

# PPAR $\gamma$ inhibits hepatocellular carcinoma metastases *in vitro* and in mice

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**BACKGROUND:** We have previously demonstrated that peroxisome proliferator-activated receptor (PPAR $\gamma$ ) activation inhibits hepatocarcinogenesis. We aim to investigate the effect of PPAR $\gamma$  on hepatocellular carcinoma (HCC) metastatic potential and explore its underlying mechanisms.

**METHODS:** Human HCC cells (MHCC97L, BEL-7404) were infected with adenovirus-expressing PPAR $\gamma$  (Ad-PPAR $\gamma$ ) or Ad-lacZ and treated with or without PPAR $\gamma$  agonist (rosiglitazone). The effects of PPAR $\gamma$  on cell migration and invasive activity were determined by wound healing assay and Matrigel invasive model *in vitro*, and in an orthotopic liver tumour metastatic model in mice.

**RESULTS:** Pronounced expression of PPAR $\gamma$  was demonstrated in HCC cells (MHCC97L, BEL-7404) treated with Ad-PPAR $\gamma$ , rosiglitazone or Ad-PPAR $\gamma$  plus rosiglitazone, compared with control (Ad-LacZ). Such induction markedly suppressed HCC cell migration. Moreover, the invasiveness of MHCC97L and BEL-7404 cells infected with Ad-PPAR $\gamma$ , or treated with rosiglitazone was significantly diminished up to 60%. Combination of Ad-PPAR $\gamma$  and rosiglitazone showed an additive effect. Activation of PPAR $\gamma$  by rosiglitazone significantly reduced the incidence and severity of lung metastasis in an orthotopic HCC mouse model. Key mechanisms underlying the effect of PPAR $\gamma$  in HCC include upregulation of cell adhesion genes, E-cadherin and SYK (spleen tyrosine kinase), extracellular matrix regulator tissue inhibitors of metalloproteinase (TIMP) 3, tumour suppressor gene retinoblastoma 1, and downregulation of pro-metastatic genes MMP9 (matrix metalloproteinase 9), MMP13, HPSE (heparanase), and Hepatocyte growth factor (HGF). Direct transcriptional regulation of TIMP3, MMP9, MMP13, and HPSE by PPAR $\gamma$  was shown by ChIP-PCR.

**CONCLUSION:** Peroxisome proliferator-activated receptor-gamma exerts an inhibitory effect on the invasive and metastatic potential of HCC *in vitro* and *in vivo*, and is thus, a target for the prevention and treatment of HCC metastases.

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Despite significant advances in early detection and therapy, hepatocellular carcinoma (HCC) still remains the third leading cause of cancer-related deaths worldwide (Bosch *et al*, 2004). The high mortality rate of HCC is mainly attributable to late presentation at advanced stage, where curative surgical resection is no longer feasible or of limited efficacy (Mann *et al*, 2007). Tumour recurrence in HCC can occur as metastases, whereas more than 90% of HCC-related deaths are the result of secondary local or distant disease. However, efficacious or curative drug therapy for HCC and its metastases remains elusive.

Peroxisome proliferator-activated receptor-gamma (PPAR $\gamma$ ) is a ligand-activated transcription factor that belongs to the nuclear

hormone receptor super family; its roles include control of several biological processes related to growth, differentiation, cell cycle, and apoptosis (Koeffler 2003). Activation of PPAR $\gamma$  has been shown to inhibit proliferation in several cancers *in vitro* and *in vivo* (Koeffler 2003; Grommes *et al*, 2004). Our group has recently reported that PPAR $\gamma$  activation by its agonist (Yu *et al*, 2006) or ectopic expression of PPAR $\gamma$  by Ad-PPAR $\gamma$  transfection (Yu *et al*, 2010) inhibits HCC growth and progression by suppressing cell proliferation, inducing cell apoptosis, and causing cell cycle arrest (Yu *et al*, 2006, 2010). The PPAR $\gamma$  expression in HCC is significantly reduced in tumour tissues compared with surrounding non-tumourous liver, especially in poorly differentiated tumour than in well-differentiated tumour (Yu *et al*, 2006). Peroxisome proliferator-activated receptor-gamma also has a role in inhibiting tumour growth and metastatic spread in colon (Takano *et al*, 2008) and thyroid cancers (Ohta *et al*, 2001; Chen *et al*, 2006) as well as lung carcinoma (Panigrahy *et al*, 2002). However, PPAR $\gamma$ 's effect on invasive and metastatic potential of HCC has yet to be defined.

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The aim of the present study was to determine the effect and the underlying molecular mechanism of PPAR $\gamma$  on HCC cell migration and invasion using HCC cell lines and formation of distant metastases *in vivo* in an orthotopic murine liver tumour model.

## MATERIALS AND METHODS

### Human HCC cell lines and culture

The human HCC cell line MHCC97L, stably labelled with luciferase, was a gift from K Man, Department of Surgery, The University of Hong Kong (Man *et al*, 2010). BEL-7404 was obtained from the Institute of Biochemistry and Cell Biology (SIBS, Shanghai, China) (Chen *et al*, 1980). Cells were cultured in DMEM (Dulbecco's modified Eagle medium) supplemented with 10% foetal bovine serum (Invitrogen, Carlsbad, CA, USA) and incubated at 37 °C and 5% CO<sub>2</sub>.

### Adenovirus-mediated PPAR $\gamma$ gene transfer

Recombinant adenovirus expressing the mouse PPAR $\gamma$ -1 cDNA (Ad-PPAR $\gamma$ ) or *E. coli*  $\beta$ -galactosidase gene (Ad-LacZ, control adenovirus vector) (gift from JK Reddy, Department of Pathology, Feinberg School of Medicine, Northwestern University, Chicago) was propagated, isolated in human embryonic kidney 293 (HEK293) cells, then purified with Adeno-X Maxi Purification Kit (Clontech, Mountain View, CA, USA); the adeno virus with infectious titre range from  $1.0 \times 10^9$  to  $10^{10}$  pfu (plaque-forming unit) ml<sup>-1</sup> was stored at -80 °C until use.

### RNA extraction, cDNA synthesis, and RT-PCR

Total RNA was extracted from cell pellets by Trizol (Invitrogen) and reverse transcribed into cDNA using MultiScribe Reverse Transcriptase (Applied Biosystems, Foster city, CA, USA) according to the manufacturer's instructions. The target gene expression was determined by RT-PCR using specific primers of target genes (Table 1). GAPDH was served as an internal control for total cDNA content. Samples were amplified using the ABI Prism 7700 Sequence Detection System (Applied Biosystems).

### Tumour cell migration assay

Wound healing assay was performed for analysis of cell migration *in vitro*. Briefly, MHCC97L ( $5 \times 10^5$  cells per well) or BEL-7404 ( $5 \times 10^5$  cells per well) cells were seeded in 12-well plates and infected with Ad-LacZ (70 multiplicities of infection, MOI) or Ad-PPAR $\gamma$  (70 MOI), and treated with or without rosiglitazone (50  $\mu$ M) at 37 °C until 90% confluent (Yu *et al*, 2010). Sterile tips were used to scratch cell layers, which were subsequently washed with PBS, and cultured with DMEM media and 1% FBS. Cells were photographed (phase-contrast microscope) at 0, 24, 36, and 48 h after incubation. The distance travelled by cells was measured between the two boundaries of an acellular area and results of treatment groups expressed as a ratio to Ad-LacZ-treated cells. Each experiment was performed in triplicate.

### Tumour cells invasion assay

Matrigel invasion assay (Becton Dickinson, Waltham, MA, USA) was performed as previously described (Yu *et al*, 2009). MHCC97L and BEL-7404 cells infected with Ad-PPAR $\gamma$  or Ad-LacZ ( $2.5 \times 10^4$  per well) treated with or without rosiglitazone (a selective PPAR $\gamma$  agonist) at 0, 24, 36, and 48 h, then harvested and added into the trans-well containing 600  $\mu$ l DMEM media and 10% FBS in the lower chamber. After 48 h, cells that had invaded through the Matrigel membrane were stained with crystal violet, and counted

(four high-power fields,  $\times 100$  magnification). Experiments were conducted in triplicate.

### Orthotopic murine liver tumour model of distant metastasis

An orthotopic HCC metastasis mouse model was established using MHCC97L, which has metastatic potential to lung (Man *et al*, 2010). MHCC97L cells ( $2 \times 10^6$  cells in 0.1 ml PBS) were injected subcutaneously into the left dorsal flank of 4-week-old male Balb/c nude mice. Subcutaneous tumours were harvested once the subcutaneous tumours reached about 10 mm<sup>3</sup> and cut into 1.0 mm<sup>3</sup> pieces. One piece of tumour was then implanted into the left liver lobes in a separate group of nude mice (6-week-old) (10 per group) (Man *et al*, 2010). After tumour implantation, mice were randomly treated with or without rosiglitazone (200 p.p.m. in chow), a dosage was selected base on our previous experiments (Yu *et al*, 2010). Liver tumour growth and lung metastasis were monitored by Xenogen IVIS-200, an optical *in vivo* imaging system (Caliper Life Science, Hopkinton, MA, USA) weekly. Mice were euthanised at week 7 after tumour implantation (Man *et al*, 2010), tumours and lung nodules were analysed histologically. Signal intensity of tumours detected by Xenogen IVIS was expressed as Radiant Efficiency (radiance/illumination power density =  $\text{ps}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ ). All experimental procedures were approved by the Animal Ethics Committee of the Chinese University of Hong Kong.

### cDNA expression array

Gene expression profiles were analysed by the Human Tumour Metastasis PCR Array according to the protocol (SABiosciences, Frederick, MD, USA). Briefly, total RNA was extracted from MHCC97L cells infection with Ad-PPAR $\gamma$  (70 MOI) or Ad-LacZ (70 MOI) (control) for 48 h. One  $\mu$ g of total RNA was treated and cDNA was prepared using RT<sup>2</sup> First Strand Kit (SABiosciences). Pairs of test and control samples were mixed with RT<sup>2</sup> qPCR Master mix, distributed to PCR array in 96-well plates, cycling with real-time PCR. Each array contained 84 genes with ascribed functions related to metastasis pathways. Data were analysed using SABiosciences software. Genes with fold-changes more than or less than 1.5 were considered to be of biological significance.

### Chromatin immunoprecipitation (ChIP) assay

Chromatin immunoprecipitation analysis was performed using Red ChIP Kit (Diagenode, Liège, Belgium). After transfection with Ad-PPAR $\gamma$  (70 MOI) or Ad-LacZ (70 MOI) for 48 h, MHCC97L cells were fixed and collected for ChIP assay. DNA-protein complexes were precipitated using specific antibody of PPAR $\gamma$  (Santa Cruz Biotechnology, Santa Cruz, CA, USA). DNA fragments were de-cross-linked and purified from complexes; immunoprecipitated and input DNA were used as templates for ChIP-PCR.

### Characterisation of PPAR $\gamma$ -binding region and semi-quantitation of ChIP-PCR

To evaluate the direct modulation of transcriptional activity on the promoters of metastasis-related genes by PPAR $\gamma$ , the Genomatix tool, ModelInspector, was used to scan all the known PPAR $\gamma$ -binding regions linked to metastasis-related genes. Human promoter regions (size between 2 kb) in the Genomatix promoter database were scanned. Matched binding sites were selected with core and matrix similarity of  $> 0.8$  ([http://www.genomatix.de/online\\_help/help\\_matinspector/matinspector\\_help.html](http://www.genomatix.de/online_help/help_matinspector/matinspector_help.html)). The predicted PPAR $\gamma$ -binding sites on the promoter of target genes were validated by ChIP-PCR (specific primers listed in Table 1).

**Table 1** Primer sequences for semi-quantitative PCR detection

Gene	Forward primer (5' to 3')	Reverse primer (5' to 3')
<i>mRNA primers</i>		
MMP9	TTGACAGCGACAAGAAGTGG	GCCATTCACGTCGTCCTTAT
MMP13	GAAGATGATTTGTCTGAGGAA	GCCGAAGAAAGACTGCATT
GAPDH	ACAACAGCCTCAAGATCATCAG	GGTCCACCACTGACACGTTG
<i>DNA primers</i>		
TIMP3 promoter 1	AGGGTCTTTGCACTTGCTGT	ATCCTCGCTGAGAAGTGGAC
MMP9 promoter 1	TGGGGAGGATATCTGACCTG	AAGAGCACAAGGGTGGACTG
MMP9 promoter 2	CAGGGCTGGAGAAGTAAAAG	CCTGCCAAAAGACCATGATTC
MMP13 promoter 1	GAAAAAGTCGCCACGTAAGC	CCTGGGGACTGTTGTCTTTC
MMP13 promoter 2	GTTCTGACCTGAGCAGCAT	TCCCCTGCAGAAGTAATGG
HPSE promoter	GGGTGGTTGATCTCTTCCA	CCTTCTCTCCCATCTAGC

## Western blot analysis

Total protein was extracted from cell pellets and protein concentration measured by Bradford assay (Bio-Rad, Hercules, CA, USA). A total of 30 mg of protein was separated by 12% sodium dodecyl sulphate-polyacrylamide gel electrophoresis, then transferred onto equilibrated polyvinylidene difluoride membrane (Amersham Biosciences, Buckinghamshire, UK). Membranes were probed with primary antibodies for tissue inhibitors of metalloproteinase 3 (TIMP3), heparanase (HPSE), and E-cadherin (Santa Cruz Biotechnology).

## Statistical analysis

Data were presented as means  $\pm$  s.d. Multiple group comparisons were analysed by one-way ANOVA after Bonferroni's correction. Non-parametric data between two groups was computed by Chi-square test or Fisher Exact test. The difference for two different groups was determined by Student's *t* test. A *P*-value of less than 0.05 was considered statistically significant.

## RESULTS

### Peroxisome proliferator-activated receptor-gamma suppresses HCC cell migration and invasiveness of MHCC97L and BEL-7404 human HCC cell lines

The MHCC97L and BEL-7404 cells were infected with Ad-PPAR $\gamma$  or Ad-LacZ (control) in the presence or absence of rosiglitazone for 48 h and induction of PPAR $\gamma$  was confirmed by Western blot (Figure 1A). Enhanced PPAR $\gamma$  expression by Ad-PPAR $\gamma$  or rosiglitazone, markedly slowed cell migration scratchy 'wound' at edges of MHCC97L and BEL-7404 HCC cells (Figure 1B). Quantitative analyses at 36 h confirmed a significant reduction in wound closure in Ad-PPAR $\gamma$  or rosiglitazone-treated cells compared with Ad-LacZ-infected control cells (Figure 1C). There appeared to be an additive effect of Ad-PPAR $\gamma$  plus rosiglitazone compared with Ad-PPAR $\gamma$  or rosiglitazone only in BEL-7404 cell line (Figure 1C).

To study the effect of PPAR $\gamma$  conferred on the invasiveness of HCC, MHCC97L and BEL-7404 cells were infected with Ad-PPAR $\gamma$ , or treated with rosiglitazone using a Matrigel model (Figure 2A). *In vitro* invasively growing HCC cells were significantly impaired by up to 60% when infected with Ad-PPAR $\gamma$  or primed by rosiglitazone at 48 h (Figure 2B). Moreover, the combination of Ad-PPAR $\gamma$  and rosiglitazone incrementally suppressed cell invasion compared with Ad-PPAR $\gamma$  or rosiglitazone alone (Figure 2B).

### Activation of PPAR $\gamma$ by rosiglitazone inhibits HCC metastases to the lung in vivo

In light of the observed anti-migration and anti-invasion effects of PPAR $\gamma$  on HCC cell lines *in vitro*, we tested whether activation of

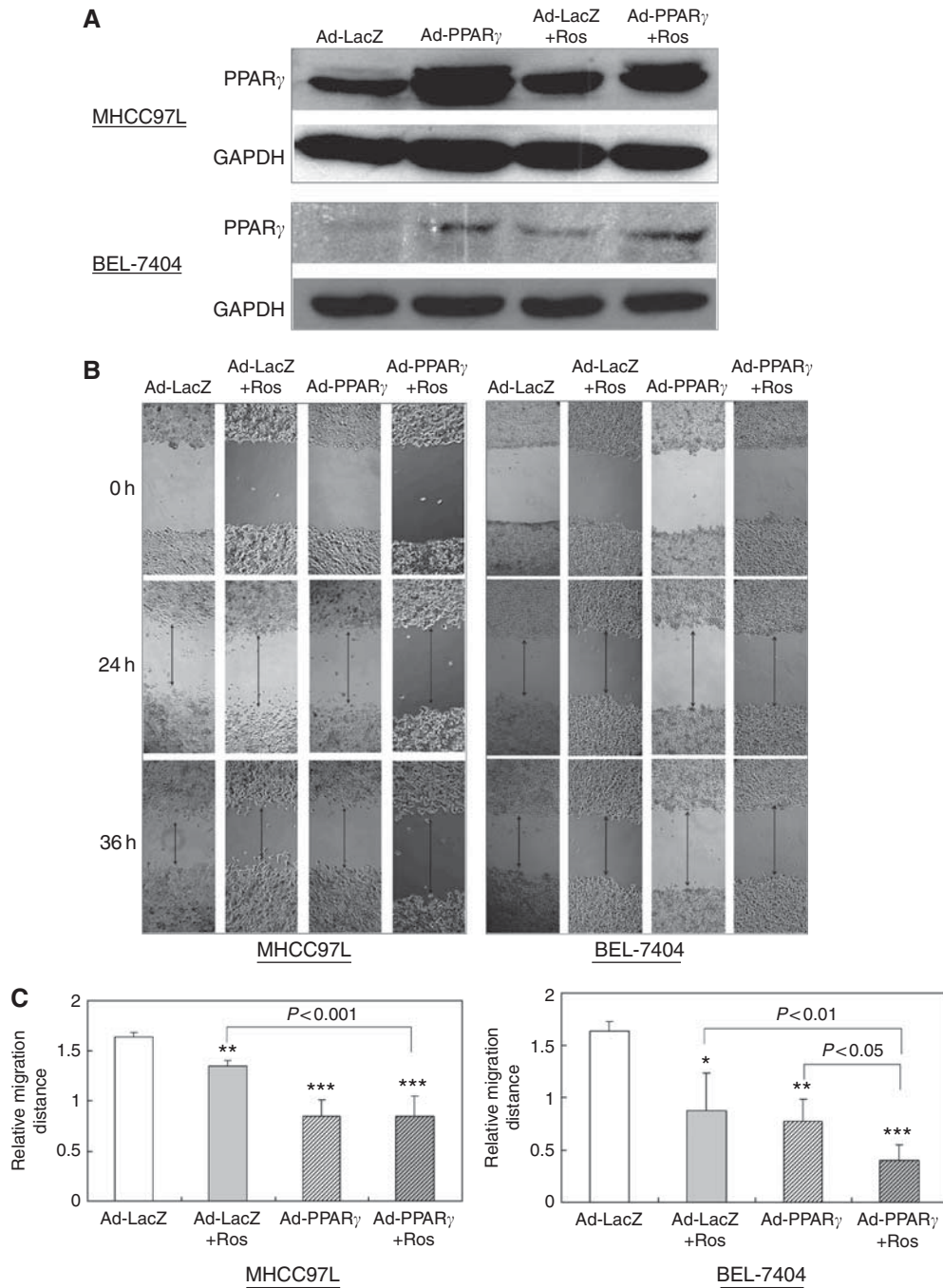
PPAR $\gamma$  by rosiglitazone could alter metastatic potential of MHCC97L *in vivo* in an orthotopic metastasis mouse model, where subcutaneously grown tumours derived from MHCC97L cells expressing luciferase were implanted into the livers of nude mice; small successful transplantation of tumours were confirmed by xenogen imaging 2 weeks after surgery (Figure 3A). Mice were randomly treated with rosiglitazone or vehicle for 7 weeks and then re-imaged *in vivo*. By week 7, 87.5% (7 out of 8) of the vehicle-treated control mice demonstrated lung metastases after orthotopic implantation. In contrast, only 33% (3 out of 9) of rosiglitazone-treated animals developed lung metastases (*P* < 0.05) (Figure 3B). The luciferase signals emanating from the lungs originally from the MHCC97L cells expressing luciferase in the rosiglitazone-treated mice were significantly lower than in the vehicle-treated group ( $1.7 \times 10^5$  vs  $3.14 \times 10^6$  p s<sup>-1</sup> cm<sup>-2</sup> sr<sup>-1</sup>, *P* < 0.05) (Figure 3C). Subsequent histology confirmed that lung nodules were secondary/metastatic deposits from liver (Figure 3B). Collectively, these results provide clear evidence that PPAR $\gamma$  activation inhibits lung metastasis in an orthotopic HCC model *in vivo*.

### Peroxisome proliferator-activated receptor-gamma modulates the expression profiles of metastasis-related genes in MHCC97L cells

To elucidate the molecular mechanisms underlying the inhibitory effect of PPAR $\gamma$  on HCC cell invasiveness, gene expression profiles in Ad-PPAR $\gamma$ -infected MHCC97L were analysed using a human tumour metastasis pathway PCR array. When compared with control Ad-LacZ-infected cells, PPAR $\gamma$  altered downstream targets involved in cell adhesion, extracellular matrix (ECM) proteins, cell growth, and cell motility (Table 2), all of which are critical to the regulation of cancer cell invasiveness and metastasis. Peroxisome proliferator-activated receptor-gamma exerted its anti-metastatic effects by increasing the expression of cell adhesion genes, E-cadherin (5.2-fold), spleen tyrosine kinase (SYK) (1.7-fold), and ECM regulator metalloproteinase inhibitor 3 (TIMP3) (7.2-fold), a physiological inhibitor of matrix metalloproteinases (MMPs). The PPAR $\gamma$  also suppressed expression of pro-metastatic genes, such as MMP9 (–1.7-fold), MMP13 (–2.0-fold), HPSE (–6.5-fold), and significantly diminished hepatocyte growth factor (HGF) (–2.2-fold), a cellular growth and motility regulator. Further, PPAR $\gamma$ -induced retinoblastoma 1 (RB1) expression, a potent tumour suppressor gene by four-fold (Table 2).

To validate these changes on expression profiling, western blot and semi-quantitative RT-PCR were performed on MHCC97L and BEL-7404 cells infected with Ad-PPAR $\gamma$  or Ad-LacZ in the presence or absence of rosiglitazone. Ectopic expression of PPAR $\gamma$  by Ad-PPAR $\gamma$  or activation of PPAR $\gamma$  by rosiglitazone, increased E-cadherin and TIMP3 protein expression with a concomitant diminution of HPSE in both HCC cell lines (Figure 4A1). Combination of Ad-PPAR $\gamma$  and rosiglitazone exerted an additive effect on the induction of E-cadherin and TIMP3 and suppression





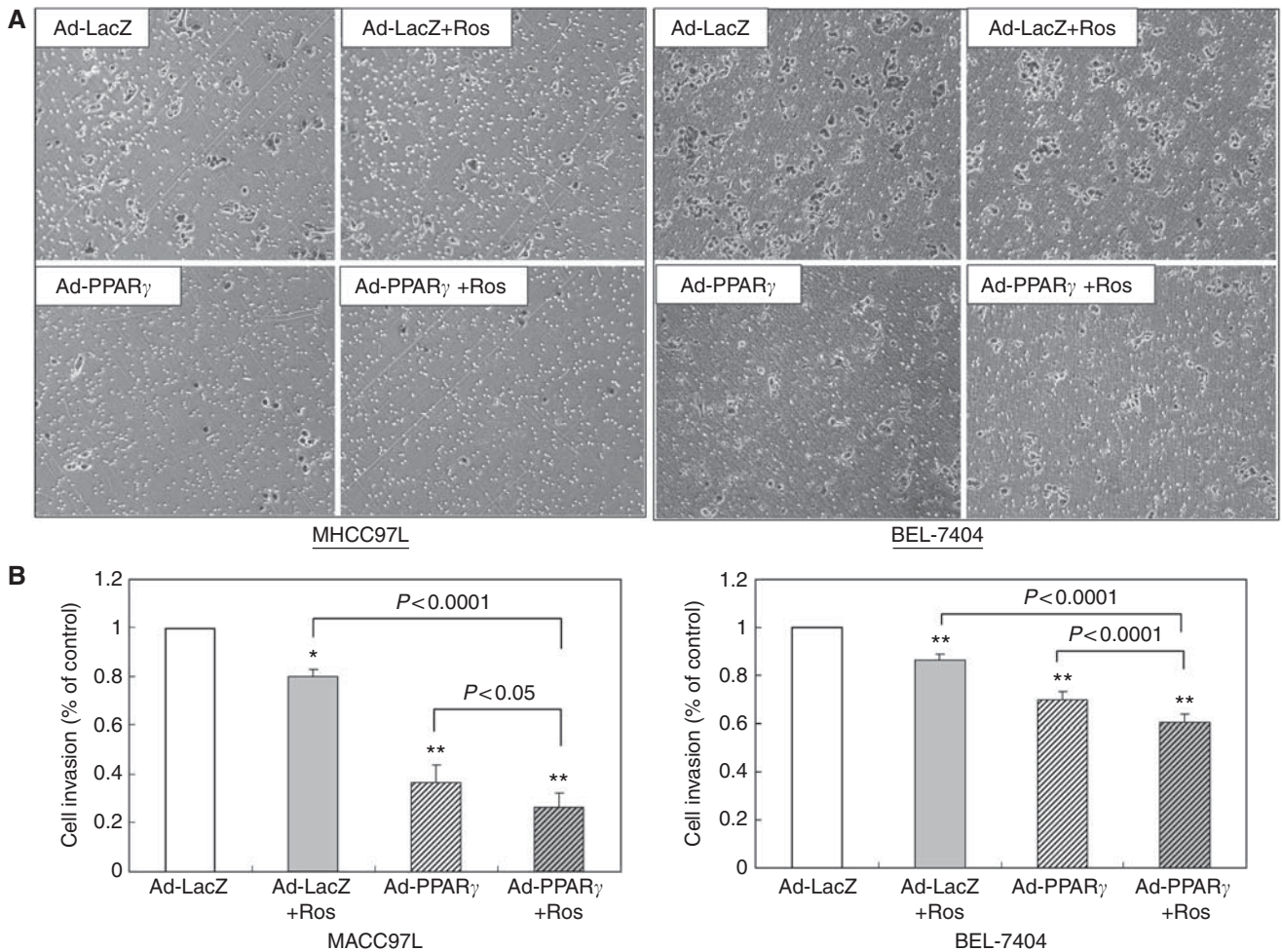
**Figure 1** Effect of PPAR $\gamma$  on HCC cells motility by wound healing assay. **(A)** Pronounced expression of PPAR $\gamma$  protein was confirmed by western blot induced in HCC cells (MHCC97L and BEL-7404) treated with rosiglitazone, Ad-PPAR $\gamma$  or rosiglitazone plus Ad-PPAR $\gamma$ . **(B)** Representative images of the cell motility in MHCC97L and BEL-7404 cells under treatment with Ad-LacZ, Ad-LacZ + rosiglitazone, Ad-PPAR $\gamma$ , or Ad-PPAR $\gamma$  + rosiglitazone at 0, 24, and 36 h, respectively. **(C)** Quantification of cell motility was made by measuring the distance travelled by the cells between the two boundaries of the acellular area, and the results of the different treatment group were expressed as a ratio to Ad-LacZ-treated cells (control). The experiment was performed for three times in triplicate. The data are expressed as means  $\pm$  s.d., \* $P$ <0.05, \*\* $P$ <0.01, \*\*\* $P$ <0.0001, compared with the Ad-lacZ.

of HPSE (Figure 4A1). A similar enhanced suppressive effect of the combination of Ad-PPAR $\gamma$  and rosiglitazone was observed on MMP9 and MMP13 mRNA expression by RT-PCR (Figure 4A2).

#### Direct transcriptional regulation of TIMP3, MMP9, MMP13, and HPSE by PPAR $\gamma$

To further determine whether PPAR $\gamma$ -mediated downstream gene expression changes were associated with direct promoter binding,

PPAR $\gamma$ -binding sites in the promoters of identified targets, TIMP3, MMP9, MMP13, and HPSE, were mined using ModelInspector software (Genomatix Software GmbH, Munich, Germany). Chromatin immunoprecipitation assay with PPAR $\gamma$  antibody was performed in MHCC97L cells followed by PCR confirmation (Figure 4B). By ChIP-PCR assay, PPAR $\gamma$  binds to the promoters of TIMP3, MMP9, MMP13, and HPSE in MHCC97L cells (Figure.4B). These findings suggest that TIMP3, MMP9, MMP13, and HPSE are direct targets of PPAR $\gamma$  in liver cancer cells.



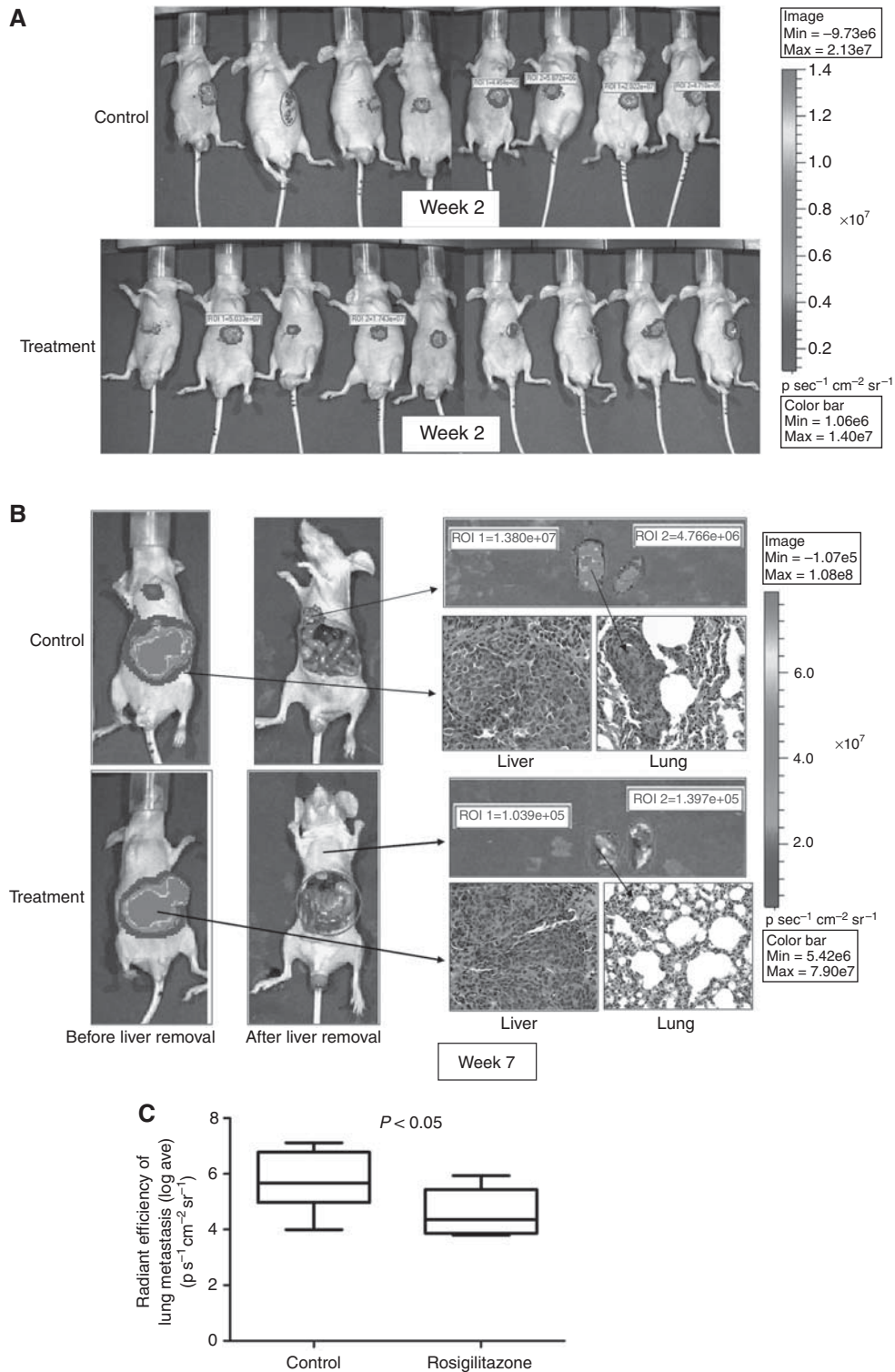
**Figure 2** Effect of PPAR $\gamma$  on HCC cells invasive ability by Matrigel invasion assay. **(A)** Representative images of the cell invasive and metastatic ability in MHCC97L and BEL-7404 cells treated with Ad-LacZ, Ad-LacZ + rosiglitazone, Ad-PPAR $\gamma$ , or Ad-PPAR $\gamma$  + rosiglitazone at 48 h. **(B)** Quantification of cell invasion was determined by counting cells that invaded through the Matrigel membrane under a light microscopy ( $\times 100$ ). The relative cell number ratio of each group was presented by comparing to the Ad-LacZ group (control). The experiment was performed for three times in triplicate. The data are expressed as mean  $\pm$  s.d., \* $P < 0.001$ , \*\* $P < 0.0001$ , compared with the Ad-lacZ.

## DISCUSSION

The significance of PPAR $\gamma$  on the process of metastasis is not well studied in contrast to the effect of PPAR $\gamma$  on tumour growth. In this study, we show that ectopic expression of PPAR $\gamma$  by Ad-PPAR or its agonist, rosiglitazone, in two HCC cell lines (MHCC97L, BEL-7404) inhibits metastatic activity *in vitro*, in particular in wound healing, cell migration, and invasion. Moreover, the combination of Ad-PPAR $\gamma$  and rosiglitazone results in an enhanced anti-metastatic effect. Together, these results indicate that restoration of PPAR $\gamma$  allow for interactions with endogenous or exogenous agonists that activate the anti-metastatic processes associated with PPAR $\gamma$ . The role of PPAR $\gamma$  in inhibiting HCC metastases *in vitro* was further elucidated in an orthotopic HCC xenograft model. In this murine model, activation of PPAR $\gamma$  suppressed HCC lung metastasis in nude mice. Surgical resection or liver transplantation is the curative mainstays of HCC management, however, post-operative recurrence predominantly related to metastasis remains a challenge. Our finding was supported by recent studies, which indicated that activation of PPAR $\gamma$  inhibits metastasis of lung cancer (Reka *et al*, 2010) and non-small cell lung cancer (Choudhary *et al*, 2010) *in vitro* and *in vivo*. Collectively, our finding that activation of PPAR $\gamma$  by rosiglitazone significantly

suppresses metastatic potential could have a beneficial impact on the clinical practice and in adjuvant therapy of HCC after surgical resection and transplantation.

The molecular mechanisms by which PPAR $\gamma$  exerts its anti-invasive and anti-metastases functions in HCC have not yet been defined. To identify key regulators of PPAR $\gamma$ -mediated anti-metastatic effect in HCC, we utilised cDNA microarray and ChIP-PCR to study MHCC97L cells infected with Ad-PPAR $\gamma$ , genes that were significantly altered in expression levels were then validated by RT-PCR and immunoblotting. We report that the suppression of cell invasion and migration mediated by PPAR $\gamma$  was mediated via downregulation of MMPs (MMP9, MMP13), increased expression of TIMP3 and E-cadherin. Of which, MMP9 and MMP13 are members of extracellular proteinases with key functions in the formation and remodelling of tumour invasion (Khasigov *et al*, 2003). Matrix metalloproteinase 9 has been described to promote tumour malignant progression, invasion, and metastatic spread by activating tumour growth factor- $\beta$  (TGF- $\beta$ ) (Yu and Stamenkovic, 2000). Whereas, MMP13 has a central role in the modulation of other MMPs (Leeman *et al*, 2002) such as stimulating pro-MMP9 activation (Knäuper *et al*, 1997). Elevated MMP13 had been shown in various human malignancies including breast cancer, colorectal neoplasms, melanoma, and squamous head and neck tumours,



**Figure 3** Activation of PPAR $\gamma$  suppressed HCC metastasis *in vivo*. **(A)** Tumours derived from the luciferase-labelled MHCC97L cells were successfully implanted orthotopically into the livers of nude mice at 2 weeks. Tumour growth in the mice was monitored by a live imaging system detecting the luciferase signal (unit photons  $s^{-1} \text{ cm}^{-2} \text{ steradian}$ ). **(B)** Lung metastasis of the HCC mice treated with or without rosiglitazone (200 p.p.m.) at 7 weeks after orthotopic implantation. The liver tumours and lung metastatic nodules were examined by Xenogen IVIS and confirmed histologically. **(C)** Luciferase signal found in the lungs in the rosiglitazone-treated group was significantly lower than in the vehicle-treated group (log base 10 value is used).

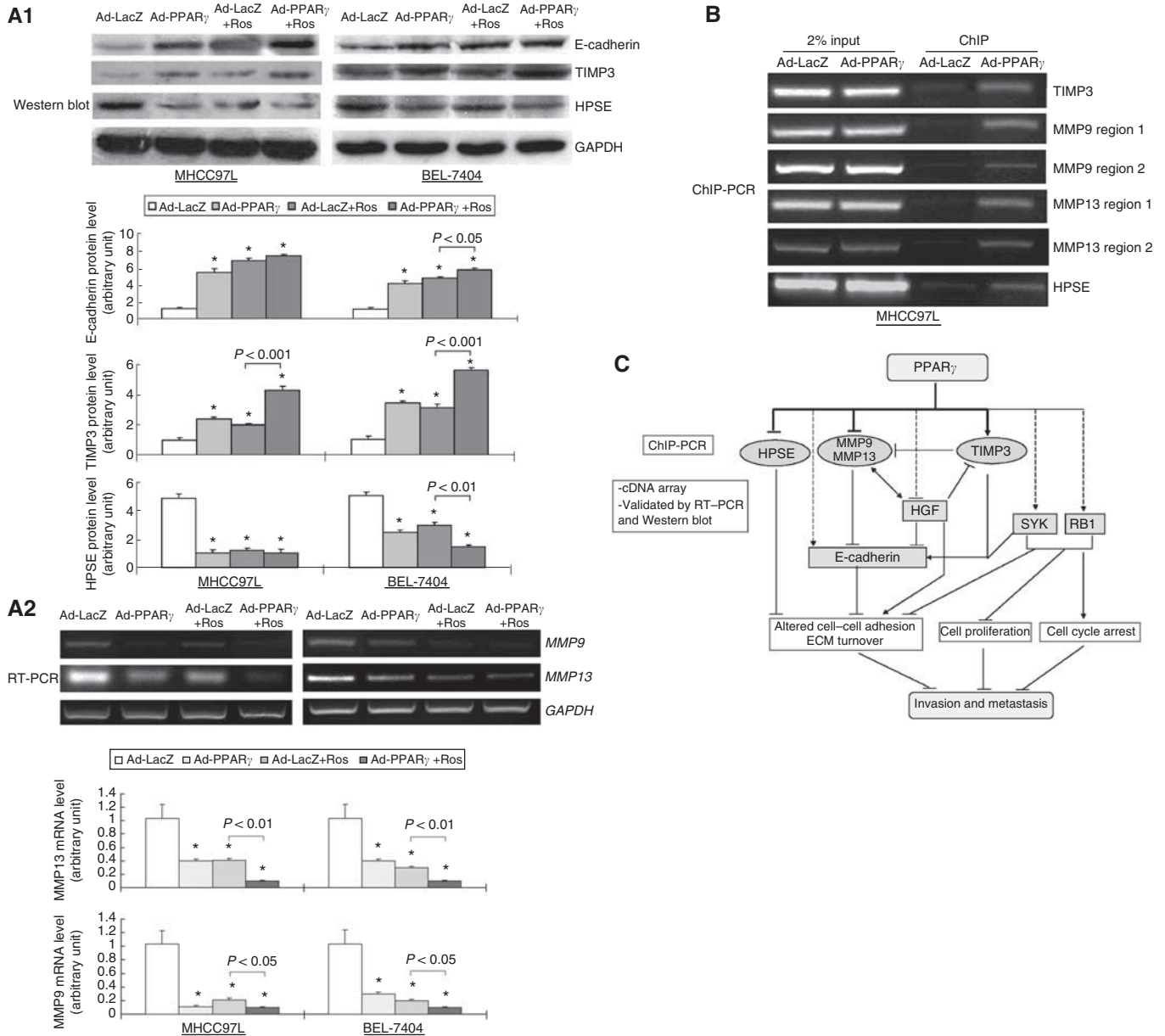
particularly at the invading edge of such cancers; increased MMP13 expression was associated with poor prognosis, tumour aggressiveness, and metastases (Leeman *et al*, 2002; Luukkaa *et al*, 2006; Kondratiev *et al*, 2008; Chang *et al*, 2009).

Tissue inhibitors of metallo proteinase 3 is an important endogenous inhibitor of MMPs. Upregulation of TIMP3 expression by PPAR $\gamma$  suggested its suppressive functions in tumour invasion and metastasis via suppressing of MMPs (Bachman *et al*, 1999;



**Table 2** Effect of PPAR $\gamma$  on its downstream gene expression profiles of cancer metastasis pathways in HCC cell lines

Full name	Gene	GeneBank	Fold Change (PPAR $\gamma$ /control)	Function
E-cadherin	CDH1	NM_004360	5.2	Cell adhesion
Spleen tyrosine kinase	SYK	NM_003177	1.7	Cell adhesion
Metalloproteinase inhibitor 3	TIMP3	NM_003810	7.2	Extracellular matrix proteins
Matrix metalloproteinase 9	MMP9	NM_004994	-1.7	Extracellular matrix proteins
Matrix metalloproteinase 13	MMP13	NM_002427	-2.0	Extracellular matrix proteins
Heparanase	HPA, HPSE	NM_006665	-6.5	Extracellular matrix proteins
Hepatocyte growth factor	HGF	NM_000601	-2.2	Cell growth and cell motility
Retinoblastoma 1	RB1	NM_000321	4.1	Cell growth



**Figure 4.** (A1) Western blots were performed to confirm the downstream gene expression regulated by PPAR $\gamma$  in MHCC97L and BEL-7404. GAPDH was used as an internal control. The relevant band densitometry analysis was performed and displayed in the lower panel. (A2) Semi-quantitative RT-PCR and real-time quantitative PCR analyses were performed to validate the candidate genes expression. The data are expressed as means  $\pm$  s.d., \* $P < 0.001$ , compared with the Ad-lacZ. (B) Chromatin Immunoprecipitation (ChIP)-qPCR was performed to identify direct targets of PPAR $\gamma$  protein. Input (2%) represents the genomic DNA. (C) Schematic diagram for the mechanisms of anti-metastasis function of PPAR $\gamma$  deriving from cDNA array, western blot, and ChIP-qPCR. PPAR $\gamma$ -mediated suppression of cell invasion and migration was associated with several biological effects: (1) Directly upregulating MMPs (MMP9, MMP13) and downregulating their inhibitor (TIMP3) by direct binding to the promoter of each targets, and subsequent modulation of cell-cell adhesion molecule E-cadherin, which in turn inhibited the cell-cell adhesion and extracellular matrix (ECM) turnover; (2) Directly inhibiting the transcription of HPSE gene, which contributes to the suppression of ECM turnover and distant metastasis; (3) Downregulation of HGF to suppress the invasive potential; and (4) Upregulation of tumour suppressors (RB1 and SYK), which protects against tumorigenesis through suppressing ECM turnover, cell proliferation, and causing cell cycle arrest. Blue colour indicates the direct targets, and green colour indicates second targets of PPAR $\gamma$ . The colour reproduction of this figure is available at the *British Journal of Cancer* online.

Wild *et al*, 2003). Matrix metalloproteinase 9 and 13 are important mediators in the turnover of ECM and degradation of cell surface molecules such as E-cadherin; they have been described to promote cancer cell migration (Cowden Dahl *et al*, 2008). Cell-cell adhesion molecule, E-cadherin, is also a key component of epithelial adherent junctions. Loss of E-cadherin expression is a hallmark of epithelial-to-mesenchymal transition, a plausible mechanism of driving cancer progression and metastasis (Onder *et al*, 2008; Makrilia *et al*, 2009). We demonstrate further that PPAR $\gamma$  inhibits transcription of HPSE by direct binding to its promoter. Upregulation of HPSE has been associated with increased lymph node, as well as distant metastases (Sanderson *et al*, 2005) and reduced post-operative survival of cancer patients (Sato *et al*, 2004).

The anti-metastasis function of PPAR $\gamma$  *in vitro* also appeared to be associated with the downregulation of HGF by cDNA array. HGF is known to act as a multifunctional growth factor and is upregulated in many human cancers including HCC (Ljubimova *et al*, 1997; Maulik *et al*, 2002). Hepatocyte growth factor drives epithelial cells to undergo EMT and can downregulate EMT-associated E-cadherin expression in murine liver tumour cells (Ding *et al*, 2010). Also, HGF has been reported to stimulate MMP9 expression (Mizuno *et al*, 2005) and increase MMP3 promoter activity in HCC (Ozaki *et al*, 2003), which can lead to increased cancer cell invasiveness (Reboul *et al*, 2001; Wang *et al*, 2007; Lee *et al*, 2010). Notably, HGF activity may be mediated by MMPs (including MMP9 and MMP13) in the extracellular matrix, and thus induce HCC cells to proliferate and invade (Monvoisin *et al*, 2002; Mohammed *et al*, 2005). In contrast, HGF may down-modulate TIMP-3 expression resulting in increased MMP accumulation, hence contributing to the invasiveness and aggressiveness in cancer cells (Castagnino *et al*, 1998). Thus, the anti-metastasis effect of PPAR $\gamma$  in HCC may be in part related to the inhibition of HGF expression (Figure 4C).

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Tumour suppressor genes, RB1 and SYK, have been reported to be dysfunctional in several cancers where aberrant expression levels appear to correlate with poor prognosis (Baillet *et al*, 2009; Kouraklis *et al*, 2009). In contrast, overexpression of RB1 or SYK in several cancer cell types can inhibit tumour growth and reduce metastasis in mouse xenografts (Valente *et al*, 1996; Coopman *et al*, 2000). Spleen tyrosine kinase also inhibits the motility of human breast cancer cells (Zhang *et al*, 2009) and promotes the formation of cell-cell contact through mediation of E-cadherin activity (Larive *et al*, 2009). In the present study, we describe a near two-fold induction of SYK and impressive upregulation by four-fold of RB1 by PPAR $\gamma$  in keeping with its proposed anti-metastatic and -invasive effects.

In conclusion, activation of PPAR $\gamma$  has demonstrated efficacy in suppressing HCC cell migration and invasion *in vitro*, and in inhibiting distant metastases from liver in an orthotopic HCC model *in vivo*. Peroxisome proliferator-activated receptor- $\gamma$  may provide a potential target for the prevention and treatment of metastatic HCC.

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## Conflict of interest

The authors declare no conflict of interest.

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