



Published in final edited form as:

Semin Cardiothorac Vasc Anesth. 2015 March ; 19(1): 49–60. doi:10.1177/1089253214553066.

Circadian Rhythms in Anesthesia and Critical Care Medicine: Potential importance of circadian disruptions

Jason Brainard¹, Merit Gobel¹, Karsten Bartels¹, Benjamin Scott¹, Michael Koeppen^{1,2}, and Tobias Eckle¹

¹Department of Anesthesiology, University of Colorado Denver, CO, USA

²Department of Anesthesiology, Ludwig-Maximilians-University, Munich, Germany

Abstract

The rotation of the earth and associated alternating cycles of light and dark—the basis of our circadian rhythms—are fundamental to human biology and culture. However, it was not until 1971 that researchers first began to describe the molecular mechanisms for the circadian system. During the last few years, groundbreaking research has revealed a multitude of circadian genes affecting a variety of clinical diseases, including diabetes, obesity, sepsis, cardiac ischemia, and sudden cardiac death. Anesthesiologists, in the operating room and intensive care units, manage these diseases on a daily basis as they significantly impact patient outcomes. Intriguingly, sedatives, anesthetics, and the ICU environment have all been shown to disrupt the circadian system in patients. In the current review we will discuss how newly acquired knowledge of circadian rhythms could lead to changes in clinical practice and new therapeutic concepts.

Circadian Rhythms: ‘External Cues’ vs ‘Internal Clock’

What would happen if there was no light? What would control the biological rhythm of a human being or a plant? Jean-Jacques d’Ortois de Mairan asked this question in 1729¹ when observing the movement of the leaves of a plant in synchrony with sun light. He noted that a 24-hour pattern in the movement of the leaves of the *Mimosa pudica* plant continued even when the plant was kept in constant darkness. He concluded that there must be an ‘internal clock’ that provided a circadian rhythm even without the presence of light. More than 200 years later, Jürgen Aschoff applied similar methods to investigations in humans by building an underground “bunker” to isolate human subjects from any external environmental cues.² Aschoff’s research demonstrated that humans exhibited a persistent 25-hour biological cycle. This 25-hour cycle is similar to previous studies examining the circadian rhythms of blind persons.³ However, it was not until researchers began experimenting with the circadian system in *Drosophila melanogaster* in the 1970’s, that identification of gene loci such as *Clock* or *Period* were identified as important regulators of these processes⁴ (Figure 1). Results demonstrated that when *Clock* or *Period* genes were disrupted in animals, the circadian rhythm was severely compromised in conditions of

Correspondence should be addressed to: Tobias Eckle, M.D., Ph.D., Associate Professor of Anesthesiology, Cardiology and Cell Biology, Department of Anesthesiology, University of Colorado Denver, 12700 E 19th Avenue, Mailstop B112, RC 2, Room 7121, Aurora, CO 80045; Office: +1-303-724-2932 or -2947, Fax: +1-303-724-2852, tobias.eckle@ucdenver.edu.

constant darkness. To emphasize the endogenous self-sustained nature of biological rhythms, Franz Halberg coined the term circadian (Latin: circa=about; dies=day) time to refer to daily rhythms that are endogenously generated.⁵ As such, any biological process in the body that repeats itself over a period of approximately 24-hours and maintains this rhythm in the absence of external stimuli is termed a *circadian rhythm*.

In contrast, the term “zeitgeber” (German for “time giver” or “synchronizer”) was first used by Jürgen Aschoff to emphasize the existence of exogenous (external) cues that influence the timing of these internal clocks.⁶ To maintain circadian synchrony, ‘zeitgebers’ induce changes in the concentrations of the molecular components of the clock to levels consistent with the appropriate stage in the 24-hour cycle, a process termed entrainment (Figure 1). Thus, circadian entrainment describes a biological rhythm that is synchronized with the external physical environment. The most dominant zeitgeber appears to be sunlight, not surprising, as it is the strongest and most dependable representation of the time of day.^{7,8}

As such, a hallmark of the mammalian circadian pacemaker – located in the suprachiasmatic nuclei (SCN) within our brain – is its ability to be synchronized by light, thus allowing organisms to adapt to temporal variations in natural light conditions.⁹ Photic stimuli are transmitted from the retina to target neurons in the brain, where they are transduced to the molecular clockwork.^{10,11} Light activation of melanopsin receptors¹¹ in the retinal ganglion cells leads to the transcriptional induction of circadian rhythm proteins (such as Clock, Bmal1, Rev-Erb, Period 1, Period 2, Cryptochrome 1 and Cryptochrome 2) and concomitant synchronization. Peripheral tissues display oscillations in circadian rhythm protein expression similar to those of the brain,^{12,13} likely through secreted signaling molecules (Figure 1).^{10,14,15}

Although it is now accepted that a component of our genome reflects the evolutionary influence of the earth’s daily rotation about its axis,¹⁶ little is known about how disturbances in this circadian system affect patient health and clinical outcomes. Further basic and clinical research addressing the importance of circadian rhythms in the context of critical care and anesthesia is highly warranted and necessary to develop a better understanding of complex pathophysiology and novel diagnostic and therapeutic approaches.

The Biology of Light

Earth’s 24-hour rotational cycle with its night and dark periods has existed for more than 4 billion years and has led to the evolution of circadian rhythms in most organisms. Studies in numerous species have demonstrated that daylight is a powerful synchronizer which resets, in an intensity-dependent manner, endogenous circadian pacemakers.^{17–21}

One of the most remarkable and measurable biological effects of light is suppression of melatonin production.²² In 1980, a study demonstrated that bright light, both sunlight and intense artificial light, could suppress melatonin production in humans.²³ This research confirmed that humans have biological rhythms cued by sunlight and further, suggested that bright artificial light could be substituted for sunlight in order to experimentally, and perhaps therapeutically, manipulate biological rhythms in humans.

Sunlight has an intensity of greater than 10,000 lux, while ordinary room light is approximately 200 lux. It is compelling that light of different intensities appears to have different effects on the human body. For greater than 4 billion years, life outside of the Earth's poles and deep oceans has evolved under consistent bright days and dark nights. With the widespread adoption of artificial electric lighting approximately 150 years ago, humans began brightly illuminating their nocturnal environments. Beyond affecting circadian rhythms, recent evidence suggests that exposure to unnatural light cycles increases the risk for cancer²⁴, sleep disturbances²⁵, and mood disorders²⁶. Further, exposure to nighttime light has been linked to changes in metabolism. Shift workers who experience sustained nighttime illumination are at increased risk for cardiovascular disease and elevated body mass index²⁷⁻³⁰ and nighttime light exposure at home is associated with increased body mass, waist circumference, elevated triglyceride levels, and poor cholesterol balance.³¹

Impact of Circadian Rhythms on Specific Clinical Disorders

While the analysis of circadian rhythm proteins and their misalignment in humans is difficult to assess, melatonin levels seem to be an excellent surrogate for a 'normal' circadian rhythm.³² As such sleep restriction has been shown to affect melatonin levels and circadian rhythms in humans.³² On a molecular level, a mutation of the human circadian rhythm protein Per2 leads to a sleep disorder that is known as 'familial advanced sleep-phase syndrome (FASPS)'.³³ Interestingly, to identify somebody with this disease, tests on melatonin levels after dawn are widely used and validated.³⁴

Recent research has revealed that sleep duration has decreased in the United States.³⁵ Simultaneously the prevalence of metabolic disease has increased over the same time period.³⁵ Numerous cross-sectional and prospective clinical studies have demonstrated that shorter-duration and poor-quality sleep predicts the development of obesity and type-2 diabetes after age, body-mass-index and various other confounding variables are taken into account.^{32,36-41} In one study, sleep restriction to four hours for six consecutive nights led to an impaired insulin sensitivity in a glucose challenge test.⁴² These observations argue for the involvement of circadian rhythms in the pathogenesis of diseases including diabetes and obesity. However, specific knowledge of circadian rhythm proteins and their molecular mechanisms will be required to prove causality.

Disruption of circadian rhythms based on genetic studies, leads to a variety of central nervous system disorders. Examples include the above mentioned sleep disorders (delayed or advanced sleep phase disorder^{33,43}) but also bipolar affective disorders.⁴⁴ Specific genetic variations in circadian clock genes have been identified for bipolar disease and schizophrenia,⁴⁵ and genetic polymorphisms in several clock genes have been linked to sleep disorders.⁴⁶

In addition to central nervous system disorders, epidemiological studies have demonstrated that late-shift and overnight workers have a higher incidence of cardiovascular disease.^{27,47-52} Evidence of an association between disrupted circadian rhythms and cardiovascular disease has been established in research on blood pressure,⁵³ heart rate,⁵⁴ endothelial function,⁵⁵ and the onset of myocardial infarction and stroke.^{55,56} These clinical

conditions all have distinct circadian patterns and disruption of biological rhythms may in particular contribute to the development of cardiovascular disease.⁵⁷ Other clinical diseases including cancer, diabetes and metabolic syndrome have also been associated with disrupted circadian rhythms.^{36–40}

Unfortunately, genetic studies on circadian rhythm proteins in relation to those specific diseases are rare. A few polymorphisms of clock genes have been found in humans that are associated with metabolic diseases. For example, polymorphisms in *Clock* and *Bmal1*, have been linked to features of the metabolic syndrome. In small sample populations, polymorphisms in the *Clock* gene have been correlated with predisposition to obesity,^{58,59} and two *Bmal1* haplotypes are associated with type 2 diabetes and hypertension.⁶⁰ Polymorphisms within other clock core genes (i.e. *Per2*) have been associated with hypertension and high fasting blood glucose in studies of similar sample size.⁶¹

Recently, several genome-wide association studies led to the unexpected discovery that melatonin, a hormone implicated in seasonal and circadian rhythms -as pointed out earlier-, may be important in the regulation of mammalian glucose levels.^{62,63} Indeed, genetic variants of the melatonin 1B receptor gene (*MTNR1B*) increase type 2 diabetes risk. In line with their role in type-2 diabetes, *MTNR1B* is expressed in pancreas cells, and melatonin modulates glucose-stimulated insulin secretion.⁶⁴ Interestingly, melatonin secretion is reported to be impaired in type 2 diabetic patients⁶⁵ and the melatonin profile relative to the feeding/fasting cycle is reversed when individuals are subjected to forced dyssynchrony.⁶⁶ These findings raise the possibility that disruption of circadian systems, either directly at the level of altered clock gene expression, or indirectly through effects on melatonin, may contribute to human metabolic syndrome and cardiovascular disease.

Novel Molecular Mechanisms

The organ-specific role of circadian rhythm proteins in the development of clinical disease has been an area of intense research over the last few years and significant advances in this field have recently been achieved. When specific circadian rhythm proteins are absent in mice, these animals develop similar medical conditions to those described in late-shift workers or patients with presumably disrupted circadian rhythms (Figure 2).

The *Clock* protein represents an important pacemaker of the circadian network acting in the SCN (Figure 1). When the *Clock* gene is deleted in mice, these animals develop 'late-shift diseases' including diabetes¹⁵ and cardiovascular disease.⁶⁷ *Clock* even directly influences the endocrine function of the pancreas. When *Clock* is specifically deleted from the pancreas, mice are unable to secrete insulin and develop type-1 diabetes (Figure 2).⁶⁸

Cryptochromes are another group of proteins known to play a role in circadian rhythms and have also been linked to the development of disease. Cryptochrome deficient mice exhibited enhanced aldosterone production leading to arterial hypertension⁶⁹ or disrupted regulation of hepatic gluconeogenesis and insulin resistance (Figure 2).⁷⁰

Acute myocardial infarction is one of the most well documented acute disease states with a diurnal or circadian incidence.^{71–73} Investigations into the molecular mechanism of this

clinical observation linked the circadian rhythm protein Per2 to myocardial ischemia.^{13,15,71,74} In a mouse model of myocardial infarction, infarct sizes exhibited a circadian pattern. Furthermore, Per2 deficiency increased the size of myocardial infarcts. In contrast, when Per2 was overexpressed by intense daylight exposure, the size of the necrotic area after myocardial infarction was significantly reduced.¹³ This study also reported elevated Per2 levels in human heart tissue of patients suffering from ischemic heart failure (Figure 2).¹³

Further studies have linked Per2 to non-cardiac peripheral ischemia. Lack of the Per2 protein was injurious in a murine model for hind limb ischemia, leading to auto-amputation of the affected legs.⁷⁵ In addition, Per2 seems to be involved in modulating the inflammatory response to tissue ischemia.⁷¹ Together, these findings indicate an important role for the circadian system, and in particular the Per2 protein, in tissue ischemia.

Sudden cardiac arrest, often a consequence of cardiac arrhythmias, also exhibits a circadian pattern. A recent study identified a transcription factor, krueppel like factor 15 (Klf15), as an important regulator of cardiac potassium channels.⁷⁶ Klf15 was shown to be transcriptionally under the control of the circadian rhythm proteins. Disruption of certain circadian rhythm proteins (Bmal1 or Per2) resulted in marked action potential prolongation due to near complete elimination of the fast component of the transient outward potassium current. As a result, deficiency or excess of Klf15 caused loss of rhythmic QT variation, abnormal repolarization and enhanced susceptibility to ventricular arrhythmias. These findings point to circadian transcription of ion channels as a mechanism for cardiac arrhythmogenesis (Figure 2).

Finally, several recent studies found an association between circadian rhythms and the immune system. In particular, Toll-like receptors (TLRs) seemed to be substantially regulated in a circadian pattern. TLRs are a class of proteins that play a key role in innate and adaptive immunity and have been implicated in several diseases, including sepsis, various immunodeficiencies, atherosclerosis, asthma and myocardial ischemia.⁷⁷ In this recent study, TLR9 exhibits circadian regulation in mice. This means that the inflammatory response to severe infection, as occurs in sepsis, is likely oscillating in a circadian fashion.⁷⁸ Other studies have demonstrated that the transcription factor Rev-Erb (Figure 1), an important regulator of the circadian network, also influences the synthesis and secretion of Interleukin-17 from T helper cells.⁷⁹ Interleukin-17 producing T helper cells are pro-inflammatory immune cells and circadian disruption has been associated with elevated intestinal T(H)17 cell frequencies and increased susceptibility to inflammatory disease (Figure 2).⁷⁹

Taken together, this group of recently published studies indicate a very important role for the circadian rhythm network and its regulation in the development and progression of various diseases, including diabetes, hypertension, heart disease and sepsis. More specifically, this work has begun to describe the precise functions of the circadian proteins in peripheral organs and the mechanisms by which they may contribute to many of the most important human diseases. Further clinical studies in humans are needed to apply this emerging knowledge to novel diagnostic and therapeutic strategies.

Implications for Clinical Practice

An improved understanding of the association between circadian rhythms and specific disease states could lead to significant changes in clinical practice and patient outcomes (Figure 2). Timing of therapeutic interventions, ranging from medication delivery to major surgery,^{80,81} may be altered based on comprehension of these biological systems. Research in chronotherapeutics⁸² has already revealed promising results by improving the therapeutic index of several drugs. Chronotherapeutics is defined as medical treatment administered according to a schedule that corresponds to a person's daily, monthly, seasonal, or yearly biological clock, in order to maximize the health benefits and minimize adverse effects. For example, as a result of circadian variations in cholesterol synthesis (via the diurnal rhythmicity of the rate limiting enzyme HMG-CoA reductase) the efficacy of cholesterol-lowering statin medications is improved when these drugs are taken at bedtime. Interestingly, one of the first wide-scale application of chronotherapeutics was in the 1960s and entailed synthetic corticosteroids.⁸³ However, the results did not necessarily translate to major changes in modern clinical practice or if changes were made they might not be recognized as chronotherapeutics.^{84,85}

Recent studies on blood pressure medication made clear that bedtime administration is more effective than administration during morning hours. In addition, reduction in blood pressure during sleep has been identified as the most significant predictor of decreased cardiovascular risk in patients. As such, patients with chronic kidney disease have a high prevalence of increased blood pressure during sleep and a blunted sleep-time-related blood pressure decline (a 'non-dipper' pattern) which is associated with disease severity. Administration of blood pressure lowering drugs at bedtime could therefore lead to significant improvement in this clinical setting.^{80,86}

Inpatient insulin dosing may be optimized by incorporating recent evidence that supports a circadian pattern to insulin secretion and insulin sensitivity⁸⁷. Further studies are required to determine the appropriate dosing and glucose level associated with best outcomes given the known dysfunction in the circadian system associated with critical illness.⁸⁸ Similarly, the improved clinical outcomes associated with intermittent versus continuous tube feeding may ultimately be explained by circadian patterns of hepatic metabolism.⁸⁹

Circadian variation in immune system function may have broad impact in infectious disease states including sepsis and septic shock. The use of corticosteroids remains a common, albeit controversial adjunct therapy for septic shock.⁹⁰ Sepsis has been shown to be associated with elevated serum concentrations of IL-17, which can in turn be dampened by treatment with hydrocortisone.⁹¹ Given the nature of circadian rhythms and a recently described regulation of IL-17 by the circadian clock,⁷⁹ it is possible that the efficacy of corticosteroids in the management of sepsis could be greatly enhanced by synchronizing administration with these rhythms. Moreover, the clinical chronotherapy of corticosteroids might not only improve desired effects but, at the same time, avoid or minimize their side effects.

While some therapies, including anticoagulants, might already be administered at the correct time of day (we know, for example that in the early morning hours coagulation is enhanced)

it remains unclear if these therapies are also effective when the normal circadian system has been disrupted. Successful pharmacotherapy may necessitate moving beyond identifying the optimal time of day for administration of a given drug (Figure 2). Indeed, restoration of a nonfunctional circadian system might be required before a treatment can be most effective. Daylight (and 'real' night) simulation on ICUs or novel drugs that could resynchronize the circadian system (Rev-Erb-agonists⁹²) hold promise as emerging therapies to restore circadian function.

Circadian Rhythms in Anesthesia

Analgesics including narcotics and various local anesthetics are used on a daily basis by anesthesiologists. Early on researchers discovered a time of day dependency for morphine-induced analgesia and duration of action for local anesthetics.^{93–95}

Interestingly, recent reports support a strong association between surgery under general anesthesia and disturbances in circadian rhythms. It is proposed that these disturbances may lead to postoperative sleep and cognitive disorders.^{96–98} Specific medications used during general anesthesia are thought to play a role in these circadian disruptions. Clinically, many patients experience profound sleep disruption and delirium following surgery and general anesthesia. Managing this effect has the potential to help expedite postoperative recovery and improve postoperative cognitive function. Restoration or resetting of the circadian rhythm following general anesthesia might help to blunt or alleviate symptoms of insomnia, confusion, and post-operative delirium. The prevention of postoperative delirium is critically important given the strong association between post-operative delirium and increased morbidity and mortality.^{99–104}

Circadian Rhythms in Critical Care Medicine

a) Effects on Sleep and Cognitive Function

Critically ill patients suffer from similar disruption in circadian rhythms and the clinical effects of altered sleep-wake cycles and cognitive dysfunction.^{105–109} Medications utilized in the care of critically ill patients overlap and have similar pharmacology with those used in general anesthesia and thus the clinical effects of altered-sleep wake cycles and cognitive function are similar. Sedative medications utilized by critical care practitioners in the treatment of agitation, delirium and insomnia likely lead to worsening of these disorders.^{110–112} Benzodiazepines appear to be one of the worst offenders and thus many experts advocate for discontinuing their use in critically ill patients.^{112–115} Unfortunately, almost all sedative agents are associated with delirium and appear to worsen sleep quality.^{110,111,116} Dexmedetomidine may be associated with the least risk of developing delirium.^{117–120}

As discussed earlier, endogenous melatonin might play an important role in the development of circadian rhythms associated diseases.^{62,63} Critically ill patients tend toward altered sleep patterns but also abnormal levels of melatonin. Results on melatonin expression have generated interest in the use of exogenous melatonin and melatonin agonists to improve sleep and cognitive function.^{104,121} Earlier this year, a promising randomized controlled trial

demonstrated effectiveness in the use of a melatonin agonist (Ramelteon) versus placebo in the prevention of delirium.¹²¹ In the context of a possible melatonin-circadian rhythm-clinical disease axis, studies on endogenous and exogenous melatonin, pharmacological agonists, and associated genetics could provide important insight into the development and treatment of critical illness.

In general, the hypothalamic-pituitary-adrenal (HPA) axis is also under the control of the circadian rhythm and plays an important role in critical illness and sleep wake patterns.^{122,123} A prospective, observational study involving 24 critically ill sedated patients demonstrated the 24-hr profiles of blood melatonin or cortisol were greatly disturbed or even abolished compared with the well-known rhythmic 24-hr patterns in healthy control subjects.¹²⁴ Currently, there are gaps in our understanding of secretory patterns and control of cortisol during illness, and these gaps limit our ability to design optimal therapeutic regimens.¹²³

Finally, environmental factors play a substantial role in the disruption of sleep-wake cycles. Critically ill patients in the intensive care unit suffer from more frequent sleep deprivation and sleep disturbances than patients on a general ward.^{105,106,125} Several factors can contribute to the increase in altered sleep-wake cycles, including noise, patient-care interactions, mechanical ventilation, pain, artificial light, fatigue, stress, delirium and other cognitive dysfunction.^{126,127} These same factors likely contribute to the increased risk of developing severe circadian rhythm disruptions (Figure 3). Clinical research concentrating on the circadian disruptions and whether interventions to maintain normal sleep-wake can improve patient outcomes are warranted.

b) Effects on Sepsis and Disease Progression

Critically ill patients, and in particular patients diagnosed with sepsis, have been shown to exhibit a very distinct metabolic phenotype.¹²⁸ These patients experience dysfunction in mitochondria, endothelia, NO synthesis and pyruvate dehydrogenase.¹²⁸ Previous studies have established that the above defects are all associated with a dysfunction of the circadian rhythm protein Per2 (Figure 4).^{13,71,75} Two recent clinical trials demonstrate disrupted circadian system function in patients with severe sepsis as demonstrated by urinary 6-sulfatoxy-melatonin production.^{129,130} This dysfunction was not observed in critically ill patients without sepsis.¹²⁹ In a rat model of sepsis, survival improved in animals maintained on a circadian light/dark cycle.¹³¹ Thus, restoration of a circadian rhythm with normal Per2 levels could be beneficial in restoring the metabolic disruption associated with sepsis (Figure 4).

Therapy

a) General Considerations

Restoration of an intact circadian system is likely complex given the multifaceted etiology for these disruptions. Genetic factors (polymorphisms in core clock genes), medications (anesthetics, benzodiazepines), and environmental factors (noise, artificial lighting) can all result in disruption of the circadian system. Biologically, circadian rhythms are controlled by a cyclical expression of circadian genes. Mutations in these genes could result in a

modification or disruption of the circadian oscillator and therefore it is important to analyze genetic factors that may contribute to circadian disruption.¹³² The discovery of novel genes involved in circadian rhythm-related diseases will open up new opportunities for therapy and can serve as biomarkers for identification and prognosis (Figure 5).

As above, avoidance of offending medications and improved environmental conditions may prevent the development and/or increase the native ability of the body to maintain or restore an intact circadian system. Clinical outcome research is warranted to test this hypothesis. Studies in ICU and non-ICU patients have demonstrated a decreased incidence in delirium and improved sleep/wake cycles with non-pharmacological and environmental treatments.^{133,134} Treatments may be very simple and cost-effective, including earplugs and eye masks^{135–137} and early mobilization.^{138,139} Future trials will help clinicians navigate the risks and benefits of interventions that may disrupt sleep and circadian function and develop guidelines for most effective patient care.

Beyond prevention of circadian disruption, it may be that enhancement of normal circadian rhythmicity has a role to play in disease states like sepsis. Recent efforts led to the discovery of specific enhancers of the circadian rhythm proteins. Compounds such as a 'RevErb' agonist⁹² were shown to enhance the amplitude of circadian rhythmicity and - even more important- were able to improve metabolism in mice.^{92,140} In addition to restoration of circadian cycles, these medications may become promising drugs in the treatment of diabetes, myocardial ischemia, sepsis and other circadian associated illnesses (Figure 6).

b) Light Therapy

Given the primary importance of light in the control of circadian rhythms,^{7,8} it can be postulated that exposure to light might be preventative or therapeutic in the treatment of circadian related illnesses. Artificial light is not as effective as sunlight in entraining the circadian oscillator due to its significantly lower intensity.^{23,141} and even if timed appropriately, may result in chronic circadian misalignment.¹⁴¹ Evidence demonstrates an association between artificial indoor lighting a deregulation of hormonal rhythms.¹⁴² Although studies from our group indicated daylight exposure in animals increased the expression of Per2 in the heart, ultimately resulting in cardio-protection, the exact timing and intensity of this exposure is unclear. Studies in animals have shown that either constant darkness or constant light were worse in an animal model for sepsis when compared to regular day/night cycles.¹³¹ These results underline the potential importance of maintaining natural day-night cycles in humans. Many intensive care units in the United States and Europe have been rebuilt to increase exposure to natural light and some new ICUs in Germany (Heart Center or ICU Charite, Berlin, Germany) have incorporated advanced noise reduction and daylight simulation. Further clinical trials on the use of natural or artificial light to prevent or treat circadian related illness are needed (Figure 6). These studies will have to define the length (12 vs 16 h) of daylight, the wavelength (blue light vs full spectrum light) and the light intensity (4, 000 vs 14,000 lux) that might be beneficial in treating illness. Finally, it remains to be seen whether such treatments will be able to prevent or restore a nonfunctional circadian rhythm network.

Summary

The circadian system influences multiple human biochemical and physiologic variables including sleep/wake cycles, body temperature, hormone secretion, metabolism and our immune systems. Recent improvements in our understanding of how circadian rhythms impact important human disease states may enable the discovery of novel therapies for critically ill patients or those undergoing general anesthesia. Future research will need to include genetic data, as well as pharmacologic and environmental factors in the maintenance and restoration of human circadian rhythms. Understanding the influence of disrupted circadian rhythms on outcomes in critical care and anesthesia and researching new therapeutic interventions might significantly improve the care we provide our patients.

Acknowledgments

Source of financial support for the work:

National Heart, Lung, and Blood Institute (NIH-NHLBI) Grant 1K08HL102267 to T.E.

The present research work is supported by National Heart, Lung, and Blood Institute Grant 1K08HL102267 to TE.

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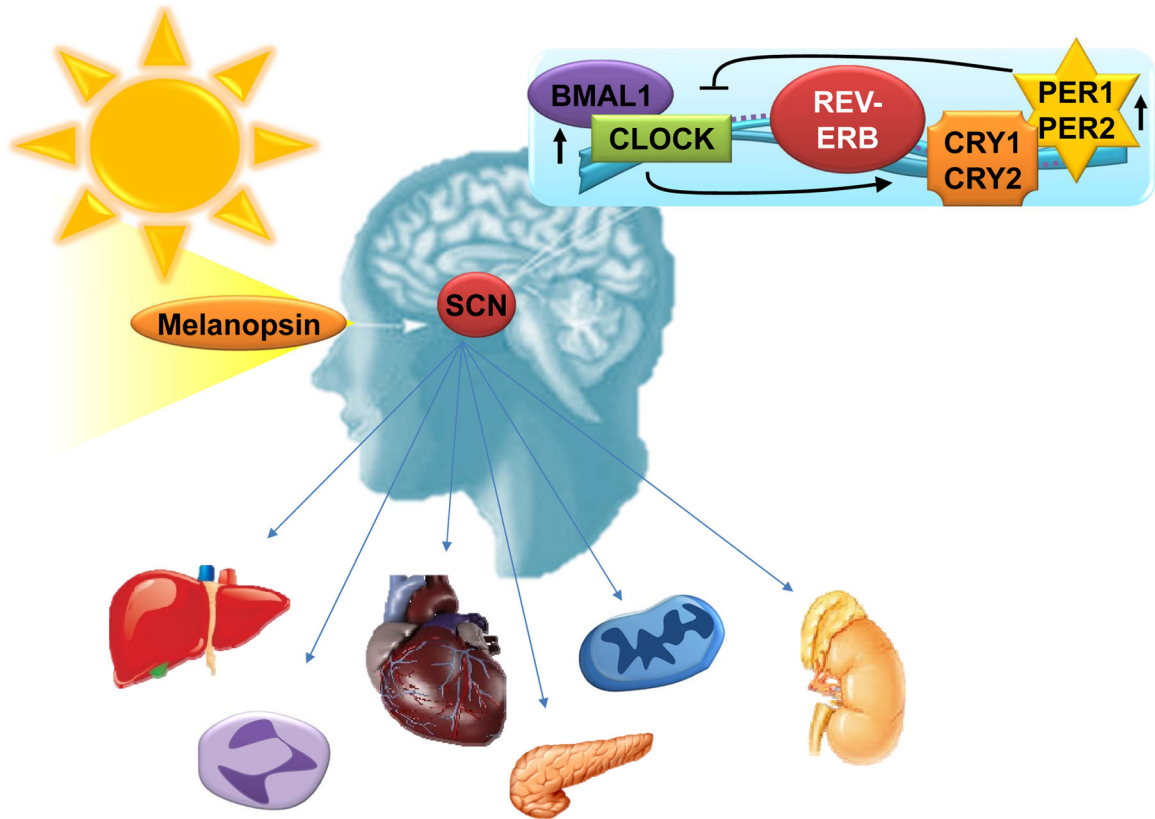


Figure 1. Regulatory mechanisms of the circadian system

The suprachiasmatic nucleus (SCN) in the brain is the central regulator of circadian rhythmicity. External stimuli such as light determine ‘Zeitgeber’ time. Light via melanopsin receptors in the retinal ganglion cells lead to the transcriptional induction of Clock and Bmal1 which leads in turn to the induction of Rev-Erb, Per1, Per2, Cry1 and Cry2. Via feedback inhibition of Clock and Bmal1 a cycle will be terminated and a new can begin. Hormonal and humoral factors are supposed to control circadian rhythms in peripheral organs.

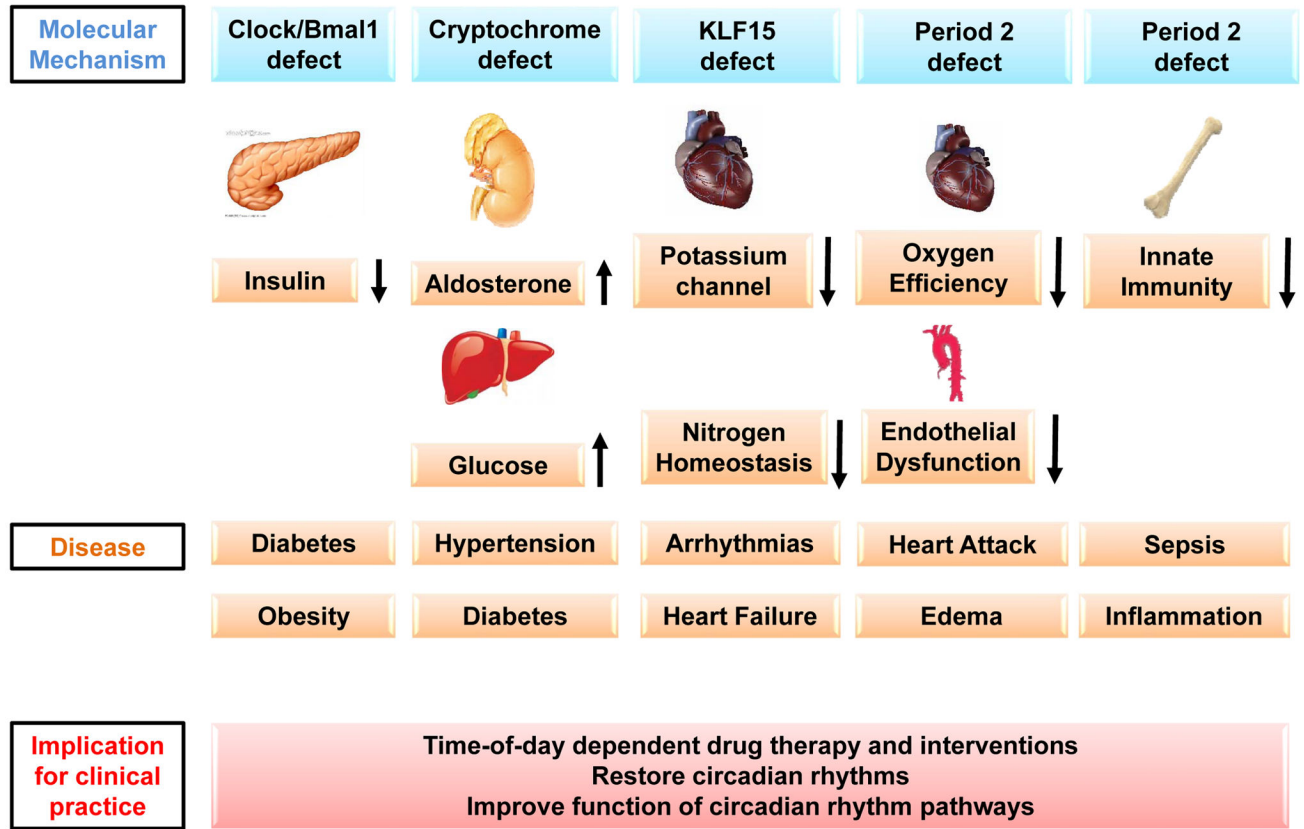


Figure 2. Disruption of the molecular ‘clock’ and disease development

Numerous recent studies provide evidence that the circadian clock influences the development and progression of disease in an experimental setting. Non-functional circadian rhythm proteins in peripheral organs were linked to very specific disease (e.g. Clock-diabetes, Cryptochrome-hypertension, Per2-heart attack etc.). These findings indicate that time-of-day dependent drug therapy or interventions might be imperative. However, more important seems to be the restoration of circadian rhythms to improve the function of circadian rhythm pathways such as insulin secretion, inflammation or metabolism.

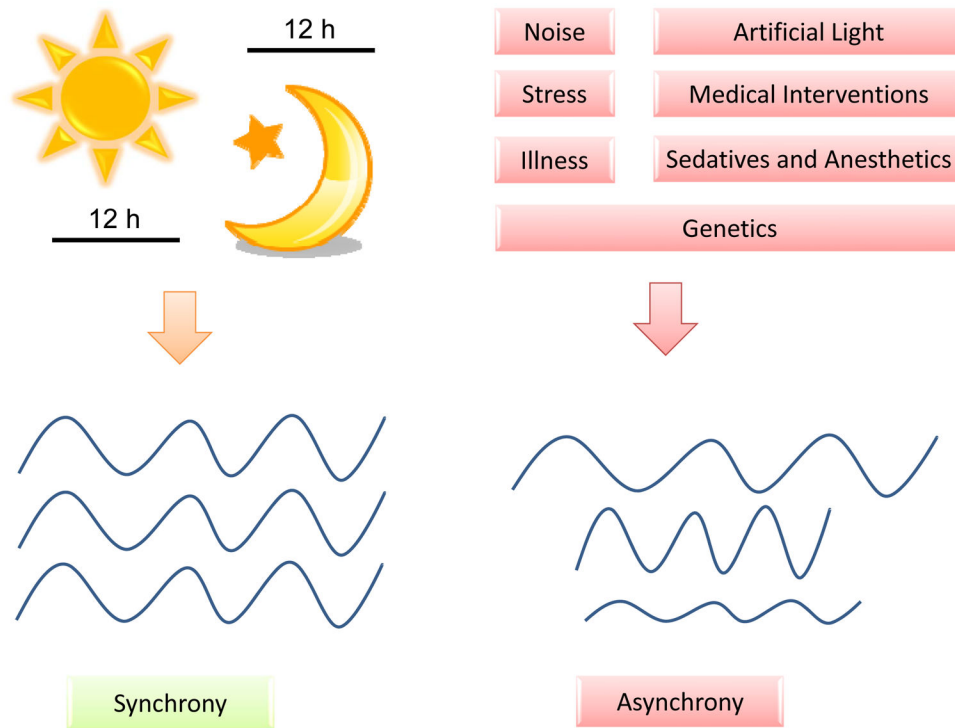


Figure 3. Factors influencing the circadian system

While a regular day/night cycles with dark, quiet nights are supposed to be the basis of a well synchronized circadian rhythm in humans, noise, interventions, artificial light and drugs on ICUs have proven to disrupt a functional circadian system and might lead to disease progression.

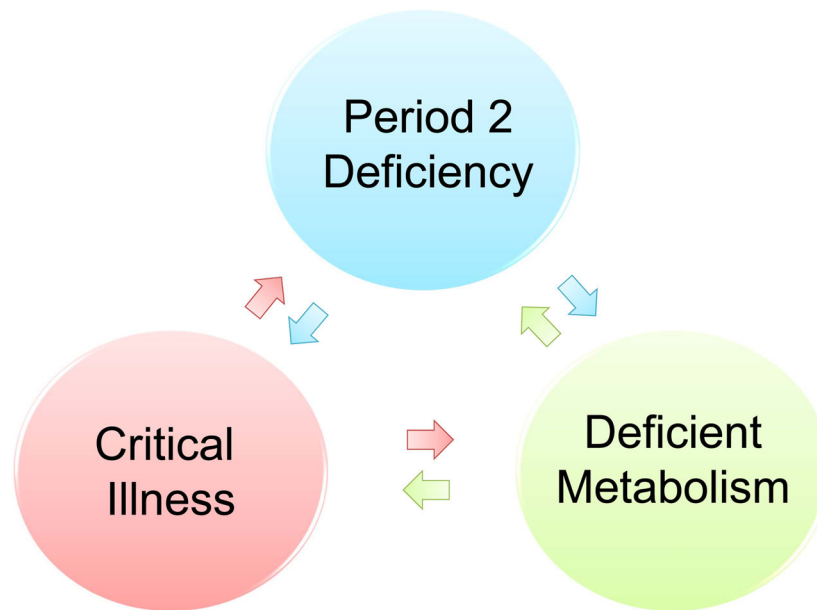


Figure 4. The link between critical illness and the circadian system

Sepsis can lead to a disrupted function of mitochondria, nonfunctional NO synthesis and deficient glycolytic pathways. Period 2 (Per2) deficiency has been associated with such metabolic alterations in mice. Therefore one could hypothesize, that restoration of a circadian rhythm with a functional Per2 protein might help to restore a nonfunctional metabolic phenotype in sepsis and thereby alleviating illness and disease progression.

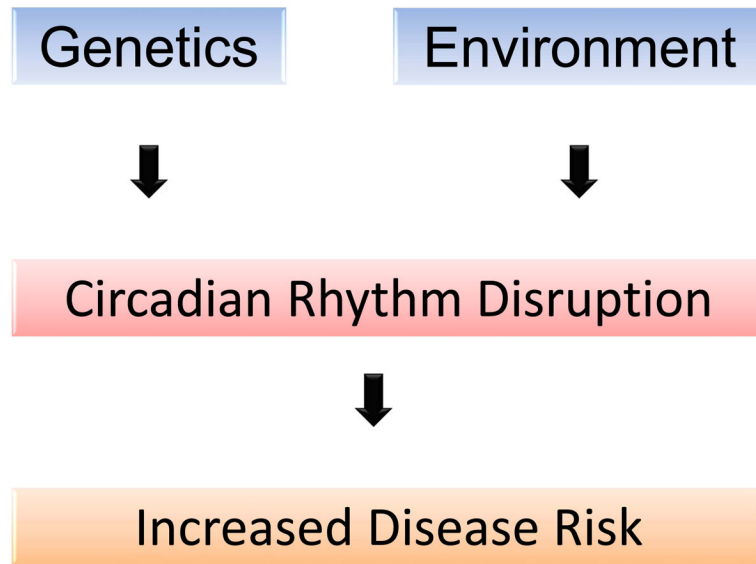


Figure 5. Model of disease development

Several environmental and genetic factors can cause disruption of the circadian rhythms. This disruption could contribute to multifactorial disease such as cardiovascular disease, a metabolic syndrome or progression of critical illness.



Figure 6. Restoration of circadian rhythms – potential for treatment

Recent improvements in our understanding of how circadian rhythms impact disease development including diabetes, hypertension, heart ischemia, stroke, sepsis or delirium, exhibits the potential to discover novel therapies for critically ill patients or those undergoing general anesthesia. Restoration of circadian rhythms might be key to treat associated disease.