Developing a Risk Index of Healthcare Provider Alertness to Improve Safety

Final Progress Report – May 31, 2011

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Structured Abstract

Purpose: To develop a risk index and schedule simulation software that can design safe schedules consistent with the Institute of Medicine's (IOM) recommendations for resident physician work hour limits. The technology is expected to facilitate the design of safe schedules, which could improve alertness and performance and reduce the risk of fatigue-related error.

Scope: Novel tools to evaluate the predicted performance of teams of residents working together over the course of a month were developed. Traditional and proposed new resident schedules from two hospitals were evaluated.

Methods: A circadian (internal timekeeping) model and a linked human performance model were used to evaluate traditional and proposed residency schedules. The model's predicted quartile performance (25%, 50%, 75%) results were plotted by day for each person on the rotation. Schedule summaries were created for each group in a rotation in order to compare different scheduling alternatives for a rotation.

Results: Schedules predicted to contain periods of poor performance were identified. The simulations found that new schedules designed according to the IOM's recommendations will result in better performance compared to traditional schedules.

This project led to practical and theoretical extensions of our scheduling research program. Our existing simulation software was improved to make simulation and evaluation of schedules easier. A new software infrastructure for automating analysis of schedules is proposed. The project facilitated the adoption of newly proposed schedules and a request to provide training in the effects poor sleep to physicians in training.

Key Words: resident, intern, physician-in-training, modeling, sleep deprivation, circadian misalignment

Purpose

Our goal was to develop a risk index of healthcare provider alertness, with the primary goals (1) to increase the readiness of physicians in training (residents) who provide primary and inpatient care at our nation's teaching hospitals by improving their sleep-work schedules and (2) to develop technology that can design schedules consistent with the relatively new national recommendations for work hour limits. Our approach is to adapt our published methods and technology (developed initially to design NASA-related mission schedules) to address resident schedule design.

Scope

Studies have demonstrated that physician sleep deprivation can result in an increased risk of medical errors and increased risk of injuries to medical residents and others (e.g., car accidents, needle stick injuries). The Institute of Medicine (IOM) report, *To Err is Human,* cites medical error as a serious risk to patients, resulting in 48,000 to 98,000 casualties each year. In response to these studies, the Accreditation Council for Graduate Medical Education in 2003 placed limitations on the number of consecutive hours a physician trainee can work, and planned to implement more stringent limits for interns (first-year residents) shortly after. In addition, following a year-long review of the literature demonstrating links between residents' traditional long work hours and safety hazards, the Institute of Medicine recommended more efforts to optimize residents' sleep and improve their performance. Residency program directors now find themselves in the difficult position of trying to schedule a small number of residents to provide 24-hour hospital coverage while ensuring that no individual exceeds the maximum allowable number of hours. Little guidance and few tools exist to aid program directors as they attempt to do so.

Methods

Redesign of Software Infrastructure

The Division of Sleep Medicine at Brigham and Women's Hospital developed Circadian Performance Simulation Software [1], a modeling program initially designed for NASA to aid in the scheduling of astronauts to optimize their performance on space missions. We sought to adapt this technology to develop a tool that could be used to schedule resident physicians in a manner that would optimize their performance. Differences in the practices between physician trainee schedules and NASA-related schedules required several alterations to our existing methods, models, and algorithms. Consequently, we expanded the design of our scheduling system, known as Shifter, to include features required for the design of resident schedules. In particular, the schedule optimization system design was modified to allow for a wider range of automatically generated recommendations.

Improvement to simulation software

Circadian Performance Simulation Software [1], our simulation software, was prototyped first in MATLAB (Mathworks, Natick, MA) and then ported to a Microsoft .NET environment. Portions of the software infrastructure redesigned were implemented in MATLAB. A minimal set of features was ported to the .NET version. The software redesign and improvements leveraged other funding sources (Klerman PI, Dean PI).

Resident work schedule simulations

For the current project, we wished to compare interns' predicted performance on proposed alternative intervention schedules to predicted performance on traditional "q3" and "q4" schedules and to each other.

Schedules

Five schedules, approximately 1 month in duration, were simulated using the mathematical model:

(1 and 2) Two newly designed schedules were evaluated. Both included two daytime interns (A,B), with six "cross-cover" night-float interns (X1-6) who were assigned to cover a month-long rotation. Interns A and B worked 5 days "on" (7:00 to 17:30) followed by 2 days "off." Two potential schedules were simulated for cross-cover night-float interns:

(1) five 14-hour shifts between 17:00 and 07:00 (contiguous) plus 2 days off; and

(2) two blocks of 3 on-1 off-2 on-1 off (2-block) at the same hours.

Based on prior research, sleep was estimated to be 6.6 hours per night for daytime interns and 5.5 hours for night-float interns. Their proposed sleep-wake schedules were simulated with the mathematical model, and the quartiles of predicted performance for each work shift were compared.

(3) Every third night extended shifts (Q3);

(4) Every fourth night extended shifts (Q4);

(5) Rapid Cycle Rotation (RCR) in which the intern works one short day shift, one 15-hour day shift (07:00-22:00), and one 16-hour night shift (21:00-13:00) [2].

The quartiles of predicted performance for each work shift and across days were computed. For model simulations, the metric used was the percentage of maximum performance output by the model. A value of ~50% (of 100% maximum) corresponds to more than 24 hours of wakefulness, which has been associated with increased medical errors and occupational injuries [3].

Results

Redesign of Software Infrastructure

The redesigned scheduling system includes modules that add new capabilities to the system. The new modules include a schedule block and a group schedule block. The schedule block allows for sleep-wake and work schedules to be specified in a systematic fashion. The group schedule block allows for multiple schedules to be analyzed and summarized as a group. Specific schedules are constructed with our schedule building blocks that correspond to commonly use scheduling primitives. Schedule construction involves linking schedule building blocks together and setting the parameters for each building block appropriately. The scheduling building block concept was initially developed for our NASA-funded work and has been expanded and reorganized to design resident schedules. Most notably, schedule building blocks have been divided into three classifications: (1) intervention building blocks, (2) schedule building blocks, and (3) work schedule building blocks (shown in Figure 1). The goal of the new classifications is to facilitate the structured accumulation and access of specialty/application-specific information. Each schedule building block allows structured accumulation of application-specific information through dynamic parameter allocation. This feature will allow for the construction of interfaces to be quickly tailored for specific applications. The schedule building blocks provide a hierarchical system for which to access and share information between modules. The motivation of the hierarchical design allows for the development of 'smart' algorithms that use schedule- and application-specific information. For example, our published circadian adjustment method uses schedule information in conjunction with predicted circadian phase to determine optimal placement of light interventions that results in optimal performance [4]. A schematic of the redesigned system is shown in Figure 2.

Improvement to simulation software

Many changes and improvements were made to CPSS to facilitate simulation and analysis of schedules. Improved procedures for summarizing performance were added specifically to analyze the resident schedules presented in this final report. CPSS's graphical user interface is shown in Figure 3. The existing source code was ported to a recent version of the .NET environment in order to make the software available on personal computers running Microsoft System 7. As part of the porting process, the CPSS framework was modified to be consistent with the software infrastructure redesign and to begin the process of developing tools for batch analysis of schedules. The CPSS software framework is shown in Figure 4.

Intervention Schedules for Physicians-in-Training

Over the entire month, the predicted performance (25%, 50%, and 75% quartiles) during the work-shift for daytime interns on intervention schedules 1 and 2 was 90.9%, 91.8%, and 94.1% of maximum performance. When the two possible night-float schedules were simulated, the quartiles of predicted performance for the contiguous night-float interns were 63.2%, 85.2%, and 94.2% (Schedule 1) and for the two-block night-float interns were 54.4%, 82.7%, and 93.8% (Schedule 2), respectively. For model simulations, a value of ~50% corresponds to >24 hours of wakefulness, which has been associated with increased medical errors and occupational injuries [3]. The proposed physician-in-training schedules are shown in Figure 5. Results are shown in Figures 6-7.

Traditional and Rapid Cycle Rotation Physician-in-Training Schedules

Over the entire month, the predicted performances (lowest (25th), median (50th), and highest (75th) quartiles) during the work-shifts schedules varied. We focused on the lowest quartiles, because this is the most sensitive metric in terms of evaluating poor performance on a work shift and the times of expected errors and accidents. For both (XC) schedules (1 and 2), the lowest quartiles of performance never strayed below 80%. In the Q3 & Q4 simulations, the lowest percentile never exceeded 60%. The RCR schedule had better performance levels than Q3 & Q4 in the lowest percentile, but they never exceeded 70%. Results are shown in Figure 8-9.

Summary of Results

Our initial results suggest that implementation of either of the new intervention schedules would improve performance over the Q3, or Q4 or RCR schedule. The revised schedule resulted in good predicted performance for daytime interns but identified periods of low performance for the night-float interns. Contiguous scheduling of night-float appears to be better than two-block scheduling based on the lowest quartile of performance.

Limitations

It is important to note that the predictions made to date using the tools developed here are sensitive to the precise amounts and timing of sleep obtained, so the findings comparing our intervention schedules to traditional and rapid cycle rotation schedules may not be generalizable to all instances of these general schedule types. Mathematical modeling, however, is capable of accounting for these nuances and evaluating the predicted effects of even subtle changes to sleep and scheduling parameters, within the constraints of the scheduling software. Future plans exist to incorporate a term for chronic sleep deprivation into the CPSS model, which is absent in these predictions, and could modify both the precise results predicted here and the assessment of the relative merits of one schedule versus another.

Significance

Mathematical modeling is an effective tool for evaluating residency schedules. The residency program we studied plans to implement the contiguous night-float schedule and educate residents on sleep deprivation, sleep hygiene, and the importance of napping before night shifts. Using the mathematical model, we can provide quantitative evidence to be used in schedule reform.

Nationally, there are approximately 100,000 interns and residents distributed throughout thousands of residency programs in tertiary care and community hospitals nationwide. If we conservatively assume that physician trainees treat 25% of the 36 million patients seen at these hospitals each year, then improved physician trainee performance can result in improved quality of care for 9 million patients annually. In addition to the direct effect to physician trainees and their patients, the methods developed in this project have the potential to provide objective assessment of current work schedule policies and to estimate projected impact of future policies under consideration.

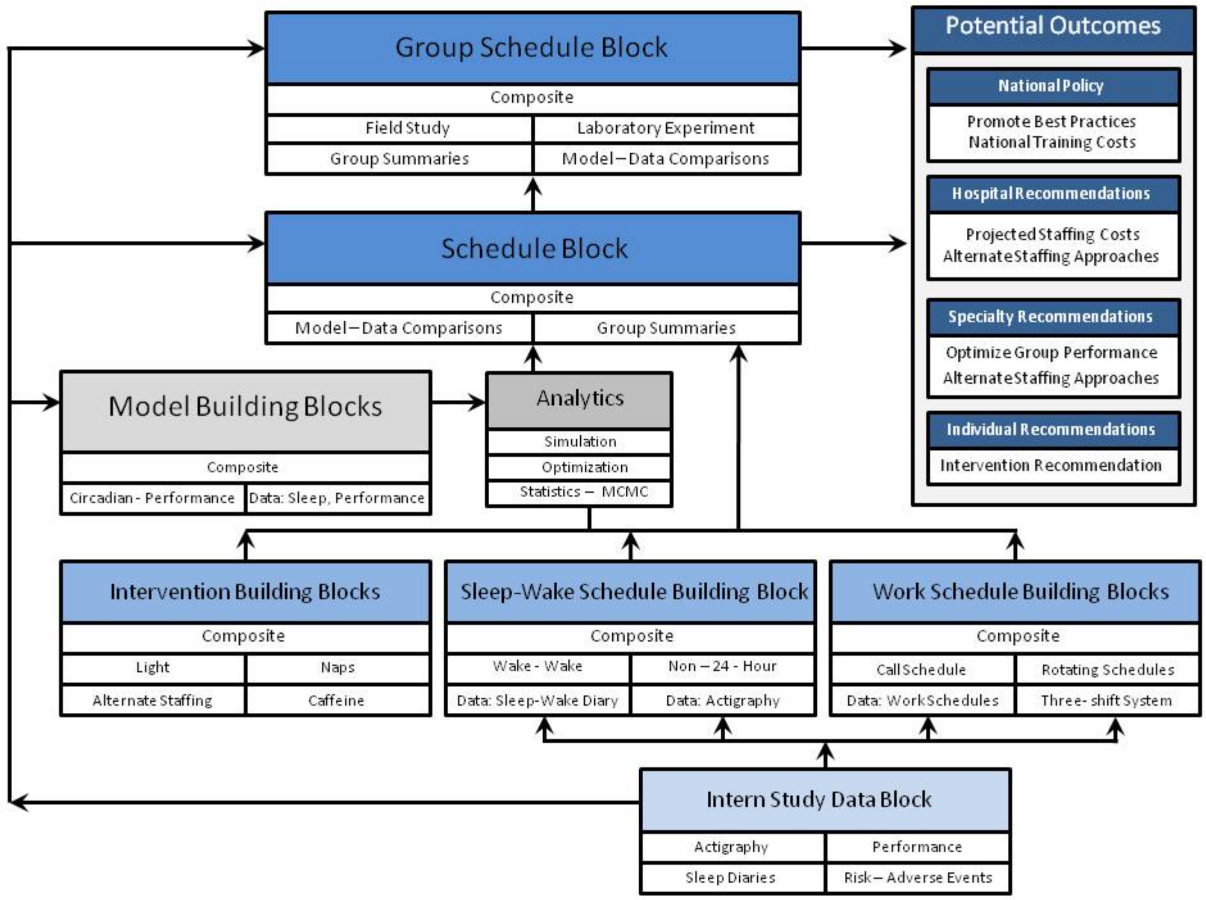

Figure 1: Hierarchical Schedule Design System Schematic. Enhancement of our published schedule building block approach to designing schedules to facilitate the analysis of groups of schedules.

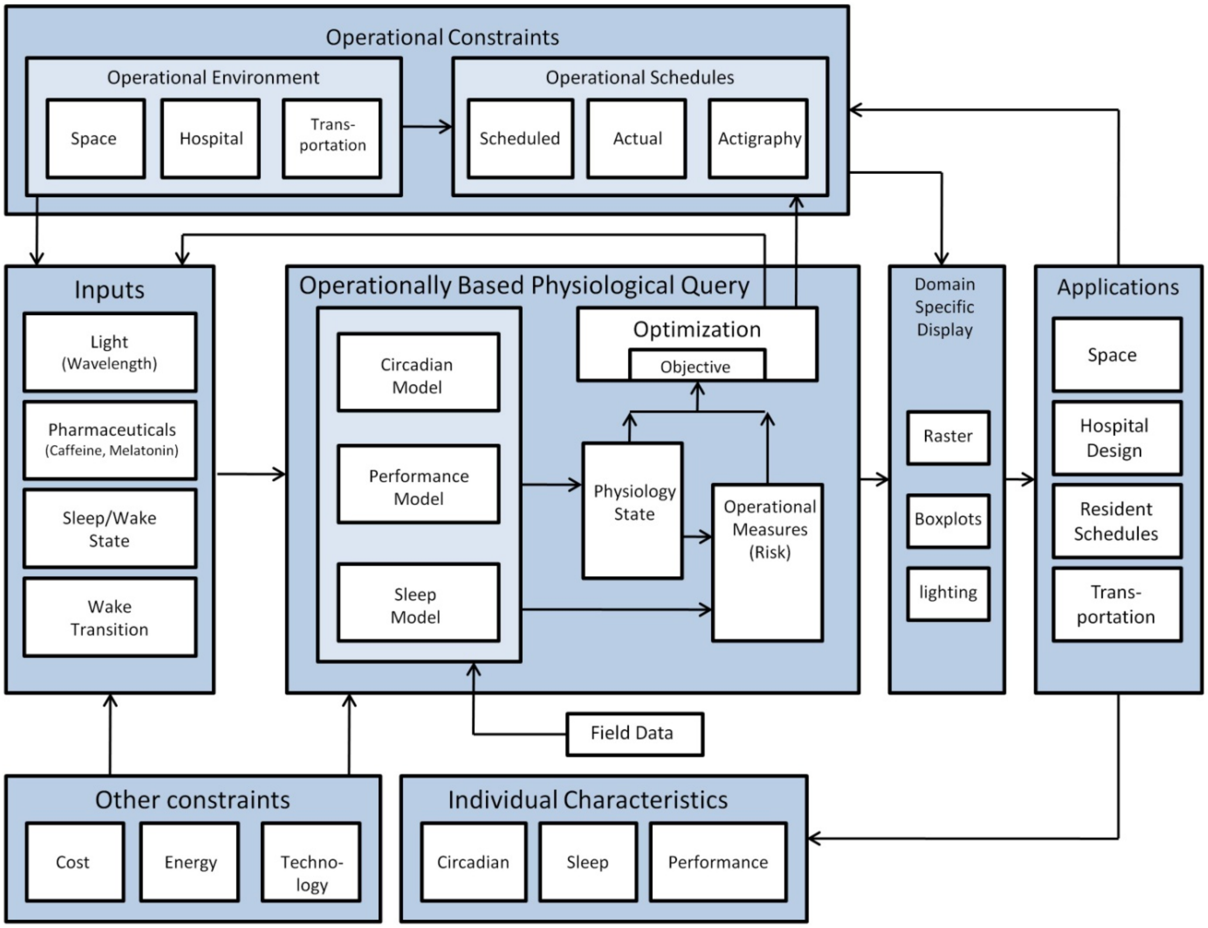

Figure 2: Design of a Flexible Schedule Optimization System. The optimization system uses mathematical models of physiological systems that affect performance to provide a structured approach to quantify the effect of operational schedules and constraints on human physiology. These quantified effects are used with specialized optimization modules called objective functions.

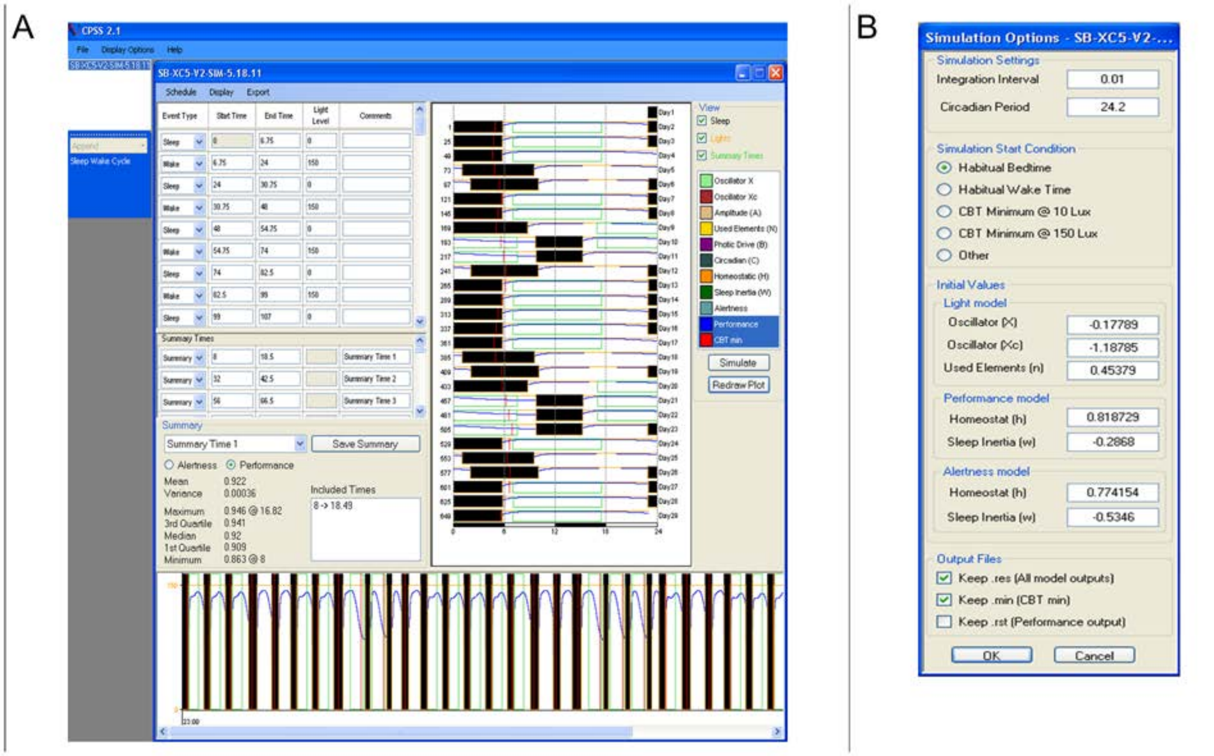

Figure 3: Graphical User Interface within the Circadian Performance Simulation Software. The graphical user interface allows the user to enter a protocol/schedule that includes sleep-wake state and light levels, simulate the schedule, and display the input and result. **(A)** A spreadsheet input allows the user to enter the events that are composed of a duration, light level, and sleep-wake state. **(B)** The contents of the protocol input is shown in a raster format. Each line corresponds to 24 hours of input. Black bars correspond to sleep. **(C)** Selection of items that controls what input and outputs are displayed. **(D)** Panel allows users to select allows the user to the raster plot of the protocol is created as the user enters each entry in the protocol. The user can select protocol regions to summarize and can select information to be displayed in rater plot and in a graph. The user can select a protocol and simulation results on the raster plot and the graph.

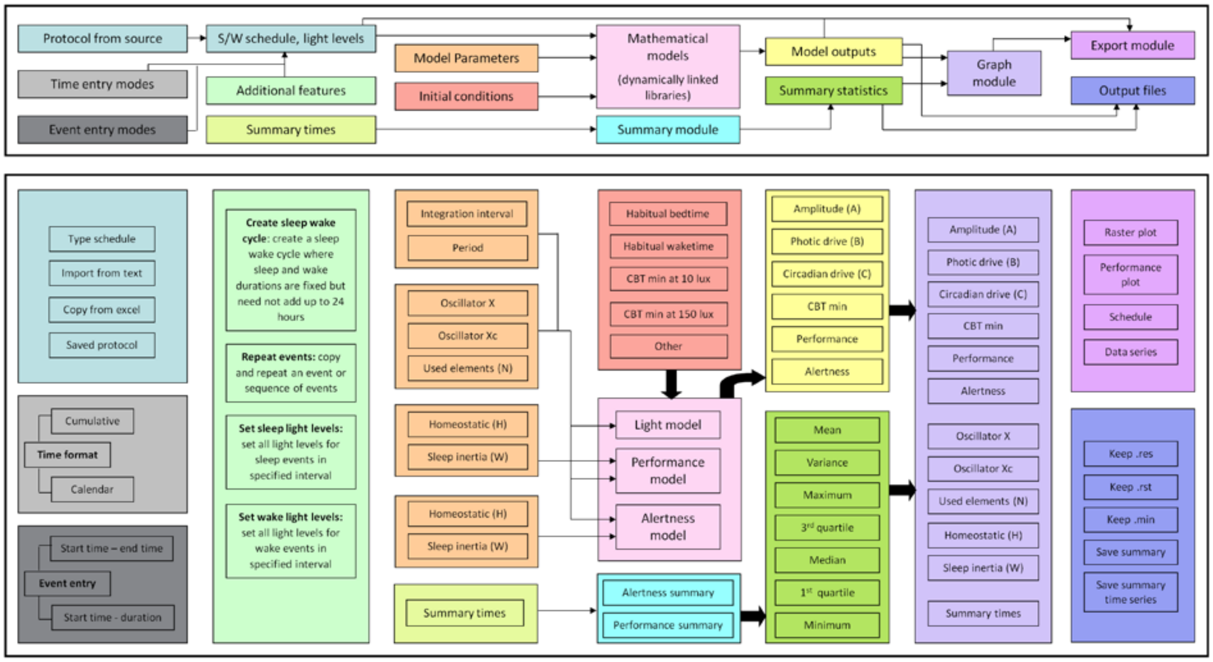

Figure 4: Schematic of the software components within the Circadian Performance Simulation Software (CPSS). A high-level schematic of the software is shown in the top rectangle, with inputs and settings on the left, models in the center, and outputs on the right. The bottom rectangle shows additional software details. Rectangles are color coded between the top and bottom rectangles.

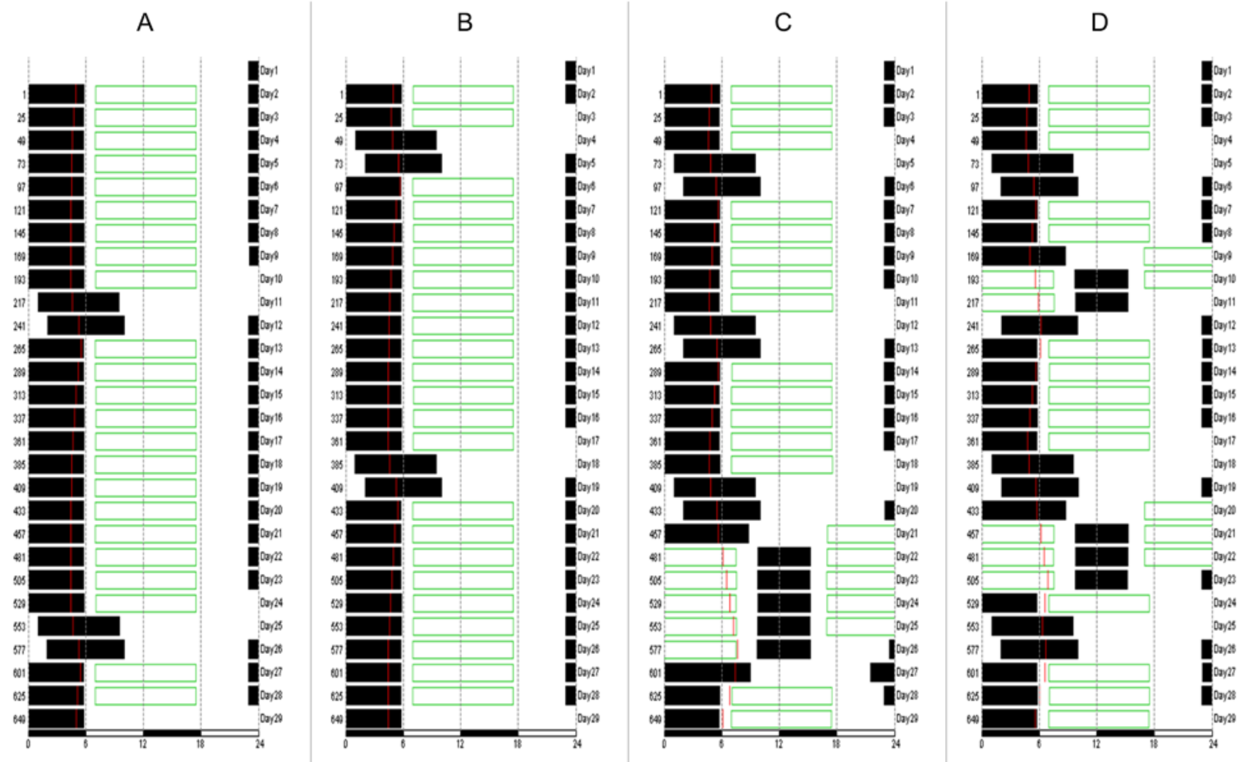

Figure 5: Simulated proposed physician-in-training schedules in raster plot format. Four examples of intervention schedules simulated: (A) the “Intern A” daytime schedule. (B) The “Intern B” schedule slightly staggered from the first. (C) A cross-cover schedule featuring a block of five 14-hour night-call shifts “XC5-V1.” (Intervention Schedule 1). (D) A cross-cover schedule featuring a block of 2, then later 3, 14-hour night shifts spread over the month “XC5-V2.” (Intervention Schedule 2)

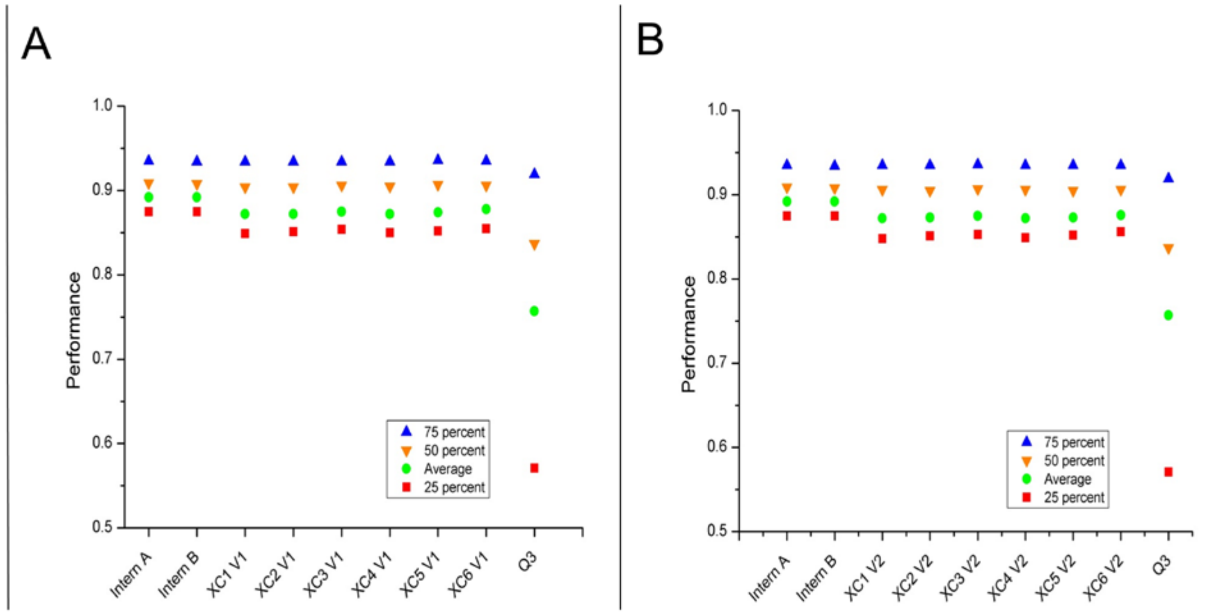

Figure 6: Simulation summary by month for legacy and invention schedule. (A) The month-long statistical results from Schedule 1 (compared with Q3 schedule for reference). (B) The month-long statistical results from the Schedule 2 (compared with Q3 schedule for reference).

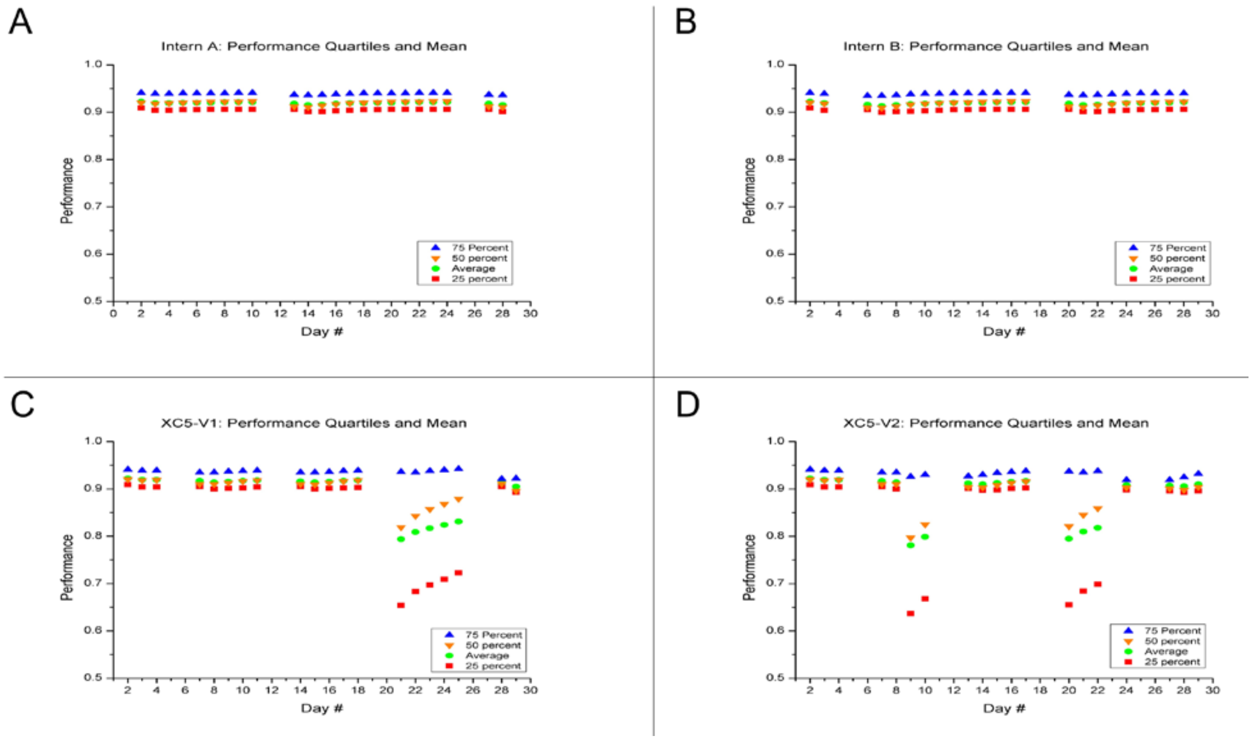

Figure 7: Examples of the plotted summary statistics exported from CPSS: (A) The "intern A" schedule exhibits high performance throughout the rotation due to consistent sleep-wake schedule and daytime orientation. (B) The "intern B" schedule also consistently displays high performance, driving up net performance for any work group that contains these strictly daytime interns. (C) An example of cross-cover schedule 1 for the 5th intern of the cross-cover group "XC5-V1" has high performance throughout most of the month and a block of nights that allows them to adjust to their night schedule and recover from the lowered performance associated with circadian misalignment, which is most severe on night 1 and progressively improves. (D) The second version (schedule 2) of cross-cover 5 has a similar level of performance throughout the daytime portion of the schedule as version one but does not give the interns as much time to adjust to night work and makes them shift back and forth more often.

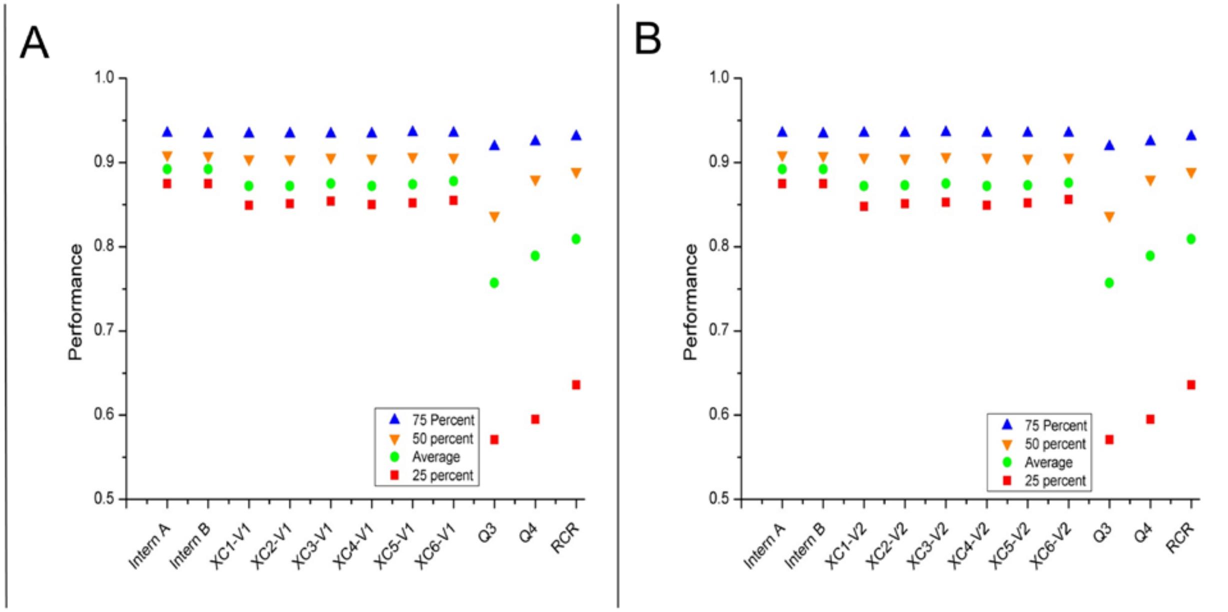

Figure 8: Simulation statistics by month for each schedule over a month. (A) Schedule 1 (V1), Q3, Q4, and RCR schedules**. (B)** Schedule 2 (V2), Q3, Q4, and RCR schedules.

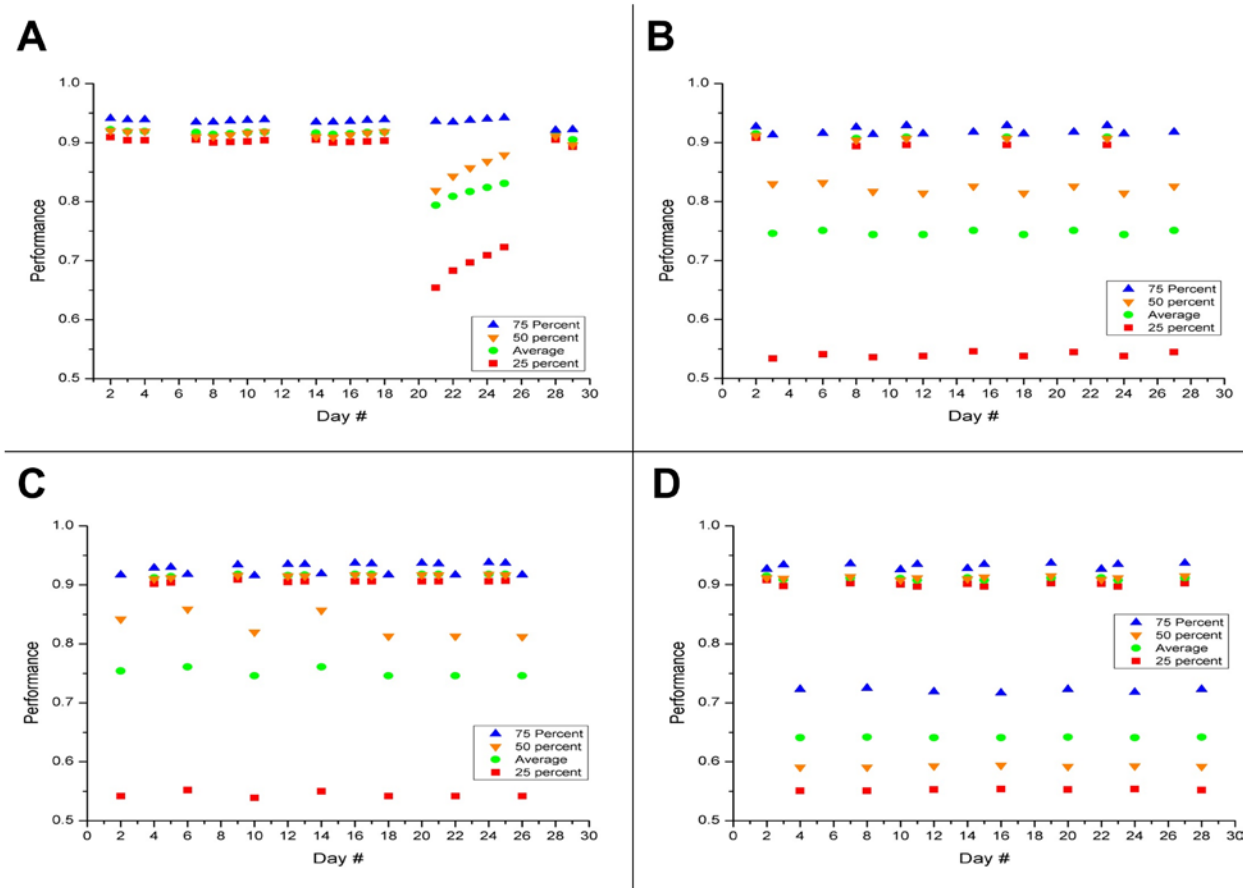

Figure 9: Summary statistics by day for each schedule. (A) The cross-cover V1 schedule, **(B)** Q3 schedule, **(C)** Q4 schedule, and **(D)** “Rapid Cycle Rotation” schedule (RCR).

List of Publications and Products (Bibliography of Published works and Electronic Resources from study

<u>Papers</u>

Dean II, DA, Forger, DB, Klerman, EB. Taking the Lag out of Jet Lag through Model Based Schedule Design, PLoS Computational Biology, June 2009.

<u>Abstracts</u>

Sullivan JP, Evans EE, Cade BE, Landrigan CP, Lockley SW. Predicting risk of cognitive performance decrements in intern work schedules. 11th meeting of the Society for Research in Biological Rhythms (SRBR), 2008

Sullivan JP, Evans EE, Cade BE, Landrigan CP, Lockley SW. Predicting risk of cognitive performance decrements during residents' commute home. 2009 International Conference on Fatigue Management in Transportation Operations: A Framework for Progress; 2009

Dean II, DA, Forger, DB, Klerman, EB. Taking the Lag out of Jet Lag with Model based Schedule Design, Conference of African American Researchers in the Mathematical Sciences, 2009 (Best Algorithm Poster Presentation Award)

Dean II, DA, Forger, DB, Klerman, EB. Using Mathematical Models of Circadian Rhythm and Human Performance to Take the Lag out of Jetlag, SIAM Annual Meeting, 2009.

Dean II, DA, Klerman, EB. From Mathematical Models to Hypothesis Generation: Examples from Experiment and Schedule design, Gordon Conference – Pineal Cell Biology, 2010.

Srinivasan, P, Dean II, DA, Silva, E, Wang, W, Beckett, SA, Duffy, JF, and Klerman, EB. Ambulatory Actigraphy Input to a Circadian-Light Model Can Predict Circadian phase, 18th International Academy of Aeronautics Humans in Space Symposium, 2011.

Srinivasan, P, Dean II, DA, Silva, E, Wang, W, Beckett, SA, Duffy, JF, and Klerman, EB. Comparison of Ambulatory Actigraphy and Sleep/wake Diary Input to a Circadian-Light Model For Predicting Circadian Phase, Sleep 2011, 2011.

Dean II, DA, Beckett, SA, Klerman, EB, Landrigan, CP. Simulations of rotation schedules for teams of resident-physicians can identify potential areas of low performance and guide residency schedule design, Sleep 2011, 2011.

Beckett, SA, Dean II, DA, Klerman, EB, Landrigan, CP. Performance simulations of current and proposed medical intern schedules highlights the need for reform, 20th International Symposium on Shiftwork and Working Time – Biological mechanisms, recovery and risk management in the 24h society, Submitted 2011.

Software

Circadian Performance Simulation Software (CPSS) ver. 2.1. The CPSS is a software application that implements the mathematical models of the effect of light on the circadian pacemaker and a linked model of human performance [5,6]. The software can be used to simulate experimental and operational schedules that results in predictions of circadian phase and human performance. A new version of the software was developed during the course of the grant and is being prepared for public release.

Schedule generation software. A new schedule design framework is proposed to incorporate the challenges identified with simulating residency schedules and comparing the simulation to data collected in the field. Future work will involve implementing the framework, which will allow for evaluation of the applicability of the mathematical predictions to operational settings.

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