

Review

Circadian Clocks and Cancer: Timekeeping Governs Cellular Metabolism

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The circadian clock is a biological mechanism that dictates an array of rhythmic physiological processes. Virtually all cells contain a functional clock whose disruption results in altered timekeeping and detrimental systemic effects, including cancer. Recent advances have connected genetic disruption of the clock with multiple transcriptional and signaling networks controlling tumor initiation and progression. An additional feature of this circadian control relies on cellular metabolism, both within the tumor microenvironment and the organism systemically. A discussion of major advances related to cancer metabolism and the circadian clock will be outlined, including new efforts related to metabolic flux of transformed cells, metabolic heterogeneity of tumors, and the implications of circadian control of these pathways.

Overview of Circadian Rhythms

The circadian clock maintains cell autonomous oscillations with a 24 hour periodicity (Figure 1 and Box 1). Yet, the clock also utilizes external synchronization by cues, such as light, temperature, and food intake, the so-called 'zeitgebers' or 'time givers' that can adapt circadian timekeeping. The mammalian pacemaker governs rhythms in sleep/wake cycles, feeding/fasting control, metabolism, hormone secretion, and immune function. Disruptions in biological rhythms result in numerous physiological disorders in organismal homeostasis, the consequences of which have been linked to several pathologies, including endocrine disruption, metabolic syndrome, and cancer [1]. Specifically, clinical and laboratory evidence has long suggested that a relationship exists between the circadian clock and tumorigenesis [2], yet the precise molecular mechanisms of this connection are not fully elucidated. Interestingly, epidemiological evidence shows a link between hormone-dependent cancers and circadian environmental disruption by shift work, light at night exposure, and late-night eating behavior [3–6]. To further support this epidemiological data, genetic disruption of the circadian clock in mouse models has revealed a strong link with specific cancers [7–9], though the precise mechanisms related to cancer initiation versus progression remain unknown. Specifically, the role of cellular metabolism in driving these transformation events, and how this is controlled by the clock and therefore disrupted during tumorigenesis, still requires further investigation.

This review serves to summarize the current state of knowledge regarding the links between the biological pacemaker and cancer, in an effort to highlight new avenues for therapeutic intervention. Specifically, we focus on several facets of tumor metabolism that can be rewired in response to circadian disruption. We extend our discussion of cancer metabolism to address differences in metabolic demand of tumors, and potential heterogeneity in fuel preference. Both clinical and laboratory data has recently relied on use of metabolic tracing *in vivo* to address these complex questions, and we highlight these efforts in terms of the power of metabolic flux and metabolic fate tracing using stable isotopes. Additionally, we discuss recent advances in teasing out how the circadian clock is implicated in regulating several pathways linked to oncogenes and tumor

Highlights

The circadian clock is a biological pacemaker mechanism that precisely controls rhythms in behavior and physiological functions controlling endocrinology, metabolism, and immune response.

Disruption of circadian rhythms has been reported to adversely alter normal physiology and results in disorders linked to metabolism, mood regulation, sleep behavior, and cancer.

Clinical data has shown that mutations and changes in expression of core clock genes is reported in several human cancers.

Use of genetic mouse models and cell lines have delineated the crosstalk of the circadian clock with several pathways linked to oncogenes and tumor suppressors, such as c-Myc, Ras, PTEN, and p53.

The circadian clock governs metabolic pathways regulating glucose utilization, amino acid uptake, lipogenesis, and β-oxidation. Therefore, deregulation of circadian rhythms impinges on metabolism and subsequent proliferation of cancer cells, which can provide new avenues for therapeutic intervention.

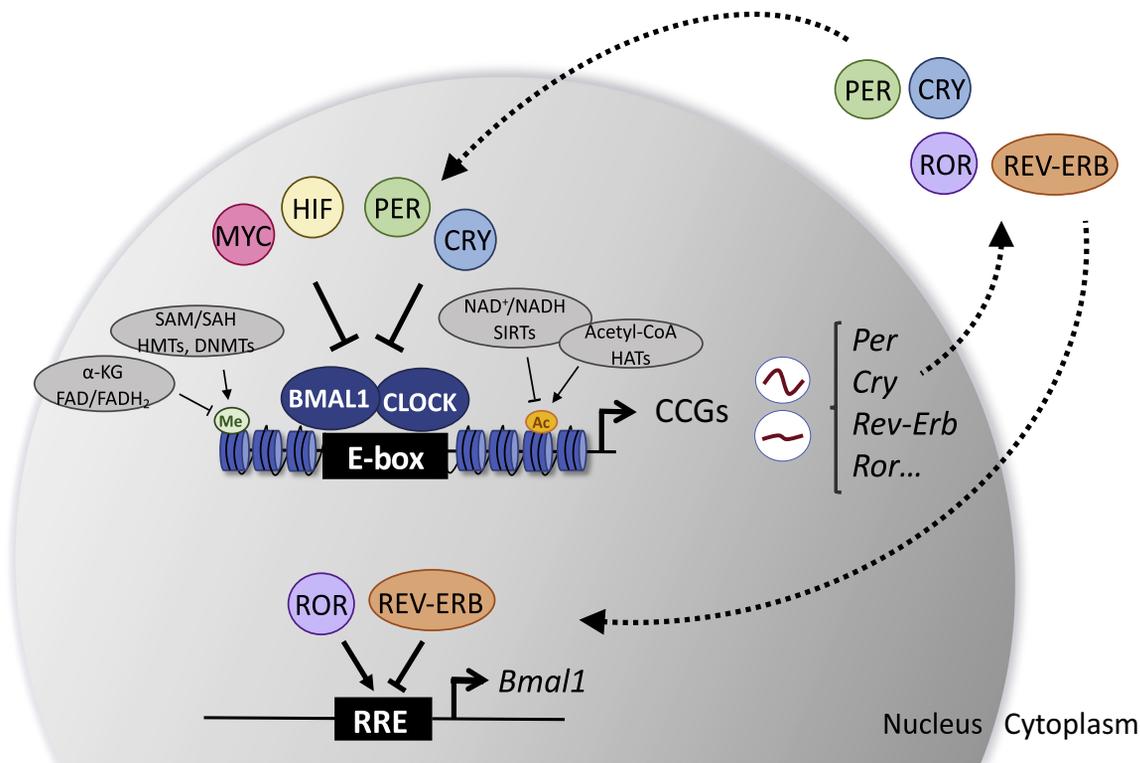
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Figure 1. The Transcriptional/Translational Feedback Loop Driving the Mammalian Circadian Clock. The circadian transcriptional/translational feedback loop (TTFL) operates within a precisely timed period of 24 hours in mammalian cells. The core clock machinery consists of the basic helix–loop–helix (bHLH) DNA-binding transcription factors, CLOCK and BMAL1 [51,151]. These transcription factors heterodimerize and bind enhancer box (E-box) sequences to control the rhythmic expression of ~10–15% of core clock and CCGs [13,104–106]. CLOCK:BMAL1-dependent transcription of CCGs peaks during the day and is inhibited by the circadian repressors, Period (PER) and Cryptochrome (CRY), at night [107–109]. An additional level of circadian regulation exists with the nuclear receptors ROR α and REV-ERB α that activate and repress transcription of *Bmal1*, respectively [113,114]. This secondary feedback loop offers an additional level of control outside the core TTFL to modulate circadian gene expression. Additional transcriptional crosstalk between the circadian machinery with MYC and HIF is also shown. Inputs of regulatory metabolites and their influence on circadian gene expression through epigenetic control are highlighted. Abbreviations: Ac, acetyl group; acetyl-CoA, acetyl coenzyme A; α -KG, α -ketoglutarate; DNMTs, DNA methyltransferases; FAD, flavin adenine dinucleotide; HATs, histone acetyltransferases; HMTs, histone methyltransferases; Me, methyl group; NAD⁺, nicotinamide adenine dinucleotide; RRE, Rev-Erb/ROR response element; SAM, s-adenosylmethionine; SAH, s-adenosylhomocysteine; SIRT6, sirtuins.

suppressors. Ultimately, our goal is to point to new directions where further research emphasis is required to fully understand how clock disruption and tumor initiation and progression converge at the molecular level.

Disruption of the Circadian Axis Is Linked to Cancer

The circadian clock is the biological pacemaker that controls rhythmic processes related to endocrinology, sleep/wake cycles, mood regulation, feeding/fasting rhythms, and overall metabolism. These circadian rhythms are cell autonomous and perpetuated in nearly all cells within a 24 hour period (Figure 1); [10]. Yet, the circadian clock is heavily dependent on external cues, or zeitgebers (e.g., light, nutritional cues, temperature), that can synchronize the otherwise self-sustained rhythms driven by the clock [11,12]. Light provides synchrony to the organism through the central circadian clock, housed within the suprachiasmatic nucleus (SCN), which is able to transmit signals to the peripheral clocks, such as liver, muscle, and skin, to maintain their rhythms in a tissue-specific manner [12,13].

Box 1. The Cogs and Gears That Drive the Mammalian Circadian Clock

The circadian molecular machinery consists of the core DNA-binding transcription factors, CLOCK and ARNTL or BMAL1, that heterodimerize and drive the oscillation of ~10–15% of genes in a defined tissue-specific program [13,51,104–106] by binding E-box sequences within the genome [51,107]; (see Figure 1 in main text). CLOCK:BMAL1-dependent transcription of core clock and CCGs peaks during the day, while transcription is inhibited by the circadian repressors, Period (PER) and Cryptochrome (CRY), at night [107,108]. The PER and CRY repressive complexes of the circadian clock have been an active area of research for several years and key structural features of these complexes have been elucidated [109–112]. An additional level of circadian regulation exists with the orphan nuclear receptors ROR α and REV-ERB α which activate and repress transcription of the *Bmal1* gene, respectively [113–116].

Moreover, regulation of circadian transcription also includes a large array of epigenetic modifications, including those modulated by histone acetyltransferases (HATs), histone deacetylases (HDACs), histone and DNA methyltransferases (HMTs and DNMTs), and demethylases, which establishes a mechanism by which the circadian transcriptional circuit can be fine-tuned over the day/night cycle (see Figure 1 in main text); [80,117–122]. For instance, the acetylation state of histone H3 (H3K9/K14) is critical in dictating circadian gene expression through CLOCK, CBP, p300, and PCAF [123–125], and these marks are conversely regulated by the HDAC activity of the mammalian sirtuins, SIRT1 and SIRT6 [80,117,118,126], and HDAC1 and HDAC3 [109,122,127]. In addition to acetylation, histone methylation has also been implicated in circadian chromatin remodeling through the histone methyltransferases (myeloid/lymphoid or mixed-lineage leukemia 1) MLL1 [120] and MLL3 [119] which are permissive for circadian gene expression. Previous studies have also described the role of EZH2 in the regulation of H3K27 methylation [128] and the role of demethylases in proper regulation of circadian gene expression [121,129]. Lastly, monoubiquitination of histone H2B has also been described as a critical aspect of crosstalk between the positive and negative limbs of the circadian TTFL [130]. Interestingly, the extent of epigenetic regulation within the context of the circadian system remains largely unexplored. This is especially important given the large array of acylation modifications that have been recently described, such as propionylation, butyrylation, and crotonylation, and their implication in regulation of gene expression specifically linked to cellular metabolism [131,132].

Early findings in the circadian field identified that mice with an ablation of the central clock located within the SCN exhibit increased growth of tumor xenografts as compared to mice with an intact circadian pacemaker [14]. Bilateral electrolytic lesions of the SCN enhanced tumor growth of implanted Glasgow osteosarcoma and pancreatic ductal adenocarcinoma (PDAC) versus sham operated mice [14]. Yet, the molecular mechanisms by which disruption of the central pacemaker results in enhanced tumor growth is unknown. These findings suggest that disruption of the synchrony between the SCN and peripheral clocks may have important physiological consequences for tumorigenesis.

To further address the role of physiological disruption of the clock and the impact of ‘desynchronization’ on tumor initiation and progression, environmental disruption paradigms have been utilized in rodent models. Chronic jet lag (CJL) refers to repeated 8 hour phase advances in the light schedule every 2 days for several weeks. This paradigm is known to simulate harsh jet lag conditions similar to that in humans and results in detrimental physiological effects in rodent models through disruption of circadian rhythms and acceleration of tumor growth *in vivo*. For instance, wild-type (WT) mice undergoing repeated jet lag manipulation display disrupted circadian gene expression, resulting in increased growth of Glasgow osteosarcoma [15] as well as enhanced incidence of lymphoma and hepatocellular carcinoma (HCC) [9,16]. Similar experiments have been performed with mice harboring mutations in clock genes, specifically *Cry1*^{2^{-/-}}, *Per2*^{2^{-/-}}, or *Per1*^{2^{-/-}};*Per2*^{mm}. These mutant mice display accelerated incidence of lymphoma, osteosarcoma, and HCC when subjected to severe CJL versus WT mice [9]. Furthermore, environmental disruption of the circadian clock can also be performed by light at night (LaN) exposure or dim LaN (dLaN), which is an increasing concern in modern society. Current protocols for LaN exposure involve changing the circadian subjective night, so that the dark period becomes shortened from a 12 hour light/12 hour dark (12:12) cycle to a 16:8 light/dark cycle for several weeks [17]. LaN and dLaN exposure (light intensity of 5 lux) are known to alter feeding behavior, circadian gene expression, and body weight in rodents [17–19], therefore defining how altered

light exposure drives tumor formation is essential. These concerns regarding circadian environmental disruption are particularly relevant to human behavior and activity patterns in developed society.

Clinical Evidence Linking the Clock with Cancer

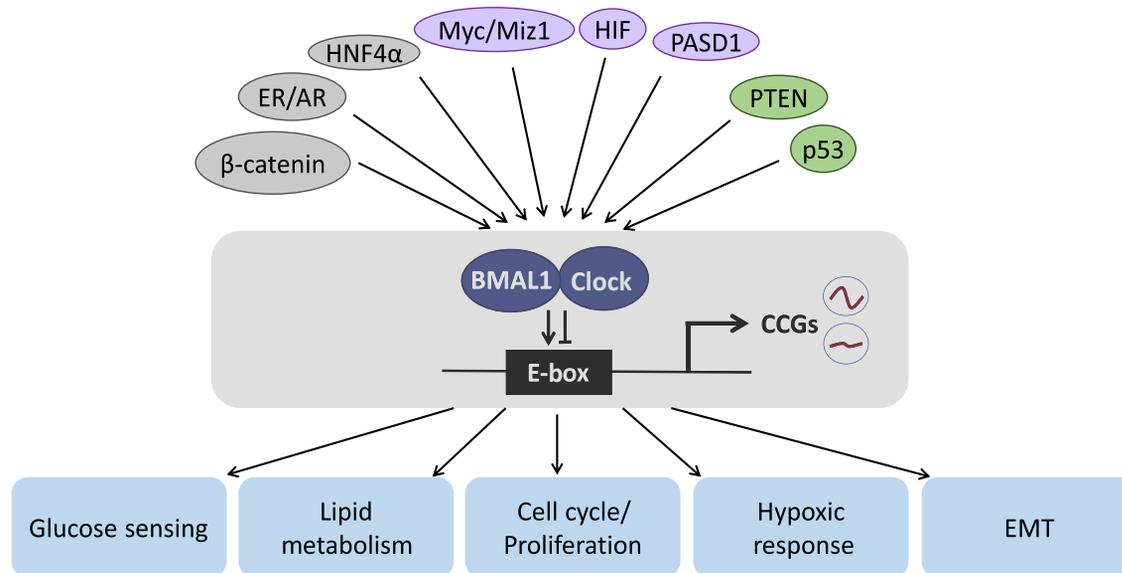
Epidemiological studies have linked circadian clock disruption through night shift work or LaN exposure with hormone-dependent cancers, and this evidence has been recently reviewed [2]. Additionally, clinical evidence connects methylation of clock gene promoters or SNPs with multiple cancer types, including breast [20,21], prostate [22,23], lung [24], colorectal [25,26], HCC [27], and other tumor types. To understand the global changes in core clock genes or clock-controlled genes (CCGs), recent bioinformatics approaches have compared patient data from The Cancer Genome Atlas (TCGA), Gene Expression Omnibus (GEO), Genomics of Drug Sensitivity in Cancer (GDSC), and the Cancer Therapeutics Response Portal (CTRP). Comparison of 14 different tumor types identified that 90.2% of 'clock genes' (both core clock genes and CCGs) were differentially expressed in at least one tumor type [28]. Interestingly, the *Arntl2* gene was up-regulated in multiple cancer types, while the circadian repressors (*Per*, *Cry*, and *ROR*) were strongly downregulated as determined by RNA sequencing analysis [28]. Moreover, these circadian repressors were significantly associated with inhibition of gene expression regulating apoptosis, cell cycle control, and DNA damage response pathways [28]. Further analysis similarly found that a coordinated signature of 12 clock genes was significantly deregulated in multiple tumor types when compared to expression in normal human tissue [29]. This omics approach reinforces the importance of circadian synchrony in maintaining cellular homeostasis and further implies that disruption of this network of precisely timed clock genes is likely involved in several human cancers.

Oncogenes and Tumor Suppressors Crosstalk with the Clock

In support of this clinical evidence, laboratory studies have helped to understand the molecular crosstalk between the circadian clock and signaling pathways regulating survival and proliferation. The role of the circadian clock and its molecular connection with several oncogenes, tumor suppressors, and other transcriptional regulatory factors will be highlighted (Figure 2).

Ras-Mediated Transformation

Ras-dependent cellular transformation models have been used to dissect the different roles of the positive and negative limbs of the circadian transcriptional/translational feedback loop (TTFL) in cancer. H-Ras-transformed human keratinocytes display a loss of *Per2* and *Bmal1* gene expression, while *Cry1* and *Clock* expression are upregulated in synchronized cells [30]. Using the *Bmal1*-luciferase reporter to determine rhythmic gene expression, induction of H-Ras or KRAS resulted in a significant lengthening of the circadian period, indicating that Ras-dependent transformation perturbs circadian gene expression [30]. Interestingly, *Per2* mutant or *Cry1/2*-deficient cells are transformed by H-Ras, while *Bmal1*-null or *Clock* mutant mouse embryonic fibroblasts (MEFs) are resistant to oncogene-induced transformation [31]. This Ras-mediated transformation was found to be dependent on activating transcription factor 4 (ATF4) activation that represses cell cycle regulators and tumor suppressors p16^{INK4a} and p19^{ARF}. These findings were further confirmed *in vivo* using a chemical carcinogen 7,12-dimethylbenz[a]anthracene (DMBA)-dependent model of skin carcinogenesis in clock mutant mice [32]. Yet, use of genetically engineered mouse models (GEMMs) whereby tumor development occurs over several months reveals that both the positive and negative components of the circadian machinery accelerate tumor formation. Crossing *Per2*^{tm/m} or *Bmal1*^{fl/fl} mice with a *Kras*^{LSL-G12D/+;p53^{fl/fl}} GEMM of lung adenocarcinoma resulted in increased tumor burden, more aggressive grade 3 and 4 lung tumors, and subsequent decreased overall survival [7]. These findings suggest that disruption



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Figure 2. Oncogenes and Tumor Suppressors Crosstalk with the Circadian Clock. An overview of the input pathways of oncogenes and tumor suppressors that are known to deregulate the circadian clock. Several nuclear hormone receptors are implicated in regulating circadian gene expression in breast [42], prostate [23], and hepatocellular carcinoma (HCC); [67]. Also, the circadian clock machinery is known to crosstalk with the MYC oncogene to regulate cell proliferation and metabolism [52,68,72]. PTEN and p53 tumor suppressors also regulate the clock, including downstream signaling cascades involving phosphatidylinositol 3-kinase/protein kinase B (PI3K/AKT); [7,56,75]. The output of this circadian crosstalk with these oncogenes and tumor suppressors results in altered circadian gene expression regulating key pathways involved in glucose sensing, lipid metabolism, cell cycle and proliferation control, modulation of the hypoxic response, and control of the epithelial to mesenchymal transition (EMT). Nuclear hormone receptors and transcriptional coregulatory proteins are shown in grey, transcription factors that directly interfere with aryl hydrocarbon receptor nuclear translocator-like protein 1:circadian locomotor cycles output kaput (CLOCK:BMAL1) transcription through enhancer box (E-box) binding are shown in purple, and tumor suppressors are indicated in green. Abbreviation: CCGs, clock-controlled genes.

or abnormal function of the circadian molecular machinery could differentially impact Ras-mediated transformation. These results could be tumor type-specific and therefore, cell type could differentially impact oncogene-induced transformation both *in vivo* and *in vitro*.

Wnt/ β -Catenin Signaling

A bidirectional crosstalk has been reported between the circadian clock machinery and Wnt/ β -catenin signaling, specifically involved in colorectal cancer (CRC). *Per2^{m/m}* mice, when crossed with the *Apc^{Min/+}* model of multiple intestinal neoplasia [33,34], developed increased numbers of intestinal and colonic polyps, as well as increased frequency of adenomas as compared to *Apc^{Min/+}* mice alone [35]. Furthermore, it has been reported that heightened β -catenin signaling in the *Apc^{Min/+}* mouse model destabilized PER2 protein levels in the intestinal mucosa through interaction with an F-box protein of the SCF ubiquitin E3 ligase family called β -TrCP [36]. This bidirectional crosstalk links β -catenin signaling with the circadian molecular machinery in the intestine. The role of the clock in other cancer types that are dependent on Wnt/ β -catenin signaling, such as gastric, breast, prostate, and melanoma, is unknown. Moreover, Wnt signaling is critically involved in development and cell fate determination. In normal intestinal stem cells, the circadian clock was found to gate cell cycle progression in the mouse epithelium through clock-dependent secretion of Wnt using 3D *in vitro* organoid models [37]. Furthermore, disruption of the circadian clock results in arrhythmic cell division of normal intestinal stem cells in *Drosophila* [38]. Therefore, disruption of the circadian clock could deregulate Wnt signaling and alter proliferative control of intestinal stem cells. What remains unknown is if circadian disruption could also impinge on Wnt signaling and cancer-initiating cells (CICs), resulting in tumorigenesis in the intestine and

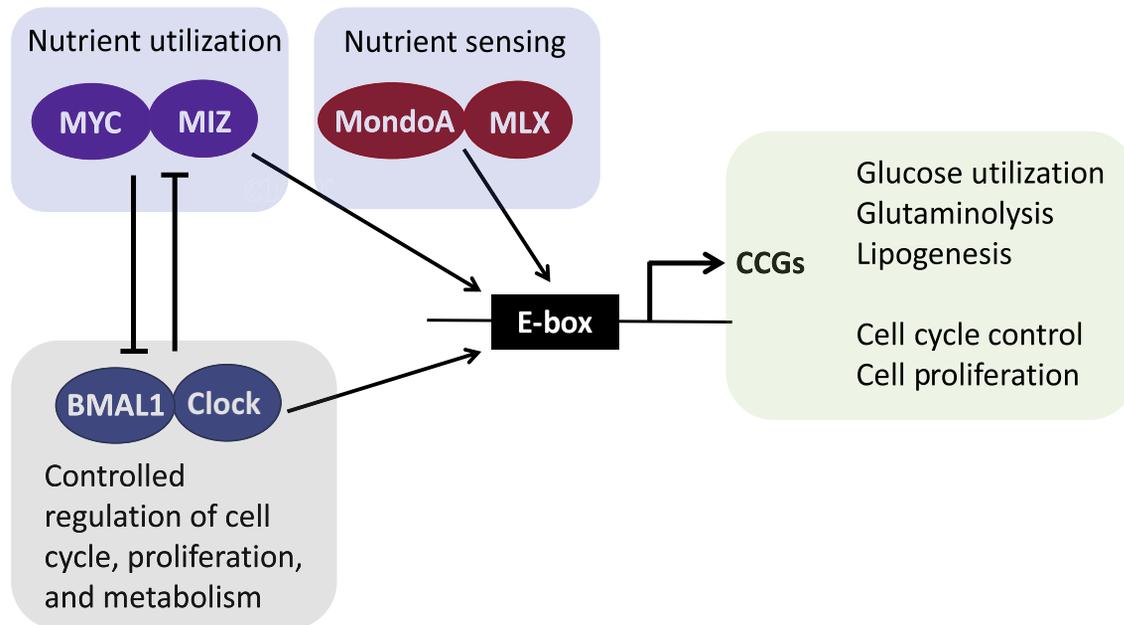
other tissues. Though the circadian clock is implicated in cancer stem cells [39,40], the precise role and detailed molecular mechanism in different cancer types is undefined.

Nuclear Hormone Receptors and Cancer

Of the 49 nuclear hormone receptors expressed in fat, liver, and skeletal muscle, 25 exhibit a rhythmic profile in gene expression [41]. One of these receptors, estrogen receptor alpha (ER α), is critically involved in hormone-dependent breast cancer and has been linked to the circadian clock. Circadian locomotor cycles output kaput (CLOCK) interacts with ER α and this interaction is enhanced by estrogen. Estrogen stimulates the sumoylation of CLOCK, which results in increased CLOCK-dependent transcriptional activity, enhanced ER α -mediated transcription, and proliferation of MCF7 and T47D breast cancer cell lines [42]. Aryl hydrocarbon receptor nuclear translocator-like protein 1 (BMAL1) is also sumoylated [43], but the role of ER/estrogenic signaling in this event is undefined. Interestingly, PER2 is also reported to regulate the stability of ER α protein levels, and *Per2* expression is estrogen-inducible, suggesting a controlled feedback mechanism [44]. Moreover, PER1 is reported to inhibit the transactivation of androgen receptor (AR) by direct interaction, and ectopic expression of *Per1* in LNCaP prostate cancer cells decreased the expression of known AR target genes [23]. Although these findings are compelling, the role of circadian clock crosstalk with nuclear hormone receptors *in vivo* is unknown. Mounting epidemiological evidence implicates shift work and LaN exposure with hormone-dependent cancers, specifically breast and prostate [3,5,45], suggesting a need to further elucidate the molecular mechanisms involved in tumorigenesis. Several additional connections likely exist between the clock, rhythmic hormone secretion, and oscillations in nuclear hormone receptors, but these links remain unexplored in several hormone-dependent cancers. For instance, the contribution of circadian regulation of the progesterone receptor in breast cancer is unexplored. Also, secretion of thyroid hormone is constant over the day/night cycle, yet the expression of thyroid hormone receptors α and β are dynamically rhythmic [41], and this establishes an interesting question that remains undefined.

c-Myc Oncogene

The c-Myc oncogene is a 'master regulator' of both cellular growth and metabolism in transformed cells [46,47]. The metabolic connections between c-Myc and the clock will be discussed in a later section, but we focus on the transcriptional regulation that is shared between these pathways. The X-ray crystal structures of the CLOCK:BMAL1 and MYC-MAX heterodimers reveal a basic helix-loop-helix (bHLH) domain [48,49] that is required to recognize E-box sequences [50,51]. This common E-box sequence could suggest that a rewiring may take place during tumorigenesis, whereby the balance of clock-controlled transcription can be lost and consequently compensated by oncogenic MYC-dependent transcription (Figure 3). In support of this notion, MYC and its binding partner MIZ1 are responsible for forming a repressive complex which downregulates core clock gene expression [52]. Conversely, this transcriptional crosstalk can be extended in that the circadian repressor CRY2 has been reported to promote MYC degradation through the FBXL3-containing E3 ligase, and *Cry2* deletion resulted in enhanced Myc-driven lymphomas in mice [53]. Additionally, the expression of c-Myc is negatively controlled by direct promoter binding of CLOCK:BMAL1, and MYC can repress CLOCK:BMAL1-dependent transactivation of *Per1* expression [54]. In further support of these findings, the expression of BMAL1 was found to be inversely correlated with MYC in 102 human lymphoma samples [52]. Also, *Per2* mutant mice (*Per2^{m/m}*) are susceptible to lymphoma and these mice exhibit an upregulation of c-Myc expression and its target gene *Ccnd1* [8]. Collectively, this data suggests that an inverse relationship exists between MYC and the circadian transcriptional axes that controls cellular survival and proliferation pathways. Interestingly, other examples exist whereby a transcriptional crosstalk has been demonstrated between the clock and alternative pathways in cancer.



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Figure 3. Involvement of the MYC Superfamily and the Circadian Clock in Cancer. Several reports implicate a transcriptional competition between several members of the MYC superfamily with the circadian clock. MYC/MIZ are involved in regulating cell proliferation and nutrient utilization of glucose and glutamine by repressing the circadian clock [52,68,72]. Also, the circadian repressor CRY2 has been reported to promote MYC degradation through the FBXL3-containing E3 ligase [53]. The MondoA/MLX transcriptional pathway is involved in nutrient sensing and downstream regulation of lipogenesis and glutaminolysis in different cancer types [72]. To date, the direct connection between the circadian clock and the nutrient sensing arm of MondoA remains to be defined. The consequences of this transcriptional competition between CLOCK:BMAL1 and the MYC superfamily results in regulation of gene expression programs involved in controlling the cell cycle, proliferation, and cellular metabolism. Abbreviations: CCGs, clock-controlled genes; E-box, enhancer box.

For example, the cancer/testis antigen PASD1, which is normally restricted in expression to the germline, is induced upon oncogenic transformation. PASD1 has been shown to directly interact with the CLOCK:BMAL1 complex to repress clock-dependent transcription [55]. Additional evidence of transcriptional crosstalk exists between the clock complex and hypoxia-inducible factor (HIF), and the implications of this work will be discussed in a later section.

The Tumor Suppressor p53

The tumor suppressor p53 is commonly mutated and subsequently inactivated in over 50% of human cancers [46,47]. The circadian clock is regulated by p53 as *Per2* expression is transcriptionally controlled by p53 [56]. The p53 response element overlaps with the E-box sequence in the *Per2* promoter, thereby p53 occupancy blocks CLOCK:BMAL1 promoter recruitment [56]. Is this the case for other core clock genes or CCGs, and to what extent is this co-occupancy of p53 and the clock machinery occurring genome-wide? Conversely, PER2 forms a stable complex with p53, which subsequently prevents MDM2-mediated ubiquitination and proteasomal degradation of p53 [57,58]. Therefore, modulating cellular levels of the clock proteins directly controls p53 stability, and this is supported by the finding that ectopic expression of PER2 results in nuclear shuttling of p53 [59]. Recent evidence also supports the notion that PER2 stability is regulated through an atypical circadian mechanism by which PER2 is a direct target of the ubiquitin ligase MDM2 [60]. As previously discussed, crossing *Per2^{m/m}* mice with a *Kras^{LSL-G12D/+};p53^{fl/fl}* GEMM of lung adenocarcinoma resulted in increased tumor burden, more aggressive lung tumors, and subsequent decreased overall survival [7]. Also, expression of *Per2* in A549 lung cancer cells suppresses growth and metastasis *in vitro* and *in vivo* [24]. Remarkably, the

connection between the clock and p53 has mostly focused on PER2, yet the role of other clock proteins remains unclear. However, recent work has identified that knockdown of Bmal1 in pancreatic cancer cells promotes cell growth, while ectopic expression of Bmal1 inhibits cell cycle and proliferative control in a p53-dependent manner [61]. Conversely, crossing $p53^{-/-}$ mice with $Cry1^{-/-};Cry2^{-/-}$ mutant mice resulted in a 50% extension of median lifespan as compared to $p53^{-/-}$ mice alone [62]. This data suggests differential roles of the clock proteins in regulating p53. These differences in p53 activity linked to the clock could be attributed to the multiple functions of p53 linked to UV stress, DNA damage response, DNA repair, or apoptosis pathways in a cell type-dependent manner [63–66].

Linking the Clock, Metabolism, and Cancer

The circadian clock regulates an array of metabolic processes that are critical for maintaining homeostasis (Box 2). Interestingly, several avenues have been explored to unravel how circadian alterations may impinge on metabolic pathways needed to sustain cell survival. Using environmental disruption paradigms of C/JL, nonalcoholic fatty liver disease (NAFLD) has been reported in WT mice, which can progress to steatohepatitis and eventually HCC [16]. Mechanistically, C/JL disrupts hepatic circadian gene expression as well as rhythmic metabolism, resulting in induction of hepatic cholesterol and bile acid levels that activate the oncogenic program of the nuclear receptor constitutive androstane receptor (CAR), and downstream activation of β -catenin [16]. Additionally, hepatocyte nuclear factor 4 α (HNF4 α) is a master regulator of liver-specific gene expression. A specific isoform of HNF4 α (P2-HNF4 α) is expressed in human HCC, and P2-HNF4 α represses BMAL1 transcriptional activity, including genes involved in epithelial to mesenchymal transition (EMT); [67]. Also, overexpression of BMAL1 in HNF4 α -positive HCC inhibits tumor growth *in vivo* [67]. Properly controlled rhythmic metabolism is important for cancer prevention, which is specifically highlighted in this example of HCC and C/JL-mediated disruption of hepatic metabolism. The extent of these findings is likely not limited to HCC and therefore requires further investigation in other tumor types.

Box 2. Circadian Control of Metabolism

The circadian clock controls a wide array of metabolic processes, such as glycolysis, the Krebs cycle, gluconeogenesis, mitochondrial function, lipogenesis, lipolysis, amino acid metabolism, and nucleotide synthesis. Untargeted mass spectrometry relying on metabolomics or lipidomics has identified that 30–60% of lipids, amino acids, nucleotides, carbohydrates, and cofactors/coenzymes are rhythmic [78,90,133,134]. This includes rhythmic metabolites, such as NAD⁺, FAD, acetyl-CoA, SAM/SAH, which have important implications in redox biology, mitochondrial processes, and histone/nonhistone protein modifications influencing gene expression [86,135–138]; (see Figure 1 in main text). Moreover, recent studies demonstrate that high fat diet (HFD) feeding in mice phase shifts 40–60% of circadian metabolites in liver, muscle, adipose tissues, and serum [78,90,139,140]. Also, food availability, as evidenced by time-restricted feeding or fasting, can rapidly and dynamically shift circadian gene expression [90,141–144]. Conceptually, this experimental evidence has established that circadian metabolism can exhibit plasticity, and reprogramming of transcriptional and metabolic circuits occurs in response to nutritional perturbation or challenge [78].

Furthermore, genetic disruption of the circadian clock is also linked to metabolic dysfunction in rodent models. *Clock* mutant (*Clock Δ 19*) mice are obese compared to their WT littermates and display hyperlipidemia, hepatic steatosis, hyperglycemia, and hypoinsulinemia [145]. Also, hepatic glucose production through gluconeogenesis is controlled by the circadian repressor CRY1, that subsequently regulates the activity of cAMP response element-binding protein (CREB); [146]. In addition, the hepatic clock also controls levels of sterol regulatory element-binding protein (SREBP)-dependent fatty acid, cholesterol, and bile acid production through the functions of the circadian transcriptional repressors REV-ERB α [147], and the mammalian HDAC SIRT6 [80]. Also, the conditional knockout of the pancreatic clock results in glucose intolerance and diabetes mellitus [148]. Recent work has elucidated the role of the circadian clock in pancreatic function. In both mouse [149] and human [150] pancreatic islets, the clock was found to directly regulate circadian insulin secretion, by regulating the expression of genes involved in the secretory machinery and signaling factors that control insulin release. Collectively, these findings establish a strong link between the circadian clock and control of cellular and tissue-specific metabolic pathways. The implications of these circadian metabolic pathways in sustaining tumor metabolism are discussed in the main text.

Myc and Cancer Metabolism

Upregulation of MYC has been shown to disrupt circadian gene expression and perturb circadian glucose and glutamine metabolism in cancer cells both *in vitro* [68] and *in vivo* [7]. This activity of MYC was initially reported to be dependent on the negative transcriptional arm of the clock through REV-ERB α that inhibits expression of *Bmal1* and also deregulates oscillations in metabolic sensing through AMP-activated protein kinase (AMPK) and hexokinases HK1 and HK2 [68]. Recent evidence also suggests that MYC-dependent activity may not be solely dependent on REV-ERB α [69,70]. The nutrient-sensing function of the MYC superfamily plays an important role in tumor metabolism (Figure 3). In addition to MYC, MondoA/Mlx are E-box binding transcription factors that sense glycolytic intermediates, such as glucose 6-phosphate. Depending on tumor type and metabolic fuel preference, MondoA either antagonizes MYC-dependent regulation of glycolytic genes in triple negative breast cancer [71] or coordinately regulates glutaminolysis and lipogenesis in neuroblastoma [72]. The role of MondoA in tumor metabolism involving the circadian clock machinery is currently unknown, particularly in relation to how MondoA may transcriptionally converge with CLOCK:BMAL1 activity. Yet, evidence from *Drosophila* suggest that these transcriptional networks likely intersect [73], and could therefore be important to explore within the context of tumor metabolism. Additionally, given that tumor heterogeneity in metabolic fuel preference is an important consideration [74], MYC-dependent nutrient sensing is likely far more complex than our current understanding.

PTEN, PI3K/AKT, and mTOR Signaling

Emerging evidence has started to connect the circadian clock with the tumor suppressor PTEN and additional related pathways. PTEN controls the PI3K/AKT signaling pathway, and disruption of this pathway by oxidative stress results in activation of BMAL1 in a mammalian target of rapamycin (mTOR)-dependent manner [75]. Although this study identified a potential role of both mTOR complexes, TORC1 and TORC2, in controlling the clock, further molecular studies are still required to better define this link. Yet, BMAL1 is a known substrate of the mTOR effector kinase S6K1, and this phosphorylation of BMAL1 is important for interaction with the translation machinery and subsequent rhythmic protein synthesis [76]. Also, mTOR activation results in increased expression of several members of the core clock machinery in fibroblasts which regulate circadian gene expression [77]. These results are particularly exciting and warrant further investigation given that amino acids, cellular energy levels, and growth factors, which are sensed by the mTOR pathway, are rhythmic over the day/night cycle [78–80]. Indeed, mTOR activity has been reported to be rhythmic and follow food intake, and this can be uncoupled from the light-dependent circadian mechanism [81], suggesting a central role for the circadian metabolic clock linked to mTOR activity. Recent studies reveal that PER2 functions as a scaffold protein to suppress the activity of the mTORC1 complex, and loss of PER2 enhances protein synthesis and cell proliferation [82]. The implications of rhythmic mTOR-dependent nutrient sensing and proliferation in cancer merit further investigation, as this suggests permissive time windows for optimal druggability and therapeutic targeting.

Hypoxia and HIF Signaling

Oxygen is critical for cellular respiration and the hypoxic tumor microenvironment regulates tumor metabolism and angiogenesis [46,47]. A transcriptional crosstalk has been reported between the clock and the transcription factor HIF in nontransformed cells, though the implications of these studies in tumorigenesis are possible but currently unknown. The hypoxia-response element (HRE) is an E-box like sequence that is recognized and bound by HIF under low oxygen conditions to regulate gene expression. The HRE is recognized by HIF heterodimers consisting of two similar proteins, HIF1 α and HIF1 β . Interestingly, the hypoxic response is gated by the circadian clock as the *Hif1* α promoter is directly controlled by the CLOCK:BMAL1 transcriptional

complex, which drives rhythmic gene expression of clock genes and hypoxia-dependent genes [83]. Also, blood oxygen levels exhibit daily rhythms which influence expression of core clock genes in a HIF1 α -dependent manner in several tissue types [84]. The transcriptional crosstalk between the clock and HIF is further supported by genetic data illustrating that *Bmal1*^{-/-} in C2C12 myotubes reduced anaerobic glycolysis in a HIF1 α -dependent manner [85]. An intriguing concept emerges from these findings linking HIF with a circadian transcriptional crosstalk. If the clock gates the hypoxic response by regulating gene expression, how would the oxygen-deplete tumor microenvironment be regulated by CLOCK:BMAL1-dependent transcription? Yet, if circadian gene expression is deregulated during tumorigenesis, the impact on HIF-dependent signaling could be altered in the absence of a functional clock mechanism. Additionally, oxygen levels control cellular respiration in a circadian manner [86], and how disruption of these metabolic rhythms could further drive tumor progression are unknown.

The Tumor Microenvironment and Macroenvironment

To sustain their heightened proliferation, cancer cells need to generate energy, provide reducing equivalents to drive enzymatic reactions for energy production, and produce macromolecular precursors for rapidly proliferating cells [87]. As a consequence of this heightened metabolism, tumors not only excrete metabolic intermediates into the microenvironment but also into circulation. Emerging evidence suggests that tumor metabolism extends beyond the niche of the tumor microenvironment, and this so-called tumor macroenvironment may play an important role in driving cancer proliferation [88,89]. Given that the circadian metabolic clock has the unique ability to exhibit plasticity and adapt to new metabolic perturbations via reprogramming [78,90], the question arises as to whether tumor-dependent metabolism can alter organismal homeostasis. Indeed, recent findings demonstrate that circadian metabolism in the liver is distally reprogrammed by lung adenocarcinoma, suggesting that tumor-instructed cues can mediate circadian disruption of host metabolism [91]. This tumor-dependent distal rewiring of hepatic metabolism includes deregulation of lipid metabolism, and insulin/glucose-dependent signaling [91]. Similar results have been reported in a mouse model of triple negative breast cancer, where rewiring of circadian gene expression was distally observed in the liver, resulting in increased oxidative stress [92]. The question that arises from these studies is: what is the tumor-specific advantage in distally rewiring circadian metabolism? One speculation is that this rewiring of circadian metabolism can feedback and supply additional or alternative fuel sources to support heightened metabolic demand of cancer cells. Additionally, another possibility is that deregulation of the circadian clock and metabolism could support sites of distal metastasis. However, these concepts will need to be explored experimentally.

Metabolic heterogeneity in fuel preference of different tumor types has become apparent, which underscores the complexity of cancer metabolism. First, the environment plays an important role in dictating fuel preference, and tumors *in vivo* display differences in fuel utilization versus cultured cancer cells [74]. These differences in tumor cell type and metabolic preference are being elucidated, and dependence on glucose, glutamine, aspartate, arginine, and other nutrients is becoming apparent in a cell type-dependent manner [93–96]. Yet, nutrient addiction of a tumor subtype can differ. For instance, when glutamine levels are limiting, cell proliferation can be alternatively driven by aspartate or asparagine [97,98]. This establishes an interesting paradox whereby limiting the availability of a specific nutrient may not inhibit cancer cell proliferation, as tumors can switch their fuel preference. An additional factor to consider is that abundance of these nutrients is rhythmic over the circadian cycle [78–80], which raises the possibility that fuel utilization of tumors may differ based on rhythmic availability of nutrients.

Additionally, tumors can also utilize nontraditional metabolites as fuel. For instance, patients with non-small cell lung cancer (NSCLC) exhibit metabolic heterogeneity in fuel utilization where, even

though glucose oxidation is metabolically imperative, lactate is used as a carbon source to fuel the TCA cycle [99,100]. Metabolic flux studies in GEMMs using uniformly labeled [U-¹³C]lactate (where all three carbons are heavy labeled) have demonstrated that lactate is the major carbon source for tumor TCA cycle intermediates in lung adenocarcinoma [101]. Strikingly, blood perfusion of [U-¹³C]lactate into two different lung adenocarcinoma GEMMs, *Kras*^{LSL-G12D/+}; *Trp53*^{-/-} and *Kras*^{G12D/+}; *Stk11*^{-/-}, illustrated preferential utilization of [U-¹³C]lactate over both [U-¹³C]glucose and [U-¹³C]glutamine, suggesting that circulating lactate can be a major energy source for lung tumors. These findings are intriguing, especially given that lactate is a metabolic byproduct of glycolytic metabolism, therefore tumors can rely on their metabolic intermediates to fuel cell proliferation. Importantly, these findings appear to be tumor type-specific, as a GEMM of pancreatic ductal adenocarcinoma (PDAC) instead displayed a strong preference for [U-¹³C]glutamine as a carbon feedstock of the tumor TCA cycle over glucose and lactate [101]. Moreover, in terms of nitrogen sources, a similar example has been reported in breast cancer cells where the enzymatic activity of glutamate dehydrogenase (GDH) can recycle ammonia waste into central amino acid metabolism [102]. Overall, these findings demonstrate the complexity of tumor metabolism and illustrate that certain types of metabolic byproducts can be repurposed for intratumoral energy and building block production.

Concluding Remarks and Future Directions

The precise biological timing of the circadian clock is imperative for maintaining organismal homeostasis. This review outlines several connections between the circadian biological clock and pathways regulating cell proliferation, endocrinology, and metabolism. Disruption of these pathways is linked to tumor initiation and progression, and we highlight the molecular links between the clock and oncogenes and tumor suppressors such as Ras, c-Myc, Wnt/ β -Catenin, p53, PTEN, and mTOR. Also, the circadian clock is intimately linked with intracellular and organismal metabolism. Therefore, we discuss exciting avenues that require further experimental investigation, specifically linked with tumor heterogeneity, metabolic fuel preference of cancer cells, and the consequences of tumor-derived metabolic byproducts and fuel repurposing. Recent advances highlight the potential for therapeutic targeting of the circadian clock for cancer treatment [2,103]. Yet, the molecular mechanisms of these approaches still require further examination in terms of targeting the molecular clock for cancer therapy. Several cancers highlighted throughout this article exhibit a downregulation of the circadian machinery, therefore inhibition of the circadian clock in cancer therapy may be tumor type-specific. Another point of consideration is chronotherapy, which is the optimal druggability window over the circadian cycle for effective treatment, and this approach also warrants more thorough investigation. This is especially relevant in targeting circadian metabolic pathways that can be optimally drugged based on peak metabolite levels, circadian protein expression, or enzymatic activity. Overall, the circadian clock represents an underexplored area of cancer research and treatment that is a vital connection linking tumor metabolism and oncogenic signaling networks (see Outstanding Questions).

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Outstanding Questions

What is the role of the circadian clock in regulating CICs during tumorigenesis?

Does circadian disruption preferentially alter tumor initiation or tumor progression?

Do changes in feeding and nutrition alter tumor progression? Does the type of diet or meal timing alter circadian rhythms which can adversely disrupt tumor metabolism?

How can the circadian molecular machinery be harnessed for cancer treatment? Can therapeutic targeting of the clock be tumor-specific without altering normal cells?

Can chronotherapy be used to predict drug efficacy and response? Which pathways are most sensitive to time-of-day therapeutic treatment?

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