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Dysregulation of Inflammatory Responses by Chronic Circadian Disruption

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Circadian rhythms modulate nearly every mammalian physiological process. Chronic disruption of circadian timing in shift work or during chronic jet lag in animal models leads to a higher risk of several pathologies. Many of these conditions in both shift workers and experimental models share the common risk factor of inflammation. In this study, we show that experimentally induced circadian disruption altered innate immune responses. Endotoxemic shock induced by LPS was magnified, leading to hypothermia and death after four consecutive weekly 6-h phase advances of the light/dark schedule, with 89% mortality compared with 21% in unshifted control mice. This may be due to a heightened release of proinflammatory cytokines in response to LPS treatment in shifted animals. Isolated peritoneal macrophages harvested from shifted mice exhibited a similarly heightened response to LPS in vitro, indicating that these cells are a target for jet lag. Sleep deprivation and stress are known to alter immune function and are potential mediators of the effects we describe. However, polysomnographic recording in mice exposed to the shifting schedule revealed no sleep loss, and stress measures were not altered in shifted mice. In contrast, we observed altered or abolished rhythms in the expression of clock genes in the central clock, liver, thymus, and peritoneal macrophages in mice after chronic jet lag. We conclude that circadian disruption, but not sleep loss or stress, are associated with jet lag-related dysregulation of the innate immune system. Such immune changes might be a common mechanism for the myriad negative health effects of shift work. The Journal of Immunology, 2010, 185: 5796–5805.

Nearly 15% of the working population in the United States engage in some sort of shift work (1), loosely defined to include static night shifts, flexible shifts, extended shifts, rotating shifts, and frequent international travel by airline flight crews. The sleep/wake cycle of the shift worker represents a significant departure from the world in which we evolved, where light and dark alternate reliably. The internal circadian clock system evolved as an adaptation to this predictable day/night geophysical pattern, and the biological consequences of living at odds with the normal environmental day/night cycle are just beginning to be appreciated. Exposure to nontraditional work schedules has been linked with increased risks of colorectal (2), breast (3), lymphatic (4), and prostate (5, 6) cancers, as well as with gastric ulcers (7, 8), obesity (9), diabetes (10, 11), stroke (11), coronary heart disease, atherosclerosis, and heart attack (11–14). The mechanisms for these correlations between shift work exposure and disease are unknown, however it is important to note that one common risk factor shared by many of these pathologies is inflammation.

Shift work is a complex lifestyle that to some degree includes exposure to circadian disruption, sleep disruption, altered phase angle of entrainment, and psychosocial stress. However, simple experimental jet lag in rodents reproduces some of the detrimental aspects of this lifestyle. Chronic jet lag (CJL), in which animals are housed in light cycles that are shifted to mimic eastward or westward travel at regular intervals ranging from 2 to 7 d, has been linked to more rapid tumor growth (15), cardiomyopathy (16), increased sensitivity to the intestinal irritant dextran sulfate sodium (17), and nonspecific death (18).

One potential common feature of the negative health consequences of circadian disruption may be the dysregulation of the immune system. Alterations of the sleep/wake cycle affect the number of circulating lymphocytes, NK cells, and Ab titers in humans (19) and rodents (20–22), as well as increased inflammatory cytokines such as IL-6, C-reactive protein, and TNF-α (23–26). When a challenge to the immune system is presented, the effects of these changes translate into impaired immune function. Rats that were sleep deprived showed spontaneously increased bacteremia (27). Humans also exhibited altered cellular immune responses after sleep disruption (28, 29). In many of the studies using sleep disruption, it is difficult to distinguish between effects on the immune system that could only be attributed to sleep loss versus effects of desynchrony or suppression of circadian rhythms. A comprehensive understanding of the effects of circadian disruption on immune function is lacking, but evidence does exist for a bidirec-
tional relationship between the immune system and circadian timing. For example, immune stimulation by the bacterial cell wall component LPS can alter circadian timing (30). LPS can shift the clock (31) and can alter the expression of several circadian clock genes such as Per1 (32, 33), Per2, and dbp (33). It has been suggested that the effects imposed on circadian timing by the innate immune system are mediated by proinflammatory cytokines in the brain (34).

Not only do immune signaling molecules affect circadian rhythms, the circadian system regulates the immune system. Circadian regulation is reported for many immune markers, including IL-2, IL-10, GM-CSF, CCR2, IL-6, IL-1β, TNF-α, MCP-1/2E, IFN-γ, and IFNRs (35–38). Genetic manipulations of circadian timing can modulate innate immunity. For example, the rhythm in IFN-γ seems to be absent in Per2 mutant mice (39), which are also deficient in their ability to produce IL-10 and IFN-γ in response to LPS (40). A dramatic phenotype of early aging and associated chronic inflammation results from the knockout of Bmal1, a uniquely nonredundant component of the circadian clock. Among other pathologies, Bmal1 knockout mice develop progressive corneal inflammation and exhibit decreased numbers of lymphocytes (41). Additionally, mice lacking both clock genes Cry1 and Cry2 exhibit exacerbated cytokine production and joint swelling after arthritic induction (42). Importantly, macrophages display endogenous rhythms in clock gene expression (38, 43), phagocytosis (38), and LPS sensitivity (43).

Regulation of inflammation by the immune system may underlie the pathologies associated with circadian desynchrony. However, much remains unknown regarding the specific effects of circadian disruption on immune function and what in fact is the role of sleep deprivation in these effects. In the present study, we provide evidence that suggests that chronic circadian desynchrony targets the immune system and its ability to adequately regulate inflammation, and that this response is independent of sleep loss or stress.

Materials and Methods

Animals and housing conditions

Per2lox Δ/mice (44), on a C57BL/6 background, 4–8 mo of age from our colony at Morehouse School of Medicine were the subjects in this study. All animals were entrained to a 12-h light/dark (LD) cycle from birth until the beginning of the experiments, with water and food available ad libitum. During light manipulations and during the immune challenge, mice were singly housed in polypropylene cages with no running wheel, inside light-tight boxes with overhead fluorescent lights of an intensity ranging from 200 to 400 lx at the level of the cage. All procedures and protocols were approved by the Morehouse School of Medicine Institutional Animal Care and Use Committee.

Core body temperature and locomotor activity recording

At least 3 wk before any light manipulations occurred, G2 E-Mitters (Respironics, Bend, OR) were implanted abdominally under isoflurane anesthesia. The telemeters allowed for continuous recording of general locomotor activity and core body temperature (Tb) before and during the immune challenge. Tb and locomotor activity recording was initiated 7 d before the LPS injection (the final week of the shift schedule) and continued for 7 d after the challenge was presented. Mice were not chronically recorded for the entire shift schedule due to the limited number of telemetry receivers.

CIL protocol

The 6-h phase advance schedule is described in Ref. 18. Briefly, the 6-h phase advance was achieved by shortening the dark period on the day of the shift. The next shift is administered on the night of the seventh day following. To compare acute versus chronic effects of our lighting manipulation, some groups of mice were exposed to a single phase advance and allowed to acclimatize to the new lights for 1, 2, or 4 wk before challenge, while other sets of animals were exposed to the phase advance once every week during four consecutive weeks. After the last shift, all groups of mice remained in the same photoperiod for at least 7 d of resynchronization before presentation of the immune challenge.

In vivo immune challenge and cytokine measurements

Ultrapure LPS from *Escherichia coli* (0111:B4; InvivoGen, San Diego, CA; 12.5 mg/kg) diluted into sterile PBS was injected i.p. into shifted mice (both one and four shifts groups) at Zeitgeber time (ZT) 3 (3 h after lights-on) on the seventh day after the last photoperiod change. Control mice were also injected with LPS at the same ZT. Body temperature, locomotor activity, and survival were recorded during the 7 d following the injection in some mice, while others with identical light history were bled for cytokine measurements. Serum from shifted mice (four shifts) and unshifted controls was separated from blood collected by retro-orbital bleeding under 2% isoflurane anesthesia at 90 min and 24 h after the LPS injection. Blood was collected in Vacutainer separator tubes (BD Biosciences, Franklin Lakes, NJ), allowed to clot for 30 min at room temperature, and then centrifuged at 9300 rpm for 15 min. Serum aliquots were collected and stored at −20 °C until analyzed. Cytokines levels were determined using a Milliplex MAP (Millipore, Bedford, MA) kit on a Luminex xMAP platform according to the instructions of the manufacturer. Isolated IL-6 measurements from serum were obtained by an ELISA kit (R&D Systems, Minneapolis, MN; product no. M6000B).

In a second experiment, we compared the in vivo cytokine release in response to a smaller, 5 mg/kg sublethal dose of LPS after one shift and four shifts, but varied the duration that the mice were allowed to adjust to the phase shift. We used serum levels of four macrophage-derived cytokines, measured at 24 h postinjection as our readout.

Macrophage (exudate) cultures

Shifted and control mice were sacrificed under 100% CO2 anesthesia, then soaked with 70% ethanol, and a small incision in the medial abdominal section was made through the skin. Next, 10 ml of 5% FBS in ice-cold PBS was injected into the abdominal cavity with a 26-gauge needle, allowing the cavity to seal itself when the syringe was retracted. The mouse was shaken vigorously for 30 s and then the peritoneal exudate cells were withdrawn in solution by extracting the FBS-PBS mix using a 21-gauge needle. Cells were collected into 15-ml tubes, centrifuged at 1500 rpm for 5 min, washed twice with RPMI 1640 media containing 10% FBS, and seeded into 35-mm dishes. The macrophages were allowed to adhere overnight inside an incubator at 37 °C under 5% CO2 according to Handel-Fernandez and Lopez (45). On the next morning, cells were washed with PBS to discard dead and nonadherent cells, and fresh RPMI 1640 media containing 10% FBS and LPS (10 μg/ml) was added for stimulation. Supernatant (200 μl) was collected at times 0, 3, 6, 12, 24, and 48 h after LPS stimulation and then frozen at −20 °C for further IL-6 quantification by ELISA (R&D Systems; product no. M6000B).

Four high-power fields (×20 magnification) were taken from each dish to quantify macrophages during the course of the LPS stimulation. The IL-6 measurements were normalized against the average cell count per high-power field.

Sleep recording during experimental jet lag

Electroencephalograph (EEG) and electromyograph (EMG) electrodes were surgically implanted in six mice for polysomnographic recording of sleep and wake states. Two stainless-steel recording screws (SmallParts, Miami Lakes, FL) were positioned contralaterally to each other on the skull surface. The first was located 1 mm anterior to bregma and 0.5 mm right of the central suture, whereas the second was located 0.5 mm posterior to lambda and 1 mm left of the central suture. A s.c. pocket was created caudally along the dorsal surface using the incision for electrode implantation. A PhysioTel telemeter (model P20-EET; Data Sciences International, St. Paul, MN) was placed in this pocket. EEG leads from the telemeter were attached to the electrode screws with silver epoxy and the assembly was covered with a small amount of dental acrylic. EMG leads from the telemeter were implanted bilaterally into the nuchal muscle. To aid the insertion, a 22-gauge needle was used as a trochar. Leads were sutured to the muscle tissue near the point of entry (6-0 braided silk). All mice were allowed to recover for at least 3 wk prior to recording. First, 1 d of baseline sleep recording was performed. Mice were then placed on a CIL schedule consisting of a 6-h phase advance every week during 4 wk. During the schedule, sleep was recorded continuously during the first 2 wk and during week 4. Polysomnographic recordings were made via a receiver placed under the cage and connected to a personal computer with Dataquest A.R.T. hardware and software (Data Sciences International).

Behavioral and hormonal measurements of stress

Two- to 6-mo-old or 15-mo-old C57BL/6J mice were housed in weekly phase-advancing light cycles. A group of young (n = 4 shifted, 4 control)
and aged (n = 17 shifted, 19 control) were sacrificed after 4 or 12 wk of shifting, respectively. Mice were bled from the orbits under isoflurane anesthesia (aged) or from the trunk following decapitation with no anesthesia (young). Serum was isolated, diluted, and assayed for corticosterone using enzyme immunoassay (IDS, Scottsdale, AZ) or ELISA (B-Bridge International, Cupertino, CA) according to the manufacturers’ instructions. Behavioral tests were performed on another set of mice (n = 14 shifted, 14 control) on the eighth day after the fourth shift. First, total ambulatory distance was measured in a plexiglass open field apparatus with photoelectric detectors (Med Associates, St. Albans, VT) for a total duration of 10 min. Half of the mice from shifted (n = 7) and control (n = 7) conditions were then tested in an open-fronted tail suspension apparatus, in which mice were suspended from their tails for 6 min by adhesive tape to a vertical metal bar equipped with a strain gauge (software and equipment from Med Associates). The other half of the mice from each condition (n = 7/condition) were then tested in a forced swim apparatus (Kinder Scientific, Poway, CA) consisting of clear plexiglass cylinders filled with distilled water (23–25°C) and equipped with photoelectric detectors. For both tail suspension and forced swim tests, immobility time was calculated as the total time of resting (no beam breaks) during the last 4 min of testing. Data were analyzed via independent samples t tests using PASW Statistics 18 (SPSS, Chicago, IL).

Gene expression measurements

Bioluminescence recording of circadian rhythms ex vivo. Both control and shifted mice (6 d after one or four shifts) were sacrificed at ZT 3 (the typical LPS injection time) and the suprachiasmatic nucleus (SCN), liver, spleen, and thymus were explanted and prepared for organotypic culture in a lumicycle apparatus (Actimetrics, Wilmette, IL) as previously described (46). These data were analyzed for both phase (see Fig. 1B) and for other circadian parameters (see Fig. 6A, 6B; 4 wk and control only).

Quantitative real-time PCR. On the seventh day after the last photoperiod shift, peritoneal macrophages were collected from shifted and control mice. RNA was promptly extracted in TRIzol reagent (Invitrogen, Carlsbad, CA), and cDNA was prepared by using the RT2 EZ first-strand cDNA kit (SABiosciences, Frederick, MD; product no. C-09) according to the manufacturer’s instructions. cDNA was amplified on a Bio-Rad CFX-96 real-time system using SYBR Green qPCR Master mix from SABiosciences (product no. PA-010). Specific primers against Per2 (product no. PPM25497E), Bmal1 (PPM25679E), and 18S rRNA (PPM57735E) were also purchased from SABiosciences. Relative expression of clock genes was normalized to the 18S rRNA levels.

Data analysis

Acrophase of the diurnal rhythms of locomotor activity on day 6 after the first and fourth shifts were calculated by a least-squares cosine fit to the raw data in 10-min bins (cosinor analysis, El Temps 1.236, Barcelona, Spain; http://www.el-temps.com). Activity onset on day 6 was the rising 24 mean crossing (50%) of daily activity counts. Core body temperature peak time was the peak calculated by the SinFit (damped) algorithm in LumiCycle analysis (Actimetrics). Phase values are all expressed in ZT.

Analysis of hypothermia during the first part of the immune challenge was achieved by collapsing temperature data into 6-h averages from hours 6 to 30 after LPS injection. Significant differences were determined by repeated measures ANOVA. Statistical analysis of survival was performed using the Cox proportional hazards model in OriginPro 8 (OriginLab, Northampton, MA). Cytokines levels are expressed as picograms per milliliter and statistical differences were determined by Student’s t test or one-way ANOVA. Sleep waveforms were classified by hand in 10-s epochs as wake (low-voltage, high-frequency EEG; high-amplitude EMG), nonrapid eye movement (NREM) sleep (high-voltage, mixed-frequency EEG; low-amplitude EMG) or rapid eye movement (REM) sleep (low-amplitude EEG with a predominance of theta activity [6–10 Hz]; very low amplitude EMG). EEG with a predominance of theta activity [6–10 Hz]; very low amplitude EMG). EEG with a predominance of theta activity [6–10 Hz]; very low amplitude EMG). Sleep latency, vigilance states, and sleep fragmentation were compared among groups by one-way ANOVA and Tukey post hoc test. Amplitude and phase values of ex vivo circadian rhythms were calculated by means of the SinFit (damped) algorithm in LumiCycle analysis software. Statistical comparison of circadian rhythm amplitude and period among groups was carried out using Student’s t test. RNA relative abundance was quantified by the comparative 2−ΔΔCt method as published by Livak and Schmittgen (47). To compare between groups (control versus shifted) relative RNA levels of each individual sample were normalized to the 24-h average value of the controls.

Results

Circadian rhythms are resynchronized at the time of the immune challenge

Using a CJL schedule of once-per-week 6-h phase advances, we challenged CJL-exposed and control mice to an LPS immune challenge. Because the sensitivity to LPS in mice is dramatically affected by the phase at which the challenge is presented (48, 49), we needed to first explore whether 7 d after the last photoperiod change was enough time for mice to resynchronize diurnal rhythms before they were injected with LPS. The mean temperature curves for shifters and controls during resynchronization to the fourth shift of the LD cycle are shown in Fig. 1A (shifters, n = 8; controls, n = 9). The gradual leftward adjustment day over day is apparent in the shifting group, as they re-entrain to the original LD cycle, on which the control mice have been consistently housed. By the last day shown, just prior to the injection the following morning, the curves coincide, indicating that the body temperature rhythms of the shifted mice have fully re-entrained to the new LD cycle. Also, note that the amplitude and waveform of the body temperature curves throughout this record are highly similar between these two groups, suggesting that thermoregulation is normal during re-entrainment.

A more comprehensive analysis of phase is provided in Fig. 1B, where the phases of locomotor activity (one phase shift, n = 6; four phase shifts, n = 8; control, n = 15), body temperature (one
phase shift, \(n = 6\); four phase shifts, \(n = 8\); control, \(n = 15\), and Per2:Luciferase rhythms from four tissues (shifters, \(n = 4–9\)/group; controls, \(n = 7–10\)) are all compared for day 6 of the first and fourth shifts. All phase markers were statistically similar among shifted and unshifted mice on this day just prior to challenge. This was true for both one shift and four shifts, indicating that the chronic nature of the 4-wk shifting schedule does not impair the capacity of mice to re-entrain to the shifted LD cycle.

**LPS injection results in persistent hypothermia and arrhythmicity after four shifts**

After 4 wk of CJL, LPS challenge (12.5 mg/kg) caused deep and persistent hypothermia, accompanied by loss of the nocturnal increase in body temperature (Fig. 2A; shifters, \(n = 5\)). Control mice (\(n = 7\)) became arrhythmic and exhibited less pronounced and less persistent hypothermia. Shifters exhibited an apparently driven rhythm in body temperature, with a peak during the day that was coincident with the environmental temperature inside the chambers (Fig. 2A, blue line). This rhythm was present even after animals had perished. When collapsed over 6-h intervals, body temperature in shifters was significantly lower than in controls (Tukey post hoc pairwise comparisons, \(p < 0.05\)) during the second, third, and fourth intervals (Fig. 2B). Although the mice were recorded for 7 d after injection, later time points were not analyzed in this fashion since most of the shifters died. The survival curves for the two groups are shown in Fig. 2C, which indicates a remarkable difference in survival. The Cox proportional hazards model estimate of risk of death for shifters was 5.7-fold higher than for controls (\(p = 0.032\)).

A single phase shift also resulted in lower mean temperature relative to controls, but only at the fourth 6-h time point (Fig. 2D; shifters, \(n = 5\); controls, \(n = 5\)). Survival appeared lower for shifters (Fig. 2E), but was not statistically different among the groups according to the Cox proportional hazards model or \(\chi^2\) goodness-of-fit for day 7.

**Dysregulation of inflammation during jet lag**

We next attempted to determine whether cytokine signaling was altered in 4-wk shifters that were challenged with LPS compared with unshifted controls. We measured serum levels of a variety of both pro- and anti-inflammatory markers using xMAP multianalyte ELISA. Fig. 3 shows systemic levels of six different cytokines measured at two time points during the inflammatory response to LPS. At 90 min following LPS challenge (12.5 mg/kg), no significant difference was found in any of the cytokines analyzed between shifters and controls. However, at 24 h, proinflammatory cytokines, including IL-1β, GM-CSF, IL-12, and IL-13, were all significantly increased (\(p < 0.05\), \(t\) test; \(n = 8\) shifters; \(n = 5\) controls) compared with levels found in unshifted LPS-injected mice. One anti-inflammatory molecule, IL-10, trended lower (\(p = 0.08\), \(t\) test) in shifted mice 24 h after LPS injection, and TNF-α, an early stage proinflammatory cytokine, was not different between control and shifted mice at either time point tested.

We next used a smaller LPS dose (5 mg/kg) to investigate whether the effects of a single shift of the LD schedule were long-lasting and contributed to the heightened immune response we observed after four consecutive shifts. The smaller dose was used to prevent severe sepsis and death, but still trigger a robust response. We found that when this dose was injected 1 wk after a single phase advance, shifted mice exhibited a similar IL-6 response to controls. However, at 24 h, proinflammatory cytokines, including IL-1β, GM-CSF, IL-12, and IL-13, were all significantly increased (\(p < 0.05\), \(t\) test; \(n = 8\) shifters; \(n = 5\) controls) compared with levels found in unshifted LPS-injected mice. One anti-inflammatory molecule, IL-10, trended lower (\(p = 0.08\), \(t\) test) in shifted mice 24 h after LPS injection, and TNF-α, an early stage proinflammatory cytokine, was not different between control and shifted mice at either time point tested.

**Peritoneal macrophages in vitro**

Since macrophages represent a primary source of cytokines involved in the initial response to LPS, we sought to determine whether macrophages were a target for the effects of CJL on the immune response. Peritoneal exudate cells, comprised mostly of macrophages (45), were harvested and cultured from mice 7 d after the last of 4 weekly phase advances. The number of macrophages we were able to collect was not statistically different between shifted and control unshifted mice (Fig. 4B, inset; \(p > 0.05\); \(n = 8\) shifters; \(n = 8\) controls). The in vitro cytokine response of those cells to LPS, even when normalized to cell number, was dramatically heightened in cultures from shifted mice (Fig. 4B, two-way ANOVA; group, \(p < 0.01\); time, \(p < 0.01\); \(n = 8\) shifters; \(n = 8\) controls). Both pro- and anti-inflammatory markers were significantly increased over controls (Fig. 4C; all comparisons, \(p < 0.01\); \(n = 8\) shifters; \(n = 8\) controls). We also found that exposure to LPS significantly increased the mRNA expression of cytokines, including TNF-α, IL-1β, IL-6, and IL-12, in macrophages from shifters relative to controls (Fig. 4D; all comparisons, \(p < 0.01\); \(n = 8\) shifters; \(n = 8\) controls). These results suggest that macrophages are a target for the effects of CJL on the immune system.
controls), indicating that CJL made macrophages more responsive to this bacterial product.

**Acute or chronic jet lag does not result in sleep loss**

We performed polysomnography to determine whether weekly 6-h phase advances result in sleep deprivation. During 24 h of baseline recording, mice exhibited spontaneous amounts of wake (676.2 ± 26.1 min), NREM sleep (693.8 ± 24.5 min), and REM sleep (70.2 ± 5.7 min) that were similar to previous reports (50, 51), suggesting that they began the protocol with optimal sleep/wake amounts. The circadian distribution of total sleep (457.2 ± 22.5 min during the light phase and 306.8 ± 14.3 min during the dark phase), sleep efficiency, and sleep consolidation were also similar to previous reports. The 24 h average quantity of NREM sleep and wake during the first and fourth phase shifts of days 1 and 6 were similar to baseline (Fig. 5A; shifters, n = 6; controls, n = 6). Rather than sleep loss, we observed an increase of REM sleep on days 1 and 6 of shift 4 (Holm–Sidak post hoc, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B. When compared with baseline recordings on the same mice, only brief arousals (defined as a wake bout with duration <20 s) were significantly increased on days 1 and 6 of shift 4 (Holm–Sidak post hoc test, p < 0.05 versus control). Two measures of sleep fragmentation, stage shifts and brief arousals, are presented in Fig. 5B.

**Central and peripheral rhythms are altered by CJL**

The amplitude and period of the circadian rhythm in mPer2-luciferase was analyzed for four tissues (n = 7–10/tissue and group) from shifted (four shifts) and control mice (Fig. 6). Effects of CJL on circadian timing were tissue-specific in nature. While SCN amplitude was increased by CJL (p < 0.05), thymus amplitude was decreased (p < 0.05). Liver amplitude trended lower for shifters (p = 0.09). Likewise, whereas SCN period was lengthened by ~0.5 h in CJL mice (p < 0.05), liver period was shortened dramatically by nearly 3 h (p < 0.01). Because ex vivo bioluminescence recording was unreliable from primary macrophage cultures due to the inconsistent effects of the isolation procedure on the recorded rhythms, we quantified relative mRNA abundance in these cells using quantitative RT-PCR on discrete cohorts of mice killed at eight times during the day and night. While Period2 mRNA was rhythmic in both groups (Fig. 6C; one-way ANOVA: controls, p < 0.01; shifted, p < 0.02), the peak was delayed by ~3 h in the shifted mice (two-way factorial ANOVA Tukey post hoc test for ZT 18, p = 0.006). While the rhythms in Bmal1 mRNA in control mice were less reliable than those for Per2 (one-way ANOVA, p = 0.06), the apparent maxima in the controls was entirely absent in shifted mice (p = 0.64), resulting in constitutively suppressed levels of Bmal1 transcript.
In this study, we used the *E. coli* endotoxin LPS, at the relatively high doses of 12.5 or 5 mg/kg to induce endotoxemic shock in mice. This is a severe challenge to the immune system that in many ways mimics sepsis (52), the tenth leading cause of death in the United States (53). We observed that chronic circadian disruption administered over 4 wk with a weekly 6-h phase advance resulted in a magnified response to the endotoxin. This change was not due to the shifters being at a different circadian phase than the controls at the time of challenge (48, 49); indeed, it required multiple shifts, as 2 or 4 wk of additional adjustment time to the advanced light cycle following a single shift did not produce the same result as four consecutive shifts.

Hypothermia in response to LPS was the prevalent response from both control and shifted mice. Cytokine signaling has been established as a mediator in the thermoregulatory response during experimental sepsis and endotoxemic shock (54, 55). Mild fever or hypothermia during infection can both serve as effective strategies for host defense (56), but both can also be dangerous if uncontrolled. Control animals were significantly better at emerging from hypothermia to survive the challenge in our study. In this regard, our initial dose of LPS (12.5 mg/kg) tested the ability of the immune system to regulate and control the inflammatory response during endotoxemic shock. Our data indicate that TNF-α levels are similar among shifters and controls at both 90 min and 24 h after challenge. Because this protein is activated early in TLR4-mediated signaling cascade after LPS stimulation, the data suggest that the initial response to LPS is unchanged between groups. It is possible, however, that measurement of TNF-α at an earlier stage could reveal an altered response, since macrophages from shifted mice do show a heightened IL-6 response to LPS stimulation in vitro at even earlier time points. At 24 h after challenge we did observe higher circulating levels of other cytokines such as IL-1β, GM-CSF, IL-12, and IL-13, which are all involved in activation of the system downstream of LPS binding to its receptor. IL-10, a potent anti-inflammatory mediator, was marginally reduced in shifters. Among other actions, IL-10 is known to inhibit IFN-γ, TNF-α, IL-12, IL-1, and IL-6 (57), promoting control of inflammation and eventual resolution of the challenge. In fact, presence of IL-10 in the circulation has a protective role against LPS-induced endotoxaemia in mice (58). These results indicate that the exacerbated response to LPS following CJL is at least partially due to a dysregulated cytokine response involving too much activation, as well as insufficient deactivation. Thus, our results suggest the need to investigate how altered circadian
rhythmicity may impinge on the mechanisms for resolution of endotoxic shock.

Our results show that even a single experience of jet lag worsened the response to high-dose LPS challenge. This raises the possibility that outbreaks of illness during and immediately following transmeridian travel (59) may be at least partially due to the effects of jet lag on the immune system. Immune system changes may also underlie the increased risks of disease in shift-working populations. Certainly, altered innate immune function could upset the balance between host and intestinal microbiota (60) and could exacerbate age-related pathologies such as heart disease, ulcers, and cancers, all of which are more prevalent among shift workers (61). Importantly, our data with a still high, but milder LPS dose (5 mg/kg) indicate that multiple shifts are required for a maximal response, further indicating that our results may be related to the health consequences of long-term shift work.

Our results provide a potential mechanism for earlier observations that showed jet lag-related increases in nonspecific death (18, 62) and colitis in response to an intestinal irritant (17). Importantly, the observation that poor circadian lighting environments may exacerbate pathological immune responses suggests that intensive care units should at least minimize disruption of daily lighting conditions to reduce the risks associated with postsurgical or injury-related infections and sepsis.

One potential mediator of the relationship between the immune and circadian systems is the pineal hormone melatonin (63–67). Melatonin has well-known effects on the immune system, and it may contribute to the control of cytokine action before and during the innate immune response (68, 69). However, because melatonin is not produced by the C57BL/6 mouse due to a mutation in serotonin N-acetyltransferase (70), our mouse model of CJL allows us to focus on the important mechanisms by which circadian disruption may directly alter the regulation of inflammation in the absence of melatonin.

We observed that isolated peritoneal macrophages harvested from shifted mice exhibited an enhanced response to LPS in vitro, identifying these immune cells as a specific target of CJL. A clock in these cells has been recently described that regulates gene expression (38, 43), phagocytosis (38), and LPS sensitivity (43). CJL may fundamentally alter this circadian regulation of macrophage function.

Sleep and stress
Sleep disruption can have profound effects on the immune system. Alterations of the sleep/wake cycle affect the number of circulating lymphocytes, NK cells, Ab titers, and levels of cytokines (19–26, 71), which translate into impaired immune function when an immune challenge is presented (27–29). Shift work may disrupt sleep and thereby lead to secondary effects on health; however, in many cases it is difficult to distinguish between effects attributed to sleep loss and effects on circadian regulation.

In this study, we could not detect evidence of sleep deprivation as a result of our jet lag paradigm. Instead of sleep loss, the data indicate that mice may gradually adjust the phase of their sleep/wake rhythm in a manner very similar to that observed in records of core body temperature (as in Fig. 1A). Therefore, we do not attribute the exacerbated response to LPS evident in shifted mice to a loss of sleep. If anything, we instead found an increase in REM sleep during adjustment to the fourth shift, which may account for the increase in brief arousals we observed on the same day (wake nearly always follows REM). This REM increase could be attributable to mild stress (72) associated with the CJL schedule, although our previous (18) and present work (Supplemental Fig. 2) strongly suggest that neither hormonal nor behavioral measures of stress are increased during or after CJL. Furthermore, a recent study indicates that the peak value, rhythm amplitude, and waveform of corticosterone excretion are not altered during the 2 wk following a single phase advance (73). Altogether, these data strongly suggest that immune changes during and after CJL are due to a mechanism independent of sleep loss or stress.

Rhythm alteration by CJL
To determine the extent to which circadian rhythms in the brain and peripheral tissues, including the immune system, were affected by
CJL, we compared the rhythms of mPer2-luciferase in cultured explants taken from naive and CJL-exposed mice. We observed tissue-specific effects of CJL on circadian parameters suggestive of dysfunction in systemic circadian organization. Phase was fully adjusted for SCN, liver, spleen, and thymus on day 6 after the fourth shift, and was therefore similar among shifted and control mice. However, amplitude of the mPer2-luciferase rhythm was increased in the SCN, but it was suppressed in the thymus (and perhaps liver) by 4 wk of CJL. Peripheral rhythm suppression during CJL observed in this study and in other studies (15) may indicate impaired communication with the SCN, an altered pattern of food intake, or an impairment in the local generation of coherent rhythmicity (perhaps via a loss of synchrony among hepatocytes and thymocytes). It is tempting to speculate that changes in rhythmicity due to CJL might impinge upon proper organ function during endotoxic challenge, as altered liver function resulted from a liver-specific Bmal1 deletion (74). Because the liver contains the largest pool of macrophages in the body, it is responsible for clearance of endotoxin and is a major source of inflammatory mediators during sepsis. The innate immune system and inflammatory processes. We specifically have identified peritoneal macrophages as a cellular target of this manipulation. However, these data do not rule out other systems that may also be negatively affected by circadian disruption. Furthermore, our model of CJL in mice simulates some but not all aspects of human shift work. Dramatic changes in the inflammatory response in our model were evident without the contribution of sleep loss, melatonin suppression, and psychosocial stress in our model, all of which are known to alter immunity in humans. However, we suggest that our results point toward a common mechanism in which lack of adequate circadian regulation results in long-lasting and potentially fatal consequences during an immune challenge. Loss or alteration of clock components has been implicated recently in dozens of diseases in both animal models and human populations, but to our knowledge, this is the first report in which a purely endogenous manipulation of the circadian system in the exacerbated response to LPS that we have observed. Our data identify one important physiological target for CJL: the innate immune system and inflammatory processes. We specifically have identified peritoneal macrophages as a cellular target of this manipulation. However, these data do not rule out other systems that may also be negatively affected by circadian disruption. Furthermore, our model of CJL in mice simulates some but not all aspects of human shift work. Dramatic changes in the inflammatory response in our model were evident without the contribution of sleep loss, melatonin suppression, and psychosocial stress in our model, all of which are known to alter immunity in humans. However, we suggest that our results point toward a common mechanism in which lack of adequate circadian regulation results in long-lasting and potentially fatal consequences during an immune challenge. Loss or alteration of clock components has been implicated recently in dozens of diseases in both animal models and human populations, but to our knowledge, this is the first report in which a purely environmental manipulation of the circadian system causes dysregulation of inflammatory responses potentially mediated by loss or alteration of clock function. Further investigation into the health effects of circadian disruption is clearly warranted.

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Disclosures
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Perspectives
We propose that circadian desynchrony alters components of the innate immune system to affect their response to a challenge. However, we cannot rule out that the effect we observe could result from the chronic alteration of the lighting environment acting directly upon the immune system without the involvement of the circadian clock. Future studies are needed to further clarify the role of the circadian system in the exacerbated response to LPS that we have described. For example, models in which clock function is altered genetically could be challenged with LPS with and without light manipulation. It seems likely that the clock system is involved, as earlier studies have suggested that schedule parameters such as shift direction impinge upon the effects of CJL on health (18), and that generalized stress is likely not involved.

Our data identify one important physiological target for CJL: the innate immune system and inflammatory processes. We specifically have identified peritoneal macrophages as a cellular target of this manipulation. However, these data do not rule out other systems that may also be negatively affected by circadian disruption. Furthermore, our model of CJL in mice simulates some but not all aspects of human shift work. Dramatic changes in the inflammatory response in our model were evident without the contribution of sleep loss, melatonin suppression, and psychosocial stress in our model, all of which are known to alter immunity in humans. However, we suggest that our results point toward a common mechanism in which lack of adequate circadian regulation results in long-lasting and potentially fatal consequences during an immune challenge. Loss or alteration of clock components has been implicated recently in dozens of diseases in both animal models and human populations, but to our knowledge, this is the first report in which a purely environmental manipulation of the circadian system causes dysregulation of inflammatory responses potentially mediated by loss or alteration of clock function. Further investigation into the health effects of circadian disruption is clearly warranted.

References


SUPPLEMENTAL FIGURE CAPTION

Figure S1 Supplemental data on sleep during CJL

A. Waveforms of total sleep for baseline and Days 1 and 6 of Shift 1. Same conventions as Figure 4C. B & C. Waveforms for total sleep were adjusted (Day 1 by 6h leftward, and Day 6 by 2h leftward) in order to compare the amplitude and waveforms across days of the shift. Shift 1 is shown in B, and Shift 4 is shown in C.
SUPPLEMENTAL FIGURE CAPTION

Fig S2  Jet lag does not increase hormonal or behavioral measures of stress

A and B: Serum corticosterone was measured on Day 7 following 4 (A) or 12 (B) consecutive weekly 6h phase advances of the 12:12 light cycle. Subjects in A (n=4 shifted and 4 control) were adult mice aged ~4 months, in B subjects were 18 months (n=17 shifted and 19 controls) at the time of blood collection. C: Mice exposed to 4 weekly phase-advances of the light cycle did not exhibit increased measures of anxiety or depression in the tail suspension (sec. of immobility, n=7 per group), forced swim (sec. of immobility, n=7 per group) or open field (total ambulatory distance, n=14 per group) tests. All comparisons not significant.