TABLE 1 Gene categories and names of differentially expressed genes regulated by miR-27a in Huh-7.5 cells

Protein function and name	Gene	Affy ID[a]	GB acc. no.[b]	Fold change		
				Pre-miR-27a/ miR-control	Anti-miR-27a/ anti-miR-control	Pre-miR-27a/ anti-miR-27a
Cytoskeleton remodeling and Wnt signaling						
Collagen, type IV, alpha 6	*COL4A6*	211473_s_at	U04845	0.85	2.19	2.58
Fibronectin 1	*FN1*	214702_at	AJ276395	0.57	1.14	2.02
Filamin A, alpha	*FLNA*	214752_x_at	AI625550	0.64	1.68	2.61
LIM domain kinase 1	*LIMK1*	204357_s_at	NM_002314	0.67	1.63	2.43
p21/Cdc42/Rac1-activated kinase 1	*PAK1*	230100_x_at	AU147145	0.63	1.58	2.53
Breast cancer anti-estrogen resistance 1	*BCAR1*	232442_at	AU147442	0.96	1.94	2.01
Frizzled homolog 3 (*Drosophila*)	*FZD3*	219683_at	NM_017412	0.51	1.30	2.55
Laminin, alpha 4	*LAMA4*	210990_s_at	U77706	0.63	1.26	2.00
Regulation of lipid metabolism						
CREB binding protein (Rubinstein-Taybi syndrome)	*CREBBP*	235858_at	BF507909	0.54	1.50	2.76
NF-Y	*NF-Y*	228431_at	AL137443	0.41	1.44	3.50
Sterol regulatory element binding transcription factor 2	*SREBF2*	242748_at	AA112403	0.47	1.11	2.35
Membrane-bound transcription factor peptidase, site 2	*MBTPS2*	1554604_at	BC036465	0.50	1.21	2.39
Adenosine A2A receptor signaling						
Mitogen-activated protein kinase kinase 7	*MAP2K7*	226053_at	AI090153	0.90	2.07	2.31
Par-6 partitioning defective 6 homolog beta	*PARD6B*	235165_at	AW151704	0.56	1.35	2.43
Rap guanine nucleotide exchange factor (GEF) 2	*RAPGEF2*	238176_at	T86196	0.46	1.36	2.98
Ribosomal protein S6 kinase, 90kDa, polypeptide 2	*RPS6KA2*	204906_at	BC002363	0.61	1.72	2.83
p53 regulation						
MDM2	*MDM2*	237891_at	AI274906	0.41	1.27	3.07
Ubiquitin B	*UBB*	217144_at	X04801	0.58	1.89	3.24
Promyelocytic leukemia	*PML*	235508_at	AW291023	0.52	1.45	2.80
SMT3 suppressor of mif two 3 homolog 1	*SUMO1*	208762_at	U83117	0.55	1.23	2.22
IL-8 in angiogenesis						
B-cell CLL/lymphoma 10	*BCL10*	1557257_at	AA994334	0.59	1.23	2.08
Janus kinase 2	*JAK2*	205841_at	NM_004972	0.77	1.71	2.23
Sphingosine-1-phosphate receptor 1						
G protein, alpha inhibiting activity polypeptide 2	*GNAI2*	201040_at	NM_002070	0.69	1.49	2.15
G protein, beta polypeptide 4	*GNB4*	223487_x_at	AW504458	0.86	1.78	2.06
Mitogen-activated protein kinase 1	*MAPK1*	1552263_at	NM_138957	0.87	1.93	2.22
GRB2-associated binding protein 1	*GAB1*	226002_at	AK022142	0.66	1.40	2.11

[a] Affy ID, Affymetrix identification number.
[b] GB acc. no., GenBank accession number.

transfection. The efficiency with which these anti-miRNAs inhibit the miRNAs is shown in Fig. 1A. Unexpectedly, inhibition of these miRNAs either had no effect or increased HCV replication in the cases of anti-miR-23a and anti-miR-27a (Fig. 1B).

To investigate the functional relevance of miR-27a in HCV replication in more detail, we evaluated JFH-1 replication in Huh-7.5 cells in which miR-27a was inhibited or overexpressed. The efficacy of miR-27a overexpression is shown in Fig. 1C. Although ectopically introduced pre-miR-27a increased miR-27a levels by approximately 30-fold, the levels of endogenous active Ago2 bound to miR-27a in RNA-induced silencing complexes increased by approximately 5-fold. The RNA and core protein levels of JFH-1 in Huh-7.5 cells decreased to 65% and 40%, respectively, following miR-27a overexpression. In contrast, the RNA and core protein levels of JFH-1 increased by 3- and 1.9-fold, respectively, following miR-27a inhibition (Fig. 1D and E). There was no significant difference in cell viability following miR-27a overexpression or inhibition (Fig. 1D). Furthermore, the rate of Huh-7.5 cell infection by JFH-1 decreased to 35% after the overexpression of miR-27a but increased 4-fold after miR-27a inhibition (Fig. 1F). Thus, miR-27a negatively regulates HCV replication and infection.

miR-27a targets the signaling pathways of cytoskeleton remodeling and lipid metabolism in Huh-7.5 cells. We next examined which signaling pathways were modulated by miR-27a. TargetScan (http://www.targetscan.org/) predicts biological targets of miRNAs by searching for the presence of conserved 8- and 7-mer sites that match the seed region of each miRNA (30). A TargetScan (release 5.2) for miR-27a predicted 921 candidate target genes, and functional gene ontology enrichment analysis of these genes by MetaCore (Thomson Reuters, New York, NY) showed that miR-27a could target the cytoskeleton remodeling and lipid metabolism signaling pathways (data not shown).

To examine whether these signaling pathways were regulated by miR-27a, gene expression profiling was carried out with Huh-7.5 cells in which miR-27a was over- or underexpressed. Transfection of cells with pre-miR-27a and pre-miR-

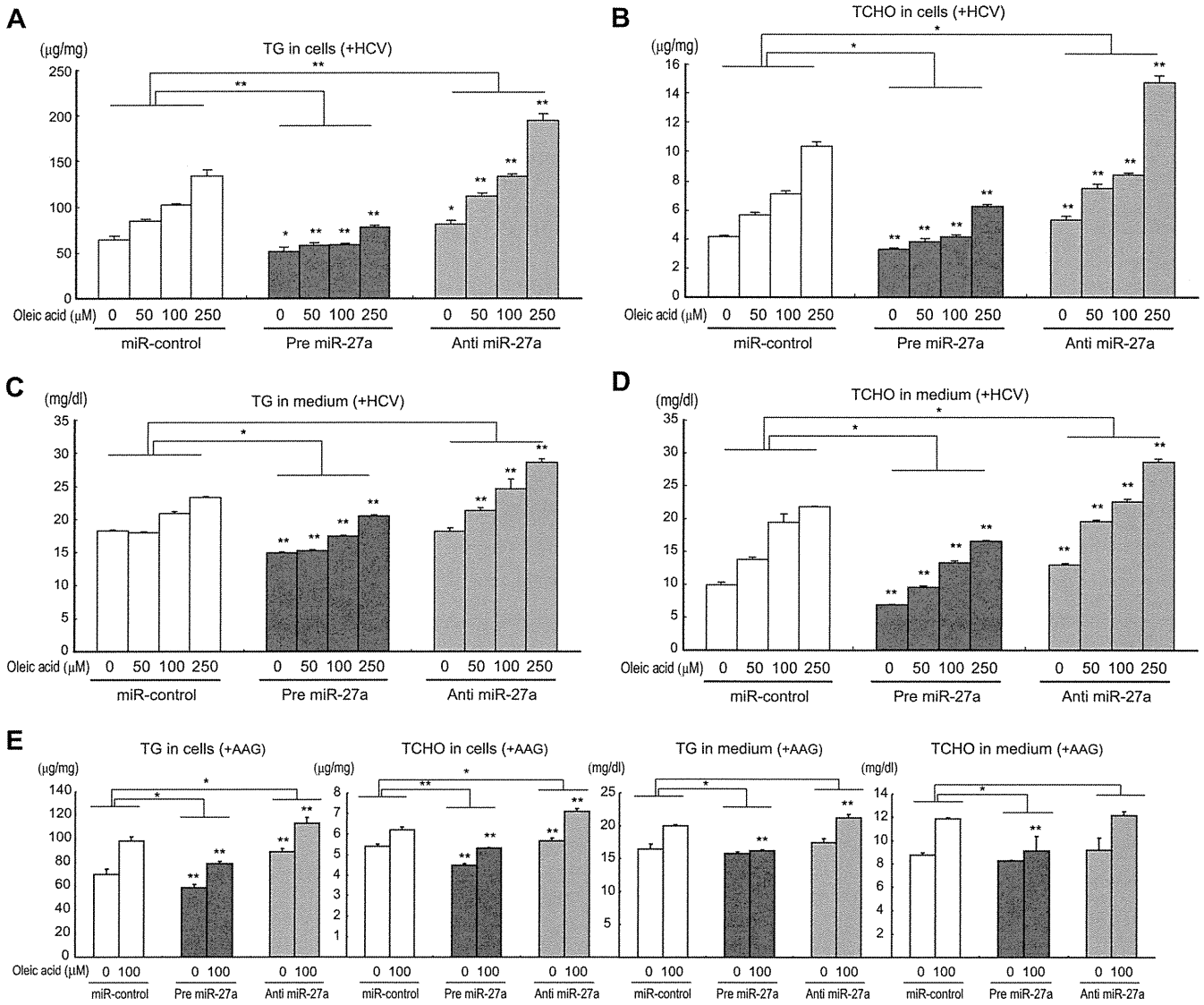

FIG 2 Changes in the lipid contents of Huh-7.5 cells and culture medium caused by pre- and anti-miR-27a. Huh-7.5 cells were transfected with replication-competent HCV RNA (H77Sv2 Gluc2A RNA [+HCV]) or replication-incompetent HCV RNA [H77Sv2 Gluc2A (AAG) (+AAG)] together with pre- or anti-miR-27a. At 24 h posttransfection, increasing amounts of oleic acid (0 to 250 μM) were added to the culture medium, and at 72 h after oleic acid treatment, TG and TCHO levels were measured in the cells and medium. Panels: A, TG in cells; B, TCHO in cells; C, TG in medium; D, TCHO in medium; E, TG and TCHO in cells and medium; A to D, +H77Sv2 Gluc2A (+HCV); E, +H77Sv2 Gluc2A (AAG) (+AAG). Lipid concentration was compared with that of miR-control and pre- or anti-miRNA ($n = 6$). All experiments were performed in duplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$.

control or with anti-miR-27a and anti-miR-control enabled the identification of down- and upregulated genes, respectively. A total of 870 genes were selected with a >2-fold anti-miR-27a/pre-miR-27a expression ratio. Pathway analysis of these genes with MetaCore revealed that they are involved in cytoskeleton remodeling signaling, including that of *COL4A6*, *FN 1*, and *PAK1*; lipid metabolism signaling, including that of *CREBBP* and *SREBF2*; A2A receptor signaling, including that of *RAPGEF2*; and p53 regulation signaling, including that of *MDM2*. These genes were repressed by miR-27a in Huh-7.5 cells (Table 1).

miR-27a reduces TG and TCHO levels in cells and culture medium. Pathway analysis of the gene expression profile regulated by miR-27a in Huh-7.5 cells revealed the presence of many genes involved in lipid metabolism-related signaling pathways. To examine the functional relevance of miR-27a in lipid metabolism, we measured the cellular levels of TG and TCHO in Huh-7.5 cells in which miR-27a was inhibited or overexpressed, respectively. As shown in Fig. 2A and B, TG and TCHO levels in Huh-7.5 cells transfected with miR-control were increased in a dose-dependent manner following the addition of oleic acid (0 to 250 μM). Pre-miR-27a repressed this increase, while anti-miR-27a significantly accelerated it. Similarly, pre-miR-27a repressed the increase in TG and TCHO in the culture medium, while anti-miR-27a significantly accelerated it (Fig. 2C and D).

Similar results were obtained with both HCV-replicating cells

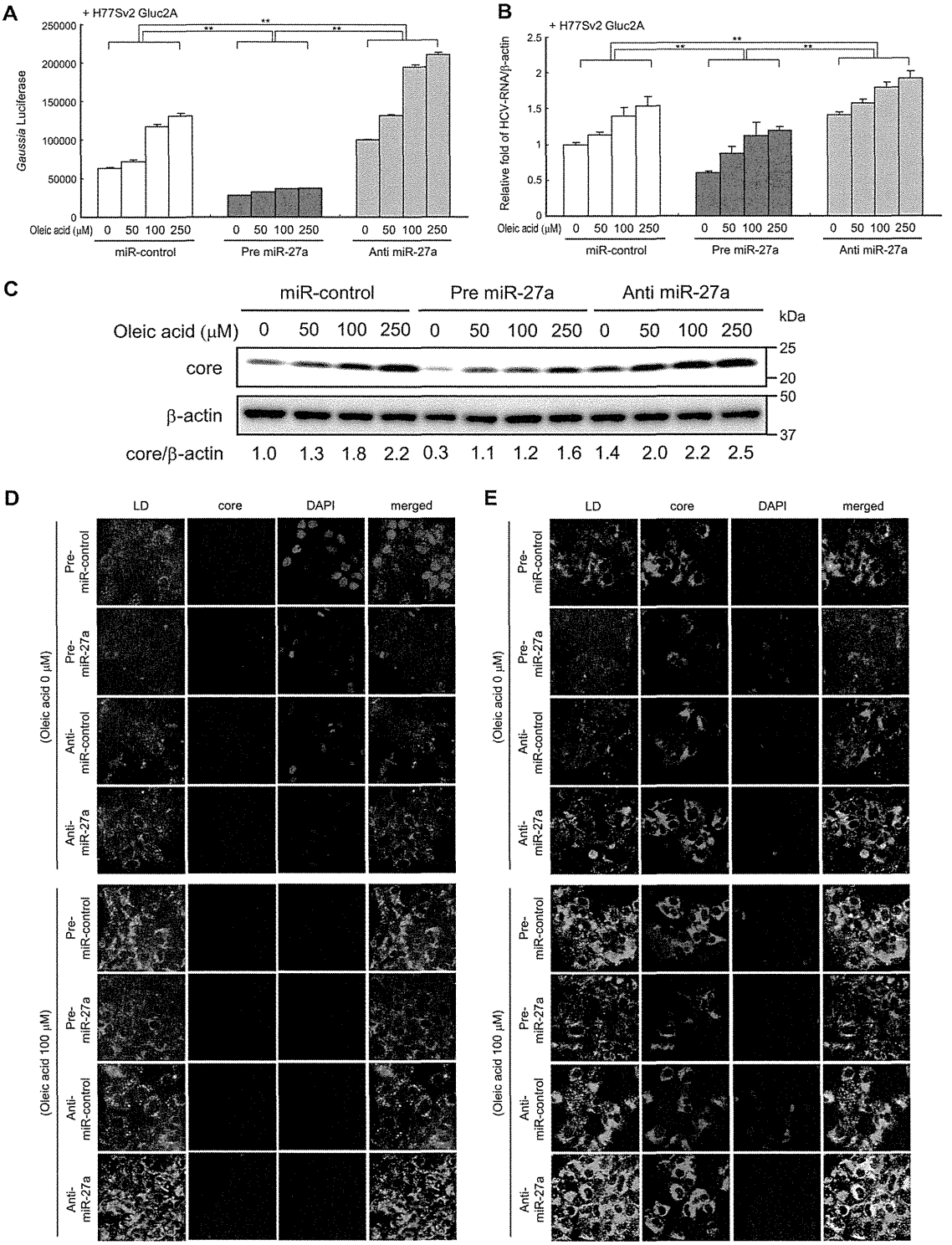

FIG 3 Changes in HCV replication in Huh-7.5 cells caused by pre- and anti-miR-27. Huh-7.5 cells were transfected with H77Sv2 Gluc2A RNA or H77Sv2 Gluc2A (AAG) RNA and pre- or anti-miR-27a. At 24 h posttransfection, increasing amounts of oleic acid (0 to 250 μM) were added to the culture medium. At 72 h after oleic acid treatment, the cells were harvested. (A) Gluc activity in the medium reflecting HCV replication in cells ($n = 6$). (B) Effects of pre- or anti-miR-27 on HCV RNA levels (RTD-PCR, $n = 6$). Experiments were performed in duplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$. (C) Western blotting of HCV core protein in the same experiments. (D and E) Confocal microscopy images of Huh-7.5 cells in the same experiments. D, +H77Sv2 Gluc2A (AAG); E, +H77Sv2 Gluc2A. Cells were fixed, permeabilized, and stained with an anti-HCV core protein antibody. Nuclei were labeled with DAPI. LDs were visualized with BODIPY 493/503 dye. Imaging was performed with a CSU-X1 confocal microscope.

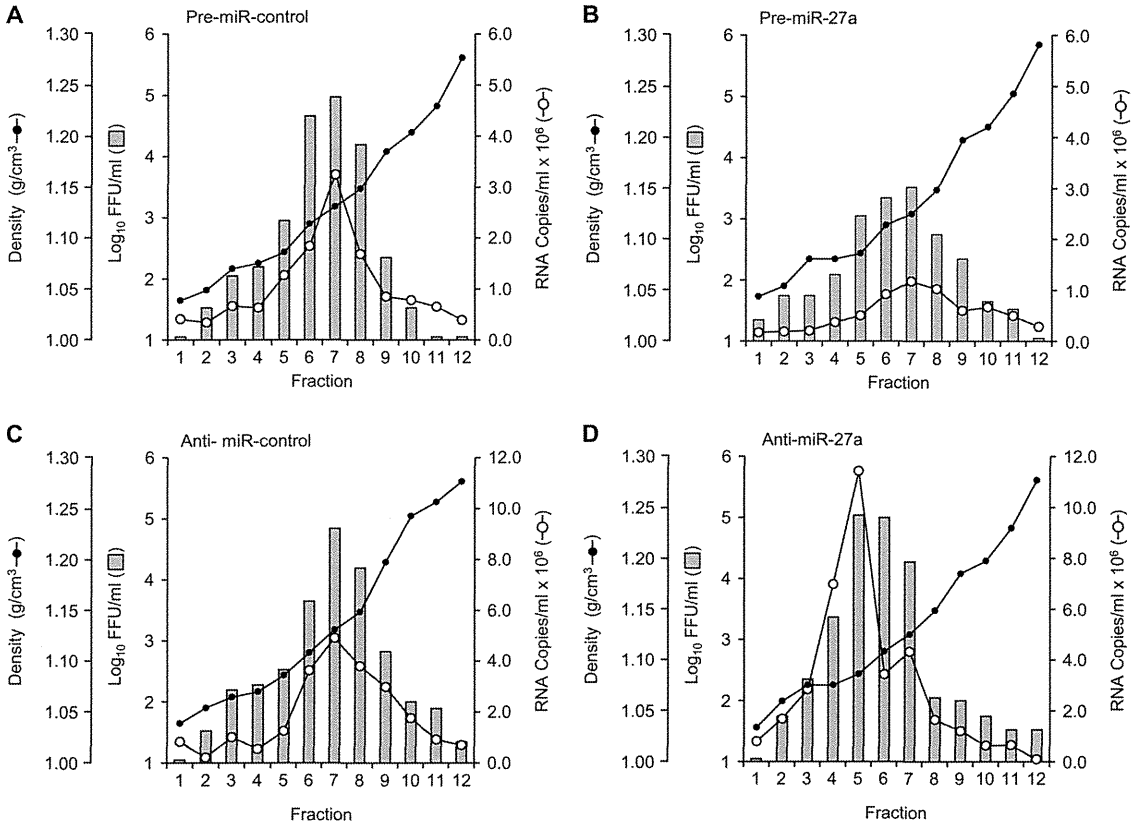

FIG 4 Equilibrium ultracentrifugation of JFH-1 particles in isopycnic iodixanol gradients. Filtered supernatant fluids collected from JFH-1 RNA- and pre- or anti-miRNA-transfected Huh-7.5 cell cultures were concentrated and used to collect fractions (500 μl each). Black circles indicate the gradient densities of the fractions, white circles indicate the HCV RNA titers, and bars indicate HCV infectivity levels. Panels: A, cells overexpressing pre-miR-control; B, cells overexpressing pre-miR-27a; C, cells overexpressing anti-miR-control; D, cells overexpressing anti-miR-27a. Experiments were repeated twice.

(+HCV) (Fig. 2A to D) and non-HCV-replicating cells (+AAG) (Fig. 2E), although the changes in the levels of TG and TCHO in the culture medium were smaller for the non-HCV-replicating cells (+AAG) (Fig. 2E). Correlating with the lipid component findings, replication of the infectious HCV clone H77Sv2 Gluc2A (21), as determined by Gluc activity in the culture medium, and the HCV RNA titer were significantly repressed by pre-miR-27a and increased by anti-miR-27a (Fig. 3A and B). This result was also confirmed by the core protein levels determined by Western blotting (Fig. 3C).

The localization of LDs and core proteins in the cells was visualized by confocal laser microscopy with a lipotropic fluorescent dye and immunostaining of the core protein (Fig. 3E). The LD and core protein levels were substantially repressed by pre-miR-27a and greatly increased by anti-miR-27a antibody. The change in the levels of LDs caused by miR-27a was observed in both HCV-replicating cells (Fig. 3E) and non-HCV-replicating cells (Fig. 3D), although the magnitude of the change was more prominent in HCV-replicating cells.

miR-27a changes the buoyant density and infectivity of HCV particles. The culture medium of Huh-7.5 cells in which JFH-1 was replicating was fractionated by iodixanol gradient centrifugation, and the buoyant density of HCV particles was evaluated (Fig. 4). When the cells were transfected with control miRNA (pre-miR-control and anti-miR-control), the HCV RNA titer (number of copies/ml) and infectivity (number of FFU/ml) peaked at fraction 7 (Fig. 4A and D) and the buoyant density of HCV was estimated at around 1.13 g/cm^3. Transfection with pre-miR-27a did not change the buoyant density of HCV, but it reduced the HCV RNA titer to 0.25-fold of the control and HCV infectivity to 0.024-fold of the control (Fig. 4B). In contrast, transfection with anti-miR-27a reduced the buoyant density of HCV from 1.13 to 1.08 g/cm^3 (Fig. 4B) and increased the HCV RNA titer to 2.1-fold of the control and infectivity to 2.5-fold of the control (Fig. 4C and D). Thus, miR-27a changed the buoyant density and infectivity of HCV.

miR-27a regulates lipid metabolism-related gene expression. The regulation of lipid metabolism-related genes by miR-27a was evaluated in Huh-7.5 cells (Fig. 5 and 6). The lipid synthesis transcription factors PPARγ, FASN, SREBP1, SREBP2, and RXRα were slightly, but significantly, induced in cells in which H77Sv2 Gluc2A replicated. The expression of lipid synthesis transcription factors was compared with that from cells carrying replication-incompetent H77Sv2 Gluc2A (AAG) (Fig. 5 and 6). Unexpectedly, lipid overload with oleic acid had no effect or rather decreased the levels of these transcription factors in non-HCV-replicating cells, probably because of negative feedback mechanisms. Conversely, in HCV-replicating cells, lipid overload with oleic acid further increased the levels of these transcription factors at both the

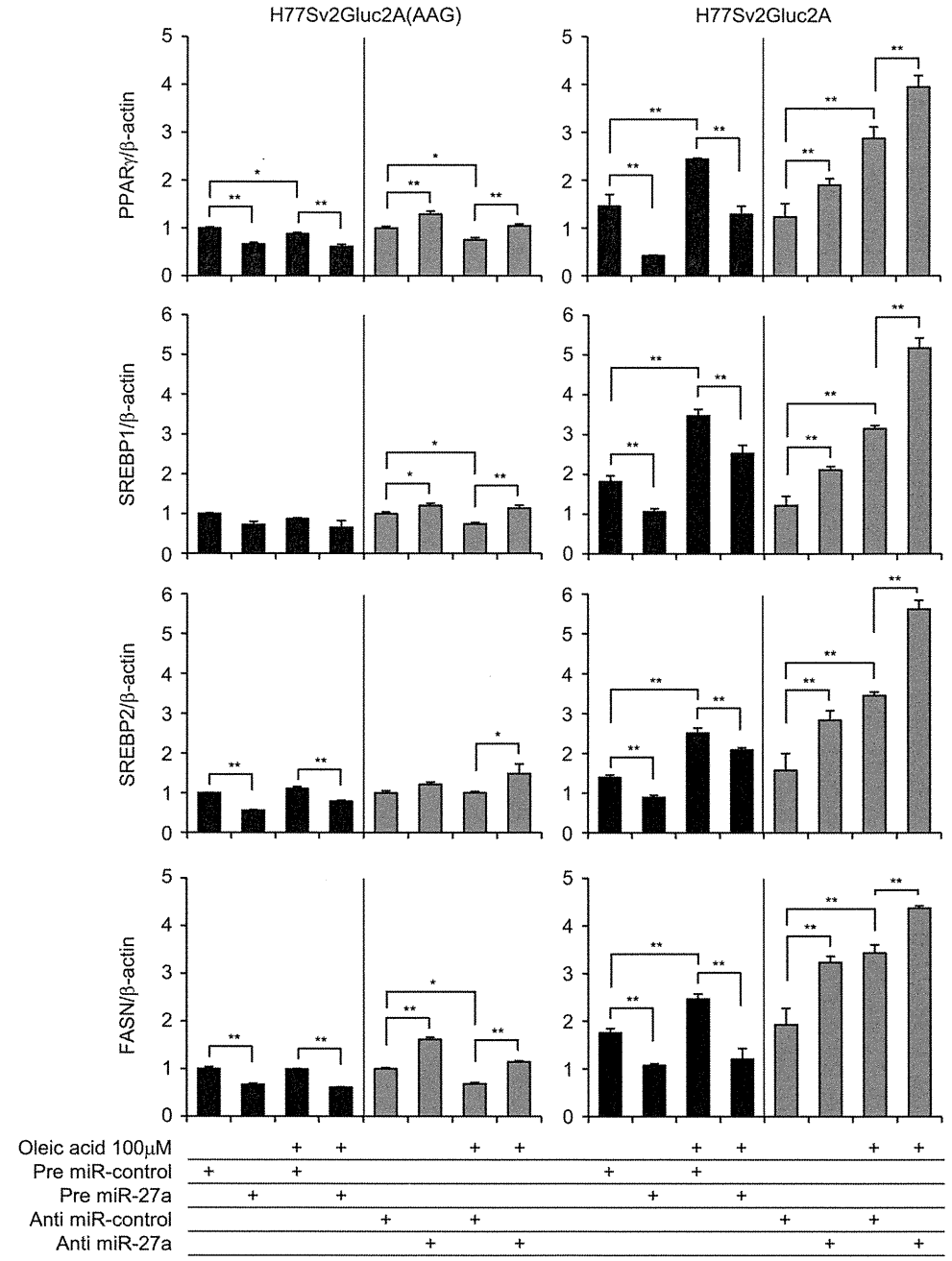

FIG 5 Expression of lipid metabolism-related transcription factors. Huh-7.5 cells were transfected with H77Sv2 Gluc2A RNA or H77Sv2 Gluc2A (AAG) RNA and pre- or anti-miR-27a. At 24 h posttransfection, oleic acid (100 μM) was added to the culture medium, and at 72 h after oleic acid treatment, *PPARγ*, *SREBP1*, *SREBP2*, and *FASN* expression levels were quantified by RTD-PCR ($n = 6$). Experiments were performed in duplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$.

mRNA and protein levels (Fig. 5 and 6A and B). Pre-miR-27a significantly repressed the levels of these transcription factors and, conversely, anti-miR-27a significantly increased their mRNA and protein levels (Fig. 5 and 6A and B). This regulation by miR-27a was observed in both HCV-replicating and non-HCV-replicating cells, although the magnitude of the change was more prominent in HCV-replicating cells (Fig. 5).

As LDs associate with the ER-derived membrane at the site of HCV replication (10) and ER stress was recently shown to promote hepatic lipogenesis and LD formation (31), we next evaluated ER stress markers. Under HCV replication and lipid overload with oleic acid, anti-miR-27a increased the expression of the ER stress markers p-PERK, p-eIF2α, and BiP in Huh-7.5 cells. Conversely, pre-miR-27a significantly decreased the expression of these markers (Fig. 6C). Cell viability decreased after anti-miR-27a transfection and increased following pre-miR-27a treatment (Fig. 6D). Thus, miR-27a repressed the ER stress that was induced by HCV replication and lipid overload.

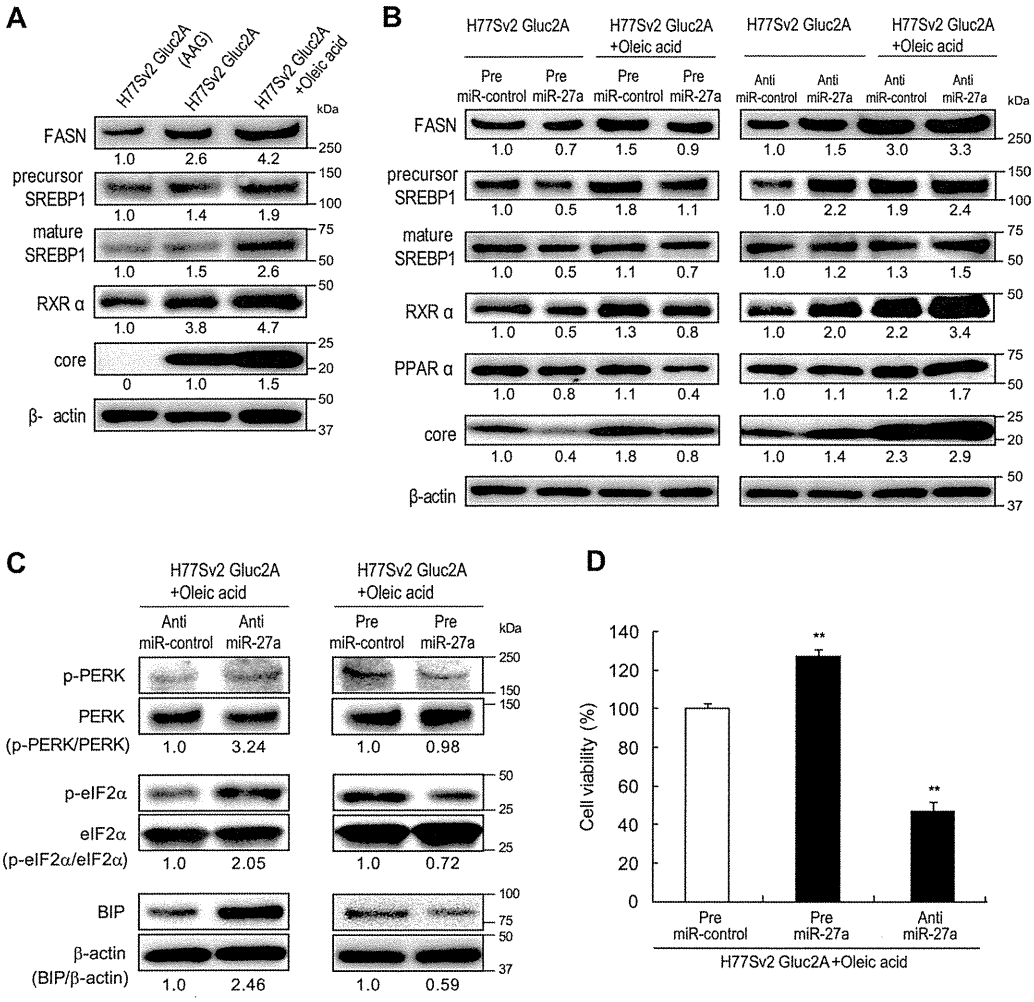

FIG 6 Expression of lipid metabolism-related transcription factors and ER stress-related factors. Huh-7.5 cells were transfected with H77Sv2 Gluc2A RNA or H77Sv2 Gluc2A (AAG) RNA and pre- or anti-miR-27a. At 24 h posttransfection, oleic acid (100 μM) was added to the culture medium. At 72 h after oleic acid treatment, the cells were harvested. (A) Western blotting of lipid metabolism-related transcription factors changed by HCV infection and oleic acid. Experiments were repeated three times. (B) Western blotting of lipid metabolism-related transcription factors changed by pre- or anti-miR-27a. Experiments were repeated three times. (C) Western blotting of ER stress-related transcription factors changed by pre- or anti-miR-27a. Experiments were repeated three times. (D) Cell viability in the same experiments was determined by MTS assay ($n = 9$). Experiments were performed in triplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$.

miR-27a targets RXRα and the ATP-binding cassette transporter ABCA1. We next analyzed the expression of miR-27a target genes. A previous report showed that miR-27a targets RXRα in rat hepatic stellate cells (32), and we confirmed that miR-27a targets the 3′ UTR of human RXRα in Huh-7.5 cells (data not shown). Although the primary sequence of the human RXRα 3′ UTR shares approximately 60% homology with the corresponding rat sequence, the putative miR-27a binding site (ACUGUGAA) is conserved among several different species. Therefore, we constructed an expression vector containing a luciferase (Luc) reporter gene fused to the human RXRα 3′ UTR (pmirGLO-RXRα 3′ UTR) and reevaluated Luc activity (data not shown). Pre-miR-27a repressed Luc activity, while anti-miR-27a significantly increased Luc activity. The introduction of three nucleotide mutations into the conserved miR-27a binding site was shown to abolish these changes in Luc activity. These results confirmed previous findings that miR-27a targets RXRα (32). RXRα interacts with liver X receptor (LXR) and regulates many lipid synthetic genes such as *SREBP1* and *FASN*. We found that the expression of *SREBP1*, *FASN*, and *SREBP2* was regulated by miR-27a (Fig. 6B) and confirmed that *PPARγ* was also regulated by miR-27a, as reported previously (Fig. 5) (33). In addition, *PPARα* was shown to be regulated by miR-27a (Fig. 6B).

We next evaluated the expression of lipid transporter genes. The ATP-binding cassette transporter ABCA1 is mutated in Tangier's disease (34) and plays an important role in the efflux of TCHO for high-density lipoprotein (HDL) synthesis (35). A recent report demonstrated a functional role for ABCA1 in hepatocyte TG secretion to the plasma and in the reduction of cellular TG levels (29). Here we found that pre-miR-27a significantly repressed ABCA1 and, conversely, that anti-miR-27a increased the mRNA and protein levels of ABCA1 (Fig. 7A and B). We identified two miR-27a binding sites (sites 1 and 2) in the 3′ UTR of ABCA1 (Fig. 7C) that were conserved between species (Fig. 7C). An expression vector containing the *luc* reporter gene fused to the human ABCA1 3′ UTR (wild type [WT]) was constructed, and a

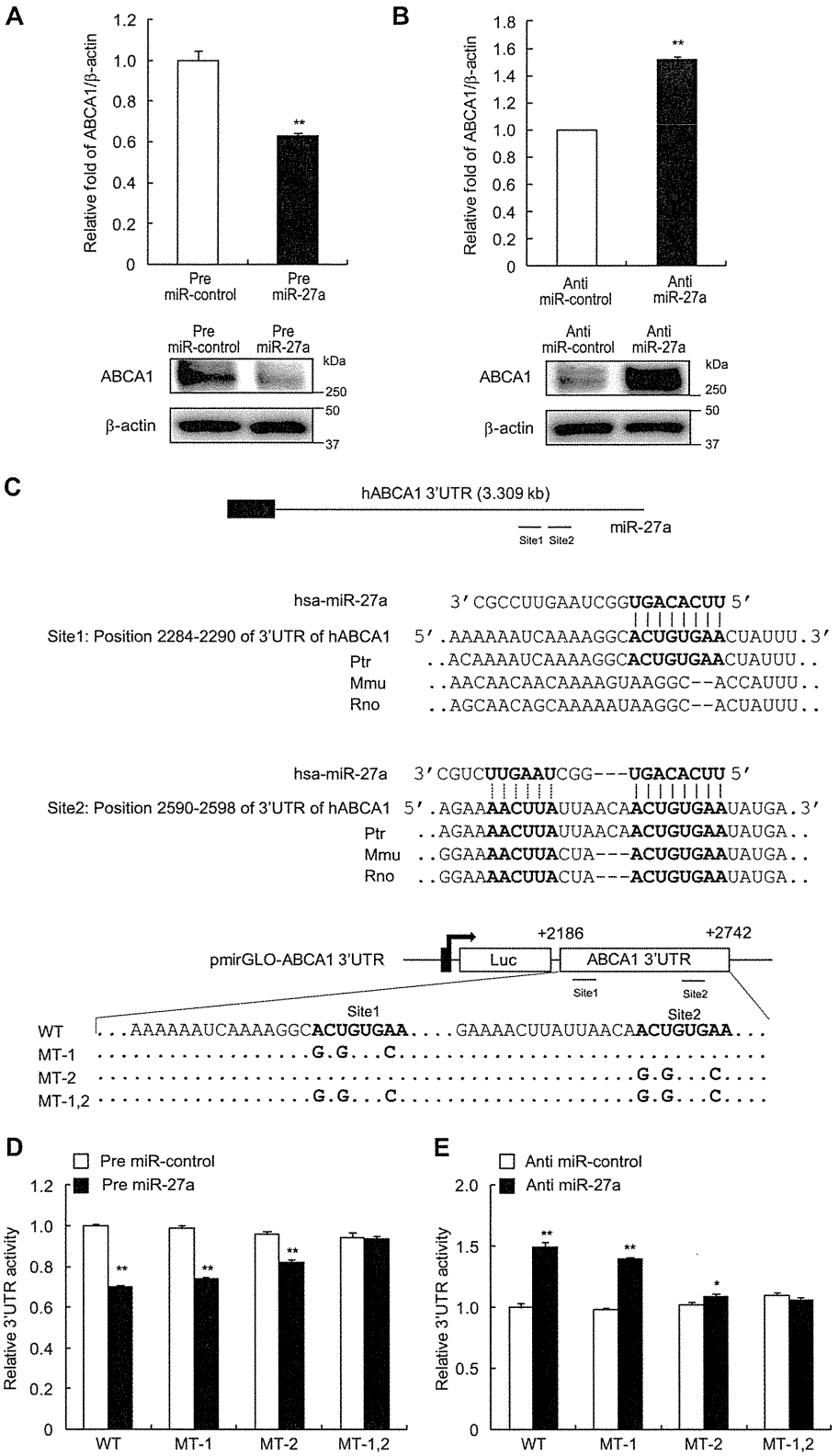

FIG 7 miR-27a targets ABCA1. (A) Regulation of ABCA1 by pre-miR-27a. RTD-PCR and Western blotting of ABCA1 in Huh-7.5 cells at 72 h posttransfection with pre-miR-control and pre-miR-27a ($n = 6$). **, $P < 0.005$. (B) Regulation of ABCA1 by anti-miR-27a. RTD-PCR and Western blotting of ABCA1 in Huh-7.5 cells at 72 h posttransfection with pre-miR-control and anti-miR-27a ($n = 6$). **, $P < 0.005$. (C) Sequence alignment of the ABCA1 3′ UTR and the construction of the luciferase (Luc) expression vector fused to the ABCA1 3′ UTR. Ptr, *Pan troglodytes*; Mmu, *Mus musculus*; Rno, *Rattus norvegicus*; WT, Luc reporter vector with the WT ABCA1 3′ UTR (2186 to 2742); MT-1, Luc reporter vector with the site 1 mutation of the WT; MT-2, Luc reporter vector with the site 2 mutation of the WT; MT-1,2, Luc reporter vector with mutations at sites 1 and 2 of the WT. (D, E) Suppression (D) or induction (E) of Luc activity with the various mutations of the ABCA1 3′ UTR by pre-miR-27a. Huh-7.5 cells were transfected with pre- or anti-miR-control or pre- or anti-miR-27a, and WT, MT-1, MT-2, and MT-1,2. Luc activities were measured at 24 h posttransfection ($n = 6$). All experiments were performed in duplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$.

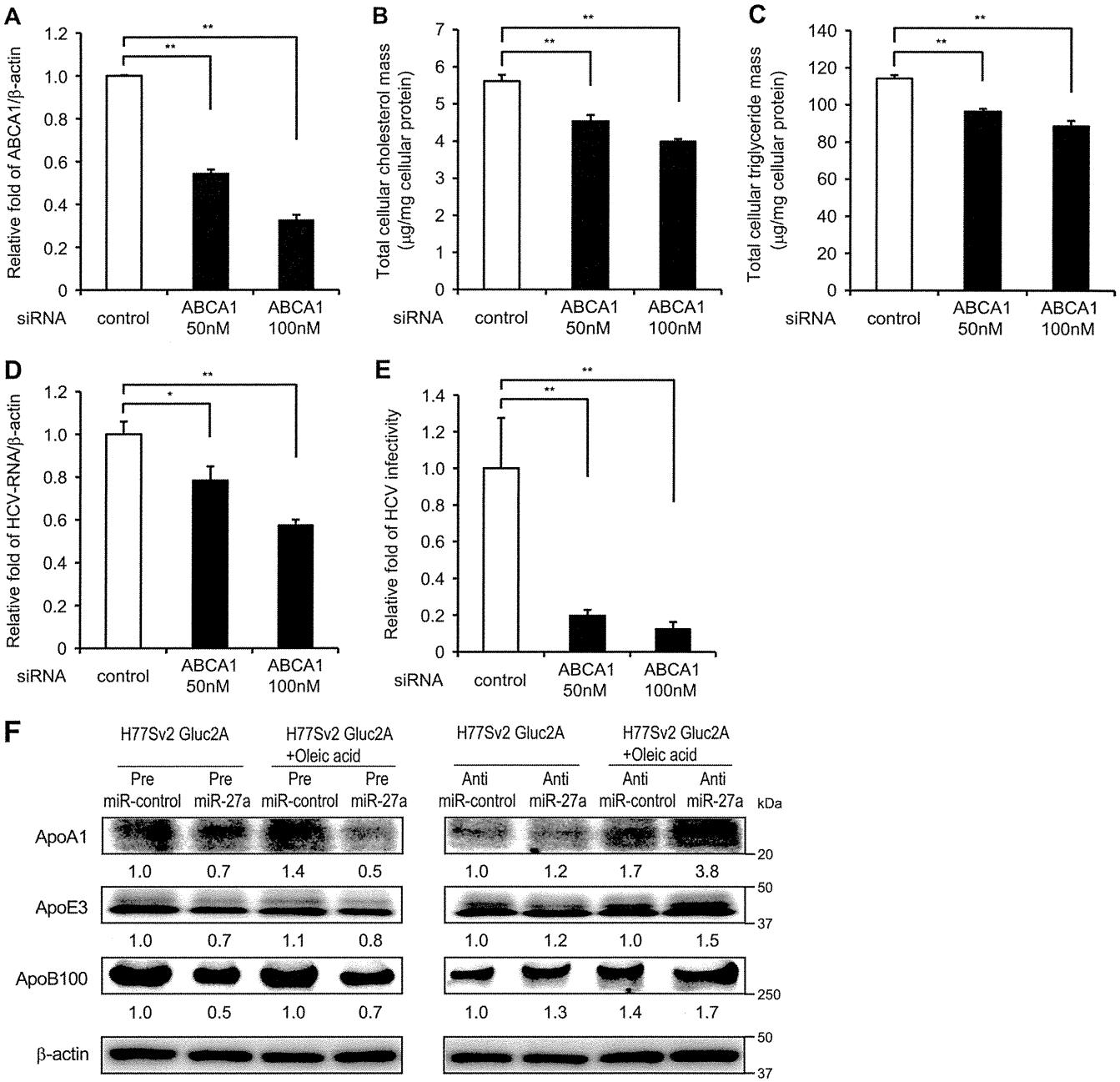

FIG 8 Suppression of ABCA1 inhibits HCV replication and infection. Huh-7.5 cells were transfected with H77Sv2 Gluc2A RNA and siRNA to ABCA1 or control siRNA. ABCA1 expression was quantified at 72 h posttransfection by RTD-PCR ($n = 6$). (A) Knockdown efficiency of ABCA1 in Huh-7.5 cells by siRNA. (B) TG concentration in cells ($n = 6$). (C) TCHO concentrations in cells ($n = 6$). (D) HCV RNA assay by RTD-PCR ($n = 6$). (E) HCV infectivity. Huh-7.5 cells were infected with HCVcc derived from ABCA1 knockdown Huh-7.5 cells. HCV RNA was quantified at 72 h postinfection by RTD-PCR ($n = 6$). Experiments were performed in duplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$. (F) Regulation of ApoA1, ApoE2, and ApoB100 by miR-27a. Experiments were performed under the same conditions as Fig. 6B and C and repeated three times.

series of mutations were introduced into the putative miR-27a binding sites (MT-1, MT-2, and MT-1,2). The Luc activity of the WT was significantly repressed by pre-miR-27a and increased by anti-miR-27a. However, there was a smaller change in Luc activity caused by pre- and anti-miR-27a in the single mutants (MT-1 and MT-2) and no change in Luc activity in the double mutant (MT-1,2) (Fig. 7D and E). These results show that miR-27a targets ABCA1 to decrease the lipid content of cells.

The functional relevance of ABCA1 in lipid metabolism and HCV replication in Huh-7.5 cells was examined by inhibiting ABCA1 with an siRNA (Fig. 8). siRNA to ABCA1 repressed the expression of ABCA1 in a dose-dependent manner (Fig. 8A). Under this condition, the cellular TG and TCHO levels decreased significantly (Fig. 8B and C) and HCV RNA levels also decreased to 57% of the control. More strikingly, HCV infectivity decreased to 12% of the control (Fig. 8D and E).

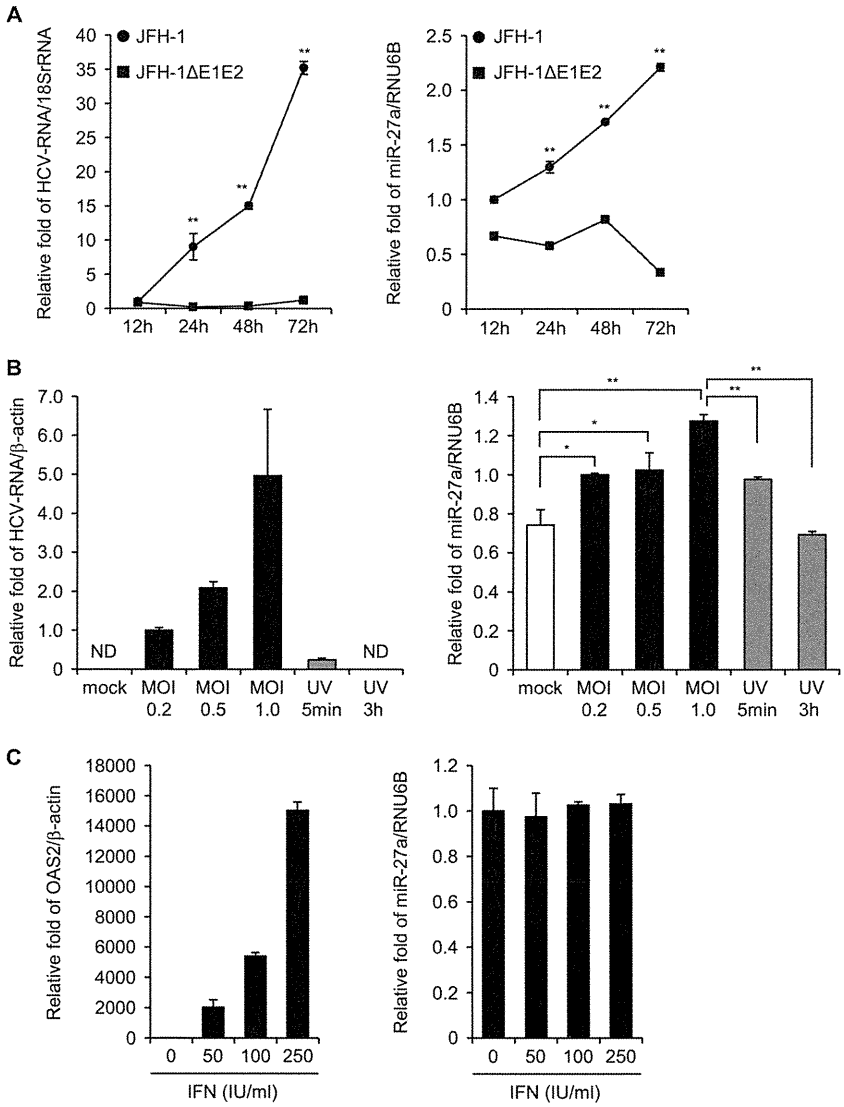

FIG 9 miR-27a is upregulated by HCV infection. (A) Kinetics of HCV replication and induction of miR-27a. Huh-7.5 cells were transfected with JFH-1 RNA or infection-incompetent JFH-1ΔE1E2 RNA (20). At 12, 24, 48, and 72 h posttransfection, HCV RNA (left) and miR-27a (right) levels were quantified by RTD-PCR ($n = 6$). (B) Induction of miR-27a and UV-irradiated HCV particles. Huh-7.5 cells were infected with infectious HCV (multiplicity of infection [MOI] of 0.2, 0.5, or 1) or UV-inactivated HCV. At 72 h postinfection, HCV RNA (left) and miR-27a (right) were quantified by RTD-PCR ($n = 6$). *, $P < 0.01$; **, $P < 0.005$; ND, not detected. (C) Induction of miR-27a and IFN-α treatment. Huh-7.5 cells were treated with different doses of IFN-α. At 24 h posttreatment, OAS2 (left) and miR-27a (right) were quantified by RTD-PCR ($n = 6$). All experiments were performed in duplicate and repeated three times. Values are means ± standard errors.

Several reports have demonstrated the importance of apolipoproteins, including the major components of VLDL and LDL apoE3 (36) and apoB100 (11), in the production of infectious HCV particles. More recently, the functional relevance of ApoA1 in HCV replication and particle production has been reported (37). Here the expression of apoA1, apoB100, and apoE3 was repressed by pre-miR-27a and increased by anti-miR-27a, suggesting that miR-27a regulates the expression of apolipoproteins to reduce the production of infectious HCV particles (Fig. 8F).

Regulation of miR-27a expression through C/EBPα. miR-27a forms a gene cluster with miR-23a and miR-24-2, and both of these miRNAs are regulated by the same promoter (38). However, no detailed analysis of the regulation of this promoter has been carried out. Because the expression of miR-27a was upregulated more in CH-C liver than CH-B liver, it could be speculated that HCV infection induces the expression of miR-27a. To examine this, we evaluated the expression of miR-27a during HCV infection (Fig. 9). The expression of miR-27a increased, correlating with the increase in JFH-1 RNA, while infection-incompetent JFH-1ΔE1E2 did not induce miR-27a expression (Fig. 9A). In addition, UV-irradiated HCV particles did not induce miR-27a expression (Fig. 9B). However, IFN-α treatment did not induce the expression of miR-27a (Fig. 9C). Thus, HCV infection was essential for induction of miR-27a expression.

We identified a C/EBPα binding site (−614 to −606), a key regulator of adipocyte differentiation, in the promoter region of miR-27a. Interestingly, H77Sv2 Gluc2A and tunicamycin

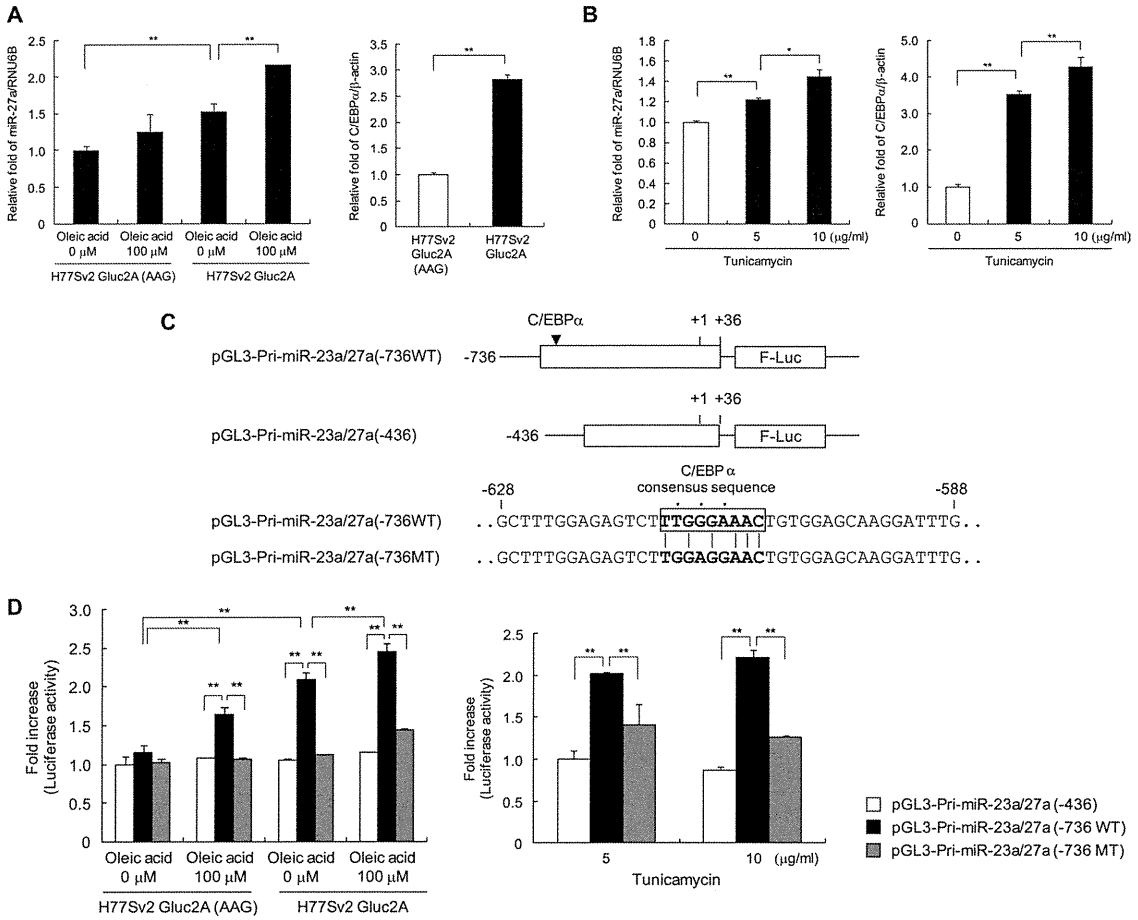

FIG 10 miR-27a is regulated by the adipocyte differentiation factor C/EBPα. (A) Induction of miR-27a and C/EBPα expression by oleic acid and HCV replication. Huh-7.5 cells were transfected with H77Sv2 Gluc2A RNA or H77Sv2 Gluc2A (AAG) RNA. At 24 h posttransfection, oleic acid (100 μM) was added to the culture medium. At 72 h after oleic acid treatment, miR-27a (left) and C/EBPα (right) levels were quantified by RTD-PCR ($n = 6$). (B) Induction of miR-27a and C/EBPα expression by tunicamycin. Huh-7.5 cells were treated with different doses of tunicamycin. At 24 h after tunicamycin treatment, miR-27a (left) and C/EBPα (right) levels were quantified by RTD-PCR ($n = 6$). (C) miR-27a promoter luciferase constructs. pGL3-Pri-miR-23a/27a(−736WT) includes −700 to +36 bp relative to the transcription initiation site of pri-miR-23a~27a~24-2. pGL3-Pri-miR-23a/27a (−436) includes −400 to +36 bp relative to the transcription initiation site of pri-miR-23a~27a~24-2, which lacks the consensus C/EBPα binding site. pGL3-Pri-miR-23a/27a(−736MT) has mutations at the −736WT C/EBPα binding site. (D) miR-27a promoter activity in Huh-7.5 cells following HCV infection and oleic acid (left) or tunicamycin (right) treatment. Reporter constructs lacking the C/EBPα binding site did not respond to any of these conditions ($n = 6$). All experiments were performed in duplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$.

significantly induced the expression of miR-27a and C/EBPα (Fig. 10A and B). To analyze the induction of miR-27a through C/EBPα, we constructed a Luc reporter construct that included the upstream promoter region (−736) of miR-27a [pGL3-Pri-miR-23a/27a(−736WT)] together with a short promoter construct (−436) lacking the C/EBPα binding site [pGL3-Pri-miR-23a/27a(−436)]. In addition, three nucleotide mutations were introduced into the C/EBPα consensus binding site to construct pGL3-Pri-miR-23a/27a(−736MT) (Fig. 10C). The activity of pGL3-Pri-miR-23a/27a(−736WT), but not that of pGL3-Pri-miR-23a/27a(−736MT) or pGL3-Pri-miR-23a/27a(−436), which both lack a C/EBPα binding site, was induced by HCV replication, lipid overload, and tunicamycin treatment (Fig. 10D). These results indicate that the regulation of miR-27a by HCV replication, lipid overload, and ER stress is mediated through C/EBPα.

Pre-miR-27a enhances IFN signaling through the reduction of lipid storage. Finally, we assessed whether miR-27a influences IFN signaling. IFN-α treatment stimulated IFN signaling in a dose-dependent manner by increasing p-STAT1 expression in Huh-7.5 cells (Fig. 11A). Oleic acid impaired this induction of p-STAT1, while pre-miR-27a restored the expression of p-STAT1 and anti-miR-27a impaired this induction by oleic acid. These findings were observed in both HCV-replicating and non-HCV-replicating cells (Fig. 11A).

HCV replication deduced from Gluc activity is shown in Fig. 11B. IFN sensitivity could be estimated by the relative fold changes in Gluc activity from the baseline activity (in the absence of IFN). The results demonstrated that oleic acid reduced IFN sensitivity, while pre-miR-27a increased IFN sensitivity under either condition with or without oleic acid (Fig. 11B).

These findings were further studied with clinical samples. The expression of miR-27a was evaluated in liver biopsy specimens obtained from 41 patients who received pegylated IFN (Peg-IFN) and ribavirin (RBV) combination therapy (Fig. 12A). Interestingly, the expression of miR-27a was significantly higher

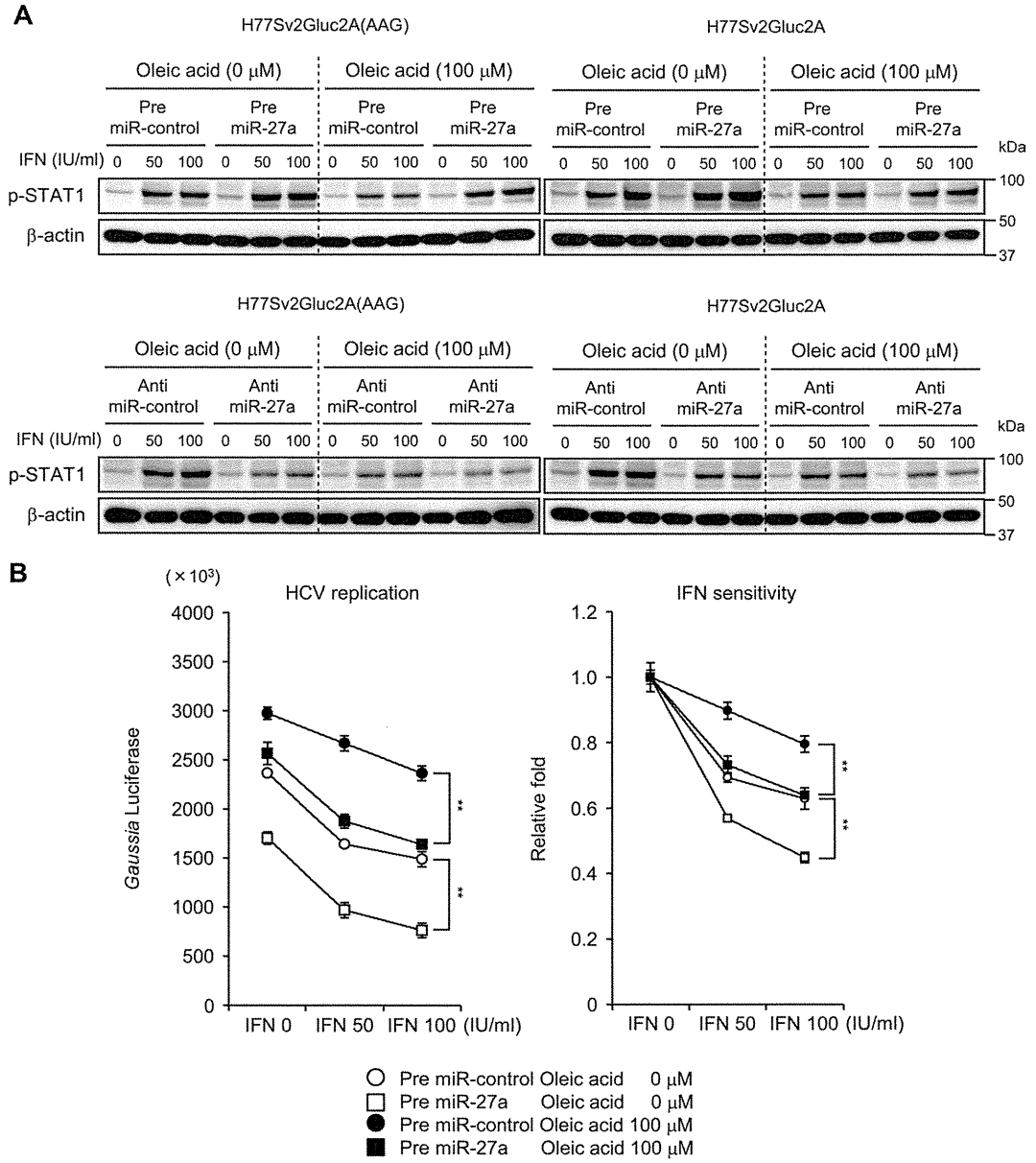

FIG 11 miR-27a restores IFN signaling impaired by lipid overload. (A) Induction of p-STAT1 expression by miR-27a. Huh-7.5 cells were transfected with H77Sv2 Gluc2A RNA or H77Sv2 Gluc2A (AAG) RNA and pre- or anti-miR-control or pre- or anti-miR-27a. At 24 h posttransfection, oleic acid (100 μM) was added to the culture medium. At 48 h after oleic acid treatment, the cells were treated with different doses of IFN-α. At 24 h after IFN treatment, p-STAT1 expression levels were determined by Western blotting. Experiments were repeated three times. (B) Absolute values of Gluc activity (left) and *n*-fold changes in Gluc activity (right) indicate IFN sensitivity ($n = 6$). Experiments were performed in duplicate and repeated three times. Values are means ± standard errors. *, $P < 0.01$; **, $P < 0.005$.

in patients with severe steatosis (grade 3 or 4) than in those with mild steatosis (grade 1 or 2) (Fig. 12B). Importantly, patients with a favorable response to treatment (sustained virological response or transient response) expressed higher miR-27a levels than patients with a poor response (nonresponse) (Fig. 12C). Although there was no significant difference in miR-27a expression according to the interleukin-28B (IL-28B) genotype (Fig. 12D and E), 17 patients had a treatment-resistant IL-28 genotype (TG at rs8099917) (39–41) and 6 of these with a favorable response to treatment expressed significantly higher miR-27a levels than the 11 with a poor response (Fig. 12E). These data suggest that miR-27a enhances IFN signaling and increases the response to IFN treatment.

DISCUSSION

Previously, we examined miRNA expression in HCC and noncancerous background liver tissue infected with HBV and HCV and showed the presence of infection-specific miRNAs that were differentially expressed according to HBV or HCV infection, but not according to the presence of HCC (2). In this study, we pursued the functional analysis of these miRNAs. Among 19 infection-specific miRNAs, we first focused on 6 that were upregulated by

A

No.	Age	Sex	Histological stage			Treatment response			IL28B SNP	
		M:F	F1	F2	F3	SVR	TR	NR	TT	TG
41	54.9±11.2	22:19	15	15	11	17	9	15	24	17

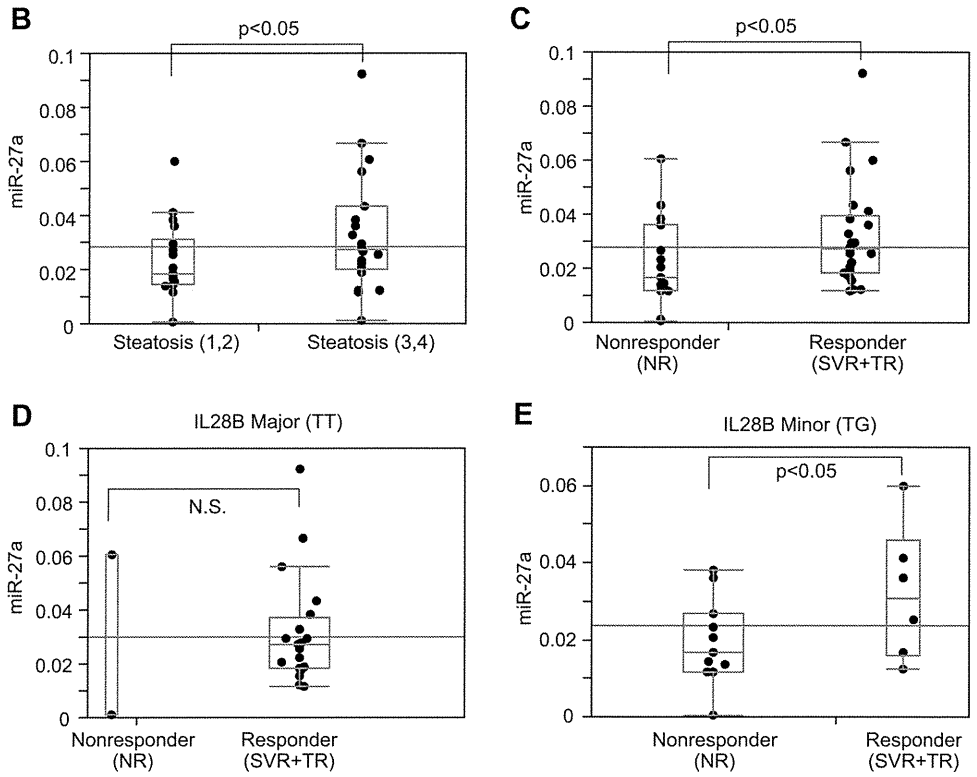

FIG 12 Expression of miR-27a in clinical samples. (A) Clinical characteristics of 41 patients who received Peg-IFN and RBV combination therapy. M:F, male/female ratio; SVR, sustained virological response; TR, transient response; NR, nonresponse; SNP, single nucleotide polymorphism. (B) Significant upregulation of miR-27a expression in the livers of patients with severe steatosis. Steatosis grades 1 and 2, $n = 19$; steatosis grades 3 and 4, $n = 22$. (C) Significant upregulation of miR-27a expression in the livers of patients with a favorable response to treatment (SVR or TR). Nonresponders; $n = 15$; responders, $n = 26$. (D) No significant difference in miR-27a expression between nonresponders and responders of the IL-28B major genotype (treatment-sensitive genotype) was observed. Nonresponders, $n = 3$; responders, $n = 21$. N.S., not significant. (E) Significant upregulation of liver miR-27a was observed in responders of the IL-28B minor genotype (treatment-resistant genotype). Nonresponders, $n = 11$; responders, $n = 6$.

HCV infection, as they were expected to have a positive role in HCV replication. However, inhibition experiments with a series of specific anti-miRNAs showed an unexpected increased in HCV replication. Closer examination clarified that miR-27a had a negative effect on HCV replication. Interestingly, profiling of gene expression in Huh-7.5 cells in which miR-27a was inhibited or overexpressed showed that miR-27a could target lipid metabolism signaling pathways. In support of these findings, the lipid content (TG and TCHO) of Huh-7.5 cells was significantly increased by anti-miR-27a and repressed by pre-miR-27a (Fig. 2 and 3). More importantly, miR-27a was involved in HCV particle formation, as demonstrated by iodixanol gradient centrifugation (Fig. 4). Anti-miR-27a reduced the buoyant density of HCV particles and increased HCV replication and infectivity, while pre-miR-27a decreased HCV replication and dramatically repressed HCV infectivity. In the buoyant-density experiment, the infectious HCV peaks were identical to the RNA peak and the lower infectious virus peak was not observed. We cannot explain this discrepancy from other studies; however, the method used to purify the virus particles could be one reason.

miR-27a regulated many lipid metabolism-related transcription factors, such as RXRα, PPARα, PPARγ, FASN, SREBP1, and SREBP2 (Fig. 5 and 6). We also confirmed that miR-27a targets RXRα in human Huh-7.5 cells, which is concordant with a previous study showing that miR-27a targets RXRα in rat hepatic stellate cells (32). Moreover, we newly demonstrated that the gene for the lipid transporter ABCA1 is a target of miR-27a. ABCA1 mediates the efflux of TCHO and phospholipids to the lipid-poor apolipoproteins ApoA1 and ApoE, which then form nascent HDLs (34, 35). It also mediates the transport of lipids between the Golgi apparatus and the cell membrane. Recently, the knockdown of ABCA1 in rat hepatoma cells increased TG secretion to the culture medium and decreased the cellular levels of FFA (29), while liver-specific ABCA1 knockout mice fed a high-fat diet showed increased plasma TG concentrations and decreased TG and TCHO contents in the liver (42). Thus, ABCA1 regulates the lipid content

of hepatocytes, as well as HDL synthesis. In this study, we confirmed that the repression of ABCA1 decreased cellular TG and TCHO levels in Huh-7.5 cells and, importantly, decreased HCV replication and strikingly repressed HCV infection (Fig. 8).

LXR/RXRα was previously shown to activate the ABCA1 promoter (34), but we clearly demonstrated here that miR-27a directly targets ABCA1. Pre-miR-27a repressed the Luc activity of a reporter construct fused with the ABCA1 3′ UTR, while anti-miR-27a increased it. We also found that miR-27a regulates the expression of ABCA1 in a 3′ UTR sequence-specific manner, as a series of mutations introduced into putative miR-27a binding sites abrogated its regulation (Fig. 7). In addition to these findings, we showed that miR-27a repressed the expression of the apolipoproteins ApoA1, ApoB100, and ApoE3, which were recently shown to play important roles in the production and formation of infectious HCV particles (Fig. 8) (11, 36, 37). Thus, miR-27a may regulate lipid metabolism by reducing lipid synthesis and increasing lipid secretion from cells.

As the expression of miR-27a was upregulated more in CH-C liver than in CH-B liver, it is speculated that miR-27a expression is induced by HCV infection. Indeed, we clearly demonstrated that miR-27a expression was induced by HCV infection, lipid overload, and tunicamycin-induced ER stress (Fig. 9). Furthermore, the adipocyte differentiation-related transcription factor C/EBPα was involved in this regulation. A central role for C/EBPα in the development of adipose tissue has been suggested, as it was found to be sufficient to trigger the differentiation of preadipocytes into mature adipocytes (43). Thus, HCV infection might trigger lipogenesis in hepatocytes by inducing C/EBPα, as shown in this study. Conversely, the induction of C/EBPα expression by miR-27a had a negative effect on lipogenesis and HCV replication. Therefore, miR-27a might play a negative feedback role in HCV infection-induced lipid storage in hepatocytes. Moreover, HCV replication might be hampered by HCV-induced miR-27a, which would partially explain the low HCV titer in CH-C liver.

Besides the anti-HCV effect of miR-27a observed in this study, an antivirus effect against murine cytomegalovirus (MCMV) infection was observed previously (44, 45). MCMV replication was initiated by miR-27a degradation from a viral transcript, while miR-27a had a negative effect on MCMV replication. It was also reported that miR-27a was the target of *Herpesvirus saimiri* U-rich RNAs and was downregulated in transformed T lymphocytes (46). Therefore, the functional relevance of miR-27a in transformed T cells should be explored in a future study. In this study, miR-27a was upregulated by HCV infection, which is in sharp contrast to MCMV and *H. saimiri* infection. Therefore, the differences in antiviral action and host cell interactions also need to be explored further.

Our assessment of miR-27a expression in patients receiving Peg-IFN and RBV combination therapy showed that those with high miR-27a levels had a more favorable treatment response (Fig. 12). Moreover, miR-27a significantly enhanced IFN signaling (Fig. 11), suggesting that it might have therapeutic benefits in combination with IFN therapy, especially in patients with the IFN-resistant IL-28B genotype, who show a more severe steatosis than those with the IFN-sensitive IL-28B genotype (39–41). Further studies should be performed to confirm these findings with more clinical samples.

Although miR-27a has been shown to be upregulated in cancers of the breast, kidney, ovary, and gastric region, its downregulation has been reported in colorectal cancer, malignant melanoma, oral squamous cell carcinoma, and acute promyelocytic leukemia (47). However, its importance in HCC remains controversial, with one report observing its upregulation compared with the level in normal liver tissue (48), while another showed lower miR-27a expression in HCC than in paired nontumor tissues (49). Moreover, our previous findings on HBV-related and HCV-related HCC showed no miR-27a upregulation compared with the level in the paired background liver (1.14-fold, $P = 0.49$).

In summary, we have revealed the important role of miR-27a in HCV replication for the first time. These findings will be applicable in the improvement of the therapeutic effects of anti-HCV therapy, especially in patients showing treatment resistance and severe hepatic steatosis.

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We have no potential competing interests to declare.

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Gene expression profiling of hepatitis B- and hepatitis C-related hepatocellular carcinoma using graphical Gaussian modeling☆

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ABSTRACT

Background & aims: Gene expression profiling of hepatocellular carcinoma (HCC) and background liver has been studied extensively; however, the relationship between the gene expression profiles of different lesions has not been assessed.
Methods: We examined the expression profiles of 34 HCC specimens (17 hepatitis B virus [HBV]-related and 17 hepatitis C virus [HCV]-related) and 71 non-tumor liver specimens (36 chronic hepatitis B [CH-B] and 35 chronic hepatitis C [CH-C]) using an in-house cDNA microarray consisting of liver-predominant genes. Graphical Gaussian modeling (GGM) was applied to elucidate the interactions of gene clusters among the HCC and non-tumor lesions.
Results: In CH-B-related HCC, the expression of vascular endothelial growth factor-family signaling and regulation of T cell differentiation, apoptosis, and survival, as well as development-related genes was up-regulated. In CH-C-related HCC, the expression of ectodermal development and cell proliferation, wnt receptor signaling, cell adhesion, and defense response genes was also up-regulated. Many of the metabolism-related genes were down-regulated in both CH-B- and CH-C-related HCC. GGM analysis of the HCC and non-tumor lesions revealed that DNA damage response genes were associated with AP1 signaling in non-tumor lesions, which mediates the expression of many genes in CH-B-related HCC. In contrast, signal transducer and activator of transcription 1 and phosphatase and tensin homolog were associated with early growth response protein 1 signaling in non-tumor lesions, which potentially promotes angiogenesis, fibrogenesis, and tumorigenesis in CH-C-related HCC.
Conclusions: Gene expression profiling of HCC and non-tumor lesions revealed the predisposing changes of gene expression in HCC. This approach has potential for the early diagnosis and possible prevention of HCC.

1. Introduction

Hepatocellular carcinoma (HCC) is one of the most common malignancies worldwide with a particularly poor patient outcome [1]. It often develops as a result of chronic liver disease associated with hepatitis B (HBV) or hepatitis C virus (HCV) infection or with other etiologies such as long-term alcohol abuse, autoimmunity, and hemochromatosis [2]. HBV and HCV infections are the leading cause of HCC in the world [3]. In Japan, approximately 85% of patients with HCC are positive for the HBV surface antigen or anti-HCV antibody. Approximately 7% of patients with HCV-related liver cirrhosis develop HCC [4] and 3% of patients with HBV-related liver cirrhosis develop HCC [5].

Gene expression analysis of HCC has revealed from previous work, the activation of the wnt/β-catenin, pRb, p53, transforming growth factor-β, mitogen-activated protein kinase, and Janus kinase/signal transducer and activator of transcription pathways, stress response signaling, and epidermal growth factor receptor [6–8]. In addition, we have previously reported that the gene expression profiles in the livers of patients with chronic hepatitis B (CH-B) and chronic hepatitis C (CH-C) were different. Pro-apoptotic and DNA repair responses were predominant in CH-B, while inflammatory and anti-apoptotic phenotypes were predominant in CH-C [9,10]. Furthermore, we optimized

Abbreviations: CH-B, chronic hepatitis B; CH-C, chronic hepatitis C; CLL, cells in liver lobules; CPA, cells in the portal area; EF, early fibrosis; EGR1, early growth response protein 1; ESR1, estrogen receptor 1; GGM, graphical Gaussian modeling; HBV, hepatitis B virus; HCC, hepatocellular carcinoma; HCV, hepatitis C virus; hTERT, human telomerase reverse transcriptase; LCM, laser capture microdissection; LF, late fibrosis; PCCM, partial correlation coefficient matrix; PTEN, phosphatase and tensin homolog; SD, standard deviation; SHC, src homology 2 domain containing; STAT1, signal transducer and activator of transcription 1; TCA, tricarboxylic acid cycle; VEGF, vascular endothelial growth factor.

☆ Conflict of interest: The authors declare no conflict of interest.

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the laser capture microdissection (LCM) method to isolate cells in liver lobules (CLL) and cells in the portal area (CPA) for detailed gene expression analysis [10,11]. However, it is still unknown how cancer signaling pathways are activated in HCC. As HCC frequently develops from a cirrhotic liver, analyzing the relationship of signaling pathways between HCC and non-cancerous liver tissue might be a useful approach for revealing the mechanism that ultimately leads to the development of HCC.

Graphical Gaussian modeling (GGM) is utilized widely to infer or test the relationships between multiple variables [12–14]. Previously, we developed a method that combines cluster analysis with GGM to infer a genetic network on the basis of expression profile data. Analysis of the expression profile of *Saccharomyces cerevisiae* revealed a model of its genetic network, and the accuracy of the inferred network was confirmed by its agreement with the cumulative results of experimental studies [15]. Therefore, GGM has the potential to be a useful analytical tool to identify the relationship between the gene expression profiles of HCC and non-cancerous liver tissue.

In the present study, we extended the analysis of gene expression in HCC and applied GGM analysis [15,16]. Indeed, our procedure inferred the relationships between gene groups defined by clustering, and its application enabled us to elucidate the framework of the gene clusters in relation to the hepatocellular carcinogenesis of CH-B and CH-C.

2. Results

2.1. Expressed genes in CH-B-related HCC

The gene expression profiles of whole liver biopsy specimens and surgically resected liver were obtained from 36 patients with CH-B, 17 with CH-B-related HCC, 35 with CH-C, and 17 with CH-C-related HCC. The clinical characteristics of the patients are shown in Supplemental Tables A and B. We categorized the F1 and F2 fibrosis stages as early fibrosis (EF; n = 13 for CH-B and n = 12 for CH-C) and the F3 and F4 fibrosis stages as late fibrosis (LF; n = 22 for CH-B and n = 23 for CH-C).

The 783 differentially expressed genes in CH-B-related HCC were identified across 20 clusters, of which 4 (Nos. 8, 9, 11, and 20) were up-regulated and 12 (No. 1–7, 12–14, 16, and 17) were down-regulated (Fig. 1 and Supplemental Table C). The up-regulated clusters were comprised angiogenesis, cell cycle, apoptosis, and survival-related genes. Placental growth factor, vascular endothelial growth factor (VEGF)-related protein, SUMO-activating enzyme subunit 2, cyclin E1, and baculoviral IAP repeat-containing 5 were up-regulated (Nos. 8, 9, and 11). In addition, oncogene-related proteins, such as v-myc myelocytomatosis viral-related oncogene (No. 9), telomerase-associated protein 1, and stathmin 1/oncoprotein 18 (No. 8), tumor marker genes, such glypican 3, and growth factors, such as midkine (No. 9), were also up-regulated. In cluster No. 20, the proliferation and invasiveness-related gene and protein tyrosine kinase 2 were up-regulated.

Down-regulation was prominent in many metabolism-related genes including ornithine aminotransferase, insulin receptor substrate 1, glutamate dehydrogenase 2, acyl-coenzyme A oxidase 2, and acetyl-coenzyme A acyltransferase 2, as well as many cytochrome P450 family genes, suggesting impaired xenobiotic, amino acid, and lipid metabolism (Nos. 6, 7, 12, 13, 16, and 17). The characteristic genes expressed in CH-B-related HCC are shown in Table 1.

2.2. Expressed genes in CH-C-related HCC

The 668 differentially expressed genes in CH-C-related HCC were identified across 18 genetic clusters, of which 5 (Nos. 10, 12, 14, 15, and 18) were up-regulated and 11 (Nos. 1–7, 11, 13, 16, and 17) were down-regulated (Fig. 2 and Supplemental Table D). Cluster No. 12 comprised immune defense response genes, such as chemokine (the C-C motif) ligand 19, natural killer cell transcript 4, major histocompatibility complex class I B, major histocompatibility complex class II DQ beta 1, and ubiquitin-specific protease 8. Cluster No. 14 comprised cytoskeleton-associated, cell cycle, mitosis-related, and MAPKKK cascade-related genes, such as tubulin, src homology 2 domain containing (SHC) transforming protein 1, sterile alpha motif domain containing 9, S100 calcium binding protein A10, annexin A2, cyclin B1, platelet-activating factor acetylhydrolase, isoform Ib, and vimentin. In cluster No. 15, glypican 3, aldo-keto reductase family 1, member B10, ATP citrate lyase, farnesyl diphosphate synthase, serine protease inhibitor, and Kazal type 1 were up-regulated. Cluster No. 15 included many candidate tumor markers of HCC. Interestingly, LCM analysis revealed that many of the up-regulated genes in clusters Nos. 12, 14, and 15 were preferentially expressed in CPA. Cluster No. 18 comprised regulation of G1/S checkpoint, signal transduction, and ectoderm development-related genes, such as bone morphogenetic protein 4, cyclin-dependent kinase inhibitor 2A, fibroblast growth factor 9, and ornithine decarboxylase 1. Similar to CH-B-related HCC, many of the metabolism-related genes, including glucose, lipid, and amino acid genes, were down-regulated. The unique feature of lipid metabolism in CH-C-related HCC was the up-regulation of cholesterol and fatty acid synthesis genes and down-regulation of cholesterol metabolism and β oxidation genes. It was characterized by the up-regulation of stearoyl-CoA desaturase, farnesyl diphosphate synthase (No. 14), and ATP citrate lyase (No. 15), and down-regulation of acetyl-coenzyme A acetyltransferase 1. The characteristic genes expressed in CH-C-related HCC are shown in Table 2. Representative gene expression levels confirmed by TaqMan PCR are shown in Supplemental Fig. C1.

Pathway analysis of the combined up- and down-regulated clusters is shown in Supplemental Fig. D and Supplemental Table E. In CH-C-related HCC, immune response- and cytoskeleton-related genes, such as actin, tubulin, and vimentin, were up-regulated, while in CH-B-related HCC, cell matrix interaction genes, such as collagen IV and matrix metalloproteinase, were up-regulated. Immune-related genes were shown to be down-regulated in both CH-C- and CH-B-related HCC by MetaCore™ database analysis (Thomson Reuters, New York, NY) (Supplemental Fig. D). Gene annotation by DAVID Bioinformatics Resources 6.7 (http://david.abcc.ncifcrf.gov/) [17] showed that oxidative phosphorylation and ATP synthesis coupled electron transport were up-regulated more in CH-C-related HCC than in CH-B-related HCC (Supplemental Table E).

2.3. Expressed genes in CH-B and CH-C

Differentially expressed genes in CH-B or CH-C were identified by backward selection, which did not include genes that were differentially expressed in CH-B- or CH-C-related HCC. As HCC frequently develops in the LF stage of liver disease, gene expression was evaluated in this stage. A total of 352 genes were differentially expressed in the LF stage of CH-B and classified into 21 clusters, of which 7 (Nos. 2, 3, 9, 10, 15, 16, and 18) were up-regulated and 11 (No. 5–7, 8, 11–14, 17, 20, and 21) were down-regulated (Supplemental Fig. B and Supplemental Table F).

In the CH-B fibrotic liver, genes involved in apoptosis, survival, and response to stress, as well as chemokine- and cytokine-related genes and wnt beta-catenin and angiogenesis-related genes, were up-regulated. Interestingly, these genes were already up-regulated in the EF stage of CH-B. In contrast, metabolism-related genes, such as those for pyruvate, cholesterol, and retinol metabolism and the mitochondrial tricarboxylic acid (TCA) cycle, were down-regulated.

In total, 214 genes were differentially expressed in the LF stage of CH-C and classified into 7 gene clusters, of which 1 was up-regulated (No. 1) and 3 were down-regulated (Nos. 3, 5, and 6) (Supplemental Fig. B and Supplemental Table G). In CH-C, genes involved in the interferon signaling pathway, leukocyte chemotaxis, and immune response were preferentially up-regulated. These genes were expressed at a significantly higher level in CPA than in CLL in the liver (No. 1). Conversely, many metabolism and liver function-related genes were down-regulated (Nos. 3, 5, and 6). These genes were expressed at significantly higher levels in CLL compared to CPA in the liver.

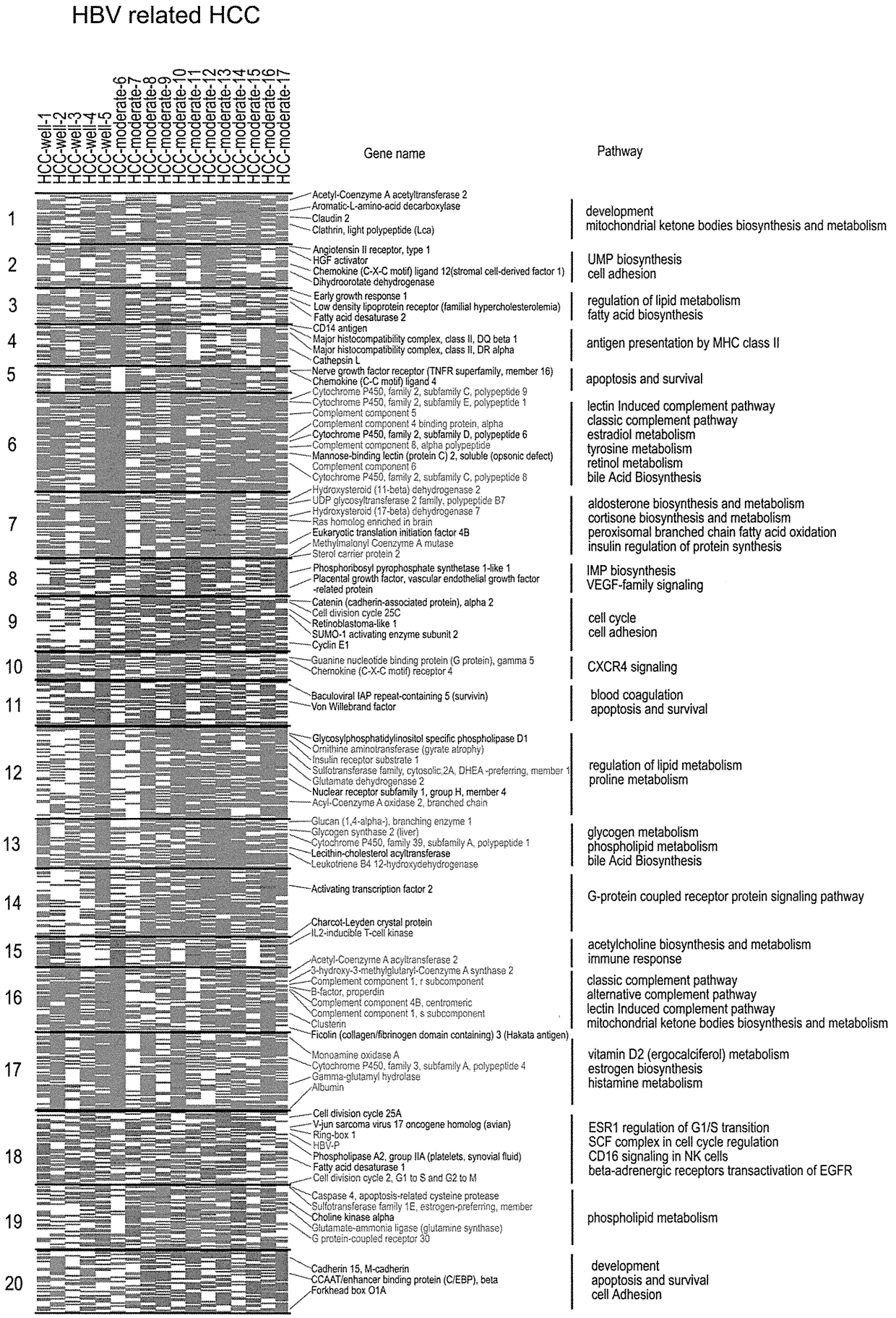
HBV related HCC
HCC-well-1
HCC-well-2
HCC-well-3
HCC-well-4
HCC-well-5
HCC-moderate-6
HCC-moderate-7
HCC-moderate-8
HCC-moderate-9
HCC-moderate-10
HCC-moderate-11
HCC-moderate-12
HCC-moderate-13
HCC-moderate-14
HCC-moderate-15
HCC-moderate-16
HCC-moderate-17
Gene name
Pathway
1
Acetyl-Coenzyme A acetyltransferase 2
Aromatic-L-amino-acid decarboxylase
Claudin 2
Clathrin, light polypeptide (Lca)
development
mitochondrial ketone bodies biosynthesis and metabolism
2
Angiotensin II receptor, type 1
HGF activator
Chemokine (C-X-C motif) ligand 12(stromal cell-derived factor 1)
Dihydroorotate dehydrogenase
UMP biosynthesis
cell adhesion
3
Early growth response 1
Low density lipoprotein receptor (familial hypercholesterolemia)
Fatty acid desaturase 2
regulation of lipid metabolism
fatty acid biosynthesis
4
CD14 antigen
Major histocompatibility complex, class II, DQ beta 1
Major histocompatibility complex, class II, DR alpha
Cathepsin L
antigen presentation by MHC class II
5
Nerve growth factor receptor (TNFR superfamily, member 16)
Chemokine (C-C motif) ligand 4
apoptosis and survival
6
Cytochrome P450, family 2, subfamily C, polypeptide 9
Cytochrome P450, family 2, subfamily E, polypeptide 1
Complement component 5
Complement component 4 binding protein, alpha
Cytochrome P450, family 2, subfamily D, polypeptide 6
Complement component 8, alpha polypeptide
Mannose-binding lectin (protein C) 2, soluble (opsonic defect)
Complement component 6
Cytochrome P450, family 2, subfamily C, polypeptide 8
lectin Induced complement pathway
classic complement pathway
estradiol metabolism
tyrosine metabolism
retinol metabolism
bile Acid Biosynthesis
7
Hydroxysteroid (11-beta) dehydrogenase 2
UDP glycosyltransferase 2 family, polypeptide B7
Hydroxysteroid (17-beta) dehydrogenase 7
Ras homolog enriched in brain
Eukaryotic translation initiation factor 4B
Methylmalonyl Coenzyme A mutase
Sterol carrier protein 2
aldosterone biosynthesis and metabolism
cortisone biosynthesis and metabolism
peroxisomal branched chain fatty acid oxidation
insulin regulation of protein synthesis
8
Phosphoribosyl pyrophosphate synthetase 1-like 1
Placental growth factor, vascular endothelial growth factor -related protein
IMP biosynthesis
VEGF-family signaling
9
Catenin (cadherin-associated protein), alpha 2
Cell division cycle 25C
Retinoblastoma-like 1
SUMO-1 activating enzyme subunit 2
Cyclin E1
cell cycle
cell adhesion
10
Guanine nucleotide binding protein (G protein), gamma 5
Chemokine (C-X-C motif) receptor 4
CXCR4 signaling
11
Baculoviral IAP repeat-containing 5 (survivin)
Von Willebrand factor
blood coagulation
apoptosis and survival
12
Glycosylphosphatidylinositol specific phospholipase D1
Ornithine aminotransferase (gyrate atrophy)
Insulin receptor substrate 1
Sulfotransferase family, cytosolic,2A, DHEA -preferring, member 1
Glutamate dehydrogenase 2
Nuclear receptor subfamily 1, group H, member 4
Acyl-Coenzyme A oxidase 2, branched chain
regulation of lipid metabolism
proline metabolism
13
Glucan (1,4-alpha-), branching enzyme 1
Glycogen synthase 2 (liver)
Cytochrome P450, family 39, subfamily A, polypeptide 1
Lecithin-cholesterol acyltransferase
Leukotriene B4 12-hydroxydehydrogenase
glycogen metabolism
phospholipid metabolism
bile Acid Biosynthesis
14
Activating transcription factor 2
G-protein coupled receptor protein signaling pathway
15
Charcot-Leyden crystal protein
IL2-inducible T-cell kinase
acetylcholine biosynthesis and metabolism
immune response
16
Acetyl-Coenzyme A acyltransferase 2
3-hydroxy-3-methylglutaryl-Coenzyme A synthase 2
Complement component 1, r subcomponent
B-factor, properdin
Complement component 4B, centromeric
Complement component 1, s subcomponent
Clusterin
Ficolin (collagen/fibrinogen domain containing) 3 (Hakata antigen)
classic complement pathway
alternative complement pathway
lectin Induced complement pathway
mitochondrial ketone bodies biosynthesis and metabolism
17
Monoamine oxidase A
Cytochrome P450, family 3, subfamily A, polypeptide 4
Gamma-glutamyl hydrolase
Albumin
vitamin D2 (ergocalciferol) metabolism
estrogen biosynthesis
histamine metabolism
18
Cell division cycle 25A
V-jun sarcoma virus 17 oncogene homolog (avian)
Ring-box 1
HBV-P
Phospholipase A2, group IIA (platelets, synovial fluid)
Fatty acid desaturase 1
Cell division cycle 2, G1 to S and G2 to M
ESR1 regulation of G1/S transition
SCF complex in cell cycle regulation
CD16 signaling in NK cells
beta-adrenergic receptors transactivation of EGFR
19
Caspase 4, apoptosis-related cysteine protease
Sulfotransferase family 1E, estrogen-preferring, member
Choline kinase alpha
Glutamate-ammonia ligase (glutamine synthase)
G protein-coupled receptor 30
phospholipid metabolism
20
Cadherin 15, M-cadherin
CCAAT/enhancer binding protein (C/EBP), beta
Forkhead box O1A
development
apoptosis and survival
cell Adhesion

Table 1
Characteristic genes expressed in CH-B-related HCC.

Genes	Symbol	GenBank ID	Cluster No.	Up- or down-regulated	GO
Placental growth factor, vascular endothelial growth factor-related protein	PGF	NM_002632	8	Up	Angiogenesis
Telomerase-associated protein 1	TEP1	NM_007110	8	Up	Telomere maintenance
Stathmin 1/oncoprotein 18	STMN1	J04991	8	Up	Microtubule depolymerization
SUMO-1 activating enzyme subunit 2	UBA2	NM_005499	9	Up	Protein modification process
Cyclin E1	CCNE1	NM_001238	9	Up	Cell cycle
V-myc myelocytomatosis viral related oncogene	MYCN	NM_005378	9	Up	Regulation of transcription from RNA polymerase II promoter
Glypican 3	GPC3	NM_004484	9	Up	Anatomical structure morphogenesis
Midkine (neurite growth-promoting factor 2)	MDK	NM_002391	9	Up	Cell differentiation
Collagen, type IV, alpha 1	COL4A1	NM_001846	9	Up	Extracellular matrix structural constituent
Gamma-aminobutyric acid (GABA) A receptor	GABRE		11	Up	ion transport
Thrombospondin 2	THBS2	NM_003247	11	Up	Cell adhesion
Transferrin receptor (p90, CD71)	TrF1	AW025110	11	Up	Cellular iron ion homeostasis
Baculoviral IAP repeat containing 5 (Survivin)	BIRC5	NM_001168	11	Up	cytokinesis
Ornithine aminotransferase	OAT	NM_000274	12	Down	Transaminase activity
Insulin receptor substrate 1	IRS1	NM_005544	12	Down	Positive regulation of mesenchymal cell proliferation
Glutamate dehydrogenase 2	GLUD2	NM_012084	12	Down	Cellular amino acid metabolic process
Acyl-CoA oxidase 2	ACOX2	NM_003500	12	Down	Lipid metabolic process
Insulin-like growth factor 2 receptor	IGF-2R	AL353625	13	Down	Transport
Leukocyte cell-derived chemotaxin 2	LECT2, IL-9	AC002428	13	Down	System development
Hydroxysteroid (11-beta) dehydrogenase 1	HSD11B1	NM_181755	13	Down	Lipid metabolic process
Diablo, IAP-binding mitochondrial protein	DIABLO	NM_019887	13	Down	Induction of apoptosis
Cytochrome P450, family 39, subfamily A, polypeptide 1	CYP39A1	NM_016593	13	Down	Bile acid biosynthetic process
N-acetyltransferase 2	NAT-2	NM_000015	13	Down	Metabolic process
Solute carrier family 39 (zinc transporter), member 14	SLC39A14	NM_015359	13	Down	Ion transport
Acetyl-coenzyme A acyltransferase 2	ACAA2	NM_006111	16	Down	Lipid metabolic process

2.4. Framework of gene clusters in relation to hepatocarcinogenesis of CH-B using GGM

We used GGM to examine the relationship between non-cancerous and HCC gene clusters. The partial correlation coefficient matrix (PCCM) generated by GGM is shown in Supplemental Tables H and I. The frame networks of genetic clusters are shown in Fig. 3. The blue lines indicate a negative partial correlation and the black lines indicate a positive partial correlation. Multiple correlations were observed within the non-cancerous and HCC clusters. In addition, some interesting correlations between non-cancerous and HCC clusters were noted. In CH-B (Fig. 3A), non-cancerous cluster No. 3 was up-regulated and correlated with HCC cluster Nos. 8 and 18. Non-cancerous cluster No. 3 was composed of wnt signaling and oxidative stress-related genes, HCC cluster No. 8 was composed of VEGF family signaling-related genes, and HCC cluster No. 18 was composed of estrogen receptor 1 (ESR1) regulation of G1/S transition-related genes. Moreover, non-cancerous cluster No. 16 correlated positively with HCC cluster No. 11 and negatively with HCC cluster No. 18. Non-cancerous cluster No. 16 was composed of cytokine production and apoptosis-related genes, while HCC cluster No. 11 was composed of apoptosis and survival-related genes. The down-regulated non-cancerous cluster No. 13 in CH-B correlated negatively with HCC cluster No. 8. Non-cancerous cluster No. 13 was composed of hepatic functional genes, such as those related to cholesterol metabolism and the TCA cycle.

The correlations between these clusters were further confirmed by examining individual gene interactions with reference to the MetaCore database (Fig. 4A). Eight genes in non-cancerous cluster Nos. 3 and 16 were directly associated with AP1 in HCC cluster No. 18. These genes are related to development and the DNA damage response. In HCC cluster No. 18, many of the cell cycle, development, immune system, and metabolism-related genes were regulated by AP1 [18–20]. In addition, it is interesting to note that the HBV transcript clustered in HCC cluster No. 18 (Fig. 1). The up-regulated HCC cluster No. 11 was associated with AP1 [21]. In addition, the down-regulated HCC cluster No. 13, which included many liver function-related genes, was also associated with AP1 [22,23]. Thus, in CH-B, the DNA damage response might trigger the signaling pathway of HCC, while AP1 in HCC is likely the key regulator of HBV-related HCC.

2.5. Framework of genetic clusters in relation to hepatocarcinogenesis of CH-C using GGM

In CH-C (Fig. 3B), the up-regulated non-cancerous cluster No. 1 correlated negatively with HCC cluster No. 9 and positively with HCC cluster No. 2. Non-cancerous cluster No. 1 was composed of interferon alpha/beta signaling pathway and leukocyte chemotaxis genes. HCC cluster No. 9 was composed of signal transduction and regulation of cell proliferation genes and associated directly with HCC cluster No. 18. HCC cluster Nos. 15 and 18 were composed of development process and wnt signaling pathway genes. HCC cluster Nos. 12 and 14 were composed of immune development, cell adhesion, and defense response genes. These clusters were directly and indirectly associated with HCC cluster No.9. HCC cluster No. 2 was composed of liver function genes, including those for lipid metabolism and iron ion transport. Non-cancerous cluster No. 7, which was composed of immune response, G-protein signaling, and regulation of lipid metabolism genes, correlated positively with HCC cluster No. 18.

Fig. 1. One way hierarchical clustering of 783 differentially expressed genes in CH-B-related HCC.A total of 783 genes were differentially expressed in CH-B-related HCC. Up-regulated genes are shown in red, down-regulated genes are shown in green, and unchanged genes are shown in white.

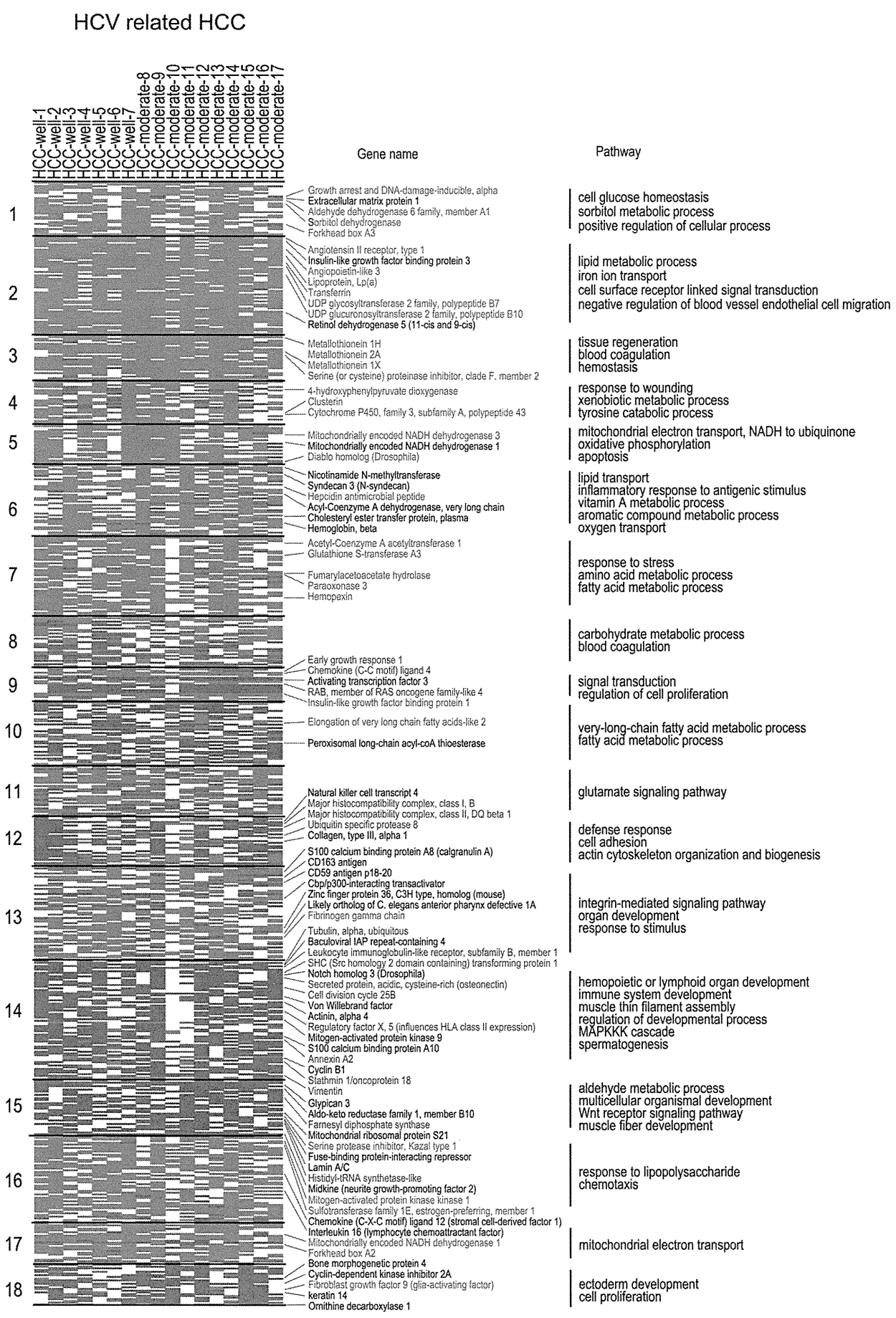
HCV related HCC
HCC-well-1
HCC-well-2
HCC-well-3
HCC-well-4
HCC-well-5
HCC-well-6
HCC-well-7
HCC-moderate-8
HCC-moderate-9
HCC-moderate-10
HCC-moderate-11
HCC-moderate-12
HCC-moderate-13
HCC-moderate-14
HCC-moderate-15
HCC-moderate-16
HCC-moderate-17
Gene name
Pathway
1
Growth arrest and DNA-damage-inducible, alpha
Extracellular matrix protein 1
Aldehyde dehydrogenase 6 family, member A1
Sorbitol dehydrogenase
Forkhead box A3
cell glucose homeostasis
sorbitol metabolic process
positive regulation of cellular process
2
Angiotensin II receptor, type 1
Insulin-like growth factor binding protein 3
Angiopoietin-like 3
Lipoprotein, Lp(a)
Transferrin
UDP glycosyltransferase 2 family, polypeptide B7
UDP glucuronosyltransferase 2 family, polypeptide B10
Retinol dehydrogenase 5 (11-cis and 9-cis)
lipid metabolic process
iron ion transport
cell surface receptor linked signal transduction
negative regulation of blood vessel endothelial cell migration
3
Metallothionein 1H
Metallothionein 2A
Metallothionein 1X
Serine (or cysteine) proteinase inhibitor, clade F, member 2
tissue regeneration
blood coagulation
hemostasis
4
4-hydroxyphenylpyruvate dioxygenase
Clusterin
Cytochrome P450, family 3, subfamily A, polypeptide 43
response to wounding
xenobiotic metabolic process
tyrosine catabolic process
5
Mitochondrially encoded NADH dehydrogenase 3
Mitochondrially encoded NADH dehydrogenase 1
Diablo homolog (Drosophila)
mitochondrial electron transport, NADH to ubiquinone
oxidative phosphorylation
apoptosis
6
Nicotinamide N-methyltransferase
Syndecan 3 (N-syndecan)
Hepcidin antimicrobial peptide
Acyl-Coenzyme A dehydrogenase, very long chain
Cholesteryl ester transfer protein, plasma
Hemoglobin, beta
lipid transport
inflammatory response to antigenic stimulus
vitamin A metabolic process
aromatic compound metabolic process
oxygen transport
7
Acetyl-Coenzyme A acetyltransferase 1
Glutathione S-transferase A3
Fumarylacetoacetate hydrolase
Paraoxonase 3
Hemopexin
response to stress
amino acid metabolic process
fatty acid metabolic process
8
carbohydrate metabolic process
blood coagulation
9
Early growth response 1
Chemokine (C-C motif) ligand 4
Activating transcription factor 3
RAB, member of RAS oncogene family-like 4
Insulin-like growth factor binding protein 1
signal transduction
regulation of cell proliferation
10
Elongation of very long chain fatty acids-like 2
Peroxisomal long-chain acyl-coA thioesterase
very-long-chain fatty acid metabolic process
fatty acid metabolic process
11
Natural killer cell transcript 4
Major histocompatibility complex, class I, B
Major histocompatibility complex, class II, DQ beta 1
glutamate signaling pathway
12
Ubiquitin specific protease 8
Collagen, type III, alpha 1
defense response
cell adhesion
actin cytoskeleton organization and biogenesis
13
S100 calcium binding protein A8 (calgranulin A)
CD163 antigen
CD59 antigen p18-20
Cbp/p300-interacting transactivator
Zinc finger protein 36, C3H type, homolog (mouse)
Likely ortholog of C. elegans anterior pharynx defective 1A
Fibrinogen gamma chain
Tubulin, alpha, ubiquitous
Baculoviral IAP repeat-containing 4
Leukocyte immunoglobulin-like receptor, subfamily B, member 1
SHC (Src homology 2 domain containing) transforming protein 1
integrin-mediated signaling pathway
organ development
response to stimulus
14
Notch homolog 3 (Drosophila)
Secreted protein, acidic, cysteine-rich (osteonectin)
Cell division cycle 25B
Von Willebrand factor
Actinin, alpha 4
Regulatory factor X, 5 (influences HLA class II expression)
Mitogen-activated protein kinase 9
S100 calcium binding protein A10
Annexin A2
Cyclin B1
hemopoietic or lymphoid organ development
immune system development
muscle thin filament assembly
regulation of developmental process
MAPKKK cascade
spermatogenesis
15
Stathmin 1/oncoprotein 18
Vimentin
Glypican 3
Aldo-keto reductase family 1, member B10
Farnesyl diphosphate synthase
Mitochondrial ribosomal protein S21
aldehyde metabolic process
multicellular organismal development
Wnt receptor signaling pathway
muscle fiber development
16
Serine protease inhibitor, Kazal type 1
Fuse-binding protein-interacting repressor
Lamin A/C
Histidyl-tRNA synthetase-like
Midkine (neurite growth-promoting factor 2)
Mitogen-activated protein kinase kinase 1
Sulfotransferase family 1E, estrogen-preferring, member 1
Chemokine (C-X-C motif) ligand 12 (stromal cell-derived factor 1)
Interleukin 16 (lymphocyte chemoattractant factor)
response to lipopolysaccharide
chemotaxis
17
Mitochondrially encoded NADH dehydrogenase 1
Forkhead box A2
mitochondrial electron transport
18
Bone morphogenetic protein 4
Cyclin-dependent kinase inhibitor 2A
Fibroblast growth factor 9 (glia-activating factor)
keratin 14
Ornithine decarboxylase 1
ectoderm development
cell proliferation

Table 2
Characteristic genes expressed in CH-C-related HCC.

Genes	Symbol	GenBank ID	Cluster No.	Up- or down-regulated	GO
Acetyl-coenzyme A acetyltransferase 1	ACAT1	NM_000019	7	Down	Metabolic process
Chemokine (C-C motif) ligand 19	CCL19	NM_006274	12	Up	Immune response
Natural killer cell transcript 4 (Interleukin 32)	IL32	NM_004221	12	Up	Immune response
Major histocompatibility complex, class I, B	HLA-B	NM_005514	12	Up	Immune response
Major histocompatibility complex, class II, DQ beta 1	HLA-DQB1	NM_002123	12	Up	Immune response
Ubiquitin specific protease 8	USP8	NM_005154	12	Up	Cell proliferation
Tubulin, alpha 1b	TUBA1B	NM_006082	14	Up	Microtubule cytoskeleton organization
Actin, alpha 2	ACTA2	NM_001613	14	Up	Vascular smooth muscle contraction
SHC transforming protein 1	SHC1	NM_183001	14	Up	Activation of MAPK activity
Sterile alpha motif domain containing 9	SAMD9	NM_017654	14	Up	Regulation of transcription, dna-dependent
S100 calcium binding protein A10	S100A10	NM_002964	14	Up	Signal transduction
Annexin A2	ANXA2	NM_017654	14	Up	Skeletal system development
Cyclin B1	CCNB1	M25753	14	Up	Cell cycle
Platelet-activating factor acetylhydrolase 1b, 3	PAFAH1B3	D63391	14	Up	Spermatogenesis
Vimentin	VIM	NM_003380	14	Up	Cell motion
Glypican 3	GPC3	NM_004484	15	Up	Anatomical structure morphogenesis
Aldo-keto reductase family 1, member B10	AKR1B10	NM_020299	15	Up	Cellular aldehyde metabolic process
ATP citrate lyase	ACLY	AI819617	15	Up	Lipid biosynthetic process
Farnesyl diphosphate synthase	FDPS	NM_002004	15	Up	Cholesterol biosynthetic process
Serine protease inhibitor, Kazal type 1	SPINK1	NM_003122	15	Up	Protein binding
Bone morphogenetic protein 4	BMP4	D30751	18	Up	Germ cell development
Cyclin-dependent kinase inhibitor 2A	CDKN2A	L27211	18	Up	Cell cycle checkpoint
Fibroblast growth factor 9	FGF9	D14838	18	Up	Signal transduction
Ornithine decarboxylase 1	ODC1	NM_002539	18	Up	Positive regulation of cell proliferation

Analysis of the individual gene interactions (Fig. 4B) showed that a key regulator gene of non-cancerous cluster No. 1, signal transducer and activator of transcription 1 (STAT1), negatively regulated early growth response protein 1 (EGR1) in HCC cluster No. 9 [24]. EGR1 was a key regulator of angiogenesis and fibrogenesis-inducing genes, such as PAI-1 (No. 9), COL1A1, and FAK1 (No. 18) [25–27]. In addition, EGR1 negatively regulated a key regulator of gluconeogenesis, PEPCK (No. 2) [28]. Thus, EGR1 regulated the tissue repair response as well as the metabolic process. In addition to STAT1, phosphatase and tensin homolog (PTEN), in non-cancerous cluster No. 7, negatively regulated FAK1 in HCC cluster No. 18 [29]. FAK1 regulated oncogene SHC (No. 14) and might be involved in the cancer signaling pathway [30,31]. Interestingly, PTEN was associated with Oct-3/4, a regulator of liver differentiation through its target gene C/EBP alpha (No. 3); C/EBP alpha regulated CYP27A1 and CYP3A5 (No. 5). Thus, in CH-C, two antitumor genes, STAT1 and PTEN, were associated with the expression of EGR1 and FAK1, which promote angiogenesis, fibrogenesis, and tumorigenesis in cancerous lesions. Interestingly, the expression of PTEN was related to the metabolic process of CH-C.

2.6. Serial gene expression in non-cancerous gene clusters and the occurrence of HCC

Analysis of the framework of gene clusters in relation to hepatocarcinogenesis by GGM and individual gene interactions revealed several key genes that were associated with hepatocarcinogenesis in non-cancerous clusters. We focused on STAT1 and PTEN in non-cancerous clusters in CH-C and evaluated serial changes of their expression at 2 time points (tumor free and tumor present) in additional 11 patients. The clinical characteristics of these patients at both time points are shown in Supplemental Table J. The expression of STAT1 and its related genes significantly decreased at the time of HCC development compared with the tumor-free time. Similarly, the expression of PTEN significantly decreased when HCC developed compared with the tumor-free time (Supplemental Fig. C2, 3).

3. Discussion

HCC frequently develops in the advanced stage of liver fibrosis. Although gene expression profiling of HCC and the background liver has been studied extensively [32–35], the relationship between the gene expression profiles of different lesions has not been elucidated. In the present study, we utilized GGM [15,16] to analyze the relationship between gene expression in HCC and non-cancerous liver. GGM is widely utilized to study gene association networks [12–14].

We first performed gene expression profiling in CH-B- and CH-C-related HCC. The up- and down-regulated genes were identified by a comparison with a single reference sample of normal liver. There may be some variations in gene expression among normal livers; however, the identified genes were characteristic of HCC and were consistent with previous reports [33,34]. Differences in the signaling pathways between CH-B- and CH-C-related HCC are clearly shown in Figs. 1 and 2 and Supplemental Fig. D. In CH-C-related HCC, immune response- and cytoskeleton-related genes, such as actin, tubulin, and vimentin, were up-regulated, while in CH-B-related HCC, cell matrix interaction genes, such as collagen IV and matrix metalloproteinase, were up-regulated. HBV-X protein reportedly promotes HCC metastasis by the up-regulation of matrix metalloproteinases [36]. The differences in the gene expression profiles between CH-C- and CH-B-related HCC were concordant with those reported previously [34,37].

In the present study, GGM analysis also revealed the interactions of each cluster within HCC as well as within non-cancerous lesions. GGM analysis in CH-B-related HCC showed that 3 up-regulated clusters and 6 down-regulated clusters were associated with each other. In CH-C-related HCC, 4 up-regulated gene clusters and 5 down-regulated gene clusters were associated with each other (Fig. 3). Interestingly, the up-regulated gene clusters were preferentially expressed in CPA in the liver. This prompted us to consider the origin of the HCC cells. Recent reports of immunohistochemical staining of liver tissue using stem cell markers, such as EpCAM and CD133, have suggested the presence of hepatic stem cells in the periportal area [38]. In contrast, many of the down-regulated genes were liver function and metabolism-related genes that were preferentially expressed in CLL in the liver.

Fig. 2. One way hierarchical clustering of 668 differentially expressed genes in CH-B-related HCC.A total of 668 genes were differentially expressed in CH-C-related HCC. Up-regulated genes are shown in red, down-regulated genes are shown in green, and unchanged genes are shown in white (Fig. 2).