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Interferon-α suppresses hepatitis B virus enhancer II activity via the protein kinase C pathway

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ABSTRACT

HBV has two enhancer (En) regions each of which promotes its own transcription. En II regulates production of pregenomic RNA, a key product of HBV replication, more strongly than En I. Although IFN-α has been found to suppress En I activity, its effect on En II activity has not been examined. Here we used luciferase assay to demonstrate that IFN-α suppresses En II activity. Analysis with several deletion/mutation constructs identified two major segments, nt 1703–1727 and nt 1746–1770, within the En II sequence as being responsible for the suppressive effects of IFN-α. Pre-treatment with protein kinase C (PKC) inhibitors blocked this effect regardless of the expression levels of phospho-STAT1 and Mx upon IFN-α stimulation. These results indicate that IFN-α suppresses En II activity via the PKC pathway, which may be an alternative suppressive pathway for HBV replication. (136 words).

Introduction

Hepatitis B virus (HBV) causes acute and chronic hepatitis in humans, and chronic infection is closely associated with the development of liver cirrhosis and hepatocellular carcinoma (Lok and McMahon, 2009). HBV has a partially double-stranded 3.2-kb DNA genome (relaxed circular (RC) DNA) in its nucleocapsid. When HBV invades host cells, RC-DNA is converted into a plasmid-like covalently closed circular DNA (cccDNA) inside the nucleus. From the cccDNA, the 3.5-, 2.4-, 2.1-, and 0.8-kb mRNAs are transcribed by cellular RNA polymerase II (Beck and Nassal, 2007). Among these RNAs, 3.5-kb pregenomic RNA (pgRNA) serves as the template of reverse transcription for synthesis of negative-strand DNA. Thus, transcription of pgRNA from cccDNA is one of the key steps in HBV replication.

In the HBV genome, there are four promoters (CP, SPI, SPII, and XP) and two transcriptional enhancer regions. Both enhancers stimulate transcription from the promoters (Antonucci and Rutter, 1989; Moolla et al., 2002; Su and Yee, 1992; Vannice and Levinson, 1988; Yee, 1989). Enhancer I (En I), which is located upstream of the X gene, activates transcription in a relatively cell-independent manner (Vannice and Levinson, 1988). In contrast, enhancer II (En II) (Fig. 1), located just upstream of CP, specifically activates transcription in hepatocytes (Wang et al., 1990; Yee, 1989; Yuh and Ting, 1990). Hepatocytes selectively express transcription factors which activate En II activity, such as HNF1 (Wang et al., 1998), HNF3 (Johnson et al., 1995; Li et al., 1995), HNF4 (Guo et al., 1993; Raney et al., 1997), CCAAT/enhancer binding protein (C/EBP) (López-Cabrera et al., 1990, 1991; Yuh and Ting, 1991) and FTF (Ishida et al., 2000; Li et al., 1998). This characterizes En II as a hepatocyte-specific *cis*-acting element. A previous report showed that, upon transfection with HBV genome, human hepatic cells, but not non-hepatic cells, were able to express pgRNA (Sureau et al., 1986). For this reason, En II is considered to regulate the production of pgRNA more strongly than En I (Yee, 1989).

Interferon-α (IFN-α) has been used as an anti-viral agent against HBV. It suppresses HBV viral load and ameliorates hepatic inflammation (Jonas et al., 2010; Liaw, 2009). Type I IFN activates the Janus kinase (JAK) bound to the cytoplasmic domain of its receptor. JAK phosphorylates transcription factors such as signal transducers and activators of transcription (STAT) 1 and STAT2. Phosphorylated STAT1 and STAT2 bind to IFN regulatory factor 9 (IRF9). These transcription factors form a complex, IFN-stimulated gene factor 3 (ISGF3). This complex binds to IFN stimulation response element (ISRE) in the promoter region of various genes, and activates interferon-stimulated genes (ISGs) (Der et al., 1998). Some of the ISGs including RNA-activated protein kinase (PKR), 2′,5′-oligoadenylate synthetases (OAS), and Mx have been shown to possess antiviral activity. ISG induction by type I IFN is considered to be the main pathway to suppressing viral replication.

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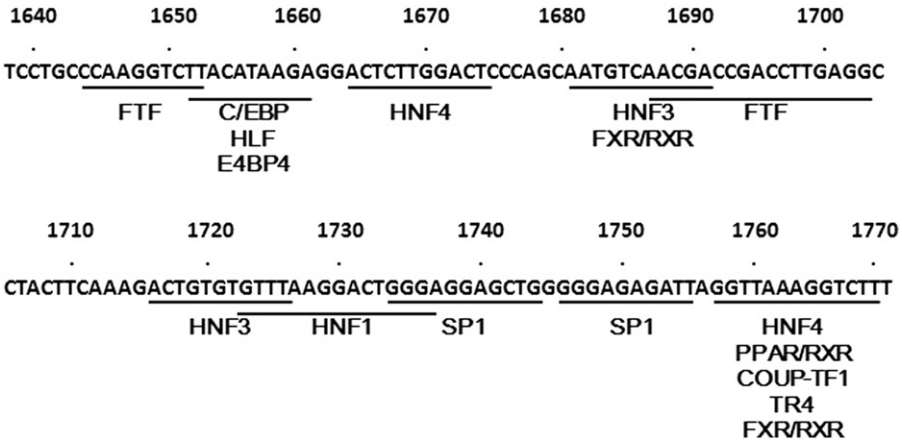

Fig. 1. Nucleotide sequences of the HBV En II region. The HBV sequence used in this study was of the *adw2* subtype (GenBank accession no. X02763). Numbering of the HBV sequence started at the unique *Eco*RI site. The underlined sequences represent the transcription factor binding sites mentioned in previous reports.

Type I IFN has been reported to inhibit HBV En I and core promoter activities (Nakao et al., 1999; Romero and Lavine, 1996; Schulte-Frohlinde et al., 2002; Tur-Kaspa et al., 1990). Nakao et al. demonstrated that IFN-α suppressed En I transcriptional activity by the binding of ISGF3 to the ISRE-like sequence in En I region (Nakao et al., 1999). However, there has been no study on the effect of IFN-α on HBV En II activity. In this study, we demonstrated that IFN-α suppressed En II activity via activation of PKC. Notably, STAT1 activation and ISG induction may be dispensable for IFN-α-mediated suppression of En II activity. This might shed light on understanding the inhibition of HBV replication by IFN-α.

Results

En II activity is down-regulated by IFN-α

We constructed a luciferase gene expression vector by inserting the En II sequence (nt 1640 to 1771) into pGL4LUC (pGL4LUC-En II). Huh-7 cells were transfected with pGL4LUC or pGL4LUC-En II, treated with or without IFN-α, and luciferase activities were evaluated. Insertion of En II increased the luciferase activity (about 228-fold) (Fig. 2A). IFN-α down-regulated the luciferase activity of pGL4LUC-En II, but did not affect that of pGL4LUC (Fig. 2B). This result suggested that IFN-α inhibited the activity of En II, and we examined the time course of IFN-α-induced suppression of En II activity. The suppressive effect of IFN-α on En II activity appeared at 3 h after administration of IFN-α, peaked at 6–12 h, and was gradually attenuated (Fig. 2C). Next, dose-response analysis showed that the En II activity was down-regulated by IFN-α in a dose-dependent manner, with the maximal suppressive effect at 300–1000 IU/m (Fig. 2D). We also examined the IFN-α-mediated suppression of En II activity in other hepatoma cell lines, PLC/PRF/5 and Hep3B. IFN-α significantly suppressed En II activities in both these cell lines (Fig. 2E). We next assessed whether or not IFN-α regulated HBV transcription in the HBV genome transfected cells by RT-PCR. HBV-RNA levels were significantly reduced by IFN-α (Fig. 2F). These results indicate that IFN-α suppresses HBV En II activity as well as its expression at a transcriptional level.

Both nt 1703–1727 and nt 1746–1770 within the En II region are required for suppression of En II activity by IFN-α

To determine the region responsible for the inhibitory effect of IFN-α on En II activity, we divided the En II sequence into six segments (Fig. 3A), and constructed plasmids containing En II sequences with deletion of each segment (pGL4LUC-En II-D1∼6). Huh-7 cells were transfected with these deleted constructs, treated with IFN-α, and then assayed for luciferase activity. None of the deletions could restore the suppressive activity by IFN-α (Fig. 3B), suggesting that there are several responsible regions for the IFN-α-induced suppression of En II activity. Next, we constructed plasmids containing four iterations of each segment within the En II sequence in tandem (pGL4LUC-En II-T1∼6) to examine the contribution of individual short fragments. IFN-α significantly suppressed the activities of pGL4LUC-En II-T2, T3, T4, T5 and -T6 in luciferase assay. Among them, the activities of pGL4LUC-En II-T4 and -T6 showed the largest suppression by IFN-α (Fig. 3C). On the basis of this result, we constructed a luciferase reporter vector with deletions of both segment 4 (nt 1703–1727) and segment 6 (nt 1746–1770) (pGL4LUC-En II-D4+6). The activity of this dual-deleted construct did not show a significant change due to IFN-α (Fig. 3D). These results suggest that both nt 1703–1727 and nt 1746–1770 within the En II region are required for the suppression of En II activity by IFN-α.

IFN-α-mediated suppression of En II activity is dependent on JAK activation

IFN-induced signal transduction occurs through the sequential activation of JAKs and STATs (Darnell et al., 1994). We examined the role of JAK in the inhibition of En II activity. JAK inhibitor alone did not affect En II activity. But the pre-treatment of the cells with JAK inhibitor completely blocked the suppressive effect of IFN-α on En II activity (Fig. 4A). The effect of JAK inhibitor was confirmed by the reducion of Mx induction in Western blot analysis (Fig. 4B). This result demonstrates that JAK activation is necessary for the IFN-α-induced suppression of En II activity.

The PKC pathway is involved in IFN-α-mediated suppression of En II activity

Previous reports demonstrated that type I IFN activated various kinases such as MAPK family members (MEK/ERK and p38 MAPK) (David et al., 1995; Goh et al., 1999), PI3K/Akt (Uddin et al., 1995), JNK (Caraglia et al., 1999) and protein kinase C (PKC) (Uddin et al., 2002). Here we examined the involvement of alternative pathways by pre-treatment with inhibitors for various kinases, including MEK, p38 MAPK, PI3K/Akt, JNK and PKC. The name of each inhibitors and its target kinase is commented in Table 1. As shown in Fig. 5A, only staurosporine, a PKC inhibitor, blocked the inhibitory effect of IFN-α, and other inhibitors did

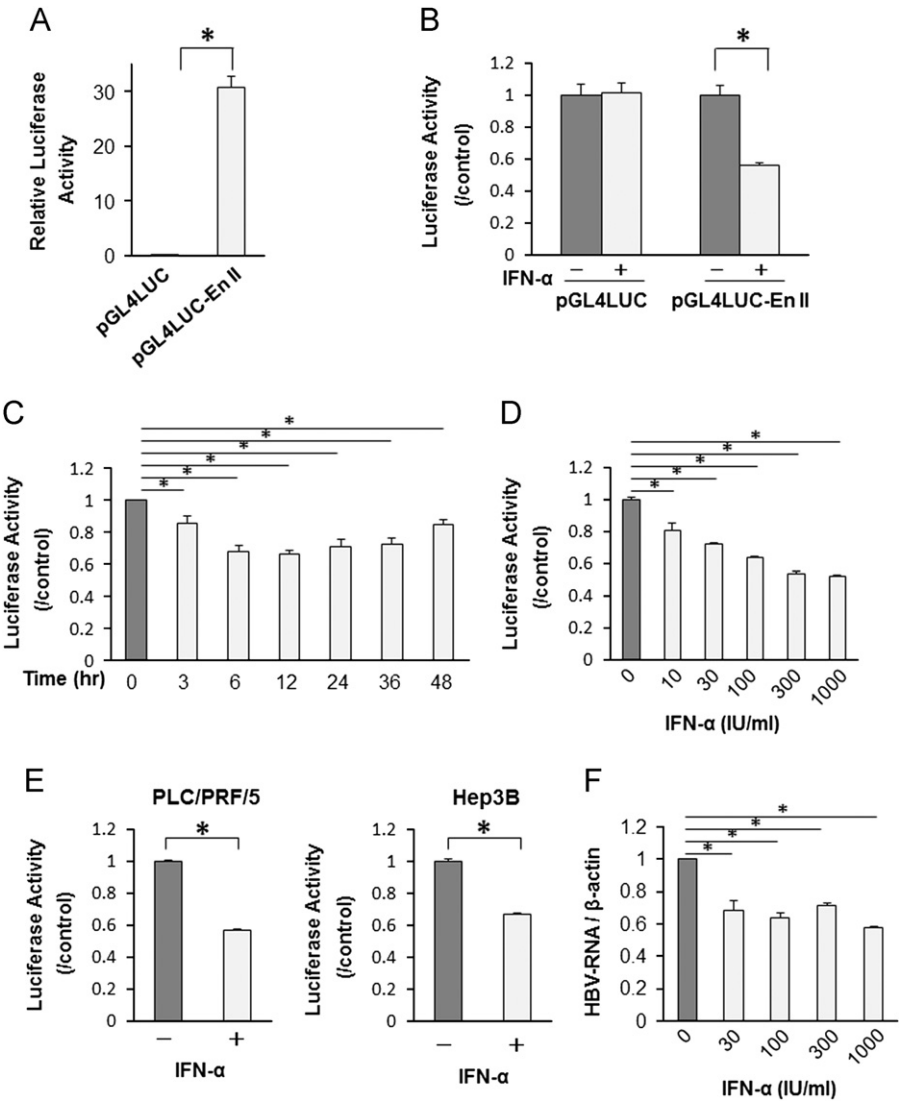

Fig. 2. Suppression of HBV En II transcriptional activity and reduction of HBV-RNA by IFN-α. A, B. Huh-7 cells were transfected with pGL4LUC or pGL4LUC-En II or incubated with or without IFN-α (100 IU/ml). After 24 h, the activity of firefly luciferase was evaluated. C. Huh-7 cells were transfected with pGL4LUC-En II, and incubated with IFN-α (100 IU/ml). Luciferase activities were evaluated at the indicated times. D. Huh-7 cells were transfected with various concentrations (0–1000 IU/ml) of IFN-α for 12 h and luciferase activities were evaluated. E. PLC/PRF/5 cells (left panel) and Hep3B (right panel) cells were transfected with pGL4LUC-En II, and incubated with or without IFN-α (300 IU/ml). Luciferase activities were evaluated. F. Huh-7 cells were transfected with pHBV1.5, and treated with IFN-α at various concentrations (0–1000 IU/ml). At 72 h after IFN-α treatment, cells were harvested, and the abundances of HBV-RNA were evaluated by quantitative RT-PCR. The HBV-RNA level of the IFN-α treated cells was normalized with that of non-treated cells. $^{*}p < 0.05$. "/control" on the vertical axis means the ratio of luciferase activity of IFN-α treated cells normalized with that of non-treated cells.

not. Since staurosporine is a PKC inhibitor showing broad-spectrum activity (Marte et al., 1994), we also examined other inhibitors specific for PKC isoforms. Previous reports demonstrated that IFN-α activated PKC-α/β and PKC-δ (Pfeffer et al., 1990; Uddin et al., 2002). Indeed, activation of PKC-α/β and PKC-δ by IFN-α was confirmed by immunoblot analysis (Fig. 5B). Thus, we examined the PKC inhibitors rottlerin and Gö6976 (Gschwendt et al., 1994; Martiny-Baron et al., 1993). All PKC inhibitors blocked the suppression of En II activity by IFN-α (Fig. 5C). These results suggest that several isoforms of PKC are involved in the IFN-α-mediated suppression of En II activity. We also examined STAT1 activation and ISGs induction by IFN-α in cells pre-treated with these PKC inhibitors using immunoblot analysis (Fig. 5D). Expression levels of phospho-STAT1 and Mx differed among these PKC inhibitors. Staurosporine and Gö6976 slightly diminished the activation of STAT1, but rottlerin did not. This result suggests that PKC isoforms might not strongly regulate activation of STAT1. Rottlerin, a specific inhibitor for PKC-δ, inhibited the induction of Mx, which agreed with previous findings (Kaur et al., 2005). Staurosporine and Gö6976 did not suppress Mx expression. Taken together, all these PKC inhibitors blocked the suppression of En II activity by IFN-α regardless of the expression levels of phospho-STAT1 and Mx. These results suggest that STAT1 activation and ISG induction may be dispensable for the IFN-α-mediated suppression of En II activity. Next, we examined the effect of phorbol 12-myristate 13-acetate (PMA), a PKC activator (Castagna et al., 1982; Griner and Kazanietz, 2007). PMA suppressed En II activity (Fig. 5E), and PMA stimulation did not result in STAT1 phosphorylation and Mx induction (Fig. 5F), suggesting that suppression of En II by PMA is independent of STAT1 activation and ISG induction. On the basis of these findings, we conclude that IFN-α suppresses En II activity via the PKC pathway, which may not involve STAT1 activation and ISG induction.

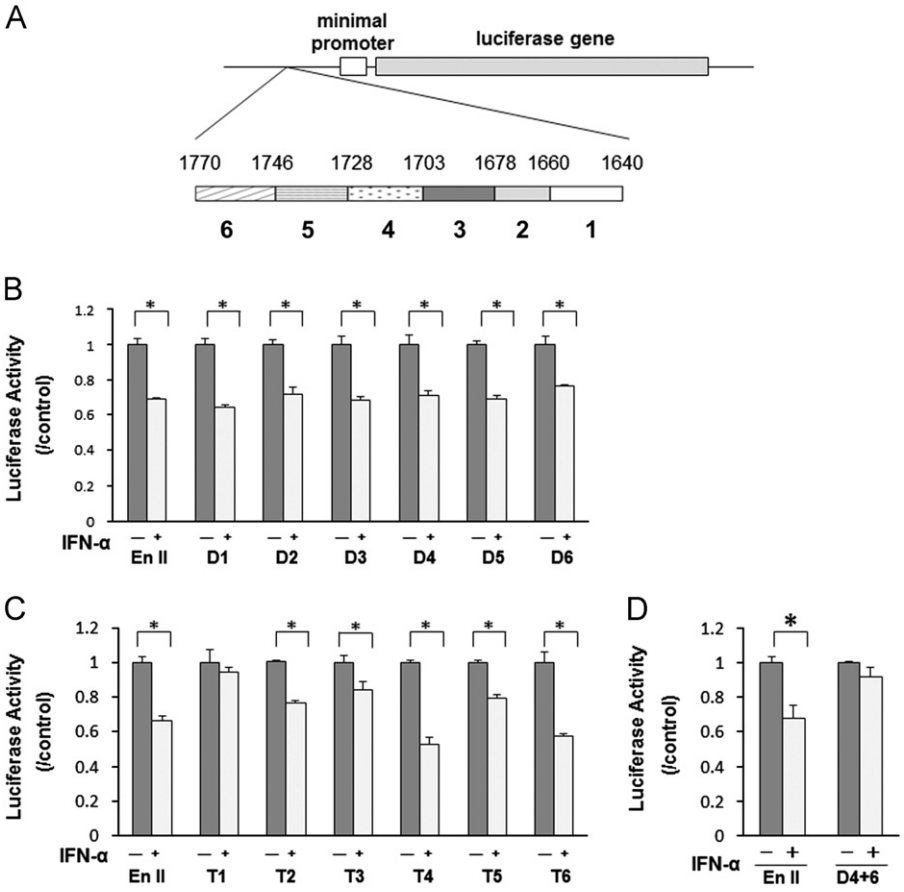

Fig. 3. Deletion/mutational analysis to identify the responsive sequence for the suppressive effect of IFN-α on En II. A. Scheme of pGL4LUC-En II and six segments defined within the En II sequence. The En II sequence was integrated just upstream of the minimal promoter of pGL4LUC. B. Huh-7 cells were transfected with the reporter vectors with deletion of each segment (pGL4LUC-En II-D1∼6), incubated with 300 IU/ml IFN-α for 12 h, and luciferase activities were evaluated. C. Plasmids containing four iterations of each segment within En II sequence in tandem (pGL4LUC-En II-T1∼6) were generated and luciferase activities were evaluated similarly. D. Plasmid with deletion of both nt 1703–1727 and nt 1746–1770 (pGL4LUC-En II-D4+6) was constructed and luciferase activities were evaluated similarly. $^{*}p < 0.05$. "/control" on the vertical axis means the ratio of luciferase activity of IFN-α treated cells normalized with that of non-treated cells.

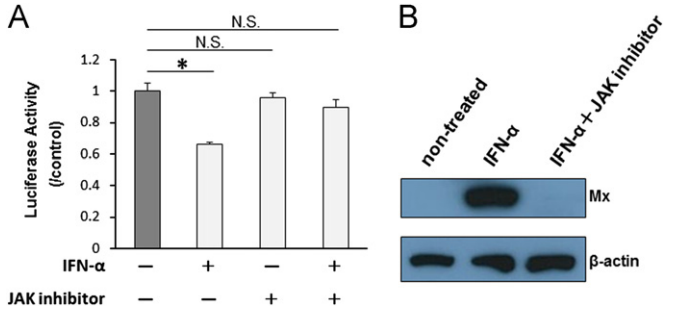

Fig. 4. Involvement of JAK activation in the IFN-α-induced suppression of En II activity. A. Huh-7 cells were transfected with pGL4LUC-En II and treated with JAK inhibitor (1 μM) for 1 h. The cells were then incubated with IFN-α(150 IU/ml) for 12 h, followed by luciferase assay. B. Huh-7 cells were pre-treated with JAK inhibitor for 1 h, and then incubated with IFN-α(150 IU/ml) for 12 h, followed by immunoblot analyses to detect Mx protein. $^{*}p < 0.05$. "/control" on the vertical axis means the ratio of luciferase activity of IFN-α treated cells normalized by that of non-treated cells.

Knockdown of a single transcription factor does not influence IFN-α-induced suppression of En II activity

We anticipated that IFN-α suppressed En II activity by functional down-regulation of some transcription factor(s) phosphorylated in a PKC-dependent manner. Among transcription factors which bind the En II region, previous reports showed that Specificity Protein 1 (Sp1) (Mahoney et al., 1992; Pal et al., 1998; Rafty and Khachigian, 2001), Retinoid X Receptor α (RXRA) (Delmotte et al., 1999) and C/EBP (Mahoney et al., 1992) were inactivated by PKC. Thus, we examined the En II response to IFN-α after knockdown of these transcription factors. C/EBP, RXR and Sp1 expression was efficiently reduced by siRNA (Fig. 6A). We observed no significant change in the suppression of En II activity compared with control siRNA (Fig. 6B). This result suggests that several transcription factors (including unknown proteins) might be involved in the IFN-α-mediated suppression of En II activity.

Table 1
A comment of the inhibitors and its target kinase.

PD98059	MEK inhibitor
SB203580	P38MAPK inhibitor
LY294002	PI3K inhibitor
Akt-1-1/2	Akt inhibitor
SP600125	JNK inhibitor
Staurosporine	PKC inhibitor with broad spectrum
Rottlerin	Inhibitor specific for PKC-δ
Gö6976	Inhibitor specific for Ca^{2+}-dependent PKC isoforms

Discussion

In the present study, we demonstrated that IFN-α suppressed HBV En II activity. The inhibition by IFN-α of En II activity could be blocked by pre-treatment with PKC inhibitors, and this

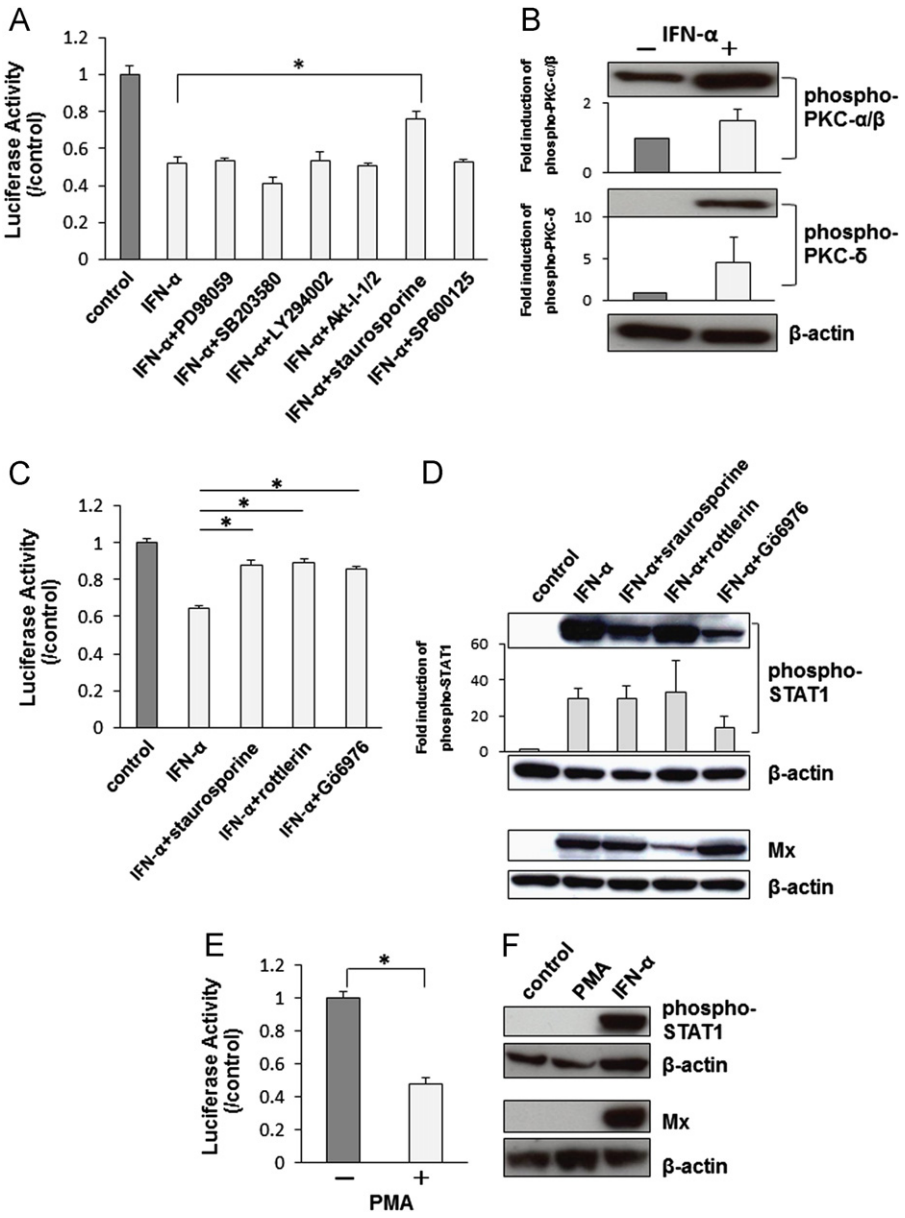

Fig. 5. PKC-dependent suppression of En II activity by IFN-α. A and C. Huh-7 cells were transfected with pGL4LUC-En II, treated separately with each kinase inhibitor for 1 h. The cells were then treated with IFN-α(1000 IU/ml) for 12 h, and luciferase activities were evaluated. B. Huh-7 cells were treated with IFN-α(1000 IU/m) for 12 h. Immunoblot analyses were performed to detect phosphorylated PKC-α/β and phosphorylated PKC-δ. Quantitative analysis of the expression level of phopho- PKC-α/β and -δ was performed by using ImageJ. Each level was normalized with that of IFN-α-non-treated cells. D. Huh-7 cells were harvested at 30 min to detect phosphorylated STAT1 and at 12 h to detect the expression of Mx after administration of IFN-α (1000 IU/m), and immunoblot analyses were performed. Quantitative analysis of the expression level of phopho-STAT1 was performed by using ImageJ. Each level was normalized with that of IFN-α-non-treated cells. E. Huh-7 cells were transfected with pGL4LUC-En II, treated with PMA (100 nM) for 12 h, and luciferase activities were evaluated. F. Huh-7 cells were treated with PMA (100 nM) or IFN-α(1000 IU/m). The cells were harvested at 30 min to detect phosphorylated STAT1 and at 12 h to detect the expression of Mx, and immunoblot analyses were performed. $^{*}p < 0.05$. "/control" on the vertical axis means the ratio of luciferase activity of IFN-α/ PMA treated cells normalized with that of non-treated cells.

blocking effect may not involve STAT1 activation and ISG induction. The latter, ISG induction via the JAK-STAT pathway, has been considered to be the main mechanism suppressing viral replication. Our findings suggest a pathway for IFN-α repression of HBV transcription other than ISG induction.

PKCs are involved in a wide variety of cell functions and signal transduction pathways regulating cell migration and polarity, proliferation, differentiation and cell death (Nishizuka, 1988). In the PKC family, there are at least ten isoforms which can be divided into three sub-groups based on their structural characteristics and cofactor requirements. These include the classical PKC (cPKC: α, βI, βII, and γ), the novel PKC (nPKC: δ, ε, η and θ), and the atypical PKC (aPKC: ζ and ι/λ) (Azzi et al., 1992; Breitkreutz et al., 2007; Kikkawa et al., 1989). IFN-α can activate multiple PKC isoforms: not only PKC-δ, but also PKC-α/β (Pfeffer et al., 1990), PKC-ε (Pfeffer et al., 1991), and PKC-θ (Srivastava et al., 2004). Despite the variety of PKC isoforms, most phosphorylate similar sequences (Breitkreutz et al., 2007). Both the PKC-α/β inhibitor (Gö6976) and PKC-δ inhibitor (rottlerin) blocked the inhibitory effect of IFN-α on En II activity. Thus, it was speculated that each PKC isoform might be similarly involved in suppressing of En II activity.

Other studies have examined the role of the PKC pathway in HBV replication. Kang et al. (2008) reported that PKC-mediated phosphorylation increased capsid assembly and stability (von Hahn et al., 2011), and von Hahn et al. (2011) reported that the

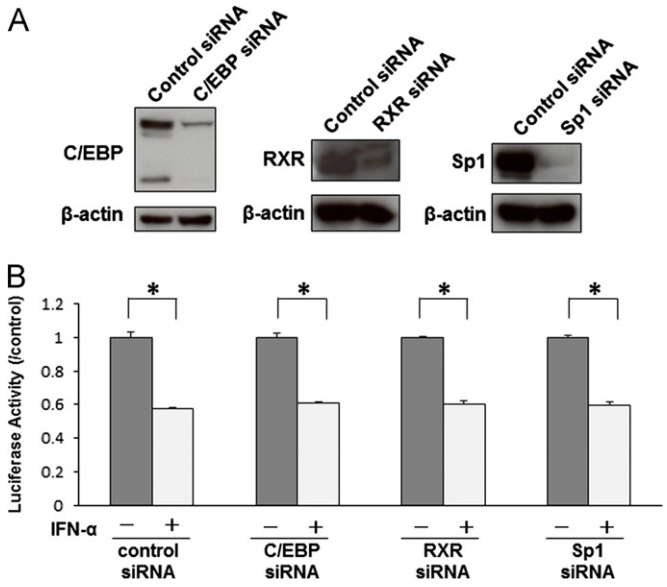

Fig. 6. IFN-α-mediated suppression on En II activity with knockdown of C/EBP, RXR and Sp1. A. Huh-7 cells were transfected with 10 nM siRNA (negative control or specific for C/EBP, RXR and Sp1). Immunoblot analyses for expressions of C/EBP, RXR, Sp1 and β-actin were performed at 48 h post siRNA transfection. B. Huh-7 cells were transfected with 10 nM siRNA (negative control or specific for C/EBP, RXR and Sp1). On the next day, si-RNA treated cells were transfected again with pGL4LUC-En II. On the following day, these transfected cells were incubated with IFN-α(1000 IU/ml) for 12 h, and luciferase activities were evaluated. "/control" on the vertical axis means the ratio of luciferase activity of IFN-α treated cells normalized with that of non-treated cells.

pan-PKC inhibitor sotrastaurin did not affect HBV replication. While the role of PKC in the HBV life cycle is still controversial, our findings suggest that PKC isoforms activated by IFN-α play inhibitory roles in HBV transcription by down-regulation of En II activity. As von Hahn et al. reported, sotrastaurin alone did not affect HBV replication. But, based on our present data about another pan-PKC inhibitor, staurosporine, we speculate that sotrastaurin may also block the inhibitory effect of IFN-α on En II activity.

We showed that knockdown of a single transcription factor did not influence the IFN-α-mediated suppression of En II activity, suggesting that several transcription factors might be involved in this suppression. We also showed that both segment 4 (nt 1703–1727) and segment 6 (nt 1746–1770) within the En II region are required for the IFN-α-induced suppression of En II activity. Although these two regions seem to be more important than the others, all the deleted version of reporter constructs showed almost completely similar suppression activities (Fig. 3B). We speculate that there may be some transcription factors which affect both the segment 4 and 6. Even if one of these regions is deleted, some factors may affect the other region, and result in the suppression of En II activity. Further study will be needed to clarify the mechanism.

Indeed, there are no identified transcription factors which could bind both segment 4 and 6. Only two transcription factors (HNF1 and 3) were reported to bind segment 4 (Johnson et al., 1995; Wang et al., 1998), and there have been no reports indicating that IFN-α or PKC inactivates HNF1 or 3. We also examined the expression levels of HNF1 and 3 of the IFN-α treated and the non-treated cells by RT-PCR. There was no significant difference in the expression of these transcription factors between the IFN-α treated and the non-treated cells (Nawa et al., unpublished data). Thus, we speculate that HNF1 or 3 might not be involved in the IFN-α mediated suppression of En II activity. There may be unknown transcription factors in the PKC pathway.

Previous reports showed that IFN-α suppressed En I activity (Nakao et al., 1999; Tur-Kaspa et al., 1990). Nakao et al. (1999) indicated that this occurred due to the binding of ISGF3 to an ISRE-like motif within the En I region. However, Rang et al. (2001) demonstrated that IFN-α reduced HBV-RNA levels derived from both HBV genome wild type and mutated ISRE-like motifs. This result contradicted the Nakao's result that the activity of the En I mutated ISRE-like motif was not suppressed by IFN-α. Schulte-Frohlinde et al. (2002) reported that IFN-α suppressed HBV core promoter regulated transcriptional activity, even when the ISRE-like motif of En I was deleted. The results of Rang et al. and Schulte-Frohlinde et al. suggest that IFN-α might suppress the activity of regions other than En I. In the present study, we demonstrated that IFN-α suppressed En II activity via the PKC pathway. En II might be one of the candidate regions down-regulated by IFN-α within the HBV genome.

Since En II activates viral transcription only in hepatocytes, it is responsible for the hepatocyte-specific gene expression of HBV. There had been no study on the effect of IFN-α on En II activity. Our study clarified that the PKC pathway is involved in the IFN-α-mediated suppression of En II activity, but may not involve ISG induction. Our result should aid in establishing better treatment with IFN-α against HBV infection. As we could not determine the molecule which inhibits En II activity by IFN-α, further study is needed to clarify this molecule and to control hepatitis B by IFN-α treatment.

Materials and methods

Plasmids

The HBV sequence used in this study was of the *adw2* subtype (GenBank accession no. X02763). Numbering of the HBV sequence started at the unique *Eco*RI site. The En II region in this study was defined as nt 1640–1771 of HBV sequence (Fig. 1) (Ishida et al., 2000). To construct pGL4LUC-En II, a plasmid containing the HBV En II region, the DNA fragment was amplified with PCR and inserted between *Hin*d III and *Nhe* I site of pGL4 Luciferase Reporter Vector (pGL4LUC) (Promega, Madison, WI). The PCR primers were as follows: 5′-CCAAGCTTCTGCCCAAGGTC-3′ and 5′-CCCGCTAGCAAAGACCTTTAACCTAATCTCCTCC-3′. The constructs of the En II sequence with various deletions were generated by modifying pGL4LUC-En II using the QuikChange Site-Directed Mutagenesis Kit (Stratagene, La Jolla, CA). The constructs containing four tandem repeats of short fragment in En II sequence were generated by inserting duplexes of synthesized oligonucleotides into the multicloning site of pGL4LUC. All of the En II sequences were inserted in the antisense orientation to evaluate their enhancer activity.

Plasmid pHBV1.5 containing a 1.5-fold-overlength genome of HBV-DNA (GenBank accession no. AF305422) has been described previously (Bruss and Ganem, 1991).

Cell lines and reagents

The human hepatocellular carcinoma cell lines Huh-7, PLC/PRF/5, and Hep3B were cultured in Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% heat-inactivated fetal bovine serum (Sigma-Aldrich, St. Louis, MO) in a humidified incubator at 5% CO_2 and 37 °C. Human natural IFN-α was kindly provided by Hayashibara Biochemical Laboratories, Inc. (Okayama, Japan).

The inhibitors/activators and the final concentrations used were: JAK inhibitor I (1 μM), PD98059 (10 μM), SB203580 (10 μM), LY294002 (10 μM), Akt-I-1/2 (5 μM), staurosporine (10 or 20 nM), rottlerin (5 μM), Gö6976 (1 μM), SP600125 (10 μM)

(Calbiochem, San Diego, CA), phorbol 12-myristate 13-acetate (PMA) (100 nM) (Sigma-Aldrich, St. Louis, MO).

Plasmid transfection and luciferase assay

Huh-7 cells were co-transfected with the firefly luciferase plasmid and pGL4-RL-tk, an expression vector of renilla luciferase, which was used as an internal control, using FuGENE HD reagent (Roche Applied Science, Indianapolis, IN) according to the manufacturer's protocol. Activities of firefly luciferase and renilla luciferase were measured using the Dual-Glo Luciferase Assay System (Promega, Madison, WI), and then relative luciferase activity was calculated by normalizing firefly luciferase activity to renilla luciferase activity.

RNA extraction

Total RNA was isolated from cells using ISOGEN (Nippon Gene, Tokyo, Japan) according to the manufacturer's protocol. The isolated RNA was treated with DNase I (Promega, Madison, WI) to avoid contamination with transfected plasmid, and then purified with a mixture of phenol, chloroform, and isoamylalcohol (pH 7.9), followed by ethanol precipitation.

Western blot analysis

Cultured cells were lysed with a lysis buffer (1% NP-40, 0.5% sodium deoxycholate, 0.1% SDS, and protein inhibitor cocktail (Nacalai Tesque), in PBS, pH 7.4). Equal amounts of protein were electrophoretically separated by polyacrylamide gel and transferred onto PVDF membrane. For immunodetection, the following antibodies were used: anti-STAT1 antibody, anti-phospho-STAT1 antibody, anti-phospho-PKC-α/β II (Thr 638/641) antibody, anti-phospho-PKC-δ (Thr 505) antibody, anti-C/EBP antibody, anti-RXR antibody, anti-Sp1 antibody, anti-β-actin antibody from Cell Signaling Technology (Beverly, MA), and anti-Mx antibody from Abcam (Cambridge, UK). The signals of phosphorylated proteins such as phospho-PKC-α/β, -δ and phospho-STAT1 were analyzed quantitatively using image analyzing software (ImageJ; version 1.45).

Small RNA interference

Stealth Select RNAi specific for STAT1 (HSS 10273) was purchased from Invitrogen (Carlsbad, CA). Silencer Select siRNA specific for C/EBP (ID: S2890), RXR (ID: S12386) and Sp1 (ID: S13319) were purchased from Ambion (Austin, TX). Stealth RNAi Negative Control Low GC Duplex (Invitrogen, Carlsbad, CA) was used as a control for the off-target effect following Stealth Select RNAi delivery. The transfections were carried out using Lipofectamine RNAiMAX (Invitrogen, Carlsbad, CA) according to the reverse transfection protocol.

Real-time reverse-transcription PCR

For cDNA synthesis, 1 μg of total RNA was reverse-transcribed using High Capacity RNA-to-DNA Master Mix (Applied Biosystems, Foster City, CA). cDNA, equivalent to 20 ng RNA, was used as a template for real-time reverse-transcription PCR (RT-PCR) using Applied Biosystems 7900HT Fast Real-Time PCR System (Applied Biosystems, Foster City, CA). mRNA expressions of C/EBP, FTF, HNF1, HNF3, and HNF4 were measured using TaqMan Gene Expression Assays and were corrected with the quantified expressions level of β-actin mRNA. Assay IDs for the genes were as follows: C/EBP (Hs00269972_s1), FTF (Hs00187067_m1), HNF1 (Hs00167041_m1), HNF3 (Hs00232754_m1), and HNF4 (Hs01023298_m1).

For the detection of pgRNA and pre-C mRNA, the primers and the probes were designed as follows according to a previous study (Laras et al., 2002): the sense primer was 5′-TCTTGTACATGTCCCACTGTTCAA-3′ (nt 1843–1866); the anti-sense primer was 5′-AATGCCATGCCCCAAAGC-3′ (nt 1890–1909); the probe was 5′-FAM-CTCCAAGCTGTGCCTT -3′ (nt 1869–1884). Since they were within precore/core coding sequence, only the total abundance of pgRNA and pre-C RNA could be detected.

Statistical analysis

Data were presented as mean ± SD. Differences between two groups were determined using Student's t-test for unpaired observations. $p < 0.05$ was considered statistically significant.

Disclosures

All authors have nothing to disclose.

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