Grove, PA) or DyLight649-conjugated goat anti-rat IgG (BioLegend, San Diego, CA) was used as secondary Abs.

Cell cultures

The mouse ES cell line E14 and two mouse iPS cell lines, 38C2 and 20D17, both of which were generated by Yamanaka and his colleagues (Okita et al., 2007), were used in this study. 38C2 was kindly provided by Dr. S. Yamanaka (Kyoto University, Kyoto, Japan), and 20D17 was purchased from Riken Bioresource Center (Tsukuba, Japan). In the present study, we mainly used 38C2 iPS cells except where otherwise indicated. Mouse ES and iPS cells were cultured in leukemia inhibitory factor-containing medium on a feeder layer of mitomycin C-inactivated mouse embryonic fibroblasts (MEF) as described previously (Tashiro et al., 2009). OP9 stromal cells were cultured in α-minimum essential medium (αMEM: Sigma, St. Louis, MO) supplemented with 20% fetal bovine serum (FBS), 2 mM L-glutamine (Invitrogen, Carlsbad, CA), and non-essential amino acid (Invitrogen).

Ad vectors

Ad vectors were constructed by an improved *in vitro* ligation method (Mizuguchi and Kay, 1998, 1999). The shuttle

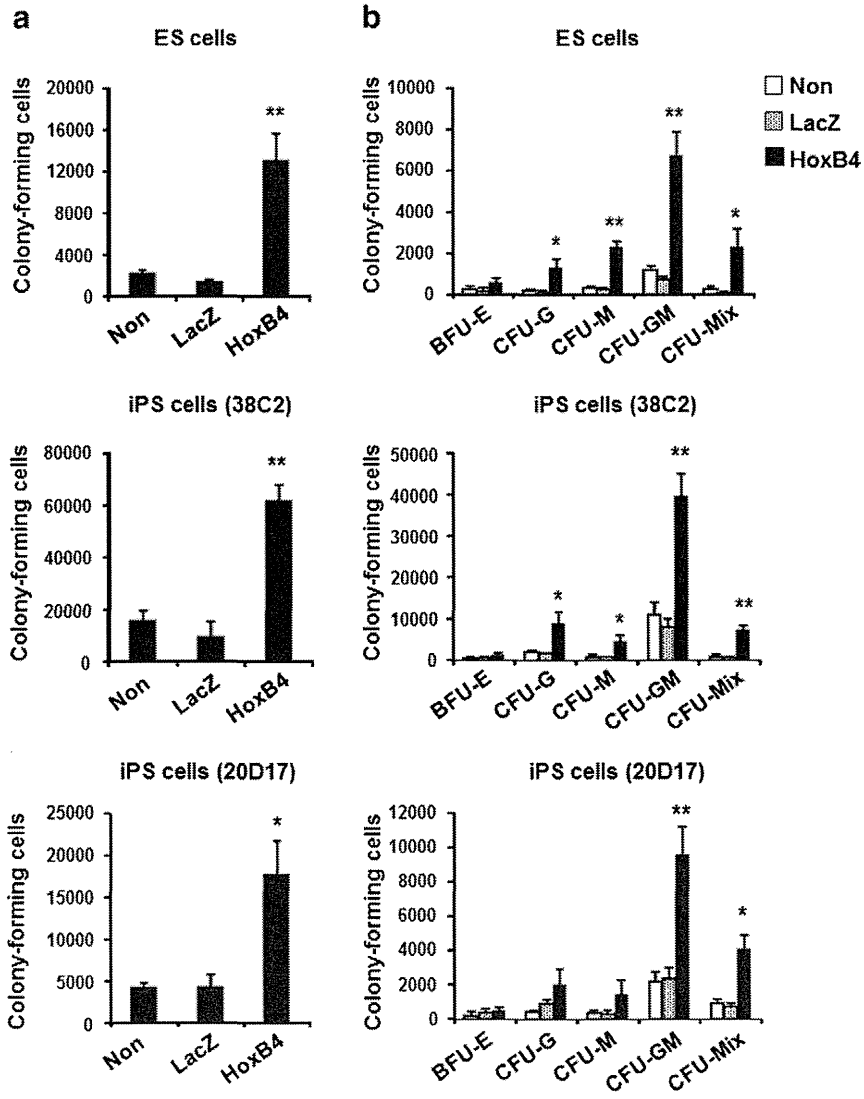

Figure 4 Significant increase of hematopoietic colony-forming cells in Ad-HoxB4-transduced hematopoietic cells. After ES-EB- or iPS-EB-derived cells were transduced with Ad-LacZ or Ad-hHoxB4, hematopoietic cells were generated by co-culturing with OP9 cells in the presence of hematopoietic cytokines for 10 days (a, b) or 20 days (c, d). A colony-forming assay was performed using methylcellulose medium, and the number of hematopoietic colonies was then counted under light microscopy. The number of total colonies (a, c) or subdivided colonies by morphological subtype (BFU-E, CFU-G, CFU-M, CFU-GM, and CFU-Mix) (b, d) generated from ES cells (E14) or iPS cells (38C2 and 20D17) was shown. Colony number was normalized to total number of the cells. Results shown were the mean of three (c, d) or four (a, b) independent experiments with indicated standard deviations. * $p<0.05$, ** $p<0.01$ as compared with non-transduced or Ad-LacZ-transduced cells. Abbreviation: BFU-E, burst-forming unit; CFU-G, colony-forming unit-granulocyte; CFU-M, CFU-monocyte; CFU-GM, CFU-granulocyte, monocyte; CFU-GEMM/CFU-Mix, CFU-granulocyte, erythrocyte, monocyte, megakryocyte.

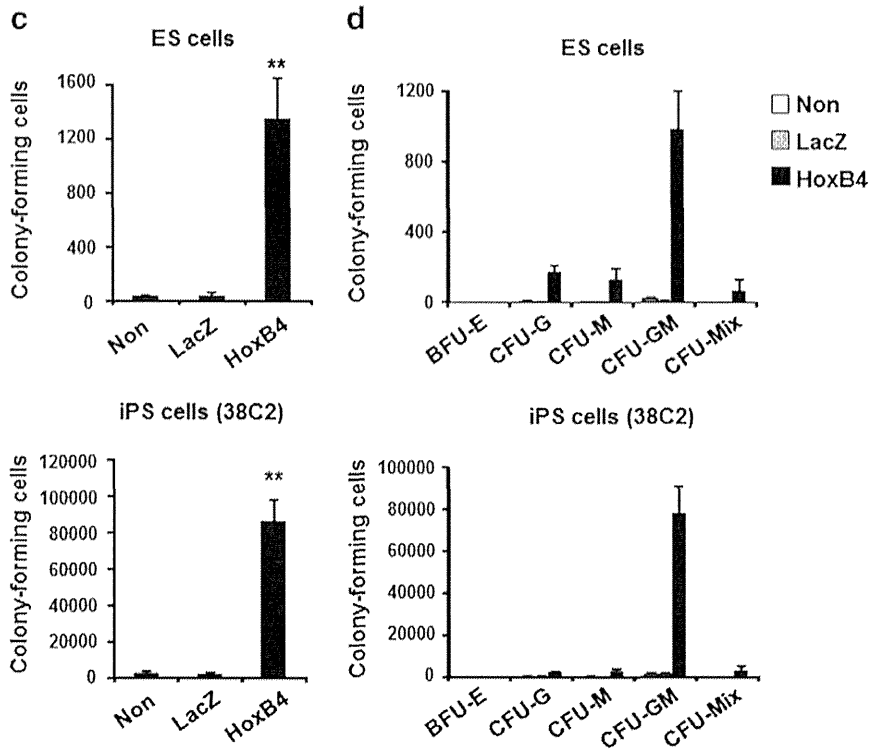

Figure 4 (*continued*).

plasmid pHMCA5, which contains the CMV enhancer/β-actin promoter with β-actin intron (CA) promoter (a kind gift from Dr. J. Miyazaki, Osaka University, Osaka, Japan) (Niwa et al., 1991), was previously constructed (Kawabata et al., 2005). The human HoxB4 (hHoxB4)-expressing plasmid, pHMCA-hHoxB4, and DsRed-expressing plasmid, pHMCA-DsRed, were generated by inserting a hHoxB4 cDNA (a kindly gift from Dr. S. Karlsson, Lund University Hospital, Lund, Sweden) and a DsRed cDNA (Clontech, Mountain View, CA), respectively, into pHMCA5. pHMCA-hHoxB4 or pHMCA-DsRed were digested with I-*Ceu*I/PI-*Sce*I and ligated into I-*Ceu*I/PI-*Sce*I-digested pAdHM4 (Mizuguchi and Kay, 1998), resulting in pAd-hHoxB4 or pAd-DsRed, respectively. Ad-hHoxB4 and Ad-DsRed were generated and purified as described previously (Tashiro et al., 2008). The CA promoter-driven β-galactosidase (LacZ)-expressing Ad vector, Ad-LacZ, and the CA promoter-driven GFP-expressing Ad vector, Ad-CA-GFP, were generated previously (Tashiro et al., 2008). The vector particle (VP) titer was determined by using a spectrophotometrical method (Maizel et al., 1968).

In vitro differentiation

Prior to embryoid body (EB) formation, mouse ES or iPS cells were suspended in differentiation medium (Dulbecco's modified Eagle's medium (Wako, Osaka, Japan) containing 15% FBS, 0.1 mM 2-mercaptoethanol (Nacalai tesque, Kyoto, Japan), 1×non-essential amino acid (Specialty Media, Inc.), 1×nucleosides (Specialty Media, Inc.), 2 mM L-glutamine (Invitrogen), and penicillin/streptomycin (Invitrogen)) and cultured on a culture dish at 37 °C for 45 min to remove MEF layers. Mouse ES cell- or iPS cell-derived EBs (ES-EBs or iPS-EBs, respectively) were generated by culturing ES or iPS cells on a round-bottom low cell binding 96-well plate (Lipidure-coat plate; Nunc) at 1×10^3 cells per well. ES-EBs or iPS-EBs were collected on day 5, and a single cell suspension was prepared by trypsin/EDTA treatment (Invitrogen) at 37 °C for 2 min. ES-EB- or iPS-EB-derived $CD41^+c\text{-}kit^+$ cells were sorted by FACSAria (BD Bioscience). The purity of the $CD41^+c\text{-}kit^+$ cells was greater than 90% based on flow cytometric analysis (Supplemental Fig. 1). Cells were then transduced with an Ad vector at 3000 vector particles (VPs)/cell for 1.5 h in a 15 ml tube. After transduction, total cells (2×10^5) or $CD41^+c\text{-}kit^+$ cells (1×10^4) were cultured on OP9 feeder cells in a well of a 6-well plate in αMEM supplemented with 20% FBS, 2 mM L-glutamine, non-essential amino acid, 0.05 mM 2-mercaptoethanol, and hematopoietic cytokines (50 ng/ml mouse stem cell factor (SCF), 50 ng/ml human Flt-3 ligand (Flt-3L), 20 ng/ml thrombopoietin (TPO), 5 ng/ml mouse interleukin (IL)-3, and 5 ng/ml human IL-6 (all from Peprotec, Rocky Hill, NJ)). After culturing with OP9 stromal cells, both non-adherent hematopoietic cells and adherent hematopoietic cells were collected as follows. The non-adherent hematopoietic cells were collected by pipetting and were transferred to 15 ml tubes. The adherent hematopoietic cells were harvested with the use of trypsin/EDTA, and then incubated in a tissue culture dish for 30 min to eliminate the OP9 cells. Floating cells were collected as hematopoietic cells and transferred to the same 15 ml tubes. These hematopoietic cells were kept on ice for further analysis.

Flow cytometry

Cells (1×10^5 to 5×10^5) were incubated with monoclonal Abs at 4 °C for 30 min and washed twice with staining buffer

Table 1 List of primers used for RT-PCR.

Gene name	Species	(5′) Sense primers (3′)	(5′)Antisense primers (3′)
GAPDH	Ms	ACCACAGTCCATGCCATCAC	TCCACCACCCTGTTGCTGTA
HoxB4	Hs	AGAGGCGAGAGAGCAGCTT	TTCCTTCTCCAGCTCCAAGA
Oct-3/4	Ms	GTTTGCCAAGCTGCTGAAGC	TCTAGCCCAAGCTGATTGGC
GFP	–	CACATGAAGCAGCACGACTT	TGCTCAGGTAGTGGTTGTCG
Flk-1	Ms	TCTGTGGTTCTGCGTGGAGA	GTATCATTTCCAACCACCC
Gata1	Ms	TTGTGAGGCCAGAGAGTGTG	TTCCTCGTCTGGATTCCATC
Gata1 (real-time PCR)	Ms	GTCAGAACCGGCCTCTCATC	GTGGTCGTTTGACAGTTAGTGCAT
Tel	Ms	CTGAAGCAGAGGAAATCTCGAATG	GGCAGGCAGTGATTATTCTCGA
c-myb	Ms	CCTCACCTCCATCTCAGCTC	GCTGGTGAGGCACTTTCTTC
β-H1	Ms	AGTCCCCATGGAGTCAAAGA	CTCAAGGAGACCTTTGCTCA
β-Major	Ms	CTGACAGATGCTCTCTTGGG	CACAACCCCAGAAACAGACA
CXCR4	Ms	GTCTATGTGGGCGTCTGGAT	GGCAGAGCTTTTGAACTTGG

(PBS/2%FBS). Dead cells were excluded from the analysis by 7-amino actinomycin D (7-AAD, eBioscience). Analysis was performed on an LSRFortessa flow cytometer by using FACS-Diva software (BD Bioscience). For detection of transgene expression by Ad vectors, EB-derived total cells or CD41$^+$c-kit$^+$ cells were transduced with Ad-DsRed or Ad-CA-GFP, respectively, for 1.5 h. At 48 h of incubation with the hematopoietic cytokines as described above, transgene expression in the cells was analyzed by flow cytometry.

Colony assay

A colony-forming assay was performed by plating ES cell-derived hematopoietic cells or iPS cell-derived hematopoietic cells into methylcellulose medium M3434 (Stem Cell Technologies, Vancouver, BC, Canada). After incubation at 37 °C and 5% CO_2 for 10 to 14 days in a humidified atmosphere, colony numbers were counted. The morphology of colonies was observed using an inverted light microscope.

RT-PCR

Total RNA was isolated with the use of ISOGENE (Nippon Gene, Tokyo, Japan). cDNA was synthesized by using Super-Script II reverse transcriptase (Invitrogen) and the oligo(dT) primer. Semi-quantitative PCR was performed with the use of TaKaRa ExTaq HS DNA polymerase (Takara, Shiga, Japan). The PCR conditions were 94 °C for 2 min, followed by the appropriate number of cycles of 94 °C for 15 s, 55 °C for 30 s with 72 °C for 30 s and a final extension of 72 °C for 1 min, except for the addition of 5% dimethyl sulfoxide in the case of hHoxB4 cDNA amplification. The product was assessed by 2% agarose gel electrophoresis followed by ethidium bromide staining. Quantitative real-time PCR was performed using StepOnePlus real-time PCR system with FAST SYBR Green Master Mix (Applied Biosystems, Foster-City, CA). The sequences of the primers used for in this study are listed in Table 1.

Supplementary materials related to this article can be found online at doi:10.1016/j.scr.2011.09.001.

Conflict of interest

The authors have no financial conflict of interest.

Acknowledgments

We thank Dr. S. Yamanaka for kindly providing the mouse iPS cell line 38C2 and 20D17. We would also like to thank Dr. J. Miyazaki and Dr. T. Imai for providing the CA promoter and anti-mouse CAR monoclonal antibody, respectively. We also thank Dr. K. Nishikawa (National Institute of Biomedical Innovation) for helpful comments. This work was supported by grants from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan and the Ministry of Health, Labour, and Welfare of Japan.

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Efficient Generation of Functional Hepatocytes From Human Embryonic Stem Cells and Induced Pluripotent Stem Cells by HNF4α Transduction

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Hepatocyte-like cells from human embryonic stem cells (ESCs) and induced pluripotent stem cells (iPSCs) are expected to be a useful source of cells drug discovery. Although we recently reported that hepatic commitment is promoted by transduction of SOX17 and HEX into human ESC- and iPSC-derived cells, these hepatocyte-like cells were not sufficiently mature for drug screening. To promote hepatic maturation, we utilized transduction of the hepatocyte nuclear factor 4α (HNF4α) gene, which is known as a master regulator of liver-specific gene expression. Adenovirus vector-mediated overexpression of HNF4α in hepatoblasts induced by SOX17 and HEX transduction led to upregulation of epithelial and mature hepatic markers such as cytochrome P450 (CYP) enzymes, and promoted hepatic maturation by activating the mesenchymal-to-epithelial transition (MET). Thus HNF4α might play an important role in the hepatic differentiation from human ESC-derived hepatoblasts by activating the MET. Furthermore, the hepatocyte like-cells could catalyze the toxication of several compounds. Our method would be a valuable tool for the efficient generation of functional hepatocytes derived from human ESCs and iPSCs, and the hepatocyte-like cells could be used for predicting drug toxicity.

Received 19 July 2011; accepted 28 September 2011; published online 8 November 2011. doi:10.1038/mt.2011.234

INTRODUCTION

Human embryonic stem cells (ESCs) and induced pluripotent stem cells (iPSCs) are able to replicate indefinitely and differentiate into most of the body's cell types.[1,2] They could provide an unlimited source of cells for various applications. Hepatocyte-like cells, which are differentiated from human ESCs and iPSCs, would be useful for basic research, regenerative medicine, and drug discovery.[3] In particular, it is expected that hepatocyte-like cells will be utilized as a tool for cytotoxicity screening in the early phase of pharmaceutical development. To catalyze the toxication of several compounds, hepatocyte-like cells need to be mature enough to exhibit hepatic functions, including high activity levels of the cytochrome P450 (CYP) enzymes. Because the present technology for the generation of hepatocyte-like cells from human ESCs and iPSCs, which is expected to be utilized for drug discovery, is not refined enough for this application, it is necessary to improve the efficiency of hepatic differentiation. Although conventional methods such as growth factor-mediated hepatic differentiation are useful to recapitulate liver development, they lead to only a heterogeneous hepatocyte population.[4–6] Recently, we showed that transcription factors are transiently transduced to promote hepatic differentiation in addition to the conventional differentiation method which uses only growth factors.[7] Ectopic expression of Sry-related HMG box 17 (SOX17) or hematopoietically expressed homeobox (HEX) by adenovirus (Ad) vectors in human ESC-derived mesendoderm or definitive endoderm (DE) cells markedly enhances the endoderm differentiation or hepatic commitment, respectively.[7,8] However, further hepatic maturation is required for drug screening.

The transcription factor hepatocyte nuclear factor 4α (HNF4α) is initially expressed in the developing hepatic diverticulum on E8.75,[9,10] and its expression is elevated as the liver develops. A previous loss-of-function study showed that HNF4α plays a critical role in liver development; conditional deletion of *HNF4α* in fetal hepatocytes results in the faint expression of many mature hepatic enzymes and the impairment of normal liver morphology.[11] The genome-scale chromatin immunoprecipitation assay showed that HNF4α binds to the promoters of nearly half of the genes expressed in the mouse liver,[12] including cell adhesion and junctional proteins,[13] which are important in

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the hepatocyte epithelial structure.[14] In addition, HNF4α plays a critical role in hepatic differentiation and in a wide variety of liver functions, including lipid and glucose metabolism.[15,16] Although HNF4α could promote transdifferentiation into hepatic lineage from hematopoietic cells,[17] the function of HNF4α in hepatic differentiation from human ESCs and iPSCs remains unknown. A previous study showed that hepatic differentiation from mouse hepatic progenitor cells is promoted by HNF4α, although many of the hepatic markers that they examined were target genes of HNF4α.[18] They transplanted the HNF4α-overexpressed mouse hepatic progenitor cells to promote hepatic differentiation, but they did not examine the markers that relate to hepatic maturation such as CYP enzymes, conjugating enzymes, and hepatic transporters.

In this study, we examined the role of HNF4α in hepatic differentiation from human ESCs and iPSCs. The human ESC- and iPSC-derived hepatoblasts, which were efficiently generated by sequential transduction of SOX17 and HEX, were transduced with HNF4α-expressing Ad vector (Ad-HNF4α), and then the expression of hepatic markers of the hepatocyte-like cells were assessed. In addition, we examined whether or not the hepatocyte-like cells, which were generated by sequential transduction of SOX17, HEX, and HNF4α, were able to predict the toxicity of several compounds.

RESULTS

Stage-specific HNF4α transduction in hepatoblasts selectively promotes hepatic differentiation

The transcription factor HNF4α plays an important role in both liver generation[11] and hepatic differentiation from human ESCs and iPSCs (**Supplementary Figure S1**). We expected that hepatic differentiation could be accelerated by HNF4α transduction. To examine the effect of forced expression of HNF4α in the hepatic differentiation from human ESC- and iPSC-derived cells, we used a fiber-modified Ad vector.[19] Initially, we optimized the time period for Ad-HNF4α transduction. Human ESC (H9)-derived DE cells (day 6) (**Supplementary Figures S2** and **S3a**), hepatoblasts (day 9) (**Supplementary Figures S2** and **S3b**), or a heterogeneous population consisting of hepatoblasts, hepatocytes, and cholangiocytes (day 12) (**Supplementary Figures S2** and **S3c**) were transduced with Ad-HNF4α and then the Ad-HNF4α-transduced cells were cultured until day 20 of differentiation (Figure 1). We ascertained the expression of exogenous *HNF4α* in human ESC-derived hepatoblasts (day 9) transduced with Ad-HNF4α (**Supplementary Figure S4**). The transduction of Ad-HNF4α into human ESC-derived hepatoblasts (day 9) led to the highest expression levels of the hepatocyte markers *albumin* (*ALB*)[20] and *α-1-antitrypsin* (Figure 1a). In contrast, the expression levels of the cholangiocyte markers *cytokeratin 7* (*CK7*)[21] and *SOX9*[22] were

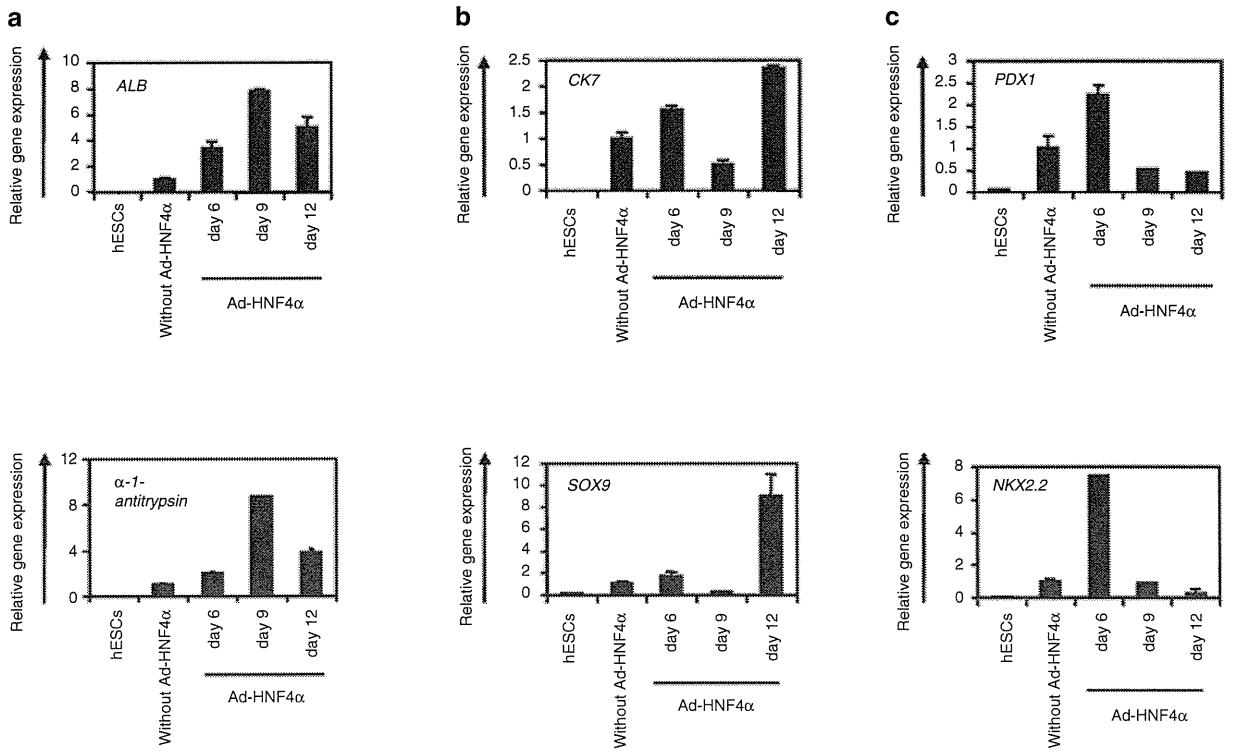

Figure 1 Transduction of HNF4α into hepatoblasts promotes hepatic differentiation. (**a**–**c**) The human ESC (H9)-derived cells, which were cultured for 6, 9, or 12 days according to the protocol described in **Figure 2a**, were transduced with 3,000 vector particles (VP)/cell of Ad-HNF4α for 1.5 hours and cultured until day 20. The gene expression levels of (**a**) hepatocyte markers (*ALB* and *α-1-antitrypsin*), (**b**) cholangiocyte markers (*CK7* and *SOX9*), and (**c**) pancreas markers (*PDX1* and *NKX2.2*) were examined by real-time RT-PCR on day 0 (human ESCs (hESCs)) or day 20 of differentiation. The horizontal axis represents the days when the cells were transduced with Ad-HNF4α. On the y-axis, the level of the cells without Ad-HNF4α transduction on day 20 was taken as 1.0. All data are represented as means ± SD (n = 3). ESC, embryonic stem cell; HNF4α, hepatocyte nuclear factor 4α; RT-PCR, reverse transcription-PCR.

downregulated in the cells transduced on day 9 as compared with nontransduced cells (Figure 1b). This might be because hepatic differentiation was selectively promoted and biliary differentiation was repressed by the transduction of HNF4α in hepatoblasts. The expression levels of the pancreas markers *PDX1*[23] and *NKX2.2*[24] did not make any change in the cells transduced on day 9 as compared with nontransduced cells (Figure 1c). Interestingly, the expression levels of the pancreas markers were upregulated, when Ad-HNF4α transduction was performed into DE cells (day 6) (Figure 1c). These results suggest that HNF4α might promote not only hepatic differentiation but also pancreatic differentiation, although the optimal stage of HNF4 transduction for the differentiation of each cell is different. We have confirmed that there was no difference between nontransduced cells and Ad-LacZ-transduced cells in the gene expression levels of all the markers investigated in Figure 1a–c (data not shown). We also confirmed that Ad vector-mediated gene expression in the human ESC-derived hepatoblasts (day 9) continued until day 14 and almost disappeared on day 18 (**Supplementary Figure S5**). These results indicated that the stage-specific HNF4α overexpression in human ESC-derived hepatoblasts (day 9) was essential for promoting efficient hepatic differentiation.

Transduction of HNF4α into human ESC- and iPSC-derived hepatoblasts efficiently promotes hepatic maturation

From the results of Figure 1, we decided to transduce hepatoblasts (day 9) with Ad-HNF4α. To determine whether hepatic maturation is promoted by Ad-HNF4α transduction, Ad-HNF4α-transduced cells were cultured until day 20 of differentiation according to the schematic protocol described in Figure 2a. After the hepatic maturation, the morphology of human ESCs was gradually changed into that of hepatocytes: polygonal with distinct round nuclei (day 20) (Figure 2b). Interestingly, a portion of the hepatocyte-like cells, which were ALB[20]-, CK18[21]-, CYP2D6-, and CYP3A4[25]-positive cells, had double nuclei, which was also observed in primary human hepatocytes (Figure 2b,c, and **Supplementary Figure S6**). We also examined the hepatic gene expression levels on day 20 of differentiation (Figure 3a,b). The gene expression analysis of *CYP1A2*, *CYP2C9*, *CYP2C19*, *CYP2D6*, *CYP3A4*, and *CYP7A1*[25] showed higher expression levels in all of Ad-SOX17-, Ad-HEX-, and Ad-HNF4α-transduced cells (three factors-transduced cells) as compared with those in both Ad-SOX17- and Ad-HEX-transduced cells (two factors-transduced cells) on day 20 (Figure 3a). The gene expression level of NADPH-CYP reductase

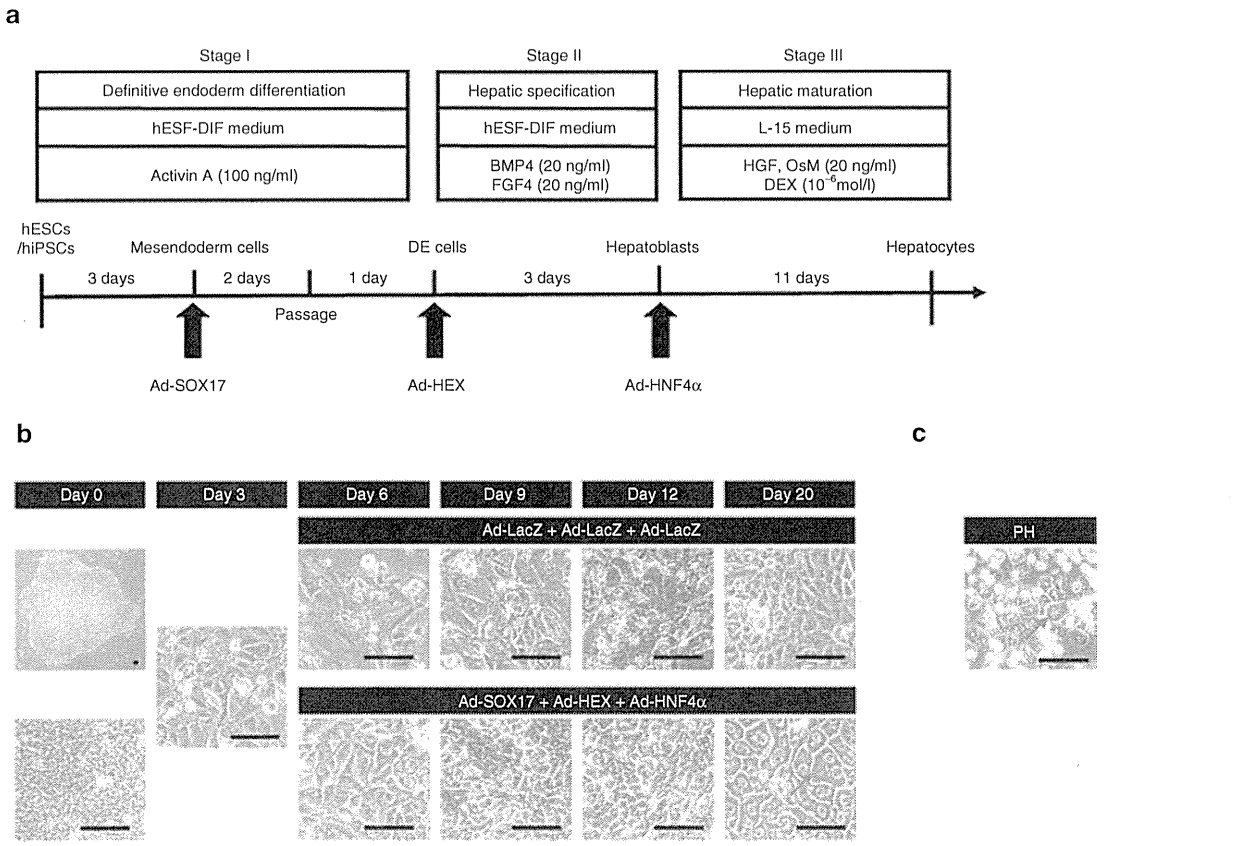

Figure 2 Hepatic differentiation of human ESCs and iPSCs transduced with three factors. (**a**) The procedure for differentiation of human ESCs and iPSCs into hepatocytes via DE cells and hepatoblasts is presented schematically. The hESF-DIF medium was supplemented with 10 μg/ml human recombinant insulin, 5 μg/ml human apotransferrin, 10 μmol/l 2-mercaptoethanol, 10 μmol/l ethanolamine, 10 μmol/l sodium selenite, and 0.5 mg/ml fatty-acid-free BSA. The L15 medium was supplemented with 8.3% tryptose phosphate broth, 8.3% FBS, 10 μmol/l hydrocortisone 21-hemisuccinate, 1 μmol/l insulin, and 25 mmol/l $NaHCO_3$. (**b**) Sequential morphological changes (day 0–20) of human ESCs (H9) differentiated into hepatocytes via DE cells and hepatoblasts are shown. Red arrow shows the cells that have double nuclei. (**c**) The morphology of primary human hepatocytes is shown. Bar represents 50 μm. BSA, bovine serum albumin; DE, definitive endoderm; ESC, embryonic stem cell; iPSC, induced pluripotent stem cell.

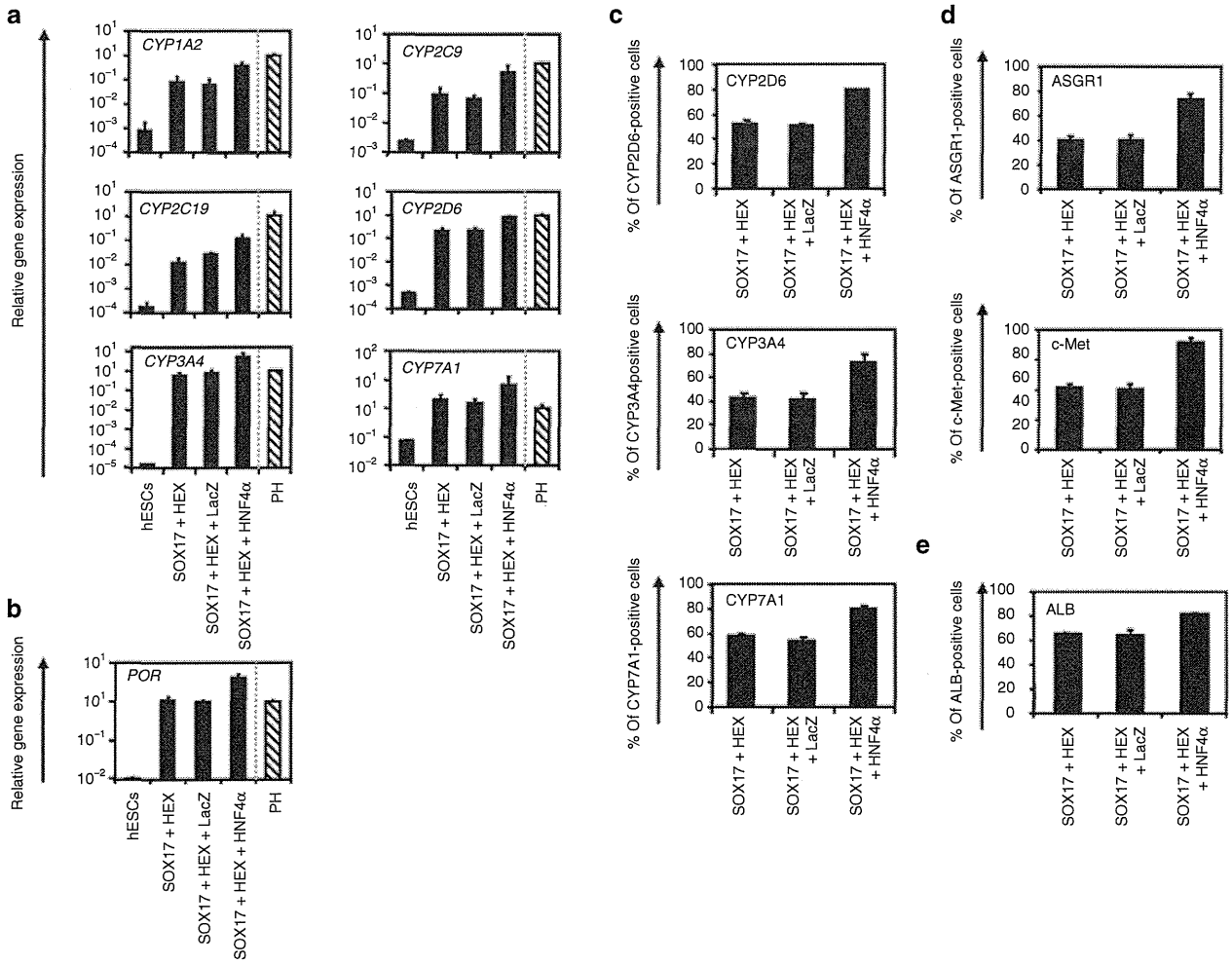

Figure 3 Transduction of HNF4α promotes hepatic maturation from human ESCs and iPSCs. (**a**,**b**) The human ESCs were differentiated into hepatocytes according to the protocol described in **Figure 2a**. On day 20 of differentiation, the gene expression levels of (**a**) CYP enzymes (*CYP1A2*, *CYP2C9*, *CYP2C19*, *CYP2D6*, *CYP3A4*, and *CYP7A1*) and (**b**) *POR* were examined by real-time RT-PCR in undifferentiated human ESCs (hESCs), the hepatocyte-like cells, and primary human hepatocytes (PH, hatched bar). On the y-axis, the expression level of primary human hepatocytes, which were cultured for 48 hours after the cells were plated, was taken as 1.0. (**c**–**e**) The hepatocyte-like cells (day 20) were subjected to immunostaining with (**c**) anti-drug-metabolizing enzymes (CYP2D6, CYP3A4, and CYP7A1), (**d**) anti-hepatic surface protein (ASGR1 and c-Met), and (**e**) anti-ALB antibodies, and then the percentage of antigen-positive cells was examined by flow cytometry on day 20 of differentiation. All data are represented as means ± SD (n = 3). ESC, embryonic stem cell; HNF4α, hepatocyte nuclear factor 4α; iPSC, induced pluripotent stem cell.

(POR)[26], which is required for the normal function of CYPs, was also higher in the three factors-transduced cells (Figure 3b). The gene expression analysis of ALB, α-1-antitrypsin (α-1-AT), transthyretin, hepatic conjugating enzymes, hepatic transporters, and hepatic transcription factors also showed higher expression levels in the three factors-transduced cells (**Supplementary Figures S7** and **S8**). Moreover, the gene expression levels of these hepatic markers of three factor-transduced cells were similar to those of primary human hepatocytes, although the levels depended on the type of gene (Figure 3a,b, and **Supplementary Figures S7** and **S8**). To confirm that similar results could be obtained with human iPSCs, we used three human iPS cell lines (201B7, Dotcom, and Tic). The gene expression of hepatic markers in human ESC- and iPSC-derived hepatocytes were analyzed by real-time reverse transcription-PCR on day 20 of differentiation. Three human iPS cell lines as well as human ESCs also effectively differentiated into hepatocytes in response to transduction of the three factors (**Supplementary Figure S9**). Interestingly, we observed differences in the hepatic maturation efficiency among the three human iPS cell lines. That is, two of the human iPS cell lines (Tic and Dotcom) were more committed to the hepatic lineage than another human iPS cell line (201B7). Because almost homogeneous hepatocyte-like cells would be more useful in basic research, regenerative medicine, and drug discovery, we also examined whether our novel methods for hepatic maturation could generate a homogeneous hepatocyte population by flow cytometry analysis (Figure 3c–e). The percentages of CYP2D6-, CYP3A4-, and CYP7A1-positive cells were ~80% in the three factors-transduced cells, while they were ~50% in the two factors-transduced cells (Figure 3c). The percentages of hepatic surface antigen (asialoglycoprotein receptor 1 (ASGR1] and met proto-oncogene (c-Met))-positive cells (Figure 3d) and ALB-positive cells (Figure 3e) were also ~80% in the three factors-transduced cells. These results indicated that a nearly homogeneous population was obtained by our differentiation protocol

using the transduction of three functional genes (SOX17, HEX, and HNF4α).

The three factors-transduced cells have characteristics of functional hepatocytes

The hepatic functions of the hepatocyte-like cells, such as the uptake of low-density lipoprotein (LDL) and CYP enzymes activity, of the hepatocyte-like cells were examined on day 20 of differentiation. Approximately 87% of the three factors-transduced cells uptook LDL in the medium, whereas only 44% of the two factors-transduced cells did so (Figure 4a). The activities of CYP enzymes of the hepatocyte-like cells were measured according to the metabolism of the CYP3A4, CYP2C9, or CYP1A2 substrates (Figure 4b). The metabolites were detected in the three factors-transduced cells and their activities were higher than those of the two factors-transduced cells (dimethyl sulfoxide (DMSO) column). We further tested the induction of CYP3A4, CYP2C9, and CYP1A2 by chemical stimulation, since CYP3A4, CYP2C9, and CYP1A2 are the important prevalent CYP isozymes in the liver and are involved in the metabolism of a significant proportion of the currently available commercial drugs (rifampicin or omeprazole column). It is well known that CYP3A4 and CYP2C9 can be induced by rifampicin, whereas CYP1A2 can be induced by omeprazole. The hepatocyte-like cells were treated with either of these. Although undifferentiated human ESCs responsed to neither rifampicin nor omeprazole (data not shown), the hepatocyte-like cells produced more metabolites in response to chemical stimulation as well as primary hepatocytes (Figure 4b). The activity levels of the hepatocyte-like cells as compared with those of primary human hepatocytes depended on the types of CYP; the CYP3A4 activity of the hepatocyte-like cells was similar to that of primary human hepatocytes, whereas the CYP2C9 and CYP1A2 activities of the hepatocyte-like cells were slightly lower than those of primary human hepatocytes (Figure 3a). These results indicated that high levels of functional CYP enzymes were detectable in the hepatocyte-like cells.

The metabolism of diverse compounds involving uptake, conjugation, and the subsequent release of the compounds is an important function of hepatocytes. Uptake and release of Indocyanine green (ICG) can often be used to identify hepatocytes in ESC differentiation models.[27] To investigate this function in our hepatocyte-like cells, we compared this ability of the three factors-transduced cells with that of the two factors-transduced cells on day 20 of differentiation (Figure 4c). The three factors-transduced cells had more ability to uptake ICG and to excrete ICG by culturing without ICG for 6 hours. We also examined whether the hepatocyte-like cells could store glycogen, a characteristic of functional hepatocytes (Figure 4d). On day 20 of differentiation, the three factors-transduced cells and the two factors-transduced cells were stained for cytoplasmic glycogen using the Periodic Acid-Schiff staining procedure. The three factors-transduced cells exhibited more abundant storage of glycogen than the two-factors-transduced cells. These results showed that abundant hepatic functions, such as uptake and excretion of ICG and storage of glycogen, were obtained by the transduction of three factors.

Many adverse drug reactions are caused by the CYP-dependent activation of drugs into reactive metabolites.[28] In order to examine metabolism-mediated toxicity and to improve the safety of drug candidates, primary human hepatocytes are widely used.[28] Because primary human hepatocytes have quite different characteristics among distinct lots and because it is difficult to purchase large amounts of primary human hepatocytes that have the same characteristics, hepatocyte-like cells are expected to be used for this purpose. To examine whether our hepatocyte-like cells could be used to predict metabolism-mediated toxicity, the hepatocyte-like cells were incubated with four substrates (troglitazone, acetaminophen, cyclophosphamide, and carbamazepine), which are known to generate toxic metabolites by CYP enzymes, and then the cell viability was measured (Figure 4e). The cell viability of the two factors plus Ad-LacZ-tansduced cells were higher than that of the three factors-transduced cells at each different concentration of four test compounds. These results indicated that the three factors-transduced cells could more efficiently metabolize the test compounds and thereby induce higher toxicity than either the two factors-transduced cells or undifferentiated human ESCs. The cell viability of the three factors-transduced cells was slightly higher than that of primary human hepatocytes.

HNF4α promotes hepatic maturation by activating mesenchymal-to-epithelial transition

HNF4α is known as a dominant regulator of the epithelial phenotype because its ectopic expression in fibroblasts (such as NIH 3T3 cells) induces mesenchymal-to-epithelial transition (MET)[11], although it is not known whether HNF4α can promote MET in hepatic differentiation. Therefore, we examined whether HNF4α transduction promotes hepatic maturation from hepatoblasts by activating MET. To clarify whether MET is activated by HNF4α transduction, the human ESC-derived hepatoblasts (day 9) were transduced with Ad-LacZ or Ad-HNF4α, and the resulting phenotype was analyzed on day 12 of differentiation (Figure 5). This time, we confirmed that HNF4α transduction decreased the population of N-cadherin (hepatoblast marker)-positive cells,[29] whereas it increased that of ALB (hepatocyte marker)-positive cells (Figure 5a). The number of CK7 (cholangiocyte marker)-positive population did not change (Figure 5a). To investigate whether these results were attributable to MET, the alteration of the expression of several mesenchymal and epithelial markers was examined (Figure 5b). The human ESC-derived hepatoblasts (day 9) were almost homogeneously N-cadherin[30] (mesenchymal marker)-positive and E-cadherin[11] (epithelial marker)-negative, demonstrating that human ESC-derived hepatoblasts have mesenchymal characteristics (Figure 5a,b). After HNF4α transduction, the number of E-cadherin-positive cells was increased and reached ~90% on day 20, whereas that of N-cadherin-positive cells was decreased and was less than 5% on day 20 (**Supplementary Figure S10**). These results indicated that MET was promoted by HNF4α transduction in hepatic differentiation from hepatoblasts. Interestingly, the number of growing cells was decreased by HNF4α transduction (Figure 5c), and the cell growth was delayed by HNF4α transduction (**Supplementary Figure S11**). This decrease in the number of growing cells might have been because the differentiation was promoted by HNF4α transduction. We also confirmed that MET was promoted by HNF4α transduction in the gene expression levels (Figure 5d).

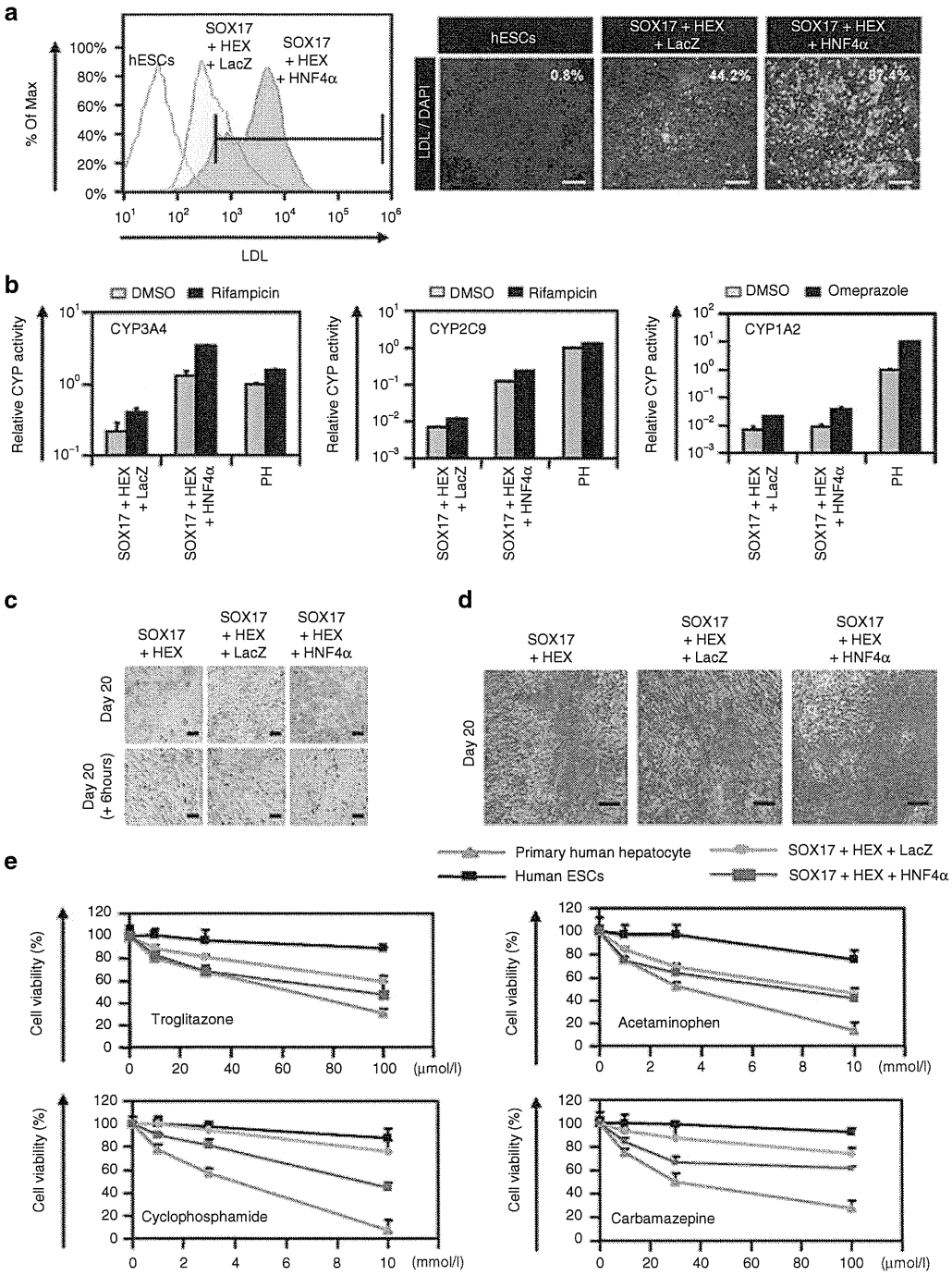

Figure 4 Transduction of the three factors enhances hepatic functions. The human ESCs were differentiated into hepatoblasts and transduced with 3,000 VP/cell of Ad-LacZ or Ad-HNF4α for 1.5 hours and cultured until day 20 of differentiation according to the protocol described in **Figure 2a**. The hepatic functions of the two factors plus Ad-LacZ-transduced cells (SOX17+HEX+LacZ) and the three factors-transduced cells (SOX17+HEX+HNF4α) were compared. (**a**) Undifferentiated human ESCs (hESCs) and the hepatocyte-like cells (day 20) were cultured with medium containing Alexa-Flour 488-labeled LDL (green) for 1 hour, and immunohistochemistry and flow cytometry analysis were performed. The percentage of LDL-positive cells was measured by flow cytometry. Nuclei were counterstained with DAPI (blue). The bar represents 100 μm. (**b**) Induction of CYP3A4 (left), CYP2C9 (middle), or CYP1A2 (right) by DMSO (gray bar), rifampicin (black bar), or omeprazole (black bar) in the hepatocyte-like cells (day 20) and primary human hepatocytes (PH), which were cultured for 48 hours after the cells were plated. On the y-axis, the activity of primary human hepatocytes that have been cultured with medium containing DMSO was taken as 1.0. (**c**) The hepatocyte-like cells (day 20) (upper column) were examined for their ability to take up Indocyanin Green (ICG) and release it 6 hours thereafter (lower column). (**d**) Glycogen storage of the hepatocyte-like cells (day 20) was assessed by Periodic Acid-Schiff (PAS) staining. PAS staining was performed on day 20 of differentiation. Glycogen storage is indicated by pink or dark red-purple cytoplasms. The bar represents 100 μm. (**e**) The cell viability of undifferentiated human ESCs (black), two factors plus Ad-LacZ-tansduced cells (green), the three factors-transduced cells (blue), and primary human hepatocytes (red) was assessed by Alamar Blue assay after 48 hours exposure to different concentrations of four test compounds (troglitazone, acetaminophen, cyclophosphamide, and carbamazepine). The cell viability is expressed as a percentage of cells treated with solvent only treat: 0.1% DMSO except for carbamazepine: 0.5% DMSO. All data are represented as means ± SD (n = 3). ESC, embryonic stem cell; DMSO, dimethyl sulfoxide; LDL, low-density lipoprotein.

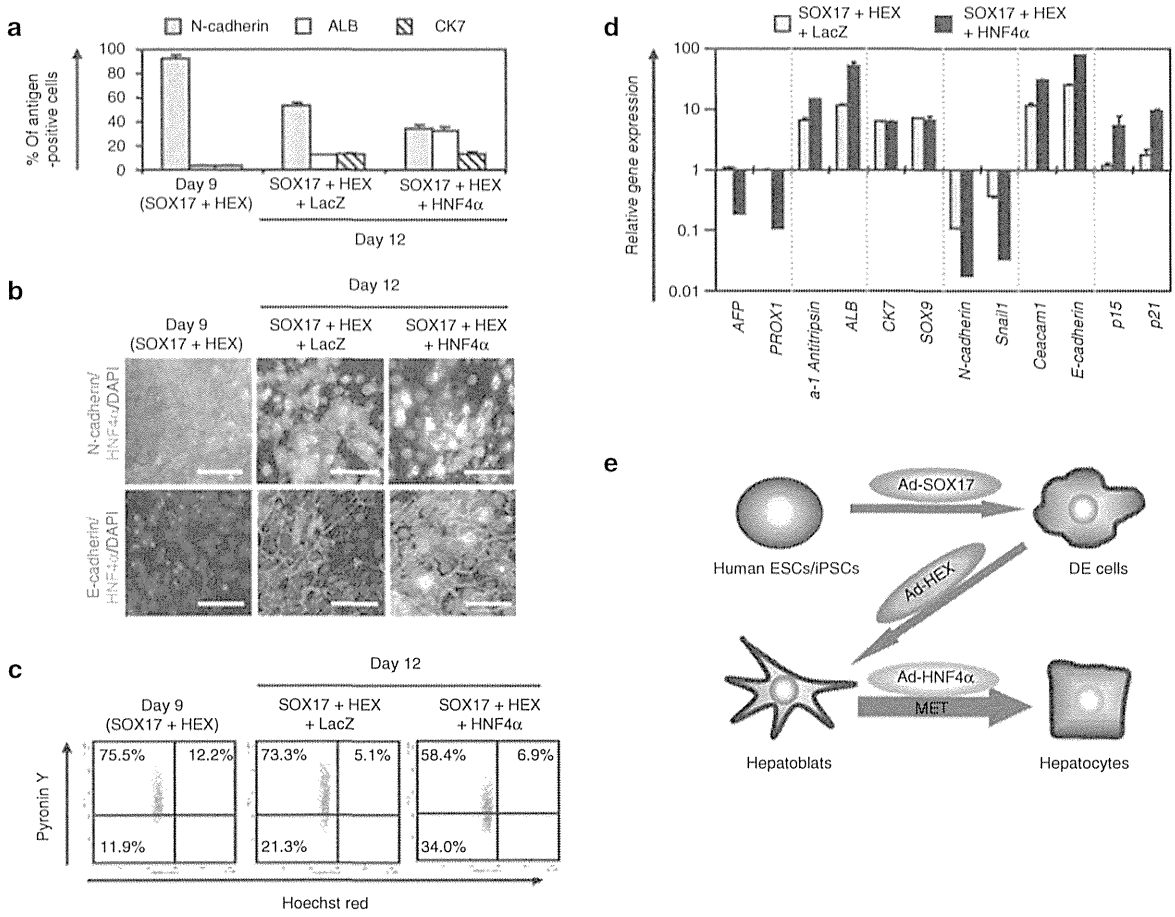

Figure 5 HNF4α promotes hepatic differentiation by activating MET. Human ESCs were differentiated into hepatoblasts according to the protocol described in **Figure 2a**, and then transduced with 3,000 VP/cell of Ad-LacZ or Ad-HNF4α for 1.5 hours, and finally cultured until day 12 of differentiation. (**a**) The hepatoblasts, two factors plus Ad-LacZ-transduced cells (SOX17+HEX+LacZ) (day 12), and the three factors-transduced cells (SOX17+HEX+HNF4α) (day 12) were subjected to immunostaining with anti-N-cadherin, ALB, or CK7 antibodies. The percentage of antigen-positive cells was measured by flow cytometry. (**b**) The cells were subjected to immunostaining with anti-N-cadherin (green), E-cadherin (green), or HNF4α (red) antibodies on day 9 or day 12 of differentiation. Nuclei were counterstained with DAPI (blue). The bar represents 50 μm. Similar results were obtained in two independent experiments. (**c**) The cell cycle was examined on day 9 or day 12 of differentiation. The cells were stained with Pyronin Y (y-axis) and Hoechst 33342 (x-axis) and then analyzed by flow cytometry. The growth fraction of cells is the population of actively dividing cells (G1/S/G2/M). (**d**) The expression levels of *AFP*, *PROX1*, *α-1-antitrypsin*, *ALB*, *CK7*, *SOX9*, *N-cadherin*, *Snail1*, *Ceacam1*, *E-cadherin*, *p15*, and *p21* were examined by real-time RT-PCR on day 9 or day 12 of differentiation. The expression level of hepatoblasts (day 9) was taken as 1.0. All data are represented as means ± SD ($n = 3$). (**e**) The model of efficient hepatic differentiation from human ESCs and iPSCs in this study is summarized. The human ESCs and iPSCs differentiate into hepatocytes via definitive endoderm and hepatoblasts. At each stage, the differentiation is promoted by stage-specific transduction of appropriate functional genes. In the last stage of hepatic differentiation, HNF4α transduction provokes hepatic maturation by activating MET. ESC, embryonic stem cell; HNF4α, hepatocyte nuclear factor 4α; iPSC, induced pluripotent stem cell; MET, mesenchymal-to-epithelial transition; RT-PCR, reverse transcription-PCR; VP, vector particle.

The gene expression levels of hepatocyte markers (*α-1-antitrypsin* and *ALB*)[20] and epithelial markers (*Ceacam1* and *E-cadherin*) were upregulated by HNF4α transduction. On the other hand, the gene expression levels of hepatoblast markers (*AFP* and *PROX1*)[31], mesenchymal markers (*N-cadherin* and *Snail*)[32], and cyclin dependent kinase inhibitor (*p15* and *p21*)[33] were downregulated by HNF4α transduction. HNF4α transduction did not change the expression levels of cholangiocyte markers (*CK7* and *SOX9*). We conclude that HNF4α promotes hepatic maturation by activating MET.

DISCUSSION

This study has two main purposes: the generation of functional hepatocytes from human ESCs and iPSCs for application to drug toxicity screening in the early phase of pharmaceutical development and; elucidation of the HNF4α function in hepatic maturation from human ESCs. We initially confirmed the importance of transcription factor HNF4α in hepatic differentiation from human ESCs by using a published data set of gene array analysis (**Supplementary Figure S1**).[34] We speculated that HNF4α transduction could enhance hepatic differentiation from human ESCs and iPSCs.

To generate functional hepatocytes from human ESCs and iPSCs and to elucidate the function of HNF4α in hepatic differentiation from human ESCs, we examined the stage-specific roles of HNF4α. We found that hepatoblast (day 9) stage-specific HNF4α transduction promoted hepatic differentiation (Figure 1). Because endogenous HNF4α is initially expressed in the hepatoblast,[9,10] our system might adequately reflect early embryogenesis. However, HNF4α transduction at an inappropriate stage (day 6 or day 12) promoted

bidirectional differentiation; heterogeneous populations, which contain the hepatocytes and pancreas cells or hepatocytes and cholangiocytes, were obtained, respectively (Figure 1), consistent with a previous report that HNF4α plays an important role not only in the liver but also in the pancreas.[12] Therefore, we concluded that HNF4α plays a significant stage-specific role in the differentiation of human ESC- and iPSC-derived hepatoblasts to hepatocytes (Figure 5e).

We found that the expression levels of the hepatic functional genes were upregulated by HNF4α transduction (Figure 3a,b, and **Supplementary Figures S7** and **S8**). Although the c/EBPα and GATA4 expression levels of the three factors-transduced cells were higher than those of primary human hepatocytes, the FOXA1, FOXA2, FOXA3, and HNF1α, which are known to be important for hepatic direct reprogramming and hepatic differentiation,[35,36] expression levels of three factors-transduced cells were slightly lower than those of primary human hepatocytes (**Supplementary Figure S8**). Therefore, additional transduction of FOXA1, FOXA2, FOXA3, and HNF1α might promote further hepatic maturation. Some previous hepatic differentiation protocols that utilized growth factors without gene transfer led to the appearance only of heterogeneous hepatocyte populations.[4–6] The HNF4α transduction led not only to the upregulation of expression levels of several hepatic markers but also to an almost homogeneous hepatocyte population; the differentiation efficacy based on CYPs, ASGR1, or ALB expression was ~80% (Figure 3c–e). The efficient hepatic maturation in this study might be attributable to the activation of many hepatocyte-associated genes by the transduction of HNF4α, which binds to the promoters of nearly half of the genes expressed in the liver.[12] In the later stage of hepatic maturation, hepatocyte-associated genes would be strongly upregulated by endogenous transcription factors but not exogenous HNF4α because transgene expression by Ad vectors was almost disappeared on day 18 (**Supplementary Figure S5**). Another reason for the efficient hepatic maturation would be that sequential transduction of SOX17, HEX, and HNF4α could mimic hepatic differentiation in early embryogenesis.

Next, we examined whether or not the hepatocyte-like cells had hepatic functions. The activity of many kinds of CYPs was upregulated by HNF4α transduction (Figure 4b). Ad-HNF4α-transduced cells exhibit many characteristics of hepatocytes: uptake of LDL, uptake and excretion of ICG, and storage of glycogen (Figure 4a,c,d). Many conventional tests of hepatic characteristics have shown that the hepatocyte-like cells have mature hepatocyte functions. Furthermore, the hepatocyte-like cells can catalyze the toxication of several compounds (Figure 4e). Although the activities to catalyze the toxication of test compounds in primary human hepatocytes are slightly higher than those in the hepatocyte-like cells, the handling of primary human hepatocytes is difficult for a number of reasons: since their source is limited, large-scale primary human hepatocytes are difficult to prepare as a homogeneous population. Therefore, the hepatocyte-like cells derived from human ESCs and iPSCs would be a valuable tool for predicting drug toxicity. To utilize the hepatocyte-like cells in a drug toxicity study, further investigation of the drug metabolism capacity and CYP induction potency will be needed.

We also investigated the mechanisms underlying efficient hepatic maturation by HNF4α transduction. Although the number of cholangiocyte populations did not change by HNF4α transduction, we found that the number of hepatoblast populations decreased and that of hepatocyte populations increased, indicating that HNF4α promotes selective hepatic differentiation from hepatoblasts (Figure 5a). As previously reported, HNF4α regulates the expression of a broad range of genes that code for cell adhesion molecules,[13] extracellular matrix components, and cytoskeletal proteins, which determine the main morphological characteristics of epithelial cells.[14,35,37] In this study, we elucidated that MET was promoted by HNF4α transduction (Figure 5b,d). Thus, we conclude that HNF4α overexpression in hepatoblasts promotes hepatic differentiation by activating MET (Figure 5e).

Using human iPSCs as well as human ESCs, we confirmed that the stage-specific overexpression of HNF4α could promote hepatic maturation (**Supplementary Figure S9**). Interestingly, the differentiation efficacies differed among human iPS cell lines: two of the human iPS cell lines (Dotcom and Tic) were more committed to the hepatic lineage than another human iPS cell line (201B7) (**Supplementary Figure S7**). Therefore, it would be necessary to select a human iPS cell line that is suitable for hepatic maturation in the case of medical applications, such as drug screening and liver transplantation. The difference of hepatic differentiation efficacy among the three iPSC lines might be due to the difference of epigenetic memory of original cells or the difference of the inserted position of the foreign genes for the reprogramming.

To control hepatic differentiation mimicking embryogenesis, we employed Ad vectors, which are one of the most efficient transient gene delivery vehicles and have been widely used in both experimental studies and clinical trials.[38] We used a fiber-modified Ad vector containing the EF-1α promoter and a stretch of lysine residue (KKKKKKK, K7) peptides in the C-terminal region of the fiber knob.[19] The K7 peptide targets heparan sulfates on the cellular surface, and the fiber-modified Ad vector containing the K7 peptides was shown to be efficient for transduction into many kinds of cells including human ESCs and human ESC-derived cells.[7–8,19] Thus, Ad vector-mediated transient gene transfer should be a powerful tool for regulating cellular differentiation.

In summary, the findings described here demonstrate that transcription factor HNF4α plays a crucial role in the hepatic differentiation from human ESC-derived hepatoblasts by activating MET (Figure 5e). In the present study, both human ESCs and iPSCs (three lines) were used and all cell lines showed efficient hepatic maturation, indicating that our protocol would be a universal tool for cell line-independent differentiation into functional hepatocytes. Moreover, the hepatocyte-like cells can catalyze the toxication of several compounds as primary human hepatocytes. Therefore, our technology, by sequential transduction of SOX17, HEX, and HNF4α, would be a valuable tool for the efficient generation of functional hepatocytes derived from human ESCs and iPSCs, and the hepatocyte-like cells could be used for the prediction of drug toxicity.

MATERIALS AND METHODS

Human ESC and iPSC culture. A human ES cell line, H9 (WiCell Research Institute, Madison, HI), was maintained on a feeder layer of mitomycin C-treated mouse embryonic fibroblasts (Millipore, Billerica, MA) with Repro Stem (Repro CELL, Tokyo, Japan) supplemented with 5 ng/ml fibroblast

growth factor 2 (FGF2) (Sigma, St Louis, MO). Human ESCs were dissociated with 0.1 mg/ml dispase (Roche Diagnostics, Indianapolis, IN) into small clumps and then were subcultured every 4 or 5 days. H9 was used following the Guidelines for Derivation and Utilization of Human Embryonic Stem Cells of the Ministry of Education, Culture, Sports, Science and Technology of Japan. Two human iPS cell lines generated from the human embryonic lung fibroblast cell line MCR5 were provided from the JCRB Cell Bank (Tic, JCRB Number: JCRB1331; and Dotcom, JCRB Number: JCRB1327).[39,40] These human iPS cell lines were maintained on a feeder layer of mitomycin C-treated mouse embryonic fibroblasts with iPSellon (Cardio, Kobe, Japan) supplemented with 10 ng/ml FGF2. Another human iPS cell line, 201B7, generated from human dermal fibroblasts was kindly provided by Dr S. Yamanaka (Kyoto University).[2] The human iPS cell line 201B7 was maintained on a feeder layer of mitomycin C-treated mouse embryonic fibroblasts with Repro Stem (Repro CELL) supplemented with 5 ng/ml FGF2 (Sigma). Human iPSCs were dissociated with 0.1 mg/ml dispase (Roche Diagnostics) into small clumps and were then subcultured every 5 or 6 days.

In vitro *differentiation*. Before the initiation of cellular differentiation, the medium of human ESCs and iPSCs was exchanged for a defined serum-free medium, hESF9, and cultured as we previously reported.[41] hESF9 consists of hESF-GRO medium (Cell Science & Technology Institute, Sendai, Japan) supplemented with 10 μg/ml human recombinant insulin, 5 μg/ml human apotransferrin, 10 μmol/l 2-mercaptoethanol, 10 μmol/l ethanolamine, 10 μmol/l sodium selenite, oleic acid conjugated with fatty-acid-free bovine albumin (BSA), 10 ng/ml FGF2, and 100 ng/ml heparin (all from Sigma).

The differentiation protocol for the induction of DE cells, hepatoblasts, and hepatocytes was based on our previous report with some modifications.[7] Briefly, in mesendoderm differentiation, human ESCs and iPSCs were dissociated into single cells and cultured for 3 days on Matrigel (Becton, Dickinson and Company, Tokyo, Japan) in hESF-DIF medium (Cell Science & Technology Institute) supplemented with 10 μg/ml human recombinant insulin, 5 μg/ml human apotransferrin, 10 μmol/l 2-mercaptoethanol, 10 μmol/l ethanolamine, 10 μmol/l sodium selenite, 0.5 mg/ml BSA, and 100 ng/ml Activin A (R&D Systems, Minneapolis, MN). To generate mesendoderm cells and DE cells, human ESC-derived cells were transduced with 3,000 vector particles (VP)/cell of Ad-SOX17 for 1.5 hours on day 3 and cultured until day 6 on Matrigel (BD) in hESF-DIF medium (Cell Science & Technology Institute) supplemented with 10 μg/ml human recombinant insulin, 5 μg/ml human apotransferrin, 10 μmol/l 2-mercaptoethanol, 10 μmol/l ethanolamine, 10 μmol/l sodium selenite, 0.5 mg/ml BSA, and 100 ng/ml Activin A (R&D Systems). For induction of hepatoblasts, the DE cells were transduced with 3,000 VP/cell of Ad-HEX for 1.5 hours on day 6 and cultured for 3 days on a Matrigel (BD) in hESF-DIF (Cell Science & Technology Institute) medium supplemented with the 10 μg/ml human recombinant insulin, 5 μg/ml human apotransferrin, 10 μmol/l 2-mercaptoethanol, 10 μmol/l ethanolamine, 10 μmol/l sodium selenite, 0.5 mg/ml BSA, 20 ng/ml bone morphogenetic protein 4 (R&D Systems), and 20 ng/ml FGF4 (R&D Systems). In hepatic differentiation, hepatoblasts were transduced with 3,000 VP/cell of Ad-LacZ or Ad-HNF4α for 1.5 hr on day 9 and were cultured for 11 days on Matrigel (BD) in L15 medium (Invitrogen, Carlsbad, CA) supplemented with 8.3% tryptose phosphate broth (BD), 8.3% fetal bovine serum (Vita, Chiba, Japan), 10 μmol/l hydrocortisone 21-hemisuccinate (Sigma), 1 μmol/l insulin, 25 mmol/l $NaHCO_3$ (Wako, Osaka, Japan), 20 ng/ml hepatocyte growth factor (R&D Systems), 20 ng/ml Oncostatin M (R&D Systems), and 10^{-6} mol/l Dexamethasone (Sigma).

***Ad vectors*.** Ad vectors were constructed by an improved *in vitro* ligation method.[42,43] The human HNF4α gene (accession number NM_000457) was amplified by PCR using primers designed to incorporate the 5′ Not I and 3′ Xba I restriction enzyme sites: Fwd 5′-ggcctctagatggaggcagggagaatg-3′ and Rev 5′-ccccgcggccgcagcggcttgctagataac-3′. The human HNF4α gene was inserted into pBSKII (Invitrogen), resulting in pBSKII-HNF4α, and then the human HNF4α gene was inserted into pHMEF5,[44] which contains the human elongation factor-1α (EF-1α) promoter, resulting in pHMEF-HNF4α. The pHMEF-HNF4α was digested with I-CeuI/PI-SceI and ligated into I-Ceu I/PI-SceI-digested pAdHM41-K7,[19] resulting in pAd-HNF4α. The human EF-1α promoter-driven LacZ-, SOX17-, or HEX-expressing Ad vectors, Ad-LacZ, Ad-SOX17, or Ad-HEX, were constructed previously.[7,8,45] Ad-LacZ, Ad-SOX17, Ad-HEX, and Ad-HNF4α, each of which contains a stretch of lysine residue (K7) peptides in the C-terminal region of the fiber knob for more efficient transduction of human ESCs, iPSCs, and DE cells, were generated and purified as described previously.[7] The VP titer was determined by using a spectrophotometric method.[46]

***LacZ assay*.** Human ESC- and iPSC-derived cells were transduced with Ad-LacZ at 3,000 VP/cell for 1.5 hours. After culturing for the indicated number of days, 5-bromo-4-chloro-3-indolyl β-D-galactopyranoside (X-Gal) staining was performed as described previously.[44]

***Flow cytometry*.** Single-cell suspensions of human ESCs, iPSCs, and their derivatives were fixed with methanol at 4 °C for 20 minutes and then incubated with the primary antibody, followed by the secondary antibody. Flow cytometry analysis was performed using a FACS LSR Fortessa flow cytometer (BD).

***RNA isolation and reverse transcription-PCR*.** Total RNA was isolated from human ESCs, iPSCs, and their derivatives using ISOGENE (Nippon Gene) according to the manufacturer's instructions. Primary human hepatocytes were purchased from CellzDirect, Durham, NC. complementary DNA was synthesized using 500 ng of total RNA with a Superscript VILO cDNA synthesis kit (Invitrogen). Real-time reverse transcription-PCR was performed with Taqman gene expression assays (Applied Biosystems, Foster City, CA) or SYBR Premix Ex Taq (TaKaRa) using an ABI PRISM 7000 Sequence Detector (Applied Biosystems). Relative quantification was performed against a standard curve and the values were normalized against the input determined for the housekeeping gene, glyceraldehyde 3-phosphate dehydrogenase. The primer sequences used in this study are described in **Supplementary Table S1**.

***Immunohistochemistry*.** The cells were fixed with methanol or 4% paraformaldehyde (Wako). After blocking with phosphate-buffered saline containing 2% BSA (Sigma) and 0.2% Triton X-100 (Sigma), the cells were incubated with primary antibody at 4 °C for 16 hours, followed by incubation with a secondary antibody that was labeled with Alexa Fluor 488 (Invitrogen) or Alexa Fluor 594 (Invitrogen) at room temperature for 1 hour. All the antibodies are listed in **Supplementary Table S2**.

***Assay for CYP activity*.** To measure cytochrome P450 3A4, 2C9, and 1A2 activity, we performed Lytic assays by using a P450-GloTM CYP3A4 Assay Kit (Promega, Madison, WI). For the CYP3A4 and 2C9 activity assay, undifferentiated human ESCs, the hepatocyte-like cells, and primary human hepatocytes were treated with rifampicin (Sigma), which is the substrate for CYP3A4 and CYP2C9, at a final concentration of 25 μmol/l or DMSO (0.1%) for 48 hours. For the CYP1A2 activity assay, undifferentiated human ESCs, the hepatocyte-like cells, and primary human hepatocytes were treated with omeprazole (Sigma), which is the substrate for CYP1A2, at a final concentration of 10 μM or DMSO (0.1%) for 48 hours. We measured the fluorescence activity with a luminometer (Lumat LB 9507; Berthold, Oak Ridge, TN) according to the manufacturer's instructions.

***Pyronin Y/Hoechst Staining*.** Human ESC-derived cells were stained with Hoechst33342 (Sigma) and Pyronin Y (PY) (Sigma) in Dulbecco's modified Eagle medium (Wako) supplemented with 0.2 mmol/l HEPES and 5% FCS (Invitrogen). Samples were then placed on ice for 15 minutes, and 7-AAD was added to a final concentration of 0.5 mg/ml for exclusion of dead cells. Fluorescence-activated cell-sorting analysis of these cells was

performed on a FACS LSR Fortessa flow cytometer (Becton Dickinson) equipped with a UV-laser.

Cellular uptake and excretion of ICG. ICG (Sigma) was dissolved in DMSO at 100 mg/ml, then added to a culture medium of the hepatocyte-like cells to a final concentration of 1 mg/ml on day 20 of differentiation. After incubation at 37 °C for 60 minutes, the medium with ICG was discarded and the cells were washed with phosphate-buffered saline. The cellular uptake of ICG was then examined by microscopy. Phosphate-buffered saline was then replaced by the culture medium and the cells were incubated at 37 °C for 6 hours. The excretion of ICG was examined by microscopy.

Periodic Acid-Schiff assay for glycogen. The hepatocyte-like cells were fixed with 4% paraformaldehyde and stained using a Periodic Acid-Schiff staining system (Sigma) on day 20 of differentiation according to the manufacturer's instructions.

Cell viability tests. Cell viability was assessed by Alamar Blue assay kit (Invitrogen). After treatment with test compounds[47–50] (troglitazone, acetaminophen, cyclophosphamide, and carbamazepine) (all from Wako) for 2 days, the culture medium was replaced with 0.5 mg/ml solution of Alamar Blue in culturing medium and cells were incubated for 3 hours at 37 °C. The supernatants of the cells were measured at a wavelength of 570 nm with background subtraction at 600 nm in a plate reader. Control refers to incubations in the absence of test compounds and was considered as 100% viability value.

Uptake of LDL. The hepatocyte-like cells were cultured with medium containing Alexa-488-labeled LDL (Invitrogen) for 1 hour, and then the cells that could uptake LDL were assessed by immunohistochemistry and flow cytometry.

Primary human hepatocytes. Cryopreserved human hepatocytes were purchased from CellzDirect (lot Hu8072). The vials of hepatocytes were rapidly thawed in a shaking water bath at 37 °C; the contents of the vial were emptied into prewarmed Cryopreserved Hepatocyte Recovery Medium (CellzDirect) and the suspension was centrifuged at 100*g* for 10 minutes at room temperature. The hepatocytes were seeded at 1.25×10^5 cells/cm^2 in hepatocyte culture medium (Lonza, Walkersville, MD) containing 10% FCS (GIBCO-BRL) onto type I collagen-coated 12-well plates. The medium was replaced with hepatocyte culture medium containing 10% FCS (GIBCO-BRL) 6 hours after seeding. The hepatocytes, which were cultured 48 hours after plating the cells, were used in the experiments.

SUPPLEMENTARY MATERIAL

Figure S1. Genome-wide screening of transcription factors involved in hepatic differentiation emphasizes the importance of the transcription factor HNF4α.
Figure S2. Summary of specific markers for DE cells, hepatoblasts, hepatocytes, cholangiocytes, and pancreas cells.
Figure S3. The formation of DE cells, hepatoblasts, hepatocytes, and cholangiocytes from human ESCs.
Figure S4. Overexpression of HNF4α mRNA in hepatoblasts by Ad-HNF4α transduction.
Figure S5. Time course of LacZ expression in hepatoblasts transduced with Ad-LacZ.
Figure S6. The morphology of the hepatocyte-like cells.
Figure S7. Upregulation of the expression levels of conjugating enzymes and hepatic transporters by HNF4α transduction.
Figure S8. Upregulation of the expression levels of hepatic transcription factors by HNF4α transduction.
Figure S9. Generation of hepatocytes from various human ES or iPS cell lines.
Figure S10. Promotion of MET by HNF4α transduction.
Figure S11. Arrest of cell growth by HNF4α transduction.
Table S1. List of Taqman probes and primers used in this study.
Table S2. List of antibodies used in this study.

ACKNOWLEDGMENTS

We thank Hiroko Matsumura and Misae Nishijima for their excellent technical support. H.M., M.K.F., and T.H. were supported by grants from the Ministry of Health, Labor, and Welfare of Japan. H.M. was also supported by Japan Research foundation For Clinical Phamacology, The Nakatomi Foundation, and The Uehara Memorial Foundation. K.K. (K. Kawabata) was supported by grants from the Ministry of Education, Sports, Science and Technology of Japan (20200076) and the Ministry of Health, Labor, and Welfare of Japan. K.K. (K. Katayama) and F.S. was supported by Program for Promotion of Fundamental Studies in Health Sciences of the National Institute of Biomedical Innovation (NIBIO).

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