatigue-related performance risks from jet lag, night work and sleep loss, global commercial aviation safely transports hundreds of millions of people each year, thanks to a long line of safety-related improvements in aviation and operational technologies (see Figure 1). However, as the demand for more flexibility in transportation industries grows, federal agencies are faced with fundamental questions. The first is whether there is some way to reduce the need for sleep? The scientific answer to this question is a firm "no". Finding ways to reduce sleep need has remained an intractable scientific problem, and no chemical or biotechnological substitute for sleep has been found.

This leads to a second question. If there is no way to eliminate sleep need, is there some way to anticipate and prevent performance risks due to fatigue? I would suggest that there is reason for optimism relative to this question. Unobtrusive, objective ways to detect fatigue in human operators have begun to be the focus of considerable research on technologies that validly and reliably predict, detect and/or prevent performance risks due to fatigue. The idea of using technology to do this in commercial aviation may cause concern or incredulity in those over 50 years of age, but I believe the concept is obvious and even attractive to many under that age. Whether it is or not, the development and application of these technologies is inevitable. The generation coming into power over the next 10-20 years grew up immersed in technology. They accept human-machine interaction in nearly all aspects of life. In their minds, the computer should be sentient-like, in that it should read human intentions, anticipate human actions, and do other things that enhance human capability. Those expectations will bring the emergence of ever-more sophisticated human-machine interfaces, which will undoubtedly change the nature of human work in all transportation modes, including commercial aviation. Fatigue is an area where such human-machine interfaces can have a profound effect by preventing, predicting, detecting and mitigating fatigue-related risks (Figure 1).

The following three concepts provide a framework for thinking about how technologies for fatigue management might be integrated into commercial aviation.

1. The integration and validation of new scientific information on human fatigue and its mitigation, and on technologies that predict and detect fatigue could form the basis for a dynamic fatigue risk management system that can be adapted to changing operational needs and idiographic factors that contribute to fatigue risk.

2. A system approach based on integrated components that are scientifically valid and operationally practical might emphasize prevention, prediction, detection and intervention to dynamically manage fatigue and risk (Figure 1).

3. The empirical development and validation of system components requires both evidence of positive benefits that exceed current practices, and evidence that there are no unwanted consequences to safety, costs or personnel. It should include the best available information on the biology of fatigue and its risk mitigation with novel technologies.

Perhaps the most compelling argument for the development of fatigue management technologies in commercial aviation is the fact that no matter what scheduling limits are placed on commercial aviation, the circadian and sleep-dependent nature of fatigue ensures it will occur in some operations—such as night flights and transmeridian flight schedules. However, this fact opens up the possibility of predicting when fatigue will occur, using mathematical models validated on sleep and circadian dynamics relative to performance (Mallis et al., 2004; Dinges, 2004). While advances in aviation technology (e.g., avionics, jet engines) and operational technology (e.g., tracking of aircraft and weather) have given air travel a good safety record, people (flight crews, maintenance personnel, air traffic controllers) remain at the heart of a safe air transit system. In this sense, the safety of commercial aviation remains human-centered. Fatigue management is designed to prevent, detect, and reduce fatigue as a risk factor in a human-centered, safety–sensitive industry. However, fatigue management technology should be more than quality of seats and bunks for crew rest in airplanes (Figure 1), which along with regulated duty-hour limits have been low-tech approaches to managing fatigue in flight crews.

Criteria for identifying human-centered technologies that predict and/or detect fatigue in flight operations have been detailed, but first and foremost is the requirement that they meet systematic scientific validity (Dinges & Mallis, 2001). This should include double-blind testing of the accuracy of a given technology relative to a gold-standard performance-based measure of fatigue, and assurance that it is accurate when used in every person. This necessitates swift elimination of invalid approaches. One cost-effective strategy to getting to the most valid technologies is to leverage what has already been discovered by research supported through other federal agencies. The biology of fatigue is common to all occupations, and some discoveries in other transportation modalities can be applied to aviation.

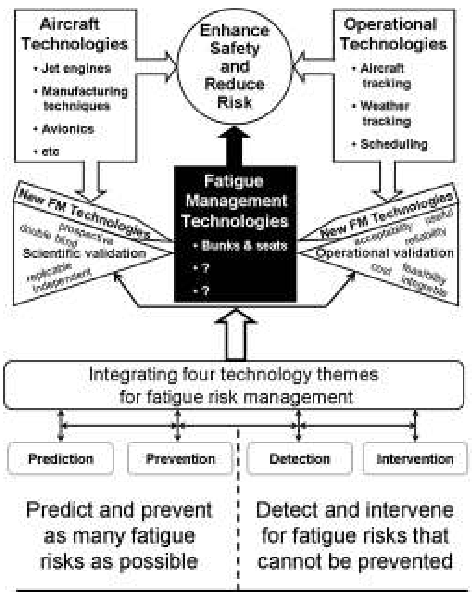

Figure 1. *Key elements of a Dynamic Fatigue Risk Management System. Fatigue management (FM) technologies have lagged behind aircraft technologies and operational technologies in efforts to enhance safety and reduce risk in commercial aviation. It is now possible to develop the former to aid in prevention of fatigue, prediction of when fatigue is most likely, detection of fatigue during operations, and interventions to reduce fatigue or its risks when it occurs.*

A scientifically valid fatigue management technology should then undergo operational validity, which refers to the extent to which a technology is feasible, reliable, and acceptable by operators in an operational environment. For example, it is obvious that a scientifically valid fatigue-detection technology must be deployable in an aircraft cockpit if it is intended to be used by pilots. Pilots must also perceive the feedback from the technology to be useful to them in managing their fatigue. The technology must work reliably, and have both high sensitivity (i.e., detect fatigue) and high specificity (i.e., detect primarily fatigue). Finally, to be used, it must be as unobtrusive as possible.

Fatigue management technologies that have potential for use in commercial aviation include the following: (1) technologies that predict the occurrence and severity of fatigue and as such can be used to create schedules that are more fatigue-management friendly; (2) technologies that help deliver education on fatigue management and optimal countermeasure use to individuals; (3) technologies in the workplace (on the operator or embedded in the work system) that detect when an individual is showing signs of fatigue; and (4) intervention technologies that help people be more alert and free of fatigue. In the following I discuss two of the more promising areas for fatigue management technologies—those that predict fatigue and those that detect fatigue.

Fatigue prediction technologies. Human performance (e.g., alertness, attention, working memory, problem solving, reaction time, situational awareness, risk taking, etc.) is dynamically controlled by the interaction of waking biological processes sensitive to time awake, sleep quantity, and circadian phase

(Durmer & Dinges, 2005; Van Dongen & Dinges, 2005). Although the effects of time awake and sleep duration can be modeled as near-linear processes within and between days, the circadian interaction with these processes makes the prediction of performance nonlinear. For example, when remaining awake for 40 hours, it is a counterintuitive fact that fatigue and performance deficits are worse at 24 hours than at 40 hours awake. The circadian system also influences the duration of recovery sleep that is possible to achieve, and the circadian system is slow to adapt to sleep in new time zones (see Figure 2). It is this nonlinearity that makes inadequate and imprecise many work-hour limits based solely on a linear model of fatigue (i.e., the longer one works the more fatigued one will become). This nonlinearity in the brain's performance capability over time is the reason that developing mathematical models that predict performance is increasingly regarded as essential.

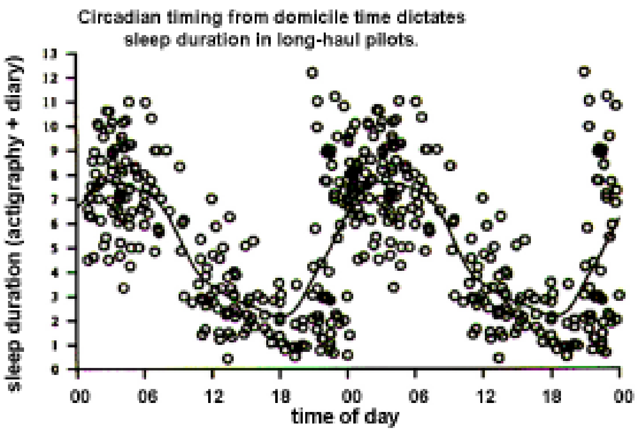

Figure 2. *Sleep durations in N = 21 long-haul commercial flight crew members flying four the middle 4 consecutive transmeridian Pacific flight legs (out of 8 legs) from the USA. Each point is a single sleep episode on layover. All four layover periods were between 21 and 29 hours. Sleep duration is double-plotted as a function of clock time in each crewmember's home. The data show that layover sleep duration was longer (>6 hours) when sleep in the layover city occurred between midnight and 9 a.m. at the crewmember's permanent home. In contrast, shorter sleep durations (<6 hours) occurred in the layover city when sleep was taken between 10 a.m. and 10 p.m. at the crewmember's permanent home. These data suggest that long-haul crews do not make a substantial circadian adjustment to the time zones they fly into, but instead experience sleep durations that more closely reflect circadian entrainment in their permanent homes. This is one major reason why fatigue management is important in long-haul commercial aviation. Data from a study by Rosekind et al. (1994).*

Mathematical models of fatigue prediction are the fatigue management technologies that have received the most attention in the past 15 years thanks to interest and support from DOD (Jewett et al., 1999), NASA and DOT (Neri, 2004). These models will again be the focus of an International Conference on Fatigue Management in Transportation Operations on March 24-26, 2009, in Boston (http://depts.washington.edu/uwconf/fmto/).

Based on the dynamic interaction of human sleep homeostatic drive and circadian rhythms, some of these mathematical models have advanced to the critical point of integrating individual differences into the modeling predictions for a more accurate estimate of the timing and magnitude of fatigue effects on individuals (Van Dongen et al., 2007), which should facilitate more precise use of countermeasures (e.g., naps, recovery sleep, caffeine intake).

Fatigue Detection Technologies. There are three scientifically-based reasons why objective fatigue detection technologies are needed in safety-sensitive operations such as commercial aviation. (1) Humans are often unable to accurately estimate how variable or uneven their alertness and performance have become due to inadequate sleep or working at night. When fatigued they tend to estimate their alertness based by their best responses and ignore their worse responses. (2) Performance deficits from fatigue accumulate over days to high levels when recovery sleep is chronically inadequate (Van Dongen et al., 2003; Belenky et al., 2003). Awareness of these cumulative deficits appears to be less accurate as performance declines (Van Dongen et al., 2003). (3) While everyone eventually develops performance deficits from fatigue, some people do so very rapidly while others take much longer, and these differences appear to be stable characteristics of people (Van Dongen et al., 2004) and therefore they may reflect biological differences among them (e.g., Viola et al., 2007). There are currently no reliable biomarkers for one's performance vulnerability to fatigue, making detection of fatigue a primary goal.

Fatigue detection technologies have been of interest to DOT for some time. A decade ago, the National Highway Traffic Safety Administration (NHTSA) and Federal Motor Carrier Safety Administration (FMCSA) had my laboratory systematically evaluate the validity of the "most promising" fatigue detection technologies, which included brain wave (EEG) measures, eye blink devices, a measure of slow eyelid closures (called PERCLOS), and a head position sensor. In a number of highly controlled, double-blind experiments, we evaluated the extent to which each technology detected the alertness of subjects over a 40-hour period, as measured by lapses of attention on the Psychomotor Vigilance Test (PVT)—a well validated and highly sensitive measure of the effects of fatigue on neurobehavioral alertness (Dorrian et al., 2005). Only PERCLOS reliably and accurately tracked PVT lapses of attention in all subjects, outperforming not only all the other technologies, but also subjects' own ratings of their fatigue and alertness (Dinges et al., 1998; 2002).

Subsequently, a group of technologies that included an infrared-based PERCLOS monitor, were evaluated in an over-the-road study of commercial drivers, to determine whether feedback from fatigue detection technologies would help truck drivers maintain their alertness in actual working conditions (Dinges et al., 2005a). The details of this study are extensive and need not be reviewed here, but suffice it to say that the infrared PERCLOS monitor did not perform well due to environmental factors (ambient light) and operator behavior (head turning to view mirrors). However, we are now developing a technique for NASA that involves optical computer recognition (machine vision) of the human face to identify expressions of stress and fatigue (Dinges et al., 2005b; Dinges et al., 2007). This system has a number of advantages. It requires no sensor or conspicuous technology, it can track the face as it moves in 3-dimensional space, and it can process information online in real time.

In the over-the-road study of the effects of feedback from fatigue-detection technologies on commercial drivers, we expected that when the technologies signaled a driver was drowsy it would result in the driver taking countermeasures, including stopping to rest or nap. However this rarely happened. On the other hand, we did find that the drivers felt the fatigue detection devices (and the PVT test they performed in the middle and at the end of each trip) informed them of their fatigue levels and prompted them to acquire more sleep on their days off duty. Both the debrief interviews Dr. Jerry Krueger did with the drivers, as well as the actiwatch data we acquired on the drivers confirmed that they increased their sleep by an average of 45 minutes on days off duty (Dinges et al., 2005a). This is a remarkable and unexpected outcome, and it suggests another purpose for fatigue detection technologies in the workplace—namely to urge operators to sleep more during off-duty periods. Recent research we have underway for NIH and NASA on recovery sleep following a period of sleep restriction reveals that getting extra sleep during off-duty periods and days off work is one of the most important fatigue countermeasures—but it will only be effective if sufficient time is permitted for sleep off duty. If we could use fatigue management technology to teach people to use their downtime to sleep more we could reduce the risk of fatigue substantially, for we know that in the US population as a whole, work duration is the primary activity that is reciprocally related to sleep duration (Basner et al., 2007).

I will end my presentation by pointing out that we do not know which fatigue management technologies will be most useful and acceptable in commercial aviation. It is fairly certain that in order for valid technologies to be used, they must not violate the privacy rights of individuals. It is for this reason that I believe the technologies should first be developed as personal aids. These technologies should be used responsibly—they are not a substitute for reasonable working conditions. It is now possible to leverage what is being done in other Federal agencies to get a leg up on which fatigue management technologies might work best in commercial aviation. I believe that information from fatigue management technologies can help people involved in commercial aviation be less fatigued and more alert, and that this is an achievable goal worthy of our best efforts.

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