

Regulation of BMAL1 Protein Stability and Circadian Function by GSK3 β -Mediated Phosphorylation

Saurabh Sahar^{1,3}, Loredana Zocchi¹, Chisato Kinoshita², Emiliana Borrelli^{2,3}, Paolo Sassone-Corsi^{1,3*}

1 Department of Pharmacology, University of California Irvine, Irvine, California, United States of America, **2** Department of Microbiology and Molecular Genetics, University of California Irvine, Irvine, California, United States of America, **3** Unite 904 INSERM 'Epigenetics and Neuronal Plasticity', University of California Irvine, Irvine, California, United States of America

Abstract

Background: Circadian rhythms govern a large array of physiological and metabolic functions. To achieve plasticity in circadian regulation, proteins constituting the molecular clock machinery undergo various post-translational modifications (PTMs), which influence their activity and intracellular localization. The core clock protein BMAL1 undergoes several PTMs. Here we report that the Akt-GSK3 β signaling pathway regulates BMAL1 protein stability and activity.

Principal Findings: GSK3 β phosphorylates BMAL1 specifically on Ser 17 and Thr 21 and primes it for ubiquitylation. In the absence of GSK3 β -mediated phosphorylation, BMAL1 becomes stabilized and BMAL1 dependent circadian gene expression is dampened. Dopamine D2 receptor mediated signaling, known to control the Akt-GSK3 β pathway, influences BMAL1 stability and *in vivo* circadian gene expression in striatal neurons.

Conclusions: These findings uncover a previously unknown mechanism of circadian clock control. The GSK3 β kinase phosphorylates BMAL1, an event that controls the stability of the protein and the amplitude of circadian oscillation. BMAL1 phosphorylation appears to be an important regulatory step in maintaining the robustness of the circadian clock.

Citation: Sahar S, Zocchi L, Kinoshita C, Borrelli E, Sassone-Corsi P (2010) Regulation of BMAL1 Protein Stability and Circadian Function by GSK3 β -Mediated Phosphorylation. PLoS ONE 5(1): e8561. doi:10.1371/journal.pone.0008561

Editor: Mikhail V. Blagosklonny, Roswell Park Cancer Institute, United States of America

Received: December 1, 2009; **Accepted:** December 11, 2009; **Published:** January 1, 2010

Copyright: © 2010 Sahar et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: S.S. was partially supported by a post-doctoral fellowship from American Heart Association, Western States Affiliates. L.Z. was supported by an American-Italian Cancer Foundation post-doctoral fellowship. Work in the laboratories is supported by the National Institute of Health (R01-DA024689; R01-GM081634-01) and the Institut National de la Sante et de la Recherche Medicale (U904) (France). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: psc@uci.edu

Introduction

Circadian (from the Latin *circa diem* meaning “about a day”) rhythms occur with a periodicity of about 24 hours and enable organisms to adapt and anticipate environmental changes. Circadian control provides an evolutionary advantage to organisms in adapting their behavior and physiology to the appropriate time of day [1,2]. Feeding behavior, sleep-wake cycles, hormonal levels and body temperature are just a few examples of physiological circadian rhythms.

From a molecular standpoint, circadian rhythms are regulated by transcriptional and post-translational feedback loops generated by a set of interplaying clock proteins. The positive limb of the mammalian clock machinery is comprised of CLOCK and BMAL1, which are transcription factors that heterodimerize through the PAS domain and induce the expression of clock-controlled genes by binding to their promoters at E-boxes. Cryptochromes (*Cry 1*, *Cry 2*) and Period genes (*Per 1*, *Per 2*, *Per 3*) are clock-controlled genes that encode proteins that form the negative limb of the circadian machinery. PER and CRY proteins are classically thought to translocate into the nucleus to inhibit CLOCK:BMAL1 mediated transcription, thereby closing the negative feedback loop [1].

Various core clock proteins undergo post-translational modifications (PTMs), a feature that is likely to contribute significantly to

the plasticity of the circadian system. PTMs have been shown to regulate distinct functions, including transcriptional activation and intracellular localization. PTMs have been proposed to participate in controlling the timing between the activation and the repression of circadian transcription [3]. Among the clock proteins, BMAL1 undergoes an extensive repertoire of PTMs, including phosphorylation [4,5,6], acetylation [7], sumoylation [8,9] and ubiquitylation [10]. Yet, the signaling pathways controlling the stability of the BMAL1 protein have not been deciphered. In the present study we have identified GSK3 β as a critical regulator of BMAL1 stability and activity. GSK3 β is a ubiquitous kinase which regulates various cellular functions, ranging from glucose homeostasis, to cell survival and cell-fate specification [11]. GSK3 β has been linked to various pathological conditions such as diabetes, Alzheimer's, cancer and bipolar disorder [12,13,14,15].

The role of GSK3 β in circadian control has been reported. The first evidence was based on the observation that *shaggy* (*sgg*), the *Drosophila* ortholog of GSK3, controls the period of circadian locomotor activity by phosphorylating TIMELESS and regulating nuclear translocation of the PERIOD/TIMELESS heterodimer [16,17]. Recently a high-throughput approach demonstrated that inhibition of GSK3 β leads to shortening of the period in cultured mammalian cells [18]. In mammals, GSK3 β has been reported to phosphorylate PER2, CRY2 and Rev-erb α . It has also been

reported that the kinase activity of GSK3 β oscillates in the central mammalian clock, suprachiasmatic nucleus (SCN) and in the peripheral clocks (liver and fibroblasts) [19]. GSK3 β mediated phosphorylation appears to have differential effect on the stability of the targeted substrates, since it has been shown to induce the degradation of CRY2 [20] and the stabilization of Rev-erb α [21]. Here we show that GSK3 β specifically phosphorylates BMAL1 and primes it for ubiquitylation, followed by proteasomal degradation. This control mechanism significantly influences the efficacy and amplitude of circadian gene expression.

Results

GSK3 β Phosphorylates BMAL1 and Primes It for Ubiquitylation

BMAL1 is a phosphoprotein targeted by various kinases [4,5,6]. We noted that BMAL1 contains 15 sites with the consensus T/SXXXS/T phosphoacceptor sequence for GSK3 β . This prompted us to determine whether GSK3 β can phosphorylate BMAL1. We performed *in vitro* kinase assays on bacterially purified GST-BMAL1 or GST alone by incubating them with recombinant GSK3 β in presence of γ^{32} P-ATP. Our results demonstrate that GST-BMAL1 was readily phosphorylated by GSK3 β , whereas GST alone, although expressed at much greater levels, was not

phosphorylated under equivalent conditions (Fig. 1A). Thus, BMAL1 appears to be an efficient substrate of GSK3 β . Furthermore, to detect physical association between BMAL1 and GSK3 β , HEK 293 cells were transiently transfected with plasmids expressing BMAL1 and CLOCK in the presence or absence of GSK3 β . Immunoprecipitation of BMAL1, either in presence or absence of CLOCK, pulled down GSK3 β , confirming that BMAL1 and GSK3 β do interact physically (Fig. 1B).

Control of clock protein stability is a key regulatory step to insure the tightness of circadian rhythms [22,23]. Moreover, it has been shown that GSK3 β -mediated phosphorylation of β -catenin, SRC-3, and Smad3 leads to ubiquitylation followed by proteasomal degradation [24,25,26]. Hence, we addressed the question of whether GSK3 β affects BMAL1 ubiquitylation. We co-expressed HIS-tagged ubiquitin along with Myc-CLOCK and Flag-Myc-BMAL1 with or without constitutively active (CA, Ser9>Ala mutation) or kinase dead (KD, Lys85>Ala) mutants of HA-tagged GSK3 β . Ubiquitylated proteins were pulled down using Ni-Sepharose beads under denaturing conditions and resolved by SDS-PAGE. Upon Western analysis using anti-Flag antibody to specifically detect BMAL1, we observed that co-expression of CA-GSK3 β greatly enhanced BMAL1 ubiquitylation, whereas co-expression of KD-GSK3 β had no effect on basal BMAL1 ubiquitylation (Fig. 1C). This result confirmed that phosphoryl-

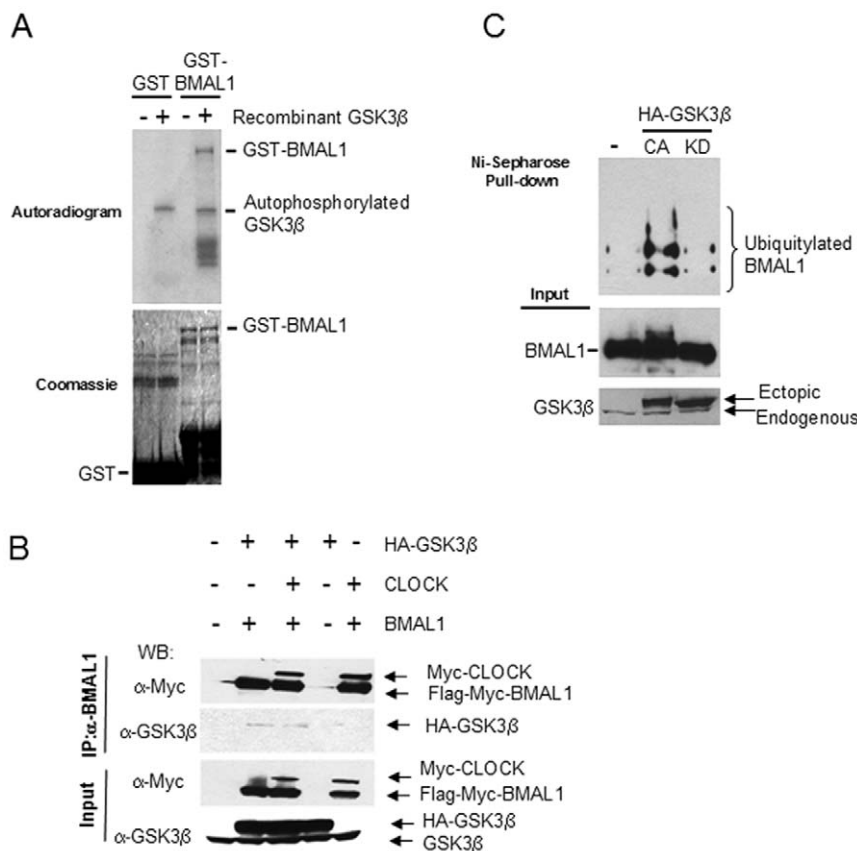


Figure 1. GSK3 β phosphorylates BMAL1 and primes it for ubiquitylation. (A) *In vitro* Kinase assay. Bacterially purified GST and GST-BMAL1 were incubated with recombinant GSK3 β in presence of γ^{32} P-ATP. Top panel shows the autoradiogram; bottom panel shows the coomassie blue staining for the same gel. (B) HEK 293 cells were transfected with plasmids expressing Flag-myc-BMAL1, myc-CLOCK with or without HA-GSK3 β . Total lysates were prepared and subjected to immunoprecipitation using anti-BMAL1 antibody. Immunoprecipitated proteins were detected by Western blotting (WB) using indicated antibodies. (C) Ubiquitylation assay. HEK 293 cells were transfected with plasmids expressing HIS-Ubiquitin, Flag-myc-BMAL1, myc-CLOCK, with or without the constitutively active (CA) or kinase dead (KD) mutants of HA-tagged GSK3 β . Ubiquitylated BMAL1 was detected by Western analysis using anti-Flag antibody. Input samples were probed with anti-Flag (to detect BMAL1) and anti-GSK3 β antibodies. doi:10.1371/journal.pone.0008561.g001

ation by GSK3 β primes BMAL1 for ubiquitylation. Thus, phosphorylation by GSK3 β appears to be an important step in BMAL1 proteosomal degradation, controlling BMAL1 cyclic protein levels.

Inhibition of GSK3 β Activity Enhances BMAL1 Stability

To further prove that phosphorylation by GSK3 β affects BMAL1 stability, we sought to inhibit GSK3 β activity. Activation of the Akt kinase results in phosphorylation and consequent inactivation of GSK3 β [27]. We transiently co-expressed BMAL1 and CLOCK, in presence or absence of a myristoylated form of Akt that turns this kinase in a constitutively active status (CA-Akt). Western analyses confirmed that co-expression of CA-Akt indeed caused an increase in phosphorylation of GSK3 β and its consequent inactivation (Fig. 2A). Interestingly, expression levels of BMAL1, but not CLOCK, was highly induced in cells that also expressed CA-Akt (Fig. 2A). These results support the notion that phosphorylation by GSK3 β might lead to BMAL1 degradation.

To further substantiate our hypothesis, we ectopically expressed BMAL1 in mouse embryo fibroblasts (MEFs) derived from WT or GSK3 β ^{-/-} mice. Myc-tagged GFP was co-expressed as a control. We observed that BMAL1 levels were much higher in GSK3 β ^{-/-} MEFs as compared to WT MEFs (Fig. 2B). GFP levels were similar in both cell lines. These results demonstrate that there is significantly higher accumulation of BMAL1 in the absence of GSK3 β . Next, we sought to rescue the GSK3 β ^{-/-} MEFs by re-introducing GSK3 β . BMAL1 was ectopically expressed by transient transfection into WT and GSK3 β ^{-/-} MEFs, in conjunction or not of a HA-tagged GSK3 β . Rescue of GSK3 β

function in the GSK3 β ^{-/-} MEFs caused a decrease in BMAL1 protein levels which returned to those in WT MEFs (Fig. 2C).

To determine whether the half-life of the endogenous BMAL1 protein depends on GSK3 β , we treated WT and GSK3 β ^{-/-} MEFs with cycloheximide to block protein synthesis. Importantly, both BMAL1 basal protein levels and its stability are much higher in the absence of GSK3 β (Fig. 2D). These results show that phosphorylation of BMAL1 by GSK3 β regulates its stability.

S17 and T21 on BMAL1 Are Targets for GSK3 β Mediated Phosphorylation

Among the 15 consensus GSK3 β sites on BMAL1, we focused our attention on two loci which contained multiple GSK3 β consensus sites in tandem. These sites included a region between residues 9 and 25, and another between residues 233 and 241 which are highly conserved in vertebrates (Fig. 3A,B). Importantly, both loci contain a motif which fits a highly stringent consensus for GSK3 β mediated phosphorylation [S/TPXXS/T]. Thus, S17 and T21 at the first locus, and T233 and S237 at the second locus, appear to be privileged candidates for phosphorylation by GSK3 β . In order to determine if any of these sites are *bona fide* targets for GSK3 β , we first analyzed the effect of point mutations at these sites on BMAL1 phosphorylation. We generated a panel of Ser>Ala mutants including: (i) S17 and T21 (S17,T21/A), (ii) T233, S237 and S241 (T233,S237,S241/A), and (iii) S17, T21, T233, S237 and S241 (S17,T21,T233,S237,S241/A). Plasmids expressing either wild type or BMAL1 mutants were co-transfected in HEK 293 cells along with a plasmid expressing Myc-CLOCK and harvested 48 hours post-transfection. Although phosphorylation was reduced

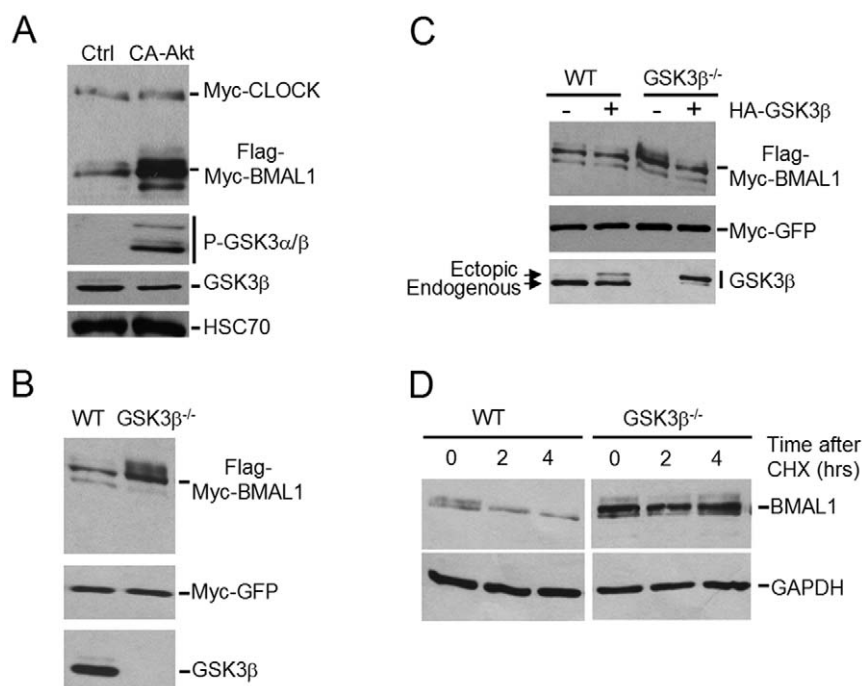


Figure 2. GSK3 β regulates BMAL1 stability. (A) HEK 293 cells were co-transfected with plasmids expressing Flag-myc-BMAL1, myc-CLOCK with or without CA-Akt. 48 hours post-transfection nuclear lysates were prepared and resolved by SDS-PAGE. CLOCK and BMAL1 levels were detected by Western analysis using anti-Myc antibody; phospho- and total GSK3 β and HSC70 (loading control) were detected by using specific antibodies. (B) WT and GSK3 β ^{-/-} MEFs were transfected with plasmids expressing Flag-myc-BMAL1, myc-CLOCK and myc-GFP. Nuclear lysates were resolved by SDS-PAGE followed by Western analysis. BMAL1 and GFP levels were detected by anti-Myc antibody. Total GSK3 β was detected using a specific antibody. (C) Same as in (B) except that indicated lanes were also transfected with a plasmid expressing HA-tagged GSK3 β . (D) WT and GSK3 β ^{-/-} MEFs were treated with 50 μ g/ml Cycloheximide (CHX), total lysates were prepared at indicated times and resolved by SDS-PAGE. Endogenous BMAL1 and GAPDH levels were detected by Western analysis using specific antibodies. Data shown is representative of three independent experiments. doi:10.1371/journal.pone.0008561.g002

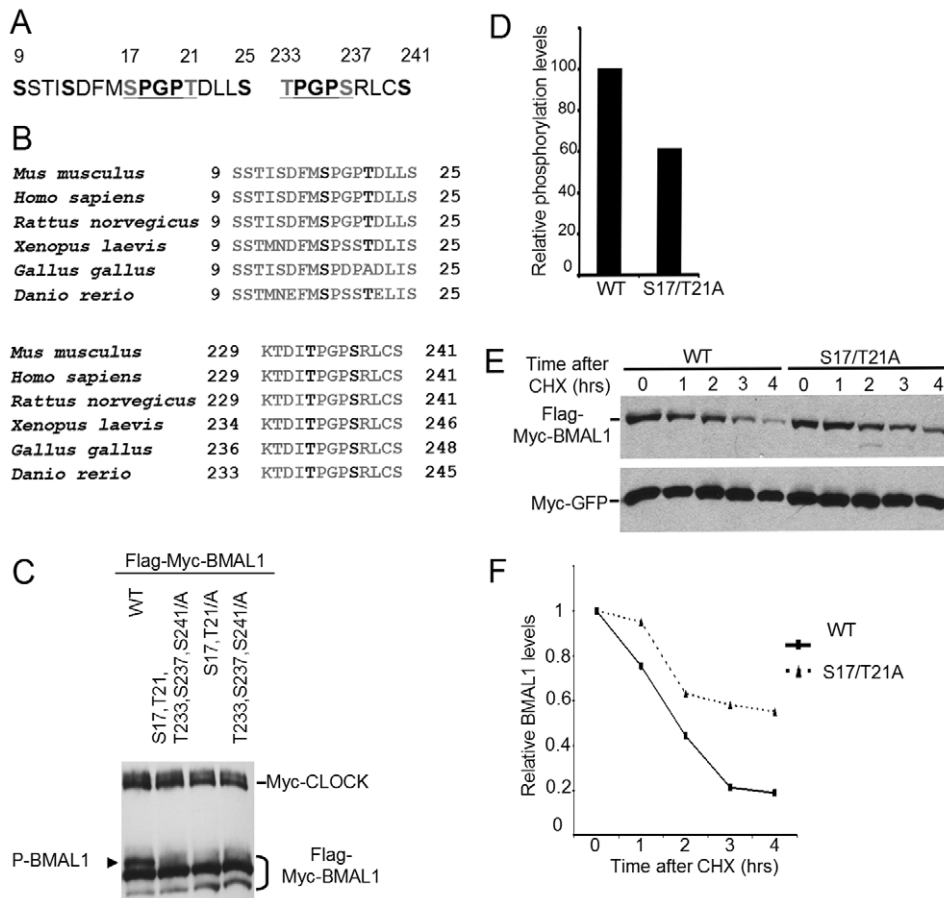


Figure 3. GSK3 β phosphorylates Ser 17 and Thr 21 on BMAL1. (A) Amino acid sequence around two putative GSK3 β consensus sites on mBMAL1. (B) Sequence alignment of the two putative GSK3 β consensus sites on BMAL1 showing conservation across species. (C) HEK 293 were transfected with plasmids expressing myc-CLOCK and WT or mutant Flag-myc-BMAL1. 48 hours post-transfection total lysates were prepared and resolved by SDS-PAGE. BMAL1 and CLOCK levels were detected by anti-Myc antibody. Slower migrating phosphorylated BMAL1 band is indicated by an arrow. (D) Bar graph representing phosphorylation levels of WT and S17,T21/A BMAL1 as analyzed by *In vitro* kinase assay (as in Fig. 1A). Data is representative of three independent experiments. (E) WT or S17,T21/A mutant of Flag-myc-BMAL1, along with myc-GFP were transiently expressed in JEG3 cells and treated with 50 μ g/ml CHX. Total lysates were prepared at indicated times and resolved by SDS-PAGE. BMAL1 and GFP levels were detected by Western analysis using anti-myc antibody. Data shown is representative of three independent experiments. (F) Line graph showing quantitation of BMAL1 levels, normalized to GFP levels, from Fig. 3E. doi:10.1371/journal.pone.0008561.g003

in all mutants, mutation of S17 and T21 caused maximal reduction in BMAL1 phosphorylation (Fig. 3C).

To prove that S17 and T21 are directly phosphorylated by GSK3 β , we performed an *in vitro* kinase assay with WT and mutant forms of GST-BMAL1. We observed that GSK3 β mediated phosphorylation of BMAL1 was reduced when S17 and T21 were mutated (Fig. 3D). This result shows that S17 and T21 are critical sites of GSK3 β -mediated phosphorylation, and indicates the presence of yet unrecognized phosphoacceptor sites in the protein. Interestingly, the importance of the S17,T21 sites is validated by the higher, albeit modest, stability of the S17,T21A-BMAL1 mutated protein as compared to the wild type BMAL1 (Fig. 3E,F).

Oscillation in GSK3 β Activity Correlates with BMAL1 Levels

Our results show that GSK3 β regulates BMAL1 levels. Thus, we questioned whether BMAL1 oscillation would be influenced in the absence of GSK3 β . To address this question, we synchronized WT and GSK3 β ^{-/-} MEFs, and analyzed BMAL1 levels by Western analysis. BMAL1 levels oscillate as expected in WT

MEFs, peaking at 6 to 12 hours post-synchronization with lowest levels at 24 hours post-synchronization (Fig. 4A). BMAL1 levels in GSK3 β ^{-/-} MEFs display only a mild oscillation, with total levels of the protein being much higher at all time points (Fig. 4A). Importantly, the *Bmal1* transcript levels and cyclic expression profile were unchanged in the GSK3 β ^{-/-} MEFs as compared to WT cells (Fig. 4B). These results indicate that GSK3 β is critical for the circadian oscillation of BMAL1 protein. It is, however, important to stress that the residual oscillation of BMAL1 in the GSK3 β ^{-/-} MEFs indicates the presence of other pathways which may contribute to BMAL1 turnover. One pathway could implicate GSK3 α , a kinase structurally similar to GSK3 β but not as comprehensively studied.

Next we analyzed whether regulation of GSK3 β activity by phosphorylation may oscillate in a circadian manner. Using anti phospho-GSK3 β antibodies we reveal that there is more phosphorylation of GSK3 β (corresponding to decreased kinase activity) at 6 to 12 hours post synchronization of the MEFs (Fig. 4C). The peak of GSK3 β phosphorylation correlates with the increase in BMAL1 protein levels; vice versa, when GSK3 β activity is high (24 to 30 hours post synchronization), BMAL1 levels are low (Fig. 4A,C).

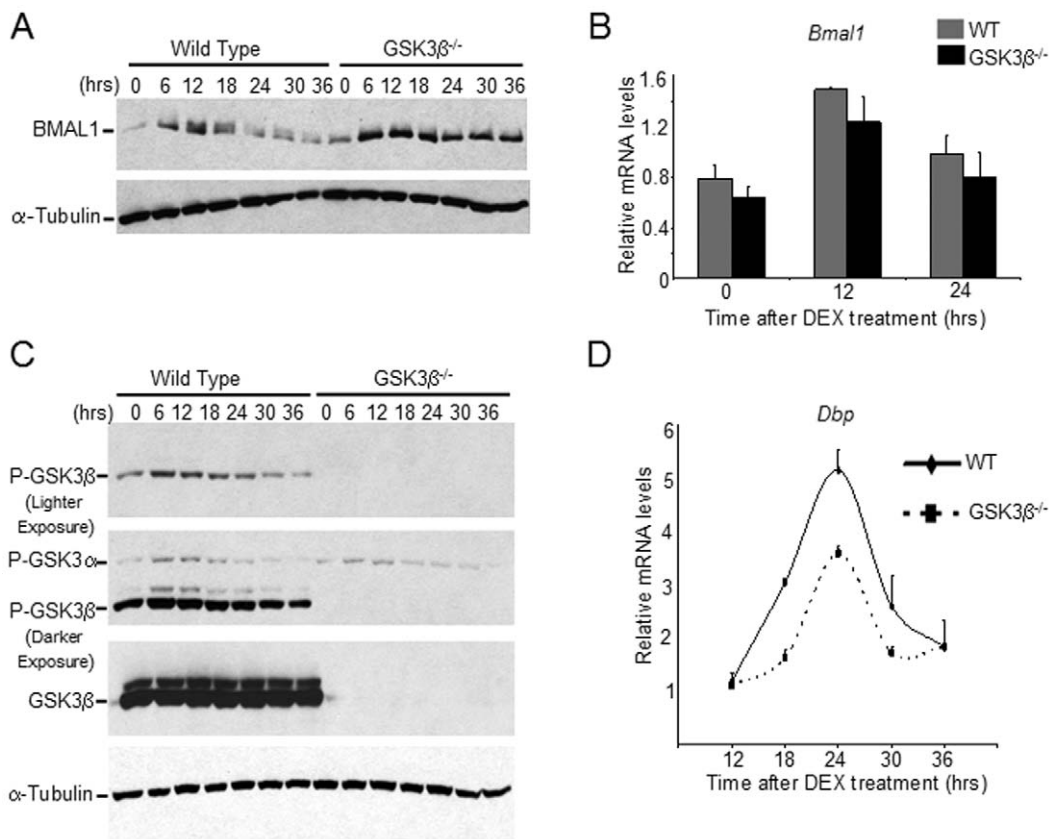


Figure 4. Circadian defects in GSK3 β ^{-/-} MEFs. WT and GSK3 β ^{-/-} MEFs were synchronized by 2 hour treatment with 100nM dexamethasone (DEX). (A) Total lysates were prepared at indicated times post synchronization and resolved by SDS-PAGE followed by Western analysis. BMAL1 and α -tubulin levels were detected by specific antibodies. (B) RNA was prepared at indicated times, reverse transcribed, and real-time PCR was performed using primers for *Bmal1* and 18S rRNA. Data is represented as relative levels of *Bmal1* normalized to 18S rRNA. (C) Same as in (A), except phospho-GSK3 α/β and total GSK3 β levels were detected by specific antibodies. (D) RNA was prepared at indicated times, reverse transcribed, and real-time PCR was performed using primers for *Dbp* and 18S rRNA. Data is represented as relative levels of *Dbp* normalized to 18S rRNA. doi:10.1371/journal.pone.0008561.g004

As it is not known whether GSK3 α activity may be circadian, we analyzed its phosphorylation in parallel with GSK3 β (Fig. 4C). GSK3 α phosphorylation oscillates with a profile analogous to GSK3 β , an event that persisted in GSK3 β ^{-/-} MEFs. This observation may suggest that GSK3 α could partially compensate for the loss of GSK3 β in circadian control, although more studies are needed to confirm whether GSK3 α plays a role in BMAL1 phosphorylation and turnover.

GSK3 β ^{-/-} MEFs Display Dampened Circadian Oscillation of *Dbp* mRNA

The regulation of BMAL1 phosphorylation and stability by GSK3 β may impact on the cyclic expression of clock-controlled genes. We thereby compared the expression profile of the *Dbp* gene in WT and GSK3 β ^{-/-} MEFs synchronized by dexamethasone. Lack of GSK3 β resulted in a significant dampening of *Dbp* oscillation as compared to WT MEFs, featuring a conserved period but decreased amplitude (Fig. 4D). These results support the notion that stabilization of BMAL1 protein levels might lead to reduction in its transcription activation ability [28].

Dopamine Signaling Regulates the Circadian Clock by Controlling BMAL1 Turnover

Dopamine signaling via the D2 receptor (D2R) has been demonstrated to modulate the Akt-GSK3 β pathway *in vivo* [29]. In

addition, we have previously reported that CLOCK:BMAL1 transcriptional activity is enhanced by activation of D2R-mediated signaling [30]. We thus used the D2R^{-/-} mice [31] as a model to analyze the effect of inactivating the GSK3 β pathway *in vivo*. To do so, we isolated the striatum from brains of mice entrained at different times of the circadian cycle (LD 12:12). While the cyclic expression profile and mRNA levels of *Bmal1* were similar in the striatum from WT and D2R^{-/-} animals (Fig. 5A), the levels of BMAL1 protein were elevated in the D2R^{-/-} mice (Fig. 5B). This result parallels the inactivation of the GSK3 β pathway observed in cultured MEFs (Fig. 4). Also, consistent with the expression profile observed in the GSK3 β ^{-/-} MEFs, the amplitude of the circadian expression of both *Dbp* and *Per2* is significantly decreased in the striatum of D2R^{-/-} mice (Fig. 5C and D). These results confirm that the GSK3 β pathway regulates circadian gene expression by controlling BMAL1 protein stability *in vivo*.

Discussion

BMAL1 is a critical regulator of the circadian clock. Its ablation in the mouse, in addition to causing arrhythmicity [32], leads to premature aging and reduced life-span [33]. BMAL1 is a crucial player in the regulation of metabolism, playing a role in adipogenesis [34] and in the control of glucose and triglycerides levels [35]. Mice with a liver specific deletion of *Bmal1* show normal locomotor activity, but the circadian expression of key

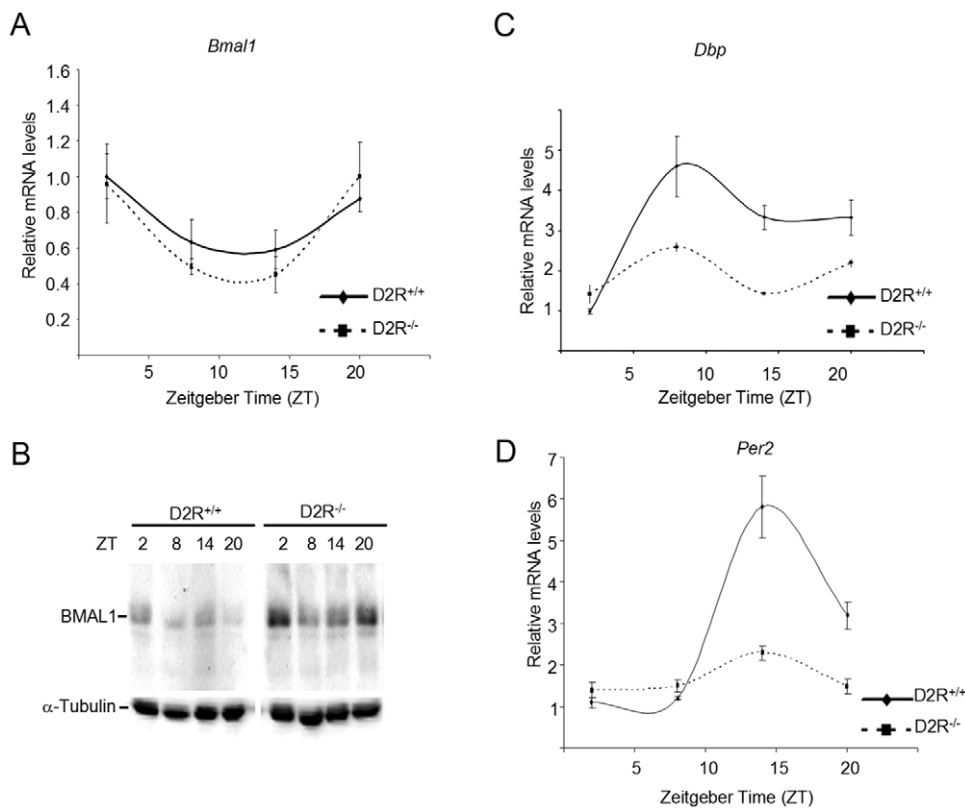


Figure 5. BMAL1 mRNA and protein levels in WT and D2R^{-/-} mice. Mice entrained in 12 hr Light – 12 hr Dark cycles were sacrificed at indicated times and their striatum was dissected out. (A) RNA was prepared at indicated times, reverse transcribed, and real-time PCR was performed using primers for *Bmal1* and 18S rRNA. Data is represented as relative levels of *Bmal1* normalized to 18S rRNA. (B) Total lysates were prepared and resolved by SDS-PAGE. BMAL1 and α -tubulin levels were detected by Western analysis using specific antibodies. (C,D) Same as in (A), except real-time PCR was performed using primers for (C) *Dbp* and (D) *Per2*. doi:10.1371/journal.pone.0008561.g005

metabolic genes, such as *glucose transporter 2 (glut2)*, is abolished. This results in mice being hypoglycemic during the fasting phase of the feeding cycle [36].

The important roles played by BMAL1 parallel multiple levels of regulation of its function. BMAL1 undergoes various PTMs, including phosphorylation, acetylation [7], sumoylation [8,9] and ubiquitylation [10]. While the functional interactions between these PTMs have not been deciphered, phosphorylation by distinct kinases appears to regulate unique activities [10,37]. Specifically, phosphorylation by Casein Kinase I ϵ (CKI ϵ) has been reported to activate BMAL1-mediated transcription [6], while phosphorylation by MAPK inhibits it [4]. Recently we have shown that CK2 α -mediated phosphorylation regulates BMAL1 intracellular localization [5]. Our present results indicate that GSK3 β activity is circadian and that BMAL1 phosphorylation by this kinase controls its stability.

Our analysis identified S17 and T21 in BMAL1 as major target sites for GSK3 β - mediated phosphorylation. While mutation of these residues leads to a reduction of phosphorylation and an increase in BMAL1 stability, we predict the presence of additional GSK3 β phosphoacceptor sites on BMAL1. Importantly, multiple phosphorylation events on a clock protein, presumably by multiple kinases appear to be a common mode of regulation. For example, it has been recently shown that the *Neurospora* clock protein FREQUENCY is phosphorylated at 75 residues [38]. The phosphorylation status of several of these residues changes according to the time of the day and regulates period length. In mammals, PER2 has been shown to be phosphorylated at 21 sites,

regulating its stability and localization [39]. While a detailed proteomic analysis of BMAL1 phosphorylation is warranted, our results reveal that GSK3 β is pivotal in circadian function as it controls the stability of a core clock regulator. Further illustrating the importance of GSK3 β in circadian regulation, a recent report demonstrated that GSK3 β can also phosphorylate CLOCK and regulate its stability [40]. It would be interesting to explore whether, similarly to what we describe here for dopamine (Fig. 5), some specific pathways known to operate via GSK3 β , such as the insulin signaling in liver [15], regulate the circadian clock by altering the phosphorylation state and the stability of BMAL1. The implication of GSK3 β in circadian control is significant, especially considering that this kinase has been linked to various diseases such as diabetes, Alzheimer's, cancer and neuropsychiatric disorders. The link between D2R signaling and BMAL1 stability is challenging, as dopamine dysfunctions underlie neurological and psychiatric disorders which are disruptive of the circadian clock. Future studies will determine whether GSK3 β -mediated disruption of normal circadian control is causally linked to some of these pathological conditions. In this sense, it is interesting that the activity of GSK3 α also oscillates in circadian manner (Fig. 4). Although our data suggests that GSK3 α might partially compensate for the loss of GSK3 β , further studies are needed to determine whether BMAL1 and other clock components can be phosphorylated by GSK3 α .

It could be argued that the effects of GSK3 β on BMAL1 are indirect. It has indeed been shown that phosphorylation of Rev-erb α by GSK3 β leads to its stabilization [21]. Since Rev-erb α is a

negative regulator of *Bmal1* transcription, it can be expected that when GSK3 β is inhibited, Rev-erb α will be less stable, and hence, *Bmal1* transcription may be de-repressed. However, our results conclusively demonstrate that the observed stabilization of BMAL1 protein upon GSK3 β inhibition is independent of Rev-erb α . The evidence in support of our argument is: (i) BMAL1 protein has a longer half-life in GSK3 β ^{-/-} MEFs when compared to WT MEFs (Fig. 2D); (ii) BMAL1 accumulation upon GSK3 β inhibition is evident not only on endogenous BMAL1, but also on ectopically expressed BMAL1 (Fig. 2). The exogenous BMAL1 is not under control of the *Bmal1* promoter and hence can not be affected by Rev-erb α ; and (iii) BMAL1 protein levels are higher in the GSK3 β ^{-/-} MEFs and D2R^{-/-} mice than in their wild type counterparts, although *Bmal1* circadian mRNA levels are virtually equivalent (Figs. 4 A,B and 5 A,B). Altogether, the present findings unequivocally show that phosphorylation of BMAL1 by GSK3 β is a critical step in the control of its stability.

Recent reports have indicated that although circadian locomotor activity persists in mice displaying constitutively higher levels of BMAL1, either due to abolished Rev-erb α expression [41] or by transgenic re-expression in *Bmal1*^{-/-} mice [42], the period length is rendered shorter. Moreover, robustness in tissue-specific circadian expression of certain clock genes (e.g. *Cry1*, *Dbp*) is compromised in these animals. These observations are in agreement with our data showing that increased BMAL1 protein levels in GSK3 β ^{-/-} MEFs and D2R^{-/-} mice does not abolish circadian gene expression, but affects its amplitude.

PTMs are often found in specific combinations in order to regulate protein activity [43]. Phosphorylation and ubiquitylation are often found to be coupled. In certain cases, such as β -catenin, I κ B α , cyclin E, SREBP1, phosphorylation of a protein generates a “Phosphodegron” which promotes recognition by ubiquitin ligases [43]. Interestingly, in case of some transcription factors, their transcriptional activation domains (TAD) and degrons are overlapping [28]. The “Black Widow” model for transcription activation suggests that certain transcription factors are active only when unstable and their ubiquitylation status positively correlates with their activity. For example, stabilization of VP16 TAD causes its inactivation [44]. The VP16 TAD signals its ubiquitylation through the Met30 ubiquitin ligase. In the absence of Met30, VP16 is more stable but is unable to activate transcription. For BMAL1, it is notable that at specific times of the day when its abundance is low, its activity is high [45]. The low abundance of BMAL1 also coincides with its high phosphorylation. Thus, we speculate that activation by BMAL1 also follows the “Black Widow” model: upon GSK3 β mediated phosphorylation and generation of phosphodegrons, ubiquitylation by yet uncharacterized ubiquitin ligases would de-stabilize and thus, activate BMAL1. Identification of the E3 ubiquitin ligase specific for BMAL1, and the sites for ubiquitylation on BMAL1 should be the subject of future studies that would provide invaluable information on the control of circadian rhythms.

Materials and Methods

Animals

Generation of D2R-deficient mice has been described [31]. The D2R-null mice and wild type mice used were littermates. Mice housed in individual cages were entrained on a L12:D12 (12 h light–12 h dark) cycle for two weeks before analyses. Mice were sacrificed at specified circadian times and striata were isolated and homogenized as described [27]. All research involving vertebrate animals has been performed under protocol approved by the Institutional Animal Care and Use Committee (IACUC). Animals are monitored on a daily

basis by both the lab and University Lab Animal Resources (ULAR) veterinary staff for signs of distress, pain, and/or infection, and are given ad libitum access to food and water. Cages were cleaned on a weekly basis and when visibly soiled to maintain a clean environment. All husbandry procedures and welfare policies are conducted according to the Guide for the Care and Use of Laboratory Animals, set forth by the Institute of Laboratory Animal Resources, Commission on Life Sciences, and National Research Council.

Reagents

Plasmid expressing a myristoylated form of AKT (constitutively active) was from Millipore (Temecula, CA). Plasmids expressing wild type, constitutively active or kinase dead forms of GSK3 β were gifts from Dr. Jim Woodgett (Samuel Lunenfeld Research Institute, Mount Sinai Hospital, Toronto, Canada). Myc-tagged Clock, Flag-Myc-tagged Bmal1, and Myc-tagged GFP plasmids have been described earlier [7]. Antibodies against phospho-GSK3 α/β were from Cell Signaling Technology (Danvers, MA); anti-Myc and anti-GAPDH from Millipore (Temecula, CA); anti-flag and anti-tubulin from Sigma (St. Louis, MO); anti-HSC70 from Santa Cruz Biotechnology, Inc (Santa Cruz, CA); and anti-total GSK3 β was from BD Biosciences (San Jose, CA). Site directed mutagenesis kit was from Stratagene (La Jolla, CA).

Cell Culture and Transfection

HEK 293 cells (ATCC, Manassas, VA) were cultured in DMEM supplemented with 10% NCS and antibiotics. JEG3 cells (ATCC, Manassas, VA) were cultured in BME supplemented with 10% FBS and antibiotics. Cells were transfected with indicated plasmids using BioT transfection reagent (Bioland Scientific LLC, Cerritos, CA) according to manufacturer’s recommendations. Mouse embryonic fibroblasts (MEFs) were cultured in DMEM supplemented with 10% FBS and antibiotics. Confluent MEFs were synchronized by treatment with 100nM Dexamethasone (Sigma, St. Louis, MO) for 2 hours. Wild type and GSK3 β ^{-/-} MEFs were generous gifts from Dr. Jim Woodgett.

Preparation of Total and Nuclear Extracts from Cultured Cells

Cells were washed twice with cold phosphate buffered saline (PBS) and lysed in RIPA buffer (50 mM Tris pH 8.0, 150 mM NaCl, 5 mM EDTA, 15 mM MgCl₂, 1% NP40, 1 \times protease inhibitor cocktail (Roche Diagnostics, Indianapolis, IN), 1mM DTT, 10 mM NaF, 1 mM PMSF). For nuclear extracts, after washing cells with cold PBS, cells were lysed with hypotonic buffer (10 mM HEPES-KOH pH 7.9, 1.5 mM MgCl₂, 10 mM KCl, 1 \times protease inhibitor cocktail, 1mM DTT, 10 mM NaF, 1 mM PMSF). Following a brief centrifugation, pellet was resuspended in hypertonic buffer (20 mM HEPES-KOH pH 7.9, 25% glycerol, 420 mM NaCl, 1.5mM MgCl₂, 0.2 mM EDTA, 1 \times protease inhibitor cocktail, 1mM DTT, 10 mM NaF, 1 mM PMSF). Supernatants were recovered as nuclear extracts.

Ubiquitylation Analysis

HEK 293 cells were co-transfected with plasmids expressing HIS-tagged ubiquitin, Myc-Clock, flag-Myc-Bmal1 and constitutively active (CA) or kinase dead (KD) mutants of HA-tagged GSK3 β . 48 hours post-transfection, cells were treated with 10 μ M MG132 for 6 hours, and then lysed in denaturing buffer containing 8 M Urea. Ubiquitylated (and thus HIS tagged) proteins were enriched with Ni-sepharose 6 fast flow beads (GE healthcare, Uppsala, Sweden) and ubiquitylated BMAL1 was detected by Western analysis with the antibody against Flag.

In Vitro Kinase Assay

Glutathione-S-transferase (GST) or GST-BMAL1 proteins were purified from BL21 strain of *Escherichia coli* using glutathione-sepharose beads (GE Healthcare, Uppsala, Sweden). Purified proteins were washed in kinase buffer (20mM Tris-HCl, pH 7.5, 10mM MgCl₂, 5mM DTT) and then incubated with or without 25 ng recombinant GSK-3 β (New England Biolabs, Ipswich, MA) in presence of 200 μ M ATP and 5 μ Ci γ ³²P ATP at 30°C for 30 min. Reaction was terminated by boiling in presence of Laemmli buffer. Samples were resolved by SDS-PAGE, stained by Coomassie blue, destained, dried and then phosphorylated. BMAL1 was detected by autoradiography.

Quantitative Real-Time RT-PCR

Each quantitative real-time RT-PCR was performed using the Chromo4 real time detection system (BIO-RAD). The PCR primers for mBmal1 mRNA, mDbp mRNA, mPer2 mRNA, 18S

rRNA are available upon request. For a 20 μ l PCR, 50 ng of cDNA template was mixed with the primers to final concentrations of 200 nM and 10 μ l of iQ SYBR Green Supermix (BIO-RAD), respectively. The reaction was first incubated at 95°C for 3 min, followed by 40 cycles at 95°C for 30 s and 60°C for 1 min.

Acknowledgments

We would like to thank all the members of the Sassone-Corsi and Borrelli laboratories for reagents and helpful discussions. We thank Dr. Jim Woodgett for providing us valuable reagents and Claudia De Mei for help with striatum dissection.

Author Contributions

Conceived and designed the experiments: SS LZ EB PSC. Performed the experiments: SS LZ CK. Analyzed the data: SS LZ EB PSC. Contributed reagents/materials/analysis tools: SS. Wrote the paper: SS PSC.

References

- Sahar S, Sassone-Corsi P (2009) Metabolism and cancer: the circadian clock connection. *Nat Rev Cancer* 9: 886–896.
- Wijnen H, Young MW (2006) Interplay of circadian clocks and metabolic rhythms. *Annu Rev Genet* 40: 409–448.
- Gallego M, Virshup DM (2007) Post-translational modifications regulate the ticking of the circadian clock. *Nat Rev Mol Cell Biol* 8: 139–148.
- Sanada K, Okano T, Fukada Y (2002) Mitogen-activated protein kinase phosphorylates and negatively regulates basic helix-loop-helix-PAS transcription factor BMAL1. *J Biol Chem* 277: 267–271.
- Tamaru T, Hirayama J, Isojima Y, Nagai K, Norioka S, et al. (2009) CK2 α phosphorylates BMAL1 to regulate the mammalian clock. *Nat Struct Mol Biol* 16: 446–448.
- Eide EJ, Vielhaber EL, Hinz WA, Virshup DM (2002) The circadian regulatory proteins BMAL1 and cryptochromes are substrates of casein kinase I ϵ . *J Biol Chem* 277: 17248–17254.
- Hirayama J, Sahar S, Grimaldi B, Tamaru T, Takamatsu K, et al. (2007) CLOCK-mediated acetylation of BMAL1 controls circadian function. *Nature* 450: 1086–1090.
- Cardone L, Hirayama J, Giordano F, Tamaru T, Palvimo JJ, et al. (2005) Circadian clock control by SUMOylation of BMAL1. *Science* 309: 1390–1394.
- Lee J, Lee Y, Lee MJ, Park E, Kang SH, et al. (2008) Dual modification of BMAL1 by SUMO2/3 and ubiquitin promotes circadian activation of the CLOCK/BMAL1 complex. *Mol Cell Biol* 28: 6056–6065.
- Kwon I, Lee J, Chang SH, Jung NC, Lee BJ, et al. (2006) BMAL1 shuttling controls transactivation and degradation of the CLOCK/BMAL1 heterodimer. *Mol Cell Biol* 26: 7318–7330.
- Doble BW, Woodgett JR (2003) GSK-3: tricks of the trade for a multi-tasking kinase. *J Cell Sci* 116: 1175–1186.
- Woodgett JR (2001) Judging a protein by more than its name: GSK-3. *Sci STKE* 2001: re12.
- MacAulay K, Woodgett JR (2008) Targeting glycogen synthase kinase-3 (GSK-3) in the treatment of Type 2 diabetes. *Expert Opin Ther Targets* 12: 1265–1274.
- Wang Z, Smith KS, Murphy M, Piloto O, Somerville TC, et al. (2008) Glycogen synthase kinase 3 in MLL leukaemia maintenance and targeted therapy. *Nature* 455: 1205–1209.
- Jope RS, Johnson GV (2004) The glamour and gloom of glycogen synthase kinase-3. *Trends Biochem Sci* 29: 95–102.
- Martinek S, Inonog S, Manoukian AS, Young MW (2001) A role for the segment polarity gene shaggy/GSK-3 in the *Drosophila* circadian clock. *Cell* 105: 769–779.
- Cyran SA, Yiannoulos G, Buchsbaum AM, Saez L, Young MW, et al. (2005) The double-time protein kinase regulates the subcellular localization of the *Drosophila* clock protein period. *J Neurosci* 25: 5430–5437.
- Hirota T, Lewis WG, Liu AC, Lee JW, Schultz PG, et al. (2008) A chemical biology approach reveals period shortening of the mammalian circadian clock by specific inhibition of GSK-3 β . *Proc Natl Acad Sci U S A* 105: 20746–20751.
- Itaka C, Miyazaki K, Akaike T, Ishida N (2005) A role for glycogen synthase kinase-3 β in the mammalian circadian clock. *J Biol Chem* 280: 29397–29402.
- Harada Y, Sakai M, Kurabayashi N, Hirota T, Fukada Y (2005) Ser-557-phosphorylated mCRY2 is degraded upon synergistic phosphorylation by glycogen synthase kinase-3 β . *J Biol Chem* 280: 31714–31721.
- Yin L, Wang J, Klein PS, Lazar MA (2006) Nuclear receptor Rev-erb α is a critical lithium-sensitive component of the circadian clock. *Science* 311: 1002–1005.
- Yagita K, Tamanini F, Yasuda M, Hoeijmakers JH, van der Horst GT, et al. (2002) Nucleocytoplasmic shuttling and mCRY-dependent inhibition of ubiquitylation of the mPER2 clock protein. *Embo J* 21: 1301–1314.
- Virshup DM, Forger DB (2007) After hours keeps clock researchers CRYing Overtime. *Cell* 129: 857–859.
- Hart M, Concordet JP, Lassot I, Albert I, del los Santos R, et al. (1999) The F-box protein beta-TrCP associates with phosphorylated beta-catenin and regulates its activity in the cell. *Curr Biol* 9: 207–210.
- Wu RC, Feng Q, Lonard DM, O'Malley BW (2007) SRC-3 coactivator functional lifetime is regulated by a phospho-dependent ubiquitin time clock. *Cell* 129: 1125–1140.
- Guo X, Ramirez A, Waddell DS, Li Z, Liu X, et al. (2008) Axin and GSK3-control Smad3 protein stability and modulate TGF- signaling. *Genes Dev* 22: 106–120.
- Beaulieu JM, Tirota E, Sotnikova TD, Masri B, Salahpour A, et al. (2007) Regulation of Akt signaling by D2 and D3 dopamine receptors in vivo. *J Neurosci* 27: 881–885.
- Muratani M, Tansey WP (2003) How the ubiquitin-proteasome system controls transcription. *Nat Rev Mol Cell Biol* 4: 192–201.
- Beaulieu JM, Sotnikova TD, Yao WD, Kockeritz L, Woodgett JR, et al. (2004) Lithium antagonizes dopamine-dependent behaviors mediated by an AKT/glycogen synthase kinase 3 signaling cascade. *Proc Natl Acad Sci U S A* 101: 5099–5104.
- Yujnovsky I, Hirayama J, Doi M, Borrelli E, Sassone-Corsi P (2006) Signaling mediated by the dopamine D2 receptor potentiates circadian regulation by CLOCK:BMAL1. *Proc Natl Acad Sci U S A* 103: 6386–6391.
- Baik JH, Picetti R, Saiardi A, Thieriet G, Dierich A, et al. (1995) Parkinsonian-like locomotor impairment in mice lacking dopamine D2 receptors. *Nature* 377: 424–428.
- Bunger MK, Wilsbacher LD, Moran SM, Clendenen C, Radcliffe LA, et al. (2000) Mop3 is an essential component of the master circadian pacemaker in mammals. *Cell* 103: 1009–1017.
- Kondratov RV, Kondratova AA, Gorbacheva VY, Vykhovanets OV, Antoch MP (2006) Early aging and age-related pathologies in mice deficient in BMAL1, the core component of the circadian clock. *Genes Dev* 20: 1868–1873.
- Shimba S, Ishii N, Ohta Y, Ohno T, Watabe Y, et al. (2005) Brain and muscle Arnt-like protein-1 (BMAL1), a component of the molecular clock, regulates adipogenesis. *Proc Natl Acad Sci U S A* 102: 12071–12076.
- Rudic RD, McNamara P, Curtis AM, Boston RC, Panda S, et al. (2004) BMAL1 and CLOCK, two essential components of the circadian clock, are involved in glucose homeostasis. *PLoS Biol* 2: e377.
- Lamia KA, Storch KF, Weitz CJ (2008) Physiological significance of a peripheral tissue circadian clock. *Proc Natl Acad Sci U S A* 105: 15172–15177.
- Kondratov RV, Chernov MV, Kondratova AA, Gorbacheva VY, Gudkov AV, et al. (2003) BMAL1-dependent circadian oscillation of nuclear CLOCK: posttranslational events induced by dimerization of transcriptional activators of the mammalian clock system. *Genes Dev* 17: 1921–1932.
- Baker CL, Kettenbach AN, Loros JJ, Gerber SA, Dunlap JC (2009) Quantitative proteomics reveals a dynamic interactome and phase-specific phosphorylation in the *Neurospora* circadian clock. *Mol Cell* 34: 354–363.
- Vanselow K, Vanselow JT, Westermarck PO, Reischl S, Maier B, et al. (2006) Differential effects of PER2 phosphorylation: molecular basis for the human familial advanced sleep phase syndrome (FASPS). *Genes Dev* 20: 2660–2672.
- Spengler ML, Kuropatwinski KK, Schumer M, Antoch MP (2009) A serine cluster mediates BMAL1-dependent CLOCK phosphorylation and degradation. *Cell Cycle* 8(24): 4138–4146.
- Preitner N, Damiola F, Lopez-Molina L, Zakany J, Duboule D, et al. (2002) The orphan nuclear receptor REV-ERB α controls circadian transcription within the positive limb of the mammalian circadian oscillator. *Cell* 110: 251–260.

42. McDearmon EL, Patel KN, Ko CH, Walisser JA, Schook AC, et al. (2006) Dissecting the functions of the mammalian clock protein BMAL1 by tissue-specific rescue in mice. *Science* 314: 1304–1308.
43. Hunter T (2007) The age of crosstalk: phosphorylation, ubiquitination, and beyond. *Mol Cell* 28: 730–738.
44. Salghetti SE, Caudy AA, Chenoweth JG, Tansey WP (2001) Regulation of transcriptional activation domain function by ubiquitin. *Science* 293: 1651–1653.
45. Lee C, Etchegaray JP, Cagampang FR, Loudon AS, Reppert SM (2001) Posttranslational mechanisms regulate the mammalian circadian clock. *Cell* 107: 855–867.