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Higher-Order Chromatin Regulation and Differential Gene Expression in the Human Tumor Necrosis Factor/Lymphotoxin Locus in Hepatocellular Carcinoma Cells

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The three-dimensional context of endogenous chromosomal regions may contribute to the regulation of gene clusters by influencing interactions between transcriptional regulatory elements. In this study, we investigated the effects of tumor necrosis factor (TNF) signaling on spatiotemporal enhancer-promoter interactions in the human *tumor necrosis factor* (*TNF*)/*lymphotoxin* (*LT*) gene locus, mediated by CCCTC-binding factor (CTCF)-dependent chromatin insulators. The cytokine genes *LTα*, *TNF*, and *LTβ* are differentially regulated by NF-κB signaling in inflammatory and oncogenic responses. We identified at least four CTCF-enriched sites with enhancer-blocking activities and a TNF-responsive TE2 enhancer in the *TNF/LT* locus. One of the CTCF-enriched sites is located between the early-inducible *LTα/TNF* promoters and the late-inducible *LTβ* promoter. Depletion of CTCF reduced *TNF* expression and accelerated *LTβ* induction. After TNF stimulation, via intrachromosomal dynamics, these insulators mediated interactions between the enhancer and the *LTα/TNF* promoters, followed by interaction with the *LTβ* promoter. These results suggest that insulators mediate the spatiotemporal control of enhancer-promoter associations in the *TNF/LT* gene cluster.

Chromosomal regions harboring different tissue-specific or cellular-state-specific gene clusters may be influenced by long-range regulatory elements and higher-order chromatin organization (45, 53, 60). Recent studies suggest that transcriptional regulatory elements, such as enhancers, promoters, and chromatin insulators, contribute to gene activation and inactivation via genome accessibility and chromosomal interactions (8, 18). Among these, chromatin insulators are boundary elements that partition the genome into chromosomal subregions, probably through their ability to block interactions between enhancers and promoters when positioned between them (enhancer-blocking effect) (7, 17, 41). However, the precise mechanisms responsible for the enhancer-blocking effect and the relationship with long-range chromatin interactions remain unclear (47, 49). The CCCTC-binding factor CTCF is a highly conserved 11-zinc-finger protein that plays crucial roles at insulator sites (44). CTCF is also reported to function in transcriptional activation (62, 73) and repression (16, 36). In the *IGF2/H19* locus, CTCF binds to the differentially methylated region (DMR) of the *H19* gene to form a predicted chromatin loop structure (6, 22, 42). Genome-wide analyses identified the distribution of the putative CTCF-binding sites and their consensus sequences (4, 27, 28, 69). We and other groups recently determined that CTCF is enriched with cohesin in at least 14,000 sites on the human genome (46, 54, 65). CTCF and cohesin cooperatively form compact chromatin loops, leading to the colocalization of gene promoters and their common enhancer in the human *apolipoprotein* gene locus (40). CTCF has been reported to interact with nuclear substructures (71, 72), chromatin remodeling factors (26, 33), RNA polymerase II (10), and CTCF itself (34, 72), as well as undergoing several posttranslational modifications of the protein (12, 29, 37, 70).

Inflammation involves the activation of a highly coordinated gene expression program (43). The tumor necrosis factor (TNF) superfamily members, TNF (initially termed TNF-α), lymphotoxin α (LTα, also termed TNF-β), and lymphotoxin β (LTβ), are major proinflammatory cytokines that mediate inflammatory responses in autocrine/paracrine manners (63). TNF and LTα form homotrimers and act as soluble ligands for the TNF receptor. In contrast, LTβ forms a heterotrimer with LTα and functions as a membrane-bound ligand for the LTβ receptor. In addition to their physiological roles, the aberrant or unbalanced expression of these cytokines is linked to pathological conditions, such as tissue damage/remodeling (38), metabolic diseases (14, 20), and cancer development (19, 23). Hepatic TNF expression is closely related to steatohepatitis (64), and LTβ expression is significantly involved in liver regeneration (3) and hepatocellular carcinomas (HCCs) (23, 67). The *TNF/LT* genes are clustered within the major histocompatibility complex (MHC) class III region on human chromosome 6p21.3, which is the most gene-dense region of the human genome (68). Interestingly, it is reported that NF-κB does not directly interact with the proximal human *TNF* promoter (9, 15, 59) and that NF-κB activation induced by TNF treatment in-

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fluences expression of the *TNF/LT* genes, resulting in the amplified inflammatory response (25). Several DNase-hypersensitive sites, generally suggestive of the presence of regulatory elements, have been found in the *TNF/LT* locus (5, 50, 56, 58). However, a transcriptional mechanism and higher-order chromatin regulation in the human *TNF/LT* locus are unknown.

Investigation of the *TNF/LT* locus identified at least four CTCF/cohesin-enriched insulators and a TNF-responsive TE2 enhancer in human hepatic cells. These CTCF-bound sequences possessed enhancer-blocking activities, and one of the insulators was located between the early-inducible *LTα/TNF* promoters and the late-inducible *LTβ* promoter. Chromosome conformation capture (3C) analyses determined that after TNF stimulation, these CTCF-bound insulators initially associated with the TE2 enhancer and the *LTα*, *TNF*, and *LTβ* promoters, followed by a persistent interaction with the TC3 insulator, the TE2 enhancer, and the *LTβ* promoter. These late-phase interactions were consistent with the formation of a place in which the late-inducible *LTβ* gene was transcriptionally active. TNF stimulation thus induces dynamic changes in higher-order chromatin organization of the overall locus, together with differential expression of the *TNF/LT* genes. Based on our findings that insulators mediate the spatiotemporal control of enhancer-promoter interactions, we propose a dynamic chromatin conformation model and enhancer-blocking mechanism mediated by insulators in the *TNF/LT* locus.

MATERIALS AND METHODS

Cell culture. Hep3B, HCT116, and HeLa cells were cultured in a 1:1 mixture of Dulbecco's modified Eagle's minimum essential medium and Ham's F-12 nutrient medium (DMEM/F12; Sigma) supplemented with 10% (vol/vol) fetal bovine serum (FBS). NeHepLxHT cells were cultured in DMEM/F12 supplemented with 10% (vol/vol) FBS, 10^{-7} M dexamethasone, 10^{-7} M insulin, and 50 μg/ml G418. For TNF stimulation, Hep3B and NeHepLxHT cells were treated with recombinant human TNF-α (210-TA; R&D Systems) at concentrations of 5 ng/ml and 0.5 ng/ml, respectively. For inhibition of NF-κB signaling, BAY11-7082 (10 μM) was added to the medium for 1 h before treatment of the cells with TNF for 0.5 or 1 h.

ChIP and quantitative PCR (qPCR) analysis. Hep3B and NeHepLxHT cells were cross-linked with 1% formaldehyde at 37°C for 10 min. Crude cell lysates were sonicated to generate DNA fragments of 200 to 500 bp. Chromatin immunoprecipitation (ChIP) was performed with anti-CTCF (07-729; Millipore), anti-RAD21 (ab992; Abcam), anti-acetylated histone H3 (06-599; Millipore), anti-acetylated histone H4 (06-866; Millipore), anti-p65 (sc-372; Santa Cruz), anti-p300 (sc-585; Santa Cruz), or anti-RNA polymerase II (phosphor-S5) antibodies (ab5131; Abcam) or with control rabbit IgG (sc-2027; Santa Cruz) (26). Cells were cross-linked for an additional 10 min when anti-p65 and anti-p300 antibodies were used.

DNA enrichment in ChIP samples was determined using qPCR analysis with an ABI Prism 7300 system (Applied Biosystems) and SYBR green fluorescence. The threshold was set to cross a point where PCR amplification was linear, and the cycle number required to reach the threshold was recorded and analyzed using the Microsoft Excel software program. PCR was performed using precipitated DNA and the input DNA. Primer sequences are listed in Table S1 in the supplemental material. Other antibodies used were anti-lamin A/C (sc-7292; Santa Cruz).

Electrophoretic mobility shift assay (EMSA). The CTCF protein was synthesized using a coupled *in vitro* transcription/translation reaction with the TNT T7 Quick system (Promega), according to the manufacturer's protocol. For supershift assays, the reaction mixture was combined with 1 μl anti-CTCF antibodies (612148; BD Biosciences) (40). The sequences of the probes were as follows: H19 DMR, 5′-TGG CAC GGA ATT GGT TGT AGT TGT GGA ATC GGA AGT GGC CGC GCG GCG GCA GTG CAG GCT CAC ACA TCA CAG CCC GAG CCC GCC CCA ACT-3; TC1, 5′-TCT CCA GCA CTT CTT GCT CAG GCA GTA CCC AAA GGG GCC GCC TGG GAG CAG CAG AGA CCA GGC CCA AAG CTG CGG GCT TAC AAC AGG TTA GCC ATC CCA-3′; TC2, 5′-AGA CCC TGG TGT CCT CTC TGG CCT TAT TTA CTC CTG GTC CTC TGC CAG CCC TGC CAC CAG ATG GCC TTC TAA CTC CTT GGT TGA AAG GCC CAT CTC ATT C-3′; TC3, 5′-CCC GGT ACA GAG AGC TGC GCA GCG TGA CCG AGC GG CCC TGG GGG TCC CCG CCG CCA GGG GGC GCC CGG CCC CGG TAG CCG ACG AGA CAG TAG AGG-3′; TC4, 5′-CTT CAC CCA GGT CTC TCC AGA GAG CCT CAG GCC GCT GCC TTT ACT TAG TTC TGT GTT CAA TGC CAG AAT GCT GCC TCC TAC AGG AAG TCC ACC TGT ATT GCC CAC ACC TCC T-3′; negative control, 5′-TGG CAA AAA GAA AGG ACA GGG CTG CAA GGA GAG TAC AGA CAT GTG CTG GTG AGT GCA CTG TCT GCA TAG TTA CAC CAG AGC ATC TTA TCA ATC AGA AAC TTA TC-3′.

Luciferase reporter assay. The reporter vector pIHLE consisted of the *luciferase* gene driven by the mouse *H19* promoter (−818 to +6 from the transcription start site), simian virus 40 (SV40) enhancer, and a 1.8-kb AatII-HindIII fragment containing the *H19* DMR insulator. The plasmid pIHLIE was constructed by inserting the 1.8-kb *H19* DMR fragment between the *luciferase* gene and the enhancer. pIHLTE plasmids were constructed by inserting fragments of about 200 bp, including TC1, TC2, TC3, and TC4, between the *luciferase* gene and the enhancer (pIHLTE-1F/1R, -2F/2R, -3F/3R, and -4F/4R, respectively). For pIHLET, TC fragments were inserted downstream of the enhancer in pIHLE (pIHLET-1F/1R, -2F/2R, -3F/3R, and -4F/4R). To prepare pIHLTE with mutations (pIHLTE-1 M, -2 M, -3 M, and -4 M), base substitutions were introduced in CTCF consensus sequences at the TC1, TC2, TC3, and TC4 sites using a PCR-based mutagenesis method.

The reporter vector pPL consisted of the *SV40* promoter and the *luciferase* gene and is identical to the pGL3-Promoter vector (Promega). pTPL, pAPL, and pBPL contained the *TNF* promoter (−1044 to +54 from the transcription start site), *LTα* promoter (−924 to +43 from the transcription start site), and *LTβ* promoter (−971 to +12 from the transcription start site), respectively, instead of the *SV40* promoter of pPL. TE1 and TE2 sequences were PCR amplified and inserted upstream of pPL, pTPL, pAPL, and pBPL (pTE1-PL, pTE2-PL, pTE1-TPL, pTE2-TPL, pTE2-APL, and pTE2-BPL). The primer sequences used to prepare the TE1 and the TE2 sequences were as follows: TE1-S, CCT GTG GCT GGA TGA AAT CT; TE1-AS, CCT GGG CAA CAA AGT GAG AC; TE2-S, CCA GGG GAG TTG TGT CTG TAA; TE2-AS, GCA GTT CGG TTC CTT GTT CT.

Reporter vectors (0.05 pmol) were transfected into Hep3B cells (1.0×10^5 cells) in a 12-well plate, using FuGene6 reagent (Roche Applied Science), and analyzed using a luciferase reporter assay system (Promega) after 24 h. For dual luciferase activities (26), values are shown as means and standard deviations of the results from at least three independent experiments.

qRT-PCR. Total RNA was isolated from cultured cells with TRIzol (Invitrogen). The cDNA synthesis used 2 μg of total RNAs that was reverse transcribed using a High Capacity cDNA reverse transcription kit (Applied Biosystems), according to the manufacturer's instructions. Quantitative PCR was performed using an ABI Prism 7300 system (Applied Biosystems) and SYBR green fluorescence. Each experiment was performed at least three times. The relative fold enrichment was quantified by normalization to *β-actin* or *glyceraldehyde-3-phosphate dehydrogenase* (*GAPDH*) gene expression. Primer sequences are listed in Table S1 in the supplemental material.

siRNA-mediated knockdown. Small interfering RNAs (siRNAs) for GL3, CTCF, and Rad21 were used as previously reported (40). RELA silencer select validated siRNA (s11914; Ambion) was used for p65 knockdown. siRNAs were transfected using the Lipofectamine RNAiMAX reagent (Invitrogen) for 48 h.

3C assay. For the chromosome conformation capture (3C) assays (21, 52), formaldehyde-cross-linked chromatin from Hep3B and NeHepLxHT cells was digested with DpnII overnight, followed by ligation with T4 DNA ligase at 16°C for 4 h. To prepare control templates for standard curves, a bacterial artificial chromosome spanning the *TNF/LT* locus RPCI11.C-47E16 was digested with Sau3AI, which is insensitive to Dam methylase, followed by random religation. After reversing the cross-links, genomic DNA was purified by phenol extraction and ethanol precipitation. The ligated products were assessed using qPCR with an ABI Prism 7300 system (Applied Biosystems) and Thunderbird SYBR qPCR Mix (Toyobo). The efficiency of DpnII digestion was evaluated after the entire 3C treatment using qPCR to amplify uncut fragments spanning the DpnII site. More than 80% of the individual restriction sites were digested in these experiments. The 3C-qPCR data were normalized to a loading control, using internal primers located in the *TNF/LT* gene locus. We gained similar results after normalization with internal primers located in *GAPDH* (data not shown). The relative frequencies of interactions between the reference and its physically close site in the control state were finally normalized to 1. Examples of the calculation for relative interacting frequencies are described in Results. Statistical analysis was performed using Student's *t* test for the results of more than three independent experiments. Primer sequences are listed in Table S1 in the supplemental material.

Immunofluorescence analysis. Cultured human cells were fixed with 4% paraformaldehyde in phosphate-buffered saline (PBS) for 10 min at room temperature. Fixed cells were rinsed three times in PBS for 5 min and permeabilized with PBS containing 0.2% Triton X-100 and 0.5% normal goat serum (NGS) for 5 min on ice. Cells were rinsed three times in PBS containing 0.5% NGS for 5 min and then incubated with rabbit anti-p65 (sc-372; Santa Cruz) for 60 min followed by secondary donkey Cy3-conjugated or Alexa Fluor 488-conjugated antibodies for 60 min. Labeled cells were washed three times in PBS for 10 min each. Samples were analyzed using a fluorescence microscope system (Orca-ER1394; Olympus).

Patients and histological assessment. A total of 38 patients (male, 29; female, 9) with HCC, who had undergone tumor resection at the National Cancer Center Hospital, Tokyo, Japan, between May 2003 and December 2005, were enrolled in the present study. The median patient age and follow-up period were 63 years and 1,719 days, respectively. Among the 38 HCC patients, 12 were immunologically positive for hepatitis C virus (HCV) infection, and 16 for persistent hepatitis B virus (HBV) infection (hepatitis B virus surface antigen positive), and 10 were negative for both HCV and HBV infection. Histological examination of noncancerous liver tissue samples revealed findings compatible with chronic hepatitis in 22 and cirrhosis in 9 and no remarkable histological findings in 7. The 38 HCCs were histologically classified into 3 well-differentiated, 27 moderately differentiated, and 8 poorly differentiated tumors. All patients were followed for more than 100 days. Clinical and pathological profiles were obtained from the medical records of the patients. This study was approved by the Ethics Committee of the National Cancer Center, Tokyo, Japan, and written informed consent was obtained from all patients.

IHC. Immunohistochemistry (IHC) for TNF and LTβ was performed using a polymer-based method with the Envision+Dual Link system-horseradish peroxidase [HRP] (DK-2600 Glostrup; Dako). Sources and dilutions of primary antibodies were as follows: anti-TNF-α (ab9579), 1:100, Abcam; anti-LTβ (ab64835), 1:50, Santa Cruz Biotechnology. Formalin-fixed, paraffin-embedded serial tissue sections (4 μm) were placed on silane-coated slides for IHC. Sections cut through the maximum tumor diameter were selected for IHC evaluation. The sections were deparaffinized and rehydrated in xylene and grade-diluted ethanol (50 to 100%) and submerged for 20 min in 0.3% hydrogen peroxide with absolute methanol to block endogenous peroxidase activity. Antigen retrieval for TNF and LTβ was carried out by heating in target retrieval solution (Tris-EDTA buffer, pH 9; Dako Cytomation) at 121°C for 10 min by a pressure cooker. After protein blocking, the sections were incubated with each primary antibody at room temperature for 1 h, followed by incubation with Envision+Dual Link reagent at room temperature for 30 min, and visualized using 3,3-diaminobenzidine tetrahydrochloride as a chromogen. Finally, the sections were counterstained with hematoxylin. Sections were gently rinsed in PBS between incubation steps. The primary antibody was omitted from the reaction sequence as a negative control.

All sections were evaluated by two pathologists, Y. Kanai and H. Ojima, with no knowledge of any clinical or pathological information. Immunoreactivities of TNF and LTβ were defined as follows: negative, no cytoplasmic staining was observed or the intensity of cytoplasmic staining was lower than that for noncancerous hepatocytes within the same section in more than 50% of cancer cells; positive, the intensity of cytoplasmic staining was equivalent to or higher than that of noncancerous hepatocytes in more than 50% of cancer cells.

Statistical analysis. Differences between groups were analyzed using Student's *t* test. A *P* value of <0.05 was considered statistically significant.

RESULTS

Distribution of CTCF-enriched sites in the human *TNF/LT* gene cluster. CTCF-enriched sites in the human *TNF/LT* gene region were investigated by checking several genome-wide CTCF-binding profiles available on websites and in our published data (40, 65). At least four CTCF-enriched sites (TC1, TC2, TC3, and TC4) were identified in this locus and were conserved among the cells tested (Fig. 1A; see also Fig. S1A in the supplemental material). There were no probe sets for the TC2 site in genome tiling arrays because of the presence of frequent repeat sequences (shown by asterisks in Fig. S1A in the supplemental material). Interestingly, TC3 was located between the *TNF* and *LTβ* gene promoters, forming the possible boundary between these adjacent chromosomal subregions.

Based on previous reports (28, 69), each TC site contained a 20-bp consensus CTCF-binding motif (Fig. 1B). To determine if CTCF bound directly to these TC sequences, we performed electrophoretic mobility shift assays (EMSAs) using radiolabeled duplex probes of approximately 100 bp for each TC site and the *in vitro* transcribed/translated CTCF protein. Similar to the DMR insulator of the *H19* gene used as a control (40), the TC probes formed complexes with CTCF and were further supershifted by anti-CTCF antibodies. In contrast, negative-control (NC) probes, which had sequences located downstream of the *NFKBIL1* gene, did not bind to CTCF. In addition, competition assays using mutated TC probes carrying base substitutions within the consensus motif showed that mutated probes did not bind to the CTCF protein (see Fig. S1B and C in the supplemental material), indicating that CTCF specifically bound to the TC sequences.

In order to clarify the localization of CTCF and the cofactor cohesin RAD21 in hepatic cells, we performed chromatin immunoprecipitation (ChIP) analyses using anti-CTCF and anti-RAD21 antibodies, followed by quantitative PCR (qPCR) (Fig. 1C and D). We used standard cell lines: Hep3B, which originates from human HCC, and NeHepLxHT, which is a telomerase-immortalized human neonatal hepatocyte line (51). Both CTCF and RAD21 bound to the TC sites but not to the NC site. RAD21 was relatively enriched with CTCF at TC1 in the *TNF/LT* locus. The CTCF enrichment at the TC sites in Hep3B cells may be remarkable due to the high expression of this gene (see Fig. S1D in the supplemental material) compared with that in NeHepLxHT cells.

Differential regulation of *TNF/LT* genes under TNF stimulation. To examine the transcriptional regulation of the *TNF/LT*

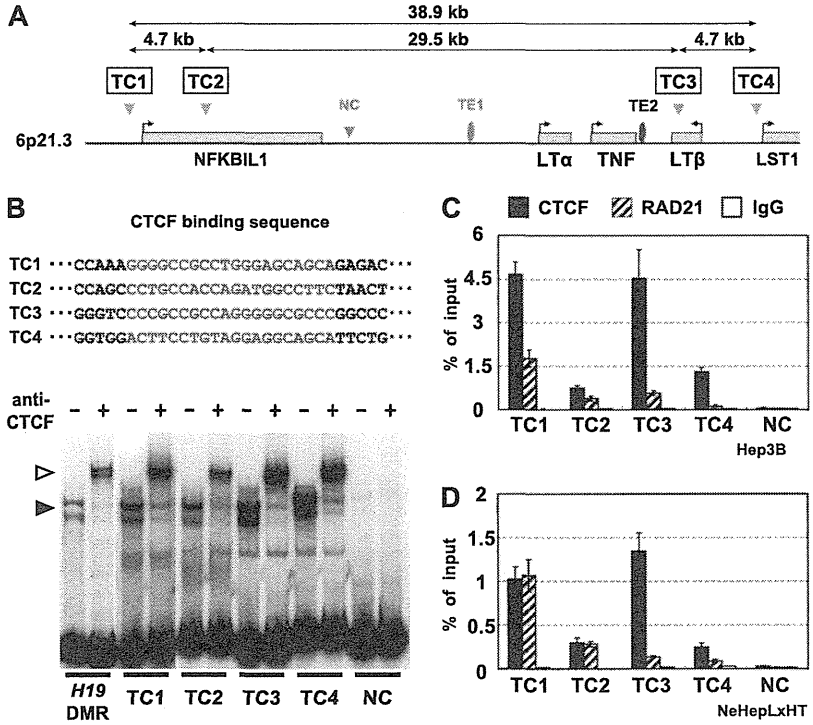


FIG 1 CTCF-enriched sites in the human *TNF/LT* gene cluster locus. (A) CTCF-enriched sites in the *TNF/LT* locus on human chromosome 6p21.3. In addition to the *NFKBIL1*, *LTα*, *TNF*, *LTβ*, and *LST1* genes, a newly identified TE2 enhancer is indicated by a red oval. Based on genome-wide CTCF-binding profiles available from websites and our published data (see Fig. S1A in the supplemental material), four enriched sites were designated TC1, TC2, TC3, and TC4. NC is used as a negative control, and TE1 is a site with no enhancer activity. (B) Direct binding of CTCF to TC sequences. Predicted CTCF-binding sequences within TC1, TC2, TC3, and TC4 sites are indicated, together with the 20-bp consensus motif (red). For EMSAs, radiolabeled duplex probes of approximately 100 bp for each TC site were incubated with anti-CTCF antibodies and synthesized CTCF. Solid and open arrowheads indicate CTCF DNA and the supershifted complexes, respectively. The *H19* DMR insulator and an intergenic unrelated sequence (NC) were used as controls. (C and D) Existence of CTCF and the cofactor cohesin RAD21 at TC sites. Chromatin immunoprecipitation analyses were carried out with anti-CTCF and anti-RAD21 antibodies and control IgG, followed by quantitative PCR with specific primers for each TC site in Hep3B cells (C) or NeHepLxHT cells (D).

genes, we performed quantitative reverse transcription (RT)-PCR (qRT-PCR) analyses with Hep3B and NeHepLxHT cells stimulated by TNF-induced NF-κB activation (Fig. 2A; see also Fig. S2A and B in the supplemental material). Expression of *LTα* and *TNF* mRNAs was markedly increased in Hep3B cells 1 h after stimulation, but *LTβ* mRNA was not simultaneously induced. Moreover, *TNF* expression seemed to be variable after the 1-h peak, while *LTα* and *LTβ* expression did not peak until 24 h after TNF treatment. Early induction of the *LTα* and *TNF* genes also occurred in NeHepLxHT cells, with subsequent expression of the *LTβ* gene. The patterns of *TNF/LT* expression differed between these cell lines, probably due to the constitutively low activation of the NF-κB pathway in Hep3B cells (see Fig. 4A) (11, 55).

Nuclear translocation of NF-κB is critical for its activation (24), and we therefore investigated its subcellular localization under TNF stimulation, using immunofluorescent staining of p65, a subunit of the NF-κB heterodimer (Fig. 2B; see also Fig. S2C in the supplemental material). Cytoplasmic p65 translocated to the nucleus at 30 min after stimulation, and this translocation was inhibited by the addition of BAY11-7082, a specific inhibitor of IκBα phosphorylation (48). The translocated p65 was found to decrease at 1 h after the stimulation (see Fig. S2D in the supplemental material). The expression status of the *TNF/LT* genes was analyzed in parallel using qRT-PCR analyses (Fig. 2C and D). TNF-induced expression of *TNF*, *LTα*, and *LTβ* was attenuated by NF-κB inhibition. Since the use of BAY11-7082 had cytotoxic effects at late time points after TNF stimulation, we carried out siRNA-mediated knockdown of p65 (see Fig. S2G and H in the supplemental material). The induction of the *TNF*, *LTα*, and *LTβ* genes was consistently inhibited by depletion of p65, indicating that the *TNF/LT* genes are regulated by NF-κB in the TNF-treated hepatic cells. Expression of the neighboring *NFKBIL1* gene was unaffected by the stimulation. TNF treatment caused no significant cell damage throughout the study (see Fig. S2E and F in the supplemental material). Thus, the *TNF/LT* genes are differentially induced by TNF-activated NF-κB signaling.

CTCF-dependent enhancer-blocking activity in the *TNF/LT* gene locus. Previous studies demonstrated that the *H19* DMR insulator contains multiple CTCF-binding sites, which are essential for enhancer-blocking activity (6, 22, 26). Luciferase reporter assays were performed with Hep3B cells to test the enhancer-blocking effects of TC1, TC2, TC3, and TC4 (Fig. 3). The presence of TC1, TC2, TC3, and TC4 between the enhancer and promoter reduced the luciferase activities to approximately 60% of those for the control pIHLE vector (pIHLTE-1F, pIHLTE-2F, pIHLTE-3F, and pIHLTE-4F). TC sequences in the opposite direction showed similar results (pIHLTE-1R, pIHLTE-2R, pIHLTE-3R, and pIHLTE-4R), indicating that the TC sites possess enhancer-block-

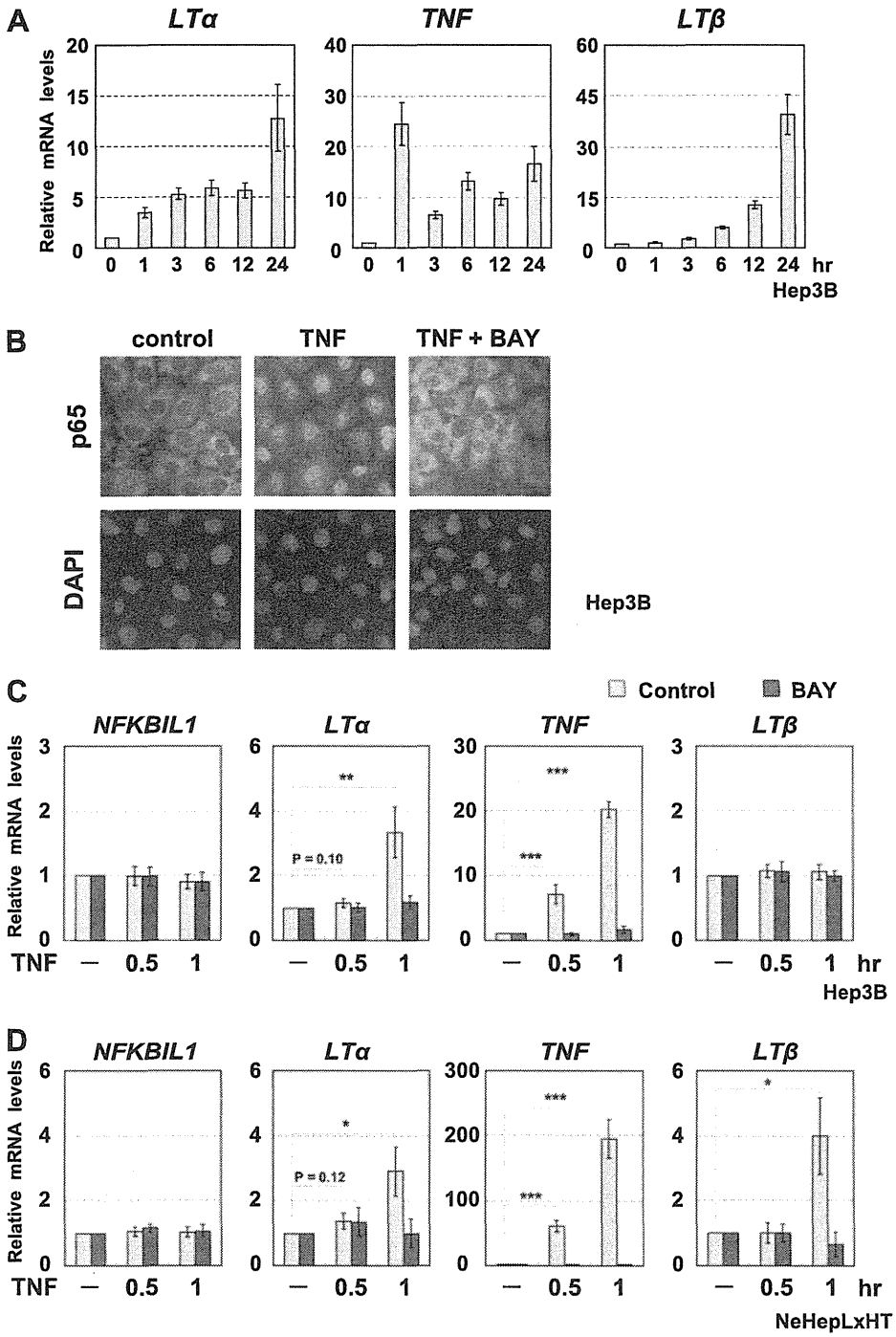


FIG 2 Differential regulation of *TNF/LT* genes under TNF stimulation. (A) Effect of TNF stimulation on *TNF/LT* expression in Hep3B cells. qRT-PCR analyses were performed with Hep3B cells under TNF treatment. (B) Nuclear translocation of NF-κB induced by TNF stimulation. The subcellular localization of the p65 subunit of the NF-κB heterodimer was analyzed by immunofluorescent staining of TNF-stimulated Hep3B cells, together with the use of BAY11-7082, an inhibitor of NF-κB activation. (C and D) NF-κB-dependent expression of the *TNF/LT* genes. TNF-induced expression of the *TNF/LT* genes was examined by qRT-PCR analyses in Hep3B (C) or NeHepLxHT (D) cells in combination with NF-κB inhibition. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.005$.

ing activities that are independent of the orientation of the sequences. To exclude the possibility that the TC sites exhibit silencer-like activities, the TC sequences were placed downstream of the enhancer (pIHLET-1F, pIHLET-1R, pIHLET-2F, pIHLET-2R, pIHLET-3F, pIHLET-3R, pIHLET-4F, and pIHLET-4R). Luciferase activity was not reduced by TC sites in this position, suggesting that TC sites do not possess silencer-like functions. The use of mutant TC sites lacking CTCF-binding function, as described

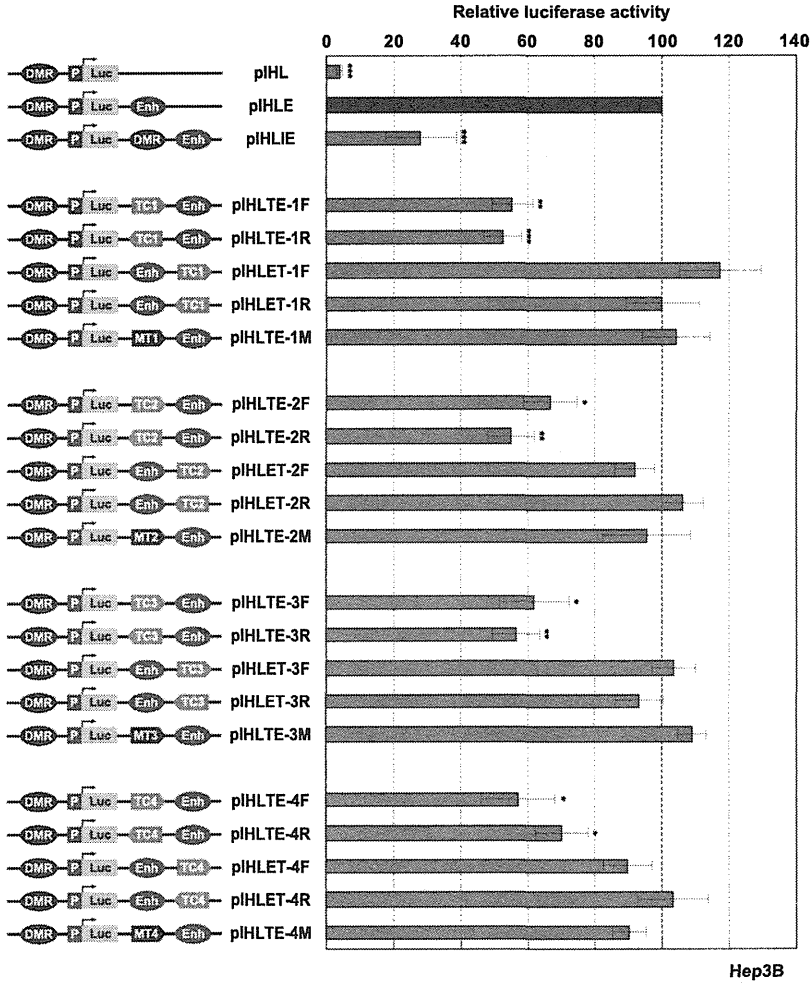


FIG 3 CTCF-dependent enhancer-blocking activity of TC sequences. pIHLTE plasmids were constructed by inserting fragments of approximately 200 bp containing wild-type or mutant-type TC (lacking the CTCF binding function) between the promoter and the enhancer in pIHLE. The *H19* DMR insulator was used as a control. For pIHLET, TC fragments were inserted downstream of the enhancer in pIHLE. The luciferase activities from pIHLE were normalized to 100. The values are given as means and standard deviations of the results from more than three independent experiments. Luc, *luciferase* gene; P, *H19* promoter; Enh, SV40 enhancer; DMR, *H19* DMR insulator; TC1-TC4, CTCF-enriched sites; MT1 to MT4, the mutant TC sequences. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.005$.

above (see Fig. S1B and C in the supplemental material), demonstrated no enhancer-blocking effects (pIHLTE-1M, pIHLTE-2M, pIHLTE-3M, and pIHLTE-4M), further suggesting that the insulator activities of the TC sites depend on CTCF. These results suggest that TC1, TC2, TC3, and TC4 are functional insulators.

Characterization of a TNF-responsive hepatic enhancer in the human *TNF/LT* locus. In order to understand the overall regulatory mechanisms in the *TNF/LT* locus, we investigated the role of transcriptional enhancers in hepatic cells. Based on several DNase-hypersensitive sites in the locus (56), modified histones, p300 binding, previously reported enhancers (HSS-9 and HSS+3) in mouse T cells (58), and κB-responsive elements conserved among humans, mice, and rats (30, 31), we chose two candidates, named TE1 and TE2, which were located about 3.5 kb upstream of the *LTα* gene and just downstream of the *TNF* gene, respectively (Fig. 1A; see also Fig. S1A in the supplemental material). Luciferase reporter assays were performed with Hep3B cells to determine if TE1 and TE2 act as enhancers (Fig. 4A). Compared to the control (pPL) and TE1 (pTE1-PL), TE2 significantly increased transcription from the *SV40*, *TNF*, *LTα*, and *LTβ* promoters (pTE2-PL, pTE2-TPL, pTE2-APL, and pTE2-BPL), probably because of the constitutively low activation of NF-κB in Hep3B cells. Under TNF stimulation, these promoter activities were further elevated. These results indicate that TE2 has a TNF-responsive enhancing effect on the *TNF/LT* gene promoters. In addition, the effect of TE2 on the *LTα* promoter seemed to be weaker than that on the *TNF* promoter. The TNF-inducible enhancer activities of TE2 were also detected in other cell lines (see Fig. S3A in the supplemental material).

NF-κB p65 cooperates with histone acetyltransferase p300 (74), which functions as a transcriptional coactivator that accumulates in active enhancer elements (61). To validate the role of TE2 as an active enhancer, we investigated recruitment of p65 and p300 to TE2 by TNF stimulation in Hep3B cells, using ChIP-qPCR assays (Fig. 4B and C). A previously demonstrated enhancer of the *MCP-1* gene (ME) was used as a control (57). Recruitment of p65

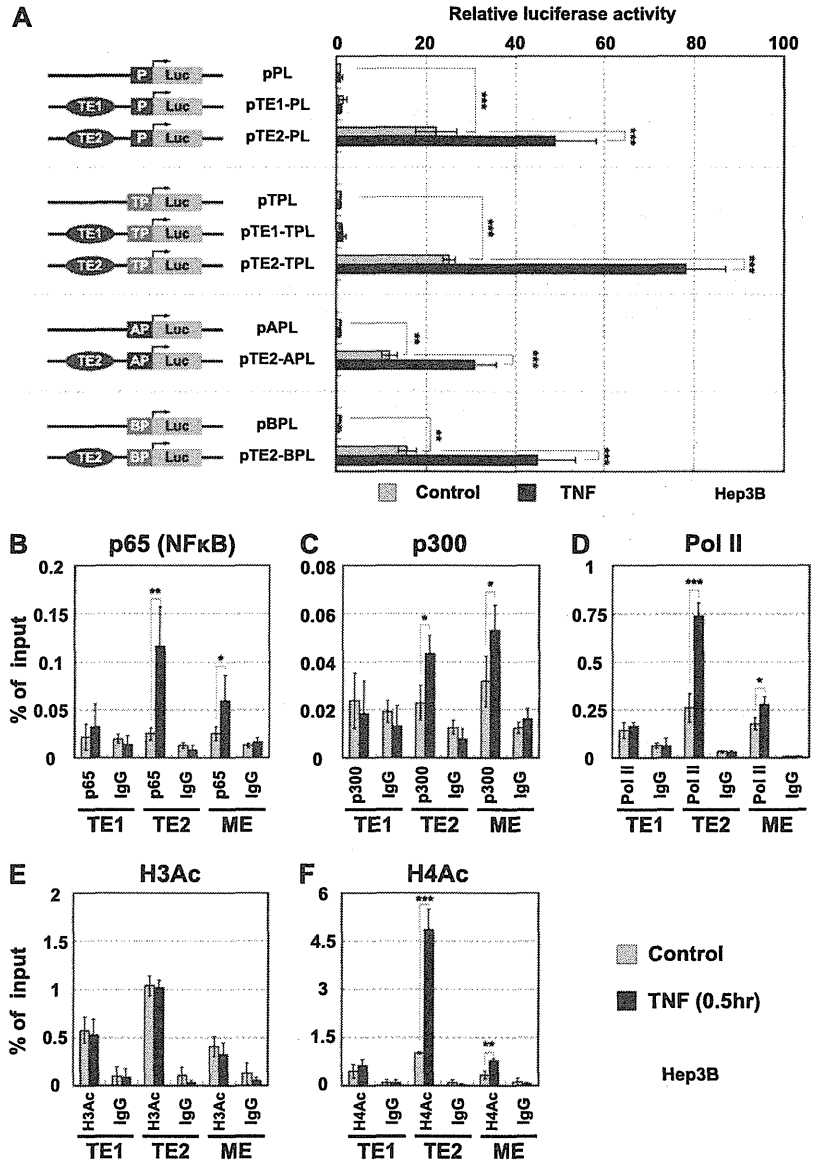


FIG 4 Characterization of TNF-responsive enhancer in the human *TNF/LT* locus. (A) Enhancer activity of TE2. The *luciferase* reporter vectors pPL, pTPL, pAPL, and pBPL contained the *SV40* promoter, *TNF* promoter, *LTα* promoter, and *LTβ* promoter, respectively. The candidate enhancers TE1 and TE2 were inserted in these vectors upstream of the promoter. Hep3B cells were transfected with the reporter vectors and treated with TNF for 3 h (solid bars). Luciferase activities were normalized to basal pPL, pTPL, pAPL, and pBPL. The values are given as means and standard deviations of the results from more than three independent experiments. P, SV40 promoter; TP, *TNF* promoter; AP, *LTα* promoter; BP, *LTβ* promoter. (B to E) The chromatin state of the TE2 enhancer in TNF-stimulated Hep3B cells. ChIP assays were performed with antibodies against p65/NF-κB (B), p300 (C), RNA polymerase II (D), or acetylated histone H3 (E) or H4 (F). The *MCP1* enhancer (ME) was used as a positive control. The values are given as means and standard deviations of the results from more than three independent experiments. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.005$.

and p300 to TE2 occurred at 0.5 h after TNF stimulation. Interestingly, RNA polymerase II (Pol II) and acetylated histone H4 were also significantly enriched at TE2 (Fig. 4D to F). In contrast, histone H3 acetylation showed no remarkable changes (Fig. 4E). It was previously reported that various stimuli, such as serum, interleukin 1β (IL-1β), gamma interferon (IFN-γ), and TNF induced the acetylation of histone H4 but not histone H3 (2, 13, 32). Similar data were obtained in NeHepLxHT cells (see Fig. S3B in the supplemental material). These results indicate that TE2 is an active enhancer, which has four putative κB-binding motifs (see Fig. S3C in the supplemental material), under TNF-stimulated conditions in hepatic cells.

CTCF and the cofactor cohesin are involved in transcriptional regulation in the *TNF/LT* gene cluster. RNA interference-mediated knockdown in Hep3B cells was used to determine if CTCF and cohesin, which are enriched at the TC insulators, were involved in transcriptional regulation in the *TNF/LT* locus. Western blot and qRT-PCR analyses showed that CTCF and RAD21

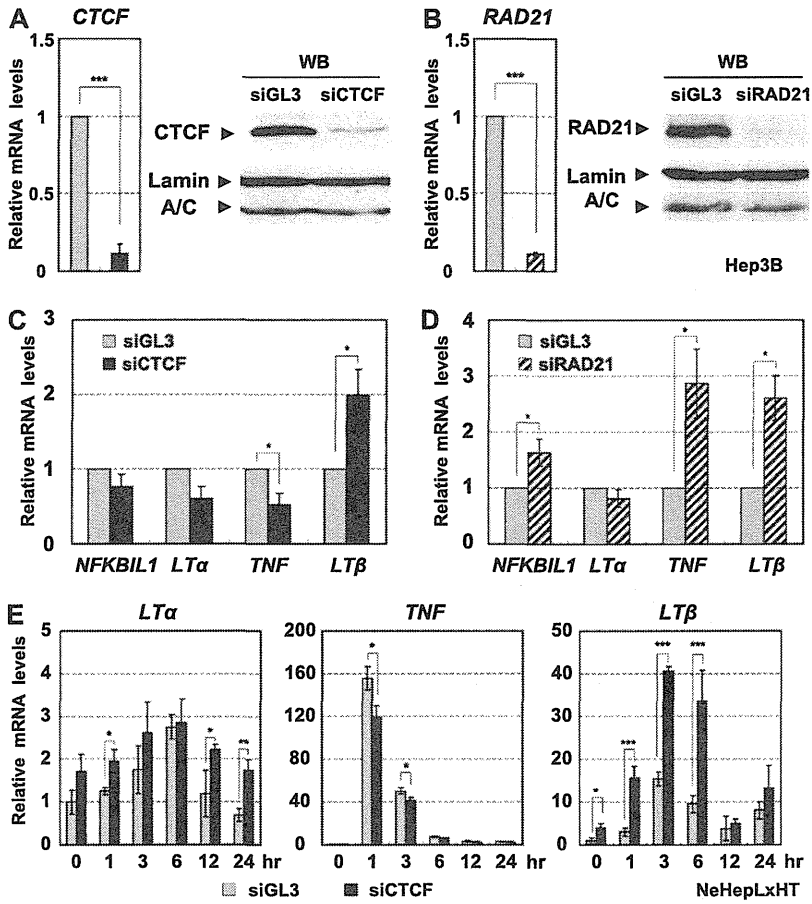


FIG 5 CTCF-mediated insulators are involved in transcriptional regulation in the *TNF/LT* gene cluster. (A and B) RNA interference-mediated knockdown of CTCF (A) and the cofactor cohesin RAD21 (B). Western blot and qRT-PCR analyses were carried out with Hep3B cells. As previously demonstrated (40), more than two distinct siRNAs against CTCF or RAD21 and control siRNAs were used in the experiments. (C and D) Effects of CTCF and RAD21 knockdown on the transcriptional status of the *TNF/LT* genes. Using qRT-PCR analyses, the transcriptional levels of these genes were analyzed relative to that of *β-actin* and were normalized with the control GL3. (E) Effect of CTCF knockdown on *TNF/LT* expression in TNF-stimulated NeHepLxHT cells. CTCF siRNAs were introduced into NeHepLxHT cells for 48 h, followed by TNF treatment for the indicated time period. Values are given as means and standard deviations of the results from more than three independent experiments. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.005$.

were depleted at both the protein and RNA levels (Fig. 5A and B). ChIP-qPCR confirmed that the amounts of CTCF and RAD21 were significantly reduced at each TC site in the knockdown cells (see Fig. S4A and B in the supplemental material). The effect of the knockdown on the constitutively low activation of the *TNF/LT* genes in Hep3B cells was tested by qRT-PCR analyses (Fig. 5C and D). The loss of CTCF reduced *TNF* expression and increased *LTβ* expression, while RAD21 depletion increased *NFKBIL1*, *TNF*, and *LTβ* expression, suggesting that CTCF and cohesin have overlapping but certain distinct roles. Indeed, cohesin was reported to be able to behave as a transcriptional regulator, independent of CTCF (46, 54, 65).

We also analyzed the effects of CTCF knockdown on *TNF/LT* genes in TNF-treated NeHepLxHT cells in which the *TNF/LT* genes are normally silenced (Fig. 5E). The loss of CTCF reduced *TNF* expression and accelerated *LTβ* induction in the stimulated cells (Fig. 5E; see also Fig. S4C to 4E in the supplemental material). These results suggest that CTCF/cohesin-mediated insulators are involved in the transcriptional regulation of the *TNF/LT* gene cluster. It is notable, however, that TNF stimulation itself did not affect the degrees of CTCF and RAD21 enrichment at each TC site (see Fig. S4F and G in the supplemental material), suggesting that higher-order chromatin regulation may be involved in the expression of the *TNF/LT* genes upon TNF stimulation. We assessed the knockdown effects with no significant cell damage throughout the study (see Fig. S4H and I in the supplemental material).

Dynamics of higher-order chromatin conformation in the *TNF/LT* locus. 3C assays were performed with Hep3B and NeHepLxHT cells to investigate higher-order chromatin regulation in the *TNF/LT* locus, where TE2 enhancer, gene promoters and TC insulators were identified as functional elements (Fig. 6; see also Fig. S5 in the supplemental material). Use of the 4-bp-recognizing restriction enzyme DpnII allowed us to examine these elements separately. Based on qPCR analyses of the intramolecular ligation products, the relative interacting frequencies of the reference site (yellow bar) with other 7 DpnII fragments containing each element in the *TNF/LT* locus were measured, as further described in Fig. S6 in the supplemental material. TE2 and TC2 were mainly chosen as the reference sites because of their effectiveness in the experiments. The efficiency of DpnII digestion of

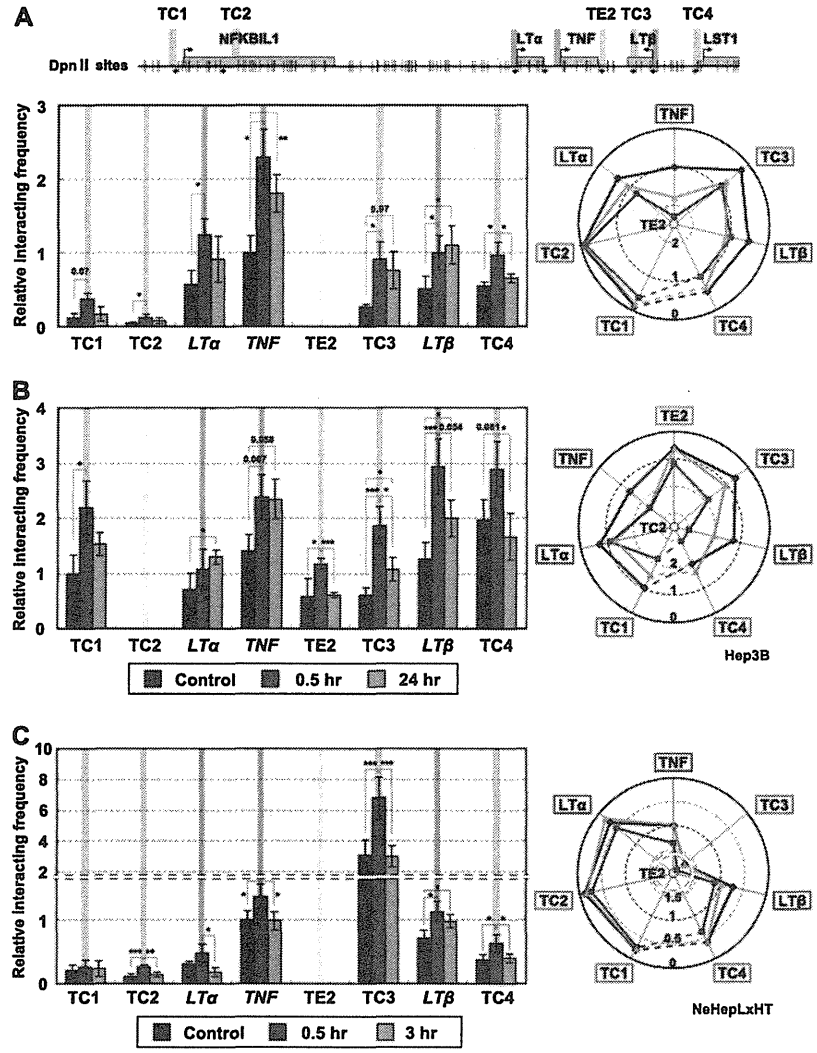
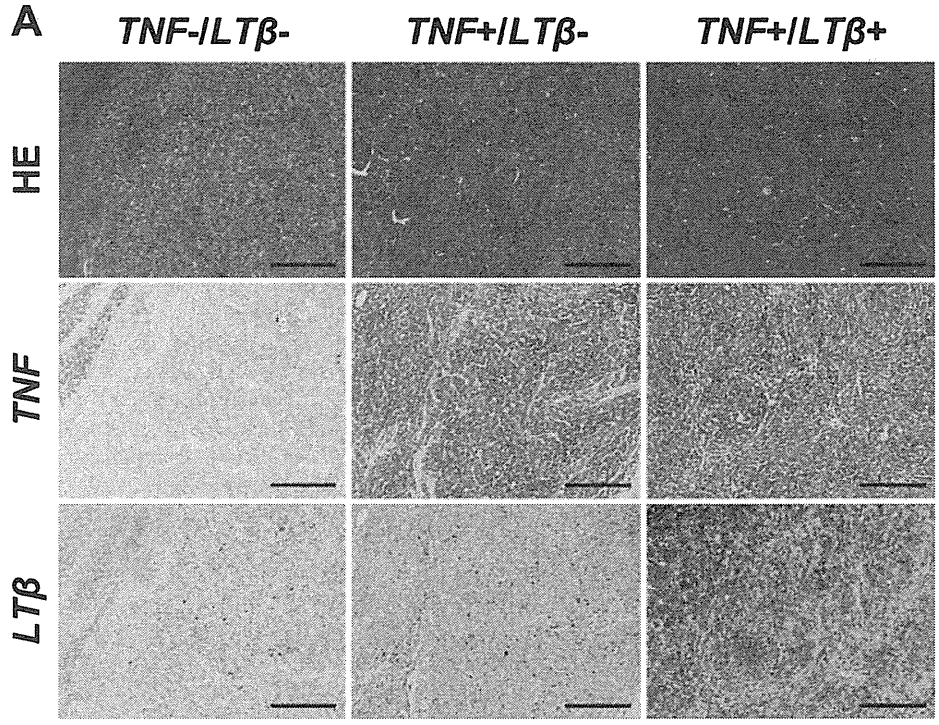


FIG 6 Dynamic changes in higher-order chromatin conformation of the *TNF/LT* locus under TNF stimulation. DpnII digestion was used to design 3C analyses to allow the examination of individual fragments containing each TC site, TNF/LT gene promoter, and TE2 enhancer. (A) The relative interacting frequencies between the reference TE2 fragment (yellow bar) and other DpnII fragments were determined by qPCR analyses of at least three distinct samples from Hep3B cells under TNF treatment. The relative frequencies of interactions between the reference TC2 (yellow bar) and other DpnII fragments in Hep3B cells (B) or between the reference TE2 (yellow bar) and other DpnII fragments in NeHepLxHT cells (C) are shown. In the right panel, the radar chart shows the average relative frequencies of interactions between the reference (central yellow circle) and each functional element. PCR amplification using internal primers located in the *TNF/LT* locus was used for a loading control to normalize the amount of DNA fragments. Efficiencies of DpnII digestion and subsequent ligation were confirmed at each restriction site used. The relative frequencies of interactions between the reference and its physically close site in the control state were normalized to 1 (TE2-*TNF* [A and C] or TC2-TC1 [B]). Control basal state, blue; *TNF*-expressing state, magenta; *TNF/LTβ*-expressing state, green. TC sites, *TNF/LT* gene promoters, and TE2 enhancer are indicated by the same color bars in the locus (upper panel) and the 3C data. The values are given as means and standard deviations of the results from more than three independent experiments. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.005$.

individual sites was > 80%, and samples without ligation gave no PCR-amplified products. We determined if CTCF knockdown affected the chromatin conformation of the *TNF/LT* locus in Hep3B cells (see Fig. S5A and B in the supplemental material). Compared with the basal control state, the frequencies of interactions of the referenced TE2 or TC2 with other fragments were mostly reduced to <50% in the CTCF-depleted cells, suggesting that CTCF is involved in the basal conformation of the locus.

To clarify the spatiotemporal chromatin dynamics of the *TNF/LT* locus, we then examined the frequencies of interaction between these regulatory elements under TNF stimulation (Fig. 6). 3C assays were carried out in the cells under the basal control state, *TNF*-expressing state (0.5 h after stimulation), and *TNF/LTβ*-expressing state (24 or 3 h after stimulation). Compared with results for the basal control state, the frequencies of TE2 interaction with other sites tested in the locus were significantly augmented in *TNF*-expressing Hep3B cells (Fig. 6A), suggesting that intrachromosomal interaction occurred in the locus. Interestingly, TE2 maintained an interaction with the *LTβ* promoter and TC3 in the *TNF/LTβ*-expressing state while remaining separate



B

TNF \ LTβ	+	-
+	12/38 (31.6 %)	10/38 (26.3 %)
-	0/38 (0 %)	16/38 (42.1 %)

FIG 7 Expression of TNF and LTβ in human hepatocellular carcinoma tissues. (A) Representative immunohistochemical staining of human HCC. When the intensity of cytoplasmic staining was equivalent to or higher than that for noncancerous hepatocytes in >50% of cancer cells, the case was defined as positively stained. Three representative cases of the 38 cancer tissue samples tested are shown. Hematoxylin-and-eosin staining (upper) and immunostaining for TNF (middle) and LTβ (lower) are shown. Scale bar, 500 μm. (B) Percentages of TNF- and LTβ-stained cancer tissues. Cases with neither TNF nor LTβ expression (TNF− LTβ−), expression of both (TNF+ LTβ+), and TNF expression alone (TNF+ LTβ−) were found in 42.1%, 31.6%, and 26.3% of the cancer tissues, respectively. No cases expressed LTβ alone. The data for each tissue are summarized in Table S2 in the supplemental material.

from other elements. We also examined the frequencies of TC2 ligation with other fragments and found that TC2 enhanced the interaction with other fragments in the *TNF*-expressing state (Fig. 6B). However, TC2 maintained its close localization with the *TNF* and *LTα* promoters, but not with other fragments, in the *TNF/LTβ*-expressing state. Using the TE2 fragment as a reference, similar data were obtained in TNF-stimulated NeHepLxHT cells (Fig. 6C), except for some interactions of TE2 with the TC3, TC1, and *LTα* promoter. Using the TC2 fragment as a reference, we did not clearly detect the interactions with other fragments in NeHepLxHT cells. Collectively, these data suggest that the enhancer-promoter interactions are selectively controlled by intrachromosomal association and subsequent dissociation of the *TNF/LT* locus upon activation of TNF signaling. To further demonstrate interactions between TC insulators in chromatin reorganization, we assessed their relative frequencies of interaction in these cells using TC4 as a reference (see Fig. S5C and D in the supplemental material). These TC sites consistently showed association in the *TNF*-expressing state and subsequent dissociation in the *TNF/LTβ*-expressing state (modeled in Fig. S7 in the supplemental material).

Expression of TNF and LTβ in human HCC tissues. To examine whether the expression of TNF and LTβ is differentially regulated *in vivo*, we carried out immunohistochemical (IHC) analyses of HCC tissues (Fig. 7). Immunoreactivities of TNF and LTβ were assessed by comparison with the intensity of cytoplasmic staining of noncancerous hepatocytes within the same section. Representative images are shown in Fig. 7A, and the data for each tissue are summarized in Table S2 in the supplemental material. As summarized in Fig. 7B, neither TNF nor LTβ expression was detected in 16 out of 38 HCCs studied (42.1%), while both were densely stained in 31.6% of the cancer tissues. Interestingly,

TNF alone was highly expressed in 10 of the 38 cancer tissues (26.3%), while LTβ alone was not detected in any cases. There may be at least two transcribed states *in vivo*, a TNF-expressing state and a TNF/LTβ-expressing state. We analyzed the correlation between the IHC data and clinical features and found no significant correlations between TNF and/or LTβ expression status and viral status, histological findings (differentiation grade of cancer, presence of chronic hepatitis or cirrhosis), or overall survival of the patients (data not shown). Although it is currently unknown whether the data for HCC tissues are related to higher-order chromatin states of the *TNF/LT* locus (shown in Fig. 6), these results suggest that differential expression of TNF and LTβ occurs *in vivo*.

DISCUSSION

The present study demonstrates the significance of the spatiotemporal regulation of gene activities and higher-order chromatin dynamics in the human *TNF/LT* locus. We identified four CTCF-dependent insulators (TC1, TC2, TC3, and TC4) and an enhancer (TE2) in hepatic cells. The well-known *H19* DMR insulator contains four CTCF binding sites, while each TC site has single CTCF binding sequence with moderate enhancer blocking activities (Fig. 3). The *LTα/TNF* promoters and TE2 were located between TC2 and TC3, while the *LTβ* promoter was between TC3 and TC4, which may play a role in differential regulation of these three genes. The *LTα/TNF* genes were immediately induced by TNF stimulation in a fashion sensitive to inhibition of NF-κB signaling, while the *LTβ* gene was expressed later, as seen in other cell types (1, 39). Our previous report on the human *apolipoprotein* gene locus suggested that CTCF insulators play an essential role in clustered gene control (40). Furthermore, the current study shows that insulator interactions are likely to mediate intrachromosomal association and subsequent dissociation following TNF signaling. The dynamic enhancer-promoter associations and differential expression in the *TNF/LT* locus may be directed by the NF-κB-related regulatory molecules.

From the viewpoint of enhancer-promoter-insulator associations, we propose a spatiotemporal dynamics model in the human *TNF/LT* locus (see Fig. S7 in the supplemental material). In the basal state, CTCF-bound TC sites, the TE2 enhancer, and the *TNF/LT* promoters are located some distance apart in the chromatin structure. After TNF signaling activation, in the *TNF*-expressing state, the TC insulators, TE2, and *TNF/LT* promoters become colocalized and form a compact chromatin structure, resulting in interactions between TE2 and the *TNF* and *LTα* promoters. Because the *LTβ* gene is not fully induced at this stage, the *LTβ* promoter is likely to be sequestered by forming a possible chromatin loop between TC3 and TC4 (see Fig. S5C and D in the supplemental material). In addition, TC sites may be involved in stabilizing the interaction between TE2 and the *TNF* promoter because of the decrease of *TNF* expression in CTCF-depleted cells (Fig. 5C and E). In the *TNF/LTβ*-expressing state, TE2 significantly maintained its interaction with the *LTβ* promoter despite a reduced association with other elements. Thus, sequential chromatin conformation changes may contribute to switching of the enhancer-promoter interaction. Posttranslational modifications of CTCF and changes in the interacting molecules may be involved in the mechanism of intrachromosomal dynamics in the *TNF/LT* locus (47).

Our study revealed that TNF signaling can induce spatiotemporal remodeling of the clustered gene region and that CTCF insulators are likely to mediate higher-order control of transient enhancer-promoter interactions in the *TNF/LT* locus. Previous studies of the *TNF/LT* locus in hematopoietic cells suggested the presence of certain regulatory elements in intron 3 of the *TNF* gene and in the final exon of the *LTβ* gene (5, 66). The sequences, including the TC3 site, showed silencer activity in human T cells, though our study indicated that TC3 had a CTCF-dependent enhancer-blocking function, suggesting that the regulatory elements may differ among cell types. We showed that CTCF-mediated higher-order chromatin is involved in *TNF/LT* gene regulation. Persistent NF-κB activation in chronic inflammation may result in the chromatin conformation of the *TNF/LT* locus being deregulated and maintained in the *TNF/LTβ*-expressing state as an epigenetic memory. Indeed, constitutive NF-κB activation was recently noted to cause *LTβ* expression in inflamed hepatocytes and HCC cells *in vivo* (35), and *LTβ* was demonstrated to be an inducer of HCC (23). The proposed higher-order chromatin conformation of the *TNF/LT* locus may be involved in these *in vivo* situations.

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ORIGINAL ARTICLE—LIVER, PANCREAS, AND BILIARY TRACT

Efficacy and safety of eltrombopag in Japanese patients with chronic liver disease and thrombocytopenia: a randomized, open-label, phase II study

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Abstract
Background Eltrombopag is an oral thrombopoietin receptor agonist that stimulates thrombopoiesis and shows higher exposure in East Asian patients than in non-Asian patients. We evaluated the pharmacokinetics, efficacy, and safety of eltrombopag in Japanese patients with thrombocytopenia associated with chronic liver disease (CLD).
Methods Thirty-eight patients with CLD and thrombocytopenia (platelets <50,000/μL) were enrolled in this phase II, open-label, dose-ranging study that consisted of 2 parts. In the first part, 12 patients received 12.5 mg of eltrombopag once daily for 2 weeks. After the evaluation of safety, 26 patients were randomly assigned to receive either 25 or 37.5 mg of eltrombopag once daily for 2 weeks in the second part.
Results Pharmacokinetics showed that the geometric means of the maximum plasma concentration (C_{max}) and the area under the curve (AUC) in the 12.5 mg group were 3,413 ng/mL and 65,236 ng h/mL, respectively. At week 2, the mean increases from baseline in platelet counts were

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24,800, 54,000, and 60,000/μL in the 12.5, 25, and 37.5 mg groups, respectively. The median platelet counts increased within 2 weeks of the beginning of administration in all groups, and remained at the same level throughout the 2-week post-treatment period in the 12.5 mg group, whereas the platelet counts peaked a week after the last treatment in both the 25 and 37.5 mg groups. Most adverse events reported were grade 1 or 2; 2 patients in the 37.5 mg group had drug-related serious adverse events.

Conclusions Eltrombopag ameliorated thrombocytopenia in Japanese patients with CLD and thrombocytopenia. The recommended dose for these patients is 25 mg daily for 2 weeks.

Keywords Thrombopoietin receptor agonist · Pharmacokinetics · Invasive procedures · Inter-ethnic difference

Introduction

Thrombocytopenia is frequently observed in patients with chronic liver disease (CLD) and is considered a surrogate marker for the severity of liver disease [1, 2]. Besides hypersplenism secondary to portal hypertension, decreased thrombopoietin (TPO) production by hepatocytes is an important cause of thrombocytopenia in this patient population [3].

Some invasive procedures, such as liver biopsy, radiofrequency ablation (RFA), and partial hepatectomy for hepatocellular carcinoma (HCC), are performed as part of the therapeutic management of patients with CLD. Thrombocytopenia often interferes with such invasive procedures and platelet transfusions may be required [4–9]. The frequency of splenectomy and platelet transfusions is significantly higher in HCC patients with severe thrombocytopenia (<50,000/μL) than in those without thrombocytopenia [10]. However, both splenectomy and platelet transfusions have limitations and disadvantages; for example, splenectomy is invasive and may be associated with life-threatening short- as well as long-term complications, and platelet transfusions are short-acting and may cause transfusion-related complications [11–14]. Thus, alternative therapeutic options to platelet transfusions or splenectomy would provide an important clinical benefit.

Eltrombopag (GlaxoSmithKline, Ware, UK) is an orally bioavailable, small-molecule, non-peptide thrombopoietin receptor (TPO-R) agonist, which has been approved for the treatment of chronic idiopathic thrombocytopenic purpura (ITP). Eltrombopag induces the proliferation and differentiation of megakaryocytes, resulting in an increase in platelet production in chimpanzees and humans [15]. Eltrombopag increases platelet counts in a dose-dependent fashion in patients with ITP and in those with thrombocytopenia with hepatitis C virus (HCV) infection, as well as in healthy volunteers [16–19].

Eltrombopag is primarily metabolized in the liver, and a higher plasma eltrombopag exposure has been reported in HCV-infected patients compared with ITP patients and healthy volunteers [20]. Furthermore, inter-ethnic differences in the pharmacokinetics of eltrombopag have been reported; the area under the curve (AUC) of eltrombopag in ITP patients and healthy volunteers was approximately 2-fold higher in East Asian subjects than in those of non-Asian origin [21]. Thus, the pharmacokinetics of eltrombopag in Japanese patients with CLD may be different from those previously reported in ITP patients and Caucasian patients [17–19].

The aim of this phase II study was to assess the efficacy and safety of eltrombopag in Japanese patients with CLD and thrombocytopenia using lower daily doses (12.5, 25, or 37.5 mg) than those typically used for Caucasian patients.

Methods

Patients

A total of 38 patients with CLD (25 with HCV infection, 7 with hepatitis B virus [HBV] infection, 1 with both HCV and HBV infections, and 5 with cryptogenic cirrhosis) were enrolled from 10 Japanese institutions between January and August 2009. Eligible patients were 20 years of age or older and had thrombocytopenia (baseline platelet counts <50,000/μL). Patients were also required to have a Child–Pugh score of 9 or less (Child–Pugh class A or B) and hemoglobin concentration of >8 g/dL for at least 4 weeks before enrollment. Platelet transfusions and interferon therapies had to be completed at least 2 and 4 weeks before enrollment, respectively.

Patients with evidence of human immunodeficiency virus (HIV) infection, evidence of portal vein thrombosis on abdominal imaging within 3 months before enrollment, a history of arterial or venous thrombosis with 2 or more thrombosis risk factors, or platelet agglutination abnormalities were excluded from the study. Patients with active World Health Organization (WHO) grade 3 or 4 bleeding were also excluded [22]. Women who were pregnant or breastfeeding were not eligible, nor were patients who required the use of polyvalent cation-containing medicines, which are known to form chelates with eltrombopag. Patients requiring medications that are known to affect platelet functions [e.g., aspirin, nonsteroidal

anti-inflammatory drugs (NSAIDs), and anti-platelet agents], and patients requiring hydroxymethylglutaryl-CoA reductase inhibitors (for which exposure might be increased by eltrombopag administration) were also excluded.

Diagnosis of liver cirrhosis was assessed by an aspartate aminotransferase-to-platelet ratio index (APRI) of >1 [23] and an FIB4 index of >3.25 according to the Practice Guideline for Liver Cirrhosis edited by the Japanese Society of Gastroenterology [24]. Creatinine clearance was estimated by the Cockroft–Gault formula [25] in a post-hoc analysis.

This study was approved by each institutional review board and was conducted in accordance with the Declaration of Helsinki, Good Clinical Practice guidelines, and local laws and regulations. All patients provided written informed consent before enrollment.

Treatments

Because inter-ethnic differences in the eltrombopag AUC have been found in earlier studies [21, 26], lower doses (12.5, 25, 37.5 mg) of eltrombopag were used than the doses (30, 50, 75 mg) used in a previous study conducted in cirrhotic patients (predominantly Caucasian) with HCV infection [18]. All doses were administered with the patients in a fasting state, in which the patients were required to refrain from food ingestion for at least 2 h pre- and post-dose.

Study design and procedures

This was a multicenter, open-label, dose-ranging phase II study that used a unique sequential design and consisted of 2 parts. In the first part, 12 patients received 12.5 mg of eltrombopag once daily for 2 weeks, and the data were reviewed by a Safety Review Committee (Fig. 1). After the evaluation of safety in the first part, in the second part 26 new patients were randomly allocated, at a 1: 1 ratio, to receive either 25 or 37.5 mg of eltrombopag once daily for 2 weeks. An additional week of treatment was allowed if platelet counts were <80,000/μL at week 2 (Fig. 1). Eltrombopag treatment was to be discontinued if platelet counts were >200,000/μL during the treatment period. Invasive procedures could be performed after the end of treatment with eltrombopag per the investigator's decision. All patients were assessed for the efficacy and safety of eltrombopag every week during the treatment period, and at 4 days, 1 week, and 2 weeks post-treatment.

The primary endpoint of the study was the change from baseline in platelet counts at the end of week 2. Secondary endpoints were: (1) response rate (achieving platelet counts of ≥80,000/μL) of eltrombopag administered for 2 weeks, or after an additional week, (2) median platelet counts, and (3) safety. The severity of adverse events was graded using the Division of AIDS Table for Grading the Severity of Adult and Pediatric Adverse Events (version 1.9, dated December 2004). The effects of pretreatment with

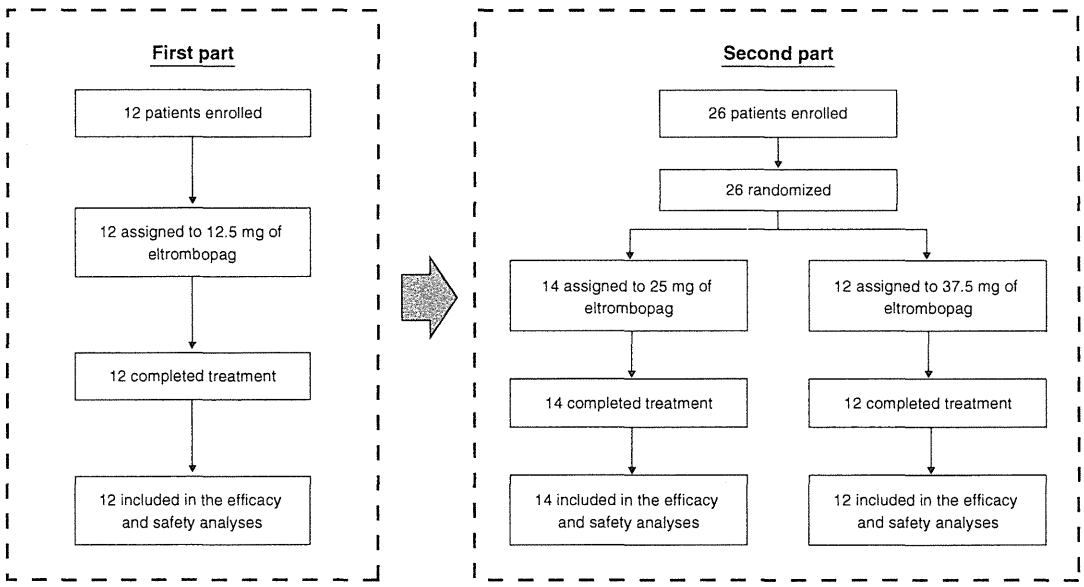

Fig. 1 Study design. The study was a multicenter, open-label, dose-ranging phase II study that used a unique sequential design and consisted of 2 parts. After review, by a Safety Review Committee, of safety data from the 12.5 mg group (first part), new patients were randomly assigned to receive 25 or 37.5 mg of eltrombopag once daily for 2 weeks in the second part

eltrombopag on the prevalence of perioperative bleeding and platelet transfusions were also evaluated when invasive procedures, such as liver biopsy, RFA, and partial hepatectomy, were performed after the end of treatment.

Randomization and masking

In the second part of this study, patients were randomly allocated to either the 25 or 37.5 mg group. Randomization was centrally performed, and the random assignment was stratified according to baseline Child–Pugh class (A or B). This study was not blinded.

Pharmacokinetics

Serial samples were collected pre-dose (prior to administration on day 14), and 1, 2, 4, 6, 8, 10, and 24 h post-dose in the 12.5 mg group. Pharmacokinetic parameters [maximum plasma concentration (C_{max}) and time to maximum plasma concentration (T_{max}), AUC_{0-t}, and $AUC_{0-\tau}$] in the 12.5 mg group were determined with actual sample times using non-compartmental analysis and summary statistics. Sparse samples were collected in the 25 or 37.5 mg group following 1 of 2 schedules: (1) pre-dose (prior to administration on day 14) and 0.5–3, and 24 h post-dose, or (2) 4–6, 8–12, and 24 h post-dose. The geometric mean of the plasma eltrombopag concentration was summarized in each group. One patient each from the 12.5 and 37.5 mg groups was excluded from the summary statistics, as these 2 patients had used a cation-containing antacid.

Statistical analyses

On the basis of a previous study [18], the changes from baseline in platelet counts at week 2 were assumed to be 30,000, 80,000, and 100,000/μL in the 12.5, 25, and 37.5 mg groups, respectively, and the standard deviation was 50,000/μL in each group. Based on Monte Carlo simulations, 12 evaluable patients per group were needed to provide 90 % or more power to detect a linear dose trend and saturation at a medium dose trend. No interim analysis was planned. Descriptive statistics and frequency tables were used to summarize demographics, baseline characteristics, and safety data. The analyses included all patients who had received at least one dose of eltrombopag.

The primary endpoint was analyzed using point estimates and 2-sided 95 % confidence intervals (CIs) by each group. In an exploratory analysis, the changes from baseline in platelet counts at week 2 were analyzed using analysis of covariance (ANCOVA), with baseline platelet counts as a covariate to detect the following dose response patterns: linearity in 3 doses, saturation at the medium dose (25 mg), or onset of response at the high dose (37.5 mg). A similar analysis, with both baseline platelet counts and Child–Pugh class as covariates, was conducted as a secondary analysis. This model used the changes in platelet counts of each patient. No adjustment for multiplicity was made because these analyses were exploratory. Other secondary endpoints were analyzed using point estimates and 2-sided 95 % CIs for each group. Analyses were based on the observed data.

This study is registered at ClinicalTrials.gov with identifier number: NCT00861601.

Role of the funding source

The protocol was developed by the principal investigators and employees of the sponsor. Data were collected and analyzed by the sponsor. All authors had access to the primary data and vouch for the completeness and accuracy of the data and analyses. Interpretation of the data and decisions related to the content of the report were made through collaboration among all authors. The corresponding author had final responsibility for the decision to submit for publication.

Results

Patient characteristics

Patients' characteristics are summarized in Table 1. There were no marked differences in age, sex, body mass index (BMI), Child–Pugh classification, or creatinine clearance among the groups. In addition, no apparent differences were seen in baseline platelet counts among the groups. All the enrolled patients showed APRI >1 and/or FIB4 >3.25 in a post-hoc analysis. Furthermore, 87 % of the enrolled patients (33/38) had 1 of the following complications of liver cirrhosis: edema (2/38), ascites (6/38), esophageal and/or gastric varices (26/38), or HCC (18/38).

Pharmacokinetics

The geometric mean of C_{max} in the 12.5 mg group was 3,413 ng/mL (95 % CI 2,549–4,570) at approximately 3.4 h after administration, and the geometric mean of the AUC (0–24) was 65,236 ng h/mL (95 % CI 46,748–91,035) (Table 2). There was no apparent difference in the mean plasma eltrombopag concentration stratified by Child–Pugh class in the 12.5 and 25 mg groups (Fig. 2a, b). However, in the 37.5 mg group a higher mean plasma concentration of eltrombopag was observed in patients with Child–Pugh class B compared with patients with Child–Pugh class A (Fig. 2c).

Table 1 Patient characteristics

		12.5 mg ($N = 12$)	25 mg ($N = 14$)	37.5 mg ($N = 12$)
Age (years)	Median (range)	63.0 (45–81)	58.0 (44–75)	69.5 (48–81)
Sex	Female/male	4/8	4/10	4/8
Body mass index (kg/m^2)	Mean ± SD	22.6 ± 2.20	25.0 ± 4.15	24.7 ± 4.72
Etiology of liver disease	HCV/HBV/cryptogenic	7/4/1	9/3/2	10/1/2[a]
Child–Pugh classification	A/B	8/4	8/6	7/5
APRI	Mean ± SD	4.3 ± 2.0	4.9 ± 2.8	4.9 ± 2.8
FIB4	Mean ± SD	12.7 ± 3.6	13.8 ± 4.5	16.5 ± 8.2
Baseline platelet count (/μL)	Median (range)	42,500 (36,000–49,000)	38,000 (19,000–48,000)	40,000 (23,000–49,000)
Total bilirubin (mg/dL)	Mean ± SD	1.51 ± 1.19	1.53 ± 0.62	1.27 ± 0.52
Creatinine (mg/dL)	Mean ± SD	0.70 ± 0.22	0.72 ± 0.16	0.83 ± 0.26
Creatinine clearance (mL/min)	Mean ± SD	93.5 ± 29.7	106.1 ± 34.9	84.2 ± 40.4

HBV hepatitis B virus, *HCV* hepatitis C virus, *SD* standard deviation, *APRI* aspartate aminotransferase-to-platelet ratio index

[a] One patient in the 37.5 mg group was infected with both HCV and HBV

Table 2 Pharmacokinetic parameters (12.5 mg eltrombopag group, log-transformed data)

	N	n[a]	Geom. mean	95 % CI of geom. mean		SD logs	%CVb
				Lower	Upper		
C_{max} (ng/mL)	12	11	3,413	2,549	4,570	0.4345	45.6
T_{max} (h)	12	11	3.44	2.459	4.823	0.5012	53.4
AUC(0–t) (ng h/mL)	12	11	65,244	46,617	91,314	0.5004	53.3
AUC(0–24) (ng h/mL)	12	11	65,236	46,748	91,035	0.4960	52.8

CI confidence interval, *Geom. mean* geometric mean, *CVb* between-subject coefficient of variance, C_{max} maximum plasma concentration, T_{max} time to maximum plasma concentration

[a] One patient was excluded from the summary statistics of pharmacokinetic parameters because the patient had used a cation-containing antacid, which affects the exposure of eltrombopag

Efficacy

Primary endpoint

Changes from baseline in platelet counts at week 2 The mean increases from baseline in platelet counts at week 2 were 24,800/μL (95 % CI 8,200–41,400), 54,000/μL (95 % CI 28,200–79,800), and 60,000/μL (95 % CI 29,300–90,700) in the 12.5, 25, and 37.5 mg groups, respectively (Fig. 3). An exploratory analysis showed statistically significant linearity in 3 doses ($p = 0.0104$) and saturation at the medium dose ($p = 0.0057$) at the 5 % significance level.

Secondary endpoints

Response rate to eltrombopag and effects of an additional 1-week treatment There were 3 (25 %), 6 (42.9 %), and 7 (58.3 %) patients in the 12.5, 25, and 37.5 mg groups, respectively, who responded (achieved platelet counts of ≥80,000/μL) to eltrombopag at week 2. Six patients in the 25 mg group and 2 patients in the 37.5 mg group with platelet counts of <80,000/μL at week 2 received an additional 1 week of treatment. Of these patients, 3 in the 25 mg group and 1 in the 37.5 mg group responded to the additional week of treatment. Platelet counts in these 4 patients increased to approximately 70,000/μL (range 69,000–74,000) by week 2.

Median platelet counts after administration of eltrombopag The median platelet count in the 12.5 mg group increased from 42,500/μL [inter-quartile range (IQR) 40,500–45,500] at baseline to 66,000/μL (IQR, 45,000–83,000) at week 2 and remained at the same level for 2 weeks post-treatment. In contrast, in the 25 and 37.5 mg groups, the median platelet counts increased to 73,000/μL (IQR, 69,000–110,000) and 81,500/μL (IQR, 69,500–114,000), respectively, by week 2. At 1-week post-treatment, the median platelet counts peaked at 119,000/μL (IQR, 90,000–141,000) and 120,000/μL (IQR, 95,500–175,500) in the 25 and 37.5 mg groups, respectively, and remained at >80,000/μL for 1 week thereafter (Fig. 4). The median increases from baseline in platelet counts at week 2 for

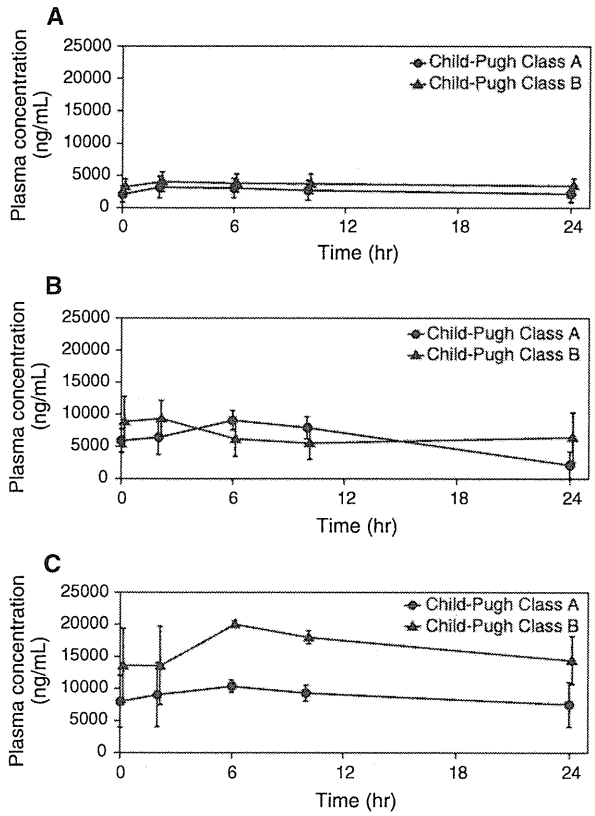

Fig. 2 Plasma eltrombopag concentration stratified by Child–Pugh class in the 12.5 mg (**a**), 25 mg (**b**), and 37.5 mg groups (**c**). One patient in the 12.5 mg group with Child–Pugh class A and another patient in the 37.5 mg group with Child–Pugh class B were excluded from summary statistics of plasma concentration, because both patients had used a cation-containing antacid, which affects the exposure of eltrombopag. Data are expressed as means ± SD

Child–Pugh class A and B, respectively, were 11,000/μL (range, −9,000 to 83,000) and 28,000 (range, 17,000–30,000) in the 12.5 mg group; 38,500/μL (range, 12,000–100,000) and 50,000 (range, 19,000–187,000) in the 25 mg group; and 46,000/μL (range, 8,000–193,000) and 50,000 (range, 20,000–91,000) in the 37.5 mg group.

Safety

The incidences of adverse events (AEs) of any grade during the study were 50 % (6/12), 50 % (7/14), and 75 % (9/12) in the 12.5, 25, and 37.5 mg groups, respectively (Table 3). Most AEs reported were grade 1 or 2 in severity. Back pain, pyrexia, and postoperative fever were the most common AEs, and they occurred mostly after invasive procedures. No grade 3 or higher AEs occurred during the treatment period. No subject discontinued eltrombopag because of AEs or platelet counts of >200,000/μL during the study.

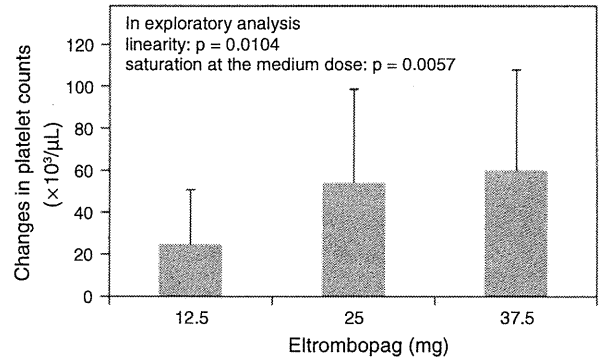

Fig. 3 Changes from baseline in platelet counts at week 2. Exploratory analyses were conducted to detect a dose response and trend, using the changes from baseline in platelet counts at week 2. These data were analyzed using analysis of covariance (ANCOVA) with baseline platelet counts as a covariate, using contrast methods for the following dose response patterns: linearity in 3 doses [contrast of 12.5, 25 and 37.5 mg: −1 0 1], saturation at the medium dose (25 mg) [contrast: −2 1 1], and onset of response at the high dose (37.5 mg) [contrast: −1 −1 2]. No adjustment for multiplicity was made. Data are expressed as means + SD

Drug-related AEs occurred in 8 % (1/12), 29 % (4/14), and 33 % (4/12) of patients in the 12.5, 25, and 37.5 mg groups, respectively (Table 3). No drug-related serious adverse events (SAEs) were seen in either the 12.5 or 25 mg groups; however, 2 patients in the 37.5 mg group experienced drug-related SAEs (Table 3).

Drug-related SAEs

SAE#1; worsening pleural effusion and development of portal vein thrombosis

A 63-year-old female cirrhotic patient with HCC, esophageal varices, and pleural effusion was administered 37.5 mg of eltrombopag daily for 14 days. Her platelet count increased from 36,000 to 127,000/μL and there were no AEs during eltrombopag administration. On day 23, the patient underwent partial splenic embolization. On day 35, grade 3 worsening pleural effusion and grade 3 portal vein thrombosis were seen. Platelet counts were 197,000 and 271,000/μL on days 22 and 35, respectively. With conservative therapy, the pleural effusion and portal vein thrombosis improved, on days 77 and 140, respectively.

SAE#2; worsening ascites

An 81-year-old female cirrhotic patient with HCC and ascites was administered 37.5 mg of eltrombopag daily for 14 days. Her platelet count increased from 49,000 to 242,000/μL. Although no thrombus was observed on computed tomography (CT) images, grade 2 worsening ascites was seen on day 11. The ascites was refractory to

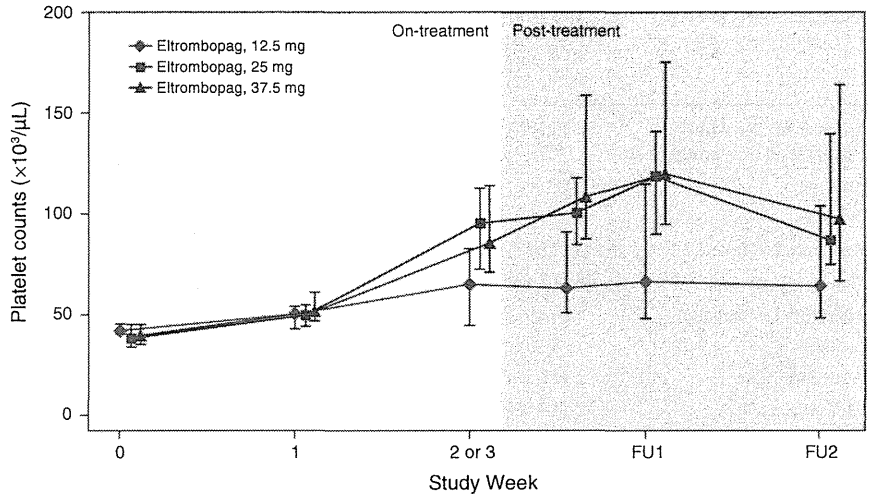

Fig. 4 Median platelet counts after treatment with eltrombopag. Platelet counts at either week 2 or 3, or at the end of treatment with eltrombopag. Platelet counts after the end of treatment include the values after invasive procedures or platelet transfusions. Data are expressed as medians with interquartile ranges (IQRs). *FU* follow up

diuretic agents and an albumin preparation and was found to be chylous on day 57. Platelet counts were 87,000 and 197,000/μL on days 9 and 57, respectively. The patient developed cachexia and renal failure, and died on day 163 (149 days after the end of eltrombopag treatment).

Effects of pretreatment with eltrombopag on the prevalence of perioperative bleeding and platelet transfusions

Of the 38 patients who received eltrombopag, 6 patients underwent a total of 7 invasive procedures with bleeding risk after the end of treatment with eltrombopag. RFA was the most common procedure during the study (Table 4). Five of these patients had platelet counts of >80,000/μL prior to undergoing their invasive procedures, and most of the procedures were safely performed without platelet transfusions (Table 4).

Discussion

This study demonstrated that significant increases in platelet counts could be achieved by 2-week administration of eltrombopag to Japanese patients with CLD and thrombocytopenia. Our results also show that a maximum of 25 mg of eltrombopag, a lower dose than that typically used in Caucasian patients, can be recommended for Japanese patients with CLD and thrombocytopenia.

In this phase II study, we investigated the pharmacokinetics of eltrombopag in Japanese patients with CLD and thrombocytopenia. An inter-ethnic difference in the pharmacokinetics of eltrombopag has been observed between East Asian and non-Asian patients with ITP, as well as between East Asian and non-Asian healthy volunteers [21]; in our study, the $AUC_{0-\tau}$ in Japanese patients receiving 37.5 mg of eltrombopag once daily was estimated to be 236 μg h/mL, which is similar to that seen in non-East Asian patients with CLD receiving 75 mg once daily in a previous study [26]. Although the mechanisms underlying an inter-ethnic difference in the pharmacokinetics of eltrombopag remain unclear, a common difference between East Asian and Caucasian ethnic groups is body weight [27]. Because the clearance of eltrombopag increased with body weight [21] and because the body weight of East Asian patients is lower than that of Caucasian patients in general, body weight differences could account for the differences in serum levels of eltrombopag seen between the two groups. A pharmacogenetic study has also been performed to investigate a relationship between gene polymorphisms and inter-ethnic differences; however, the responsible polymorphism has not been identified (data not shown). Eltrombopag is a substrate of several drug-metabolizing enzymes, including cytochrome P450 (CYP) 1A2, CYP2C8, uridine diphosphate-glucuronosyltransferase (UGT) 1A1, and UGT1A3, and the agent is also a substrate of breast cancer resistance protein [27]. Because the activities of these enzymes are known to have inter-ethnic differences [28, 29], it is possible that multiple factors, including genetic differences in metabolizing enzymes and transporters, may be involved in the observed difference [27].

In the present study, platelet counts continued to increase 1 week post-treatment and gradually decreased thereafter. This finding is similar to that seen in another study of eltrombopag in patients with CLD and thrombocytopenia; in contrast, in several studies of eltrombopag in chronic ITP, platelet counts began to decrease at 1 week post-treatment and returned to baseline levels within 2 weeks [19, 30]. Although the reason is unclear, 2