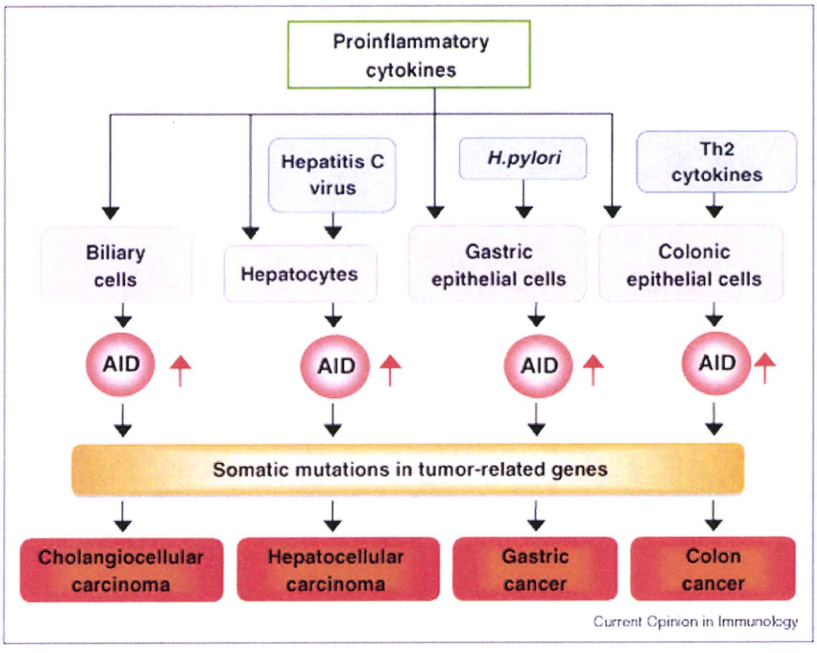
(TNF)-α and IL-1β can induce NF-κB activation in various types of cells. These hypotheses are supported by *in vitro* analyses showing that AID expression is induced in response to cagPAI-positive *H. pylori* infection or stimulation with the proinflammatory cytokine TNF-α via NF-κB signaling in cultured human gastric epithelial cells [21]. Based on the clinical course of *H. pylori*-infected individuals, both bacterial factors that are introduced into epithelial cells and the inflammatory response against *H. pylori* infection would be responsible for aberrant AID expression in gastric epithelium (Figure 1), and the direct action of the bacterial virulence factors contributes to activate AID in the early stage of *H. pylori* infection when the number of bacteria is high. In the late phase of chronic gastritis, when gastric atrophy has progressed and the number of *H. pylori* is decreased, the proinflammatory cytokine plays a central role in causing the constitutive expression of AID in gastric epithelial cells.

AID induces DNA mutations in tumor-related genes in gastric epithelial cells

The target of AID-mediated genotoxic effects is not restricted to immunoglobulin genes and several non-immunoglobulin genes are also targeted by AID in lymphocytes. Approximately 25% of expressed non-immunoglobulin genes analyzed, including Bcl6 and Cd83, accumulated AID-mediated mutations in germinal B cells [29••]. Moreover, AID produces double-strand DNA breaks throughout the genome, including *c-myc* in B cells [30,31•]. The impact of AID expression in non-lymphoid gastrointestinal epithelial cells was clarified using mouse model with constitutive and ubiquitous AID expression. AID transgenic mice accumulated somatic mutations in various tumor-related genes and developed tumors in both lymphoid and non-lymphoid tissues [32,33]. The tumors developed in the epithelial organs of AID transgenic mice included lung, liver, and gastric cancers.

The findings that AID mutagenic activity results in stomach cancer led us to speculate that *H. pylori* infection in association with aberrant AID expression contributes to human carcinogenesis via the accumulation of genetic alterations in gastric epithelial cells [21]. In *in vitro*-cultured gastric epithelial cells, cagPAI-positive *H. pylori* infection led to somatic mutations in the tumor-suppressor *TP53* gene. The number of nucleotide alterations observed in *H. pylori*-infected cells was significantly reduced by knockdown of

Figure 2



AID links inflammation and infection to cancer development in various gastrointestinal tissues. This figure is a model depicting the role of AID in the development of human cancers. Normal epithelial cells lack endogenous AID expression under physiologic conditions. *Helicobacter pylori* (*H. pylori*) infection and the resultant inflammatory stimulation, however, trigger aberrant AID expression in gastric epithelial cells. Similarly, hepatitis C virus infection and the resultant constitutive inflammation lead to AID expression in hepatocytes. In addition to proinflammatory cytokines, Th2 cytokine plays a role in the enhanced expression of AID in colonic epithelium. Constitutive AID activation in these epithelial cells results in the accumulation of somatic mutations in various target genes. If crucial nucleotide changes in the tumor-related genes are induced by AID activity, the resultant cells can acquire the transformation, leading to cancer development.

endogenous AID, indicating that the somatic mutations in the *TP53* gene in cells infected with cagPAI-positive *H. pylori* were due to the induction of endogenous AID expression in gastric cells. In wild-type mice, oral infection with cagPAI-positive *H. pylori* upregulated AID protein expression. Moreover, nucleotide alterations emerge in the *TP53* gene in stomach tissues after oral *H. pylori* infection in wild-type mice. These findings strongly suggest that *H. pylori* infection causes accumulation of somatic mutations in tumor-related genes such as *TP53* through aberrant upregulation of AID in gastric epithelial cells.

H. pylori-associated lymphoid tumorigenesis and AID expression

Low-grade lymphomas originating from MALT develop in the stomach, salivary and thyroid glands, bronchi, and small intestine, and are classified as MALT lymphoma [34,35]. The acquisition of MALT is induced before the development of lymphoma as a response to a persistent antigenic stimulation [36]. The development of gastric MALT lymphoma, a representative gastric lymphoma, is strongly associated with *H. pylori* infection [37]. The seroprevalence of *H. pylori* is higher in patients with gastric MALT lymphomas than in control patients without MALT lymphoma [38], and eradication of *H. pylori* leads to complete regression of the lymphoma in nearly 80% of patients with early-stage disease [39,40]. On the contrary, several studies have aimed to clarify the role of AID in the development of MALT lymphoma, because AID is required for the development of germinal center-derived non-Hodgkin's lymphomas [41,42•]. AID mRNA was, however, expressed in only some extranodal marginal zone B-cell MALT lymphomas [41]. More recent studies demonstrate that neoplastic marginal zone B cells did not express detectable AID, whereas AID expression was confined to reactive areas within MALT lymphomas [43,44]. In addition to the low frequency of AID upregulation in MALT lymphoma tissues, it remains unknown whether *H. pylori* infection enhances the aberrant mutagenic activity of AID in gastric B cells. Further analyses are required to determine the role of AID in the development of *H. pylori*-associated MALT lymphomas.

Conclusions

The discovery of AID was a seminal finding that greatly advanced our understanding of the molecular mechanisms involved in immunoglobulin diversification [45]. Now, AID is central to our understanding of how inflammation and infection underlie the genetic alterations required for carcinogenesis in epithelial cells [46]. Indeed, proinflammatory cytokine induction of AID expression via the NF-κB pathway is not limited to gastric epithelial cells. AID expression is mediated by the inflammatory response in a variety of epithelial cells, including human hepatocytes [47,48••], and biliary [49] and colonic epithelial cells [50•]. Aberrant AID expression in these gastrointestinal organs results in somatic mutations in various tumor-related genes. Thus, AID may have a central role in genetic susceptibility to mutagenesis, which leads to cancers in these gastrointestinal tissues upon exposure to certain inflammation or infection (Figure 2).

A characteristic of *H. pylori*-associated gastric cancer is multicentric tumor development. Patients with a history of *H. pylori*-related gastric cancer are at high risk for subsequent development of gastric cancers [51], suggesting that each epithelial cell of the *H. pylori*-infected stomach possesses sufficient genetic damage for malignant transformation. Efficient strategies to restrict aberrant AID activity might help to prevent carcinogenesis in gastric epithelial cells inflamed by *H. pylori* infection.

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Conflict of interest

None.

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Individualized Extension of Pegylated Interferon Plus Ribavirin Therapy for Recurrent Hepatitis C Genotype 1b After Living-Donor Liver Transplantation

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Background. The efficacy of combination therapy with pegylated interferon and ribavirin for recurrent hepatitis C genotype 1 after liver transplantation is limited. In this study, we designed an individualized treatment regimen with pegylated interferon and ribavirin for recurrent hepatitis C based on individual viral responses.
Methods. Thirty-four patients with recurrent hepatitis C genotype 1b after living-donor liver transplantation received combination therapy with pegylated interferon α-2b and ribavirin. Treatment was continued for an additional 12 months after serum hepatitis C virus (HCV) RNA became undetectable.
Results. Of the 34 patients, 18 became negative for serum HCV RNA within 12 months (range, 1.2–9.9 months; median, 4.0 months). The treatment for the 18 patients was individualized by adding a further 12 months of treatment after the disappearance of serum HCV RNA, resulting in treatment durations of 13.2 to 21.9 months (median, 16.0 months). Notably, 17 (94%) of the 18 patients who received the individualized extended treatment achieved sustained virologic response (SVR), resulting in a 50% SVR rate. Six patients (18%) discontinued the treatment, but none of the 18 patients who received the extended protocol withdrew from the study.
Conclusions. Individualized extension of combination therapy with pegylated interferon and ribavirin for recurrent hepatitis C after liver transplantation resulted in a high SVR rate and good tolerability.

Keywords: Hepatitis C, Liver transplantation, Extended treatment, Pegylated interferon, Ribavirin.

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Hepatitis C virus (HCV) infection is the predominant cause of cirrhosis and hepatocellular carcinoma in Japan, the United States, and western Europe. End-stage liver disease caused by HCV infection is the main indication for liver transplantation. However, almost all patients who receive liver transplantation for HCV-related liver disease develop recurrent infection, and 70% to 90% of patients suffer from histologically proven recurrent hepatitis (*1–6*). The progression of recurrent hepatitis C is often accelerated, and without appropriate antiviral therapy, 10% to 25% of patients develop cirrhosis within 5 years of transplantation, resulting in poorer prognosis for HCV-positive recipients than for HCV-negative recipients (*7*). The median interval from transplantation to cirrhosis is 10 years for transplant patients, compared with that of 20 to 40 years for nontransplant patients (*8*).

To prevent the progression of hepatitis C after liver transplantation, combination therapy with pegylated interferon and ribavirin is commonly administered for 12 months (*9, 10*). However, the efficacy of this combination therapy is limited, especially for patients infected with HCV genotype 1. A systematic review of studies on combination therapy with pegylated interferon and ribavirin for recurrent hepatitis C after liver transplantation showed that the mean sustained virologic response (SVR) rate among patients infected with HCV genotype 1 was only 28.7% (range, 12.5%–40%) (*11*). In contrast, the mean end-of-treatment virologic response was 42.2% (range, 17%–68%), indicating that virologic relapse was a major cause of the low SVR rate. Therefore, it is necessary to develop a new strategy for reducing the incidence of relapse if the SVR rate is to be increased.

Recently, trials have been conducted to evaluate whether the SVR rate in nontransplant patients with chronic

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hepatitis C genotype 1 can be improved by extending the duration of treatment (*12–17*). These trials indicated that extension of treatment from 48 to 72 weeks significantly increased the SVR rate in patients with a delayed virologic response. However, because the virologic response to the treatment varies between patients, especially between transplant recipients who frequently require dose reduction, it is desirable to individualize the treatment regimen to achieve SVR more efficiently.

In this study, we designed an individualized treatment regimen in which combination therapy with pegylated interferon α-2b and ribavirin was continued in patients for an additional 12 months after serum HCV RNA became undetectable, and the efficacy of this extended treatment in patients with recurrent hepatitis C genotype 1b who had undergone living-donor liver transplantation (LDLT) was evaluated.

EXPERIMENTAL PROCEDURES

Patients

Between February 2006 and February 2008, 40 patients were evaluated for antiviral treatment after undergoing LDLT for HCV-related liver diseases caused by HCV genotype 1b infection at the Kyoto University, and 34 patients were diagnosed as having recurrent hepatitis C. Of the 34 patients, five patients had previously been treated with interferon plus ribavirin after liver transplantation and did not achieve an SVR (*18*). Combination therapy with pegylated interferon and ribavirin was administered to the 34 patients. Eligibility criteria for the treatment were positivity for serum HCV RNA and histologic evidence of recurrent hepatitis C. Patients with a necroinflammatory activity classification of A2 or greater or a fibrosis stage of F1 or greater (METAVIR score) were treated. Exclusion criteria were a neutrophil count of less than 750/μL, a platelet count of less than 40,000/μL, a hemoglobin level of less than or equal to 9.0 g/dL, and renal insufficiency (serum creatinine levels >2 mg/dL).

Treatment Protocol and Definition of Responses to Treatment

The treatment protocol for patients with recurrent hepatitis C after liver transplantation consisted of 1.5 μg/kg of pegylated interferon α-2b once weekly plus ribavirin at an oral dose of 600 mg/day (body weight <60 kg) or 800 mg/day (body weight >60 kg). Patients who became negative for serum HCV RNA within 12 months of initiation of the combination therapy were enrolled in the individualized treatment protocol, which started when patients first became negative for serum HCV RNA and ended 12 months thereafter. The overall duration of treatment was defined as the sum of the period that elapsed before disappearance of serum HCV RNA plus 12 months for individualized treatment after the disappearance of serum HCV RNA (e.g., if serum HCV RNA became negative after 3 months, the total treatment duration was 15 months). Patients who were negative for serum HCV RNA for more than 6 months after completion of interferon therapy were defined as showing an SVR. If serum HCV RNA was positive after 12 months, the treatment protocol was discontinued and the patient was classified as having shown no response.

The dose of pegylated interferon was reduced to 0.75 μg/kg if the neutrophil count was less than 750/μL or the platelet count was less than 75,000/μL, and pegylated interferon was discontinued if the neutrophil count was less than 500/μL or the platelet count was less than 50,000/μL. The ribavirin dose was reduced to 400 mg/day if the hemoglobin level was less than 10 g/dL and to 200 mg/day if the hemoglobin level was less than 9 g/dL. Ribavirin was discontinued if the hemoglobin level was less than 8 g/dL. Granulocyte colony-stimulating factor (lenograstim, 100 μg/week) was used for neutrophil counts below 500/μL and was continued until values returned to more than 750/μL. Recombinant erythropoietin (epoetin beta, 6000 IU/week) was started if the hemoglobin level was less than 8 g/dL and was continued until it became more than 9 g/dL. Granulocyte colony-stimulating factor was used for two patients, and erythropoietin was given in four patients (Table 1).

Immunosuppression

The standard immunosuppression protocol consisted of tacrolimus and low-dose steroid therapy (*18*). The lower limit of the target for whole blood tacrolimus level was 10 to 15 ng/mL during the first 2 weeks, 10 ng/mL thereafter, and 5 to 8 ng/mL from the second month onward. Cyclosporine microemulsion was administered instead of tacrolimus to induce immunosuppression in four patients (Table 1). Steroid therapy was initiated at a dose of 10 mg/kg before graft reperfusion and then tapered down from 1 mg/kg per day on the first day to 0.3 mg/kg per day until the end of the first month, followed by 0.1 mg/kg per day until the end of the third month. Subsequently, steroid administration was terminated. Mycophenolate mofetil was administered to patients who experienced refractory rejection or required reduction of the tacrolimus or cyclosporine dose because of adverse events.

Virologic Assays and Histologic Assessment

HCV genotype was determined using a genotyping system based on polymerase chain reaction (PCR) of the core region using genotype-specific PCR primers (*19*). Serum HCV RNA load was evaluated once a month during treatment and at 6 months of follow-up after treatment using PCR and an Amplicor HCV assay (Cobas Amplicor HCV Monitor, Roche Molecular Systems, Pleasanton, CA).

Liver biopsies were evaluated if a patient had liver enzyme levels greater than twice the normal upper limit or at yearly intervals with informed consent. Necroinflammatory activity (A0–A3) and fibrosis stage (F0–F4) were assessed using the METAVIR score (*20, 21*).

Statistical Analysis

Characteristics of the patients were described and compared between patients with an SVR and patients who did not achieve an SVR (non-SVR). For continuous variables, medians and ranges are given, and the data were analyzed by the Wilcoxon test. For categorical variables, counts are given, and the data were analyzed by chi-square test. $P<0.05$ was considered significant.

TABLE 1. Characteristics of 34 patients treated with pegylated interferon and ribavirin after LDLT

	Total (n=34)	SVR (n=17)	Non-SVR (n=17)	P
Age (yr)	58 (21–68)	58 (21–68)	57 (50–66)	0.760[a]
Males/females	19/15	10/7	9/8	0.730[b]
Time since LDLT (mo)	8.0 (3.1–150.9)	7.8 (3.1–150.9)	9.0 (3.2–67.9)	0.760[a]
HCV RNA (kIU/mL)	4145 (387–5000<)	3230 (834–5000<)	5000 (387–5000<)	0.099[a]
White blood cell count (per microliters)	5100 (1700–9900)	4900 (2200–8300)	5500 (1700–9900)	0.786[a]
Neutrophil (per microliters)	2520 (830–6230)	2630 (1240–6230)	2450 (830–3810)	0.204[a]
Hemoglobin (g/dL)	12.0 (9.2–16.4)	11.6 (9.7–16.4)	12.0 (9.2–14.8)	0.786[a]
Platelet ($10^4/\mu L$)	23.8 (4.3–46.7)	23.9 (6.1–46.7)	20.6 (4.3–39.2)	0.274[a]
AST (IU/L)	78 (25–308)	79 (30–230)	68 (25–308)	0.973[a]
ALT (IU/L)	65 (21–392)	64 (28–216)	66 (21–392)	0.812[a]
ALP (IU/L)	446 (204–1583)	431 (204–1583)	468 (279–1533)	0.306[a]
γ-GTP (IU/L)	99 (23–1282)	124 (23–425)	74 (27–1282)	0.413[a]
Bilirubin (mg/dL)	0.9 (0.4–2.6)	0.8 (0.7–1.7)	0.9 (0.4–2.6)	0.540[a]
METAVIR score				
A 0/1/2/3	0/19/13/2	0/9/7/1	0/10/6/1	0.937[b]
F 0/1/2/3/4	3/24/7/0/0	0/14/3/0/0	3/10/4/0/0	0.149[b]
Immunosuppression				0.252[b]
Tacrolimus	14	6	8	
Tacrolimus+MMF	13	7	6	
Tacrolimus+prednisolone	3	3	0	
Cyclosporine	2	1	1	
Cyclosporine+MMF	2	0	2	
Trough level for tacrolimus (ng/mL)	6.1 (2.2–10.9)	6.1 (2.2–9.5)	6.2 (3.3–10.9)	0.667[a]
Dose modification of peginterferon	14	3	11	0.005[b]
Dose modification of ribavirin	27	11	16	0.034[b]
Use of G-CSF	2	0	2	0.145[b]
Use of erythropoietin	4	1	3	0.287[b]

Qualitative variables are shown in number; and quantitative variables are expressed as median (range).
[a] Wilcoxon test.
[b] χ^2 test.
AST, aspartate aminotransferase; ALT, alanine aminotransferase; ALP, alkaline phosphatase; γ-GTP, γ-glutamyl transpeptidase; MMF, mycophenolate mofetil; G-CSF, granulocyte colony-stimulating factor; LDLT, living-donor liver transplant; SVR, sustained virologic response.

RESULTS

Baseline Characteristics of Patients

We studied the baseline clinical and virologic characteristics of the 34 patients before initiation of pegylated interferon plus ribavirin therapy (Table 1). The median age of the patients at the beginning of the therapy was 58 years (range, 21–68 years). The treatment started at a median of 8.0 months (range, 3.1–150.9 months) after liver transplantation. All patients were infected with HCV genotype 1b. Median serum HCV RNA load was 4145 kIU/mL (range, 387–5000 kIU/mL), that is, most patients had an extremely high viral load. Before treatment, all patients showed necroinflammatory activity greater than A1, and 31 patients (91%) had a fibrosis score greater than F1 (METAVIR score).

Efficacy of Combination Therapy With Pegylated Interferon and Ribavirin

We studied the outcomes of the combination therapy given to 34 patients with recurrent hepatitis C genotype 1b after LDLT (Fig. 1). Serum HCV RNA became undetectable within 12 months in 18 patients (53%). The median interval between the time at which treatment was initiated and the time at which serum HCV RNA became undetectable was 4.0 months (range, 1.2–9.9 months). For these 18 patients, treatment was continued for an additional 12 months after serum HCV RNA became undetectable, resulting in a median treatment duration of 16.0 months (range, 13.2–21.9 months). Notably, 17 (94%) of these 18 patients achieved SVR. In 10 patients (29%), HCV RNA was detectable in the serum 12 months after the initiation of the treatment, and these patients were defined as having no response. For the 34 patients, including six who discontinued treatment, the SVR rate was 50%. No significant difference in baseline characteristics between 17 patients who achieved an SVR and 17 patients who did not achieve an SVR (non-SVR) was demonstrated (Table 1).

Liver biopsy was performed for 12 of the 34 patients, including six with an SVR and six with a non-SVR, at 12 to 24 months after the initiation of the treatment. Median durations from initiation of treatment to liver biopsy were 15.6 months (range, 14.7–17.5 months) in SVR group and 18.1 months (range, 12.0–21.1 months) in non-SVR group. Table 2 demonstrates the changes in histologic activity and fi-

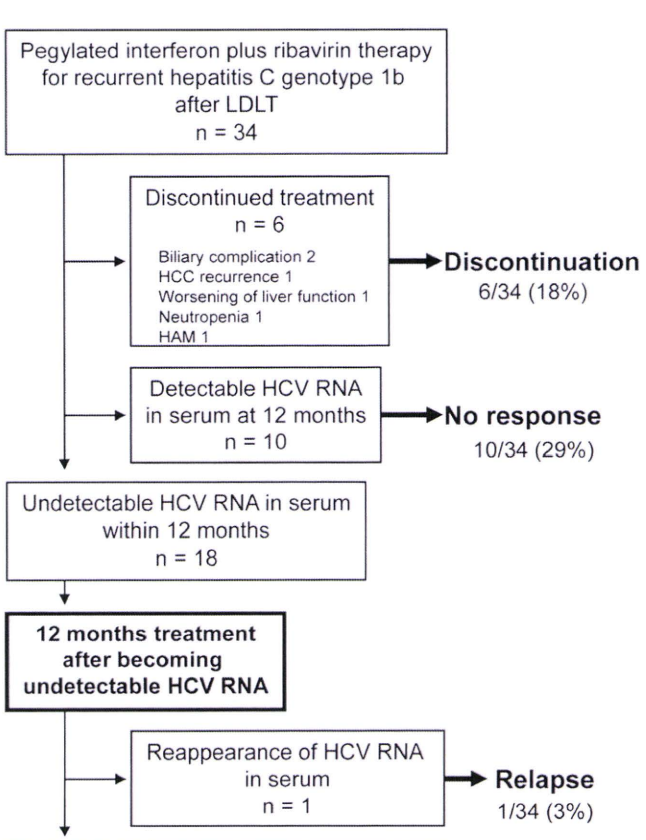

FIGURE 1. Flow diagram showing the outcome of extended pegylated interferon plus ribavirin therapy for patients with recurrent hepatitis C genotype 1b after living-donor liver transplantation. HCC, hepatocellular carcinoma; HAM, human T-lymphotropic virus (HTLV-1)-associated myelopathy; SVR, sustained virologic response.

TABLE 2. Numbers of the patients showing changes in activity grade and fibrosis score (METAVIR score) at 12 to 24 months after the initiation of treatment

	Activity		Fibrosis	
	SVR (n=6)	Non-SVR (n=6)	SVR (n=6)	Non-SVR (n=6)
Improvement	3	4	1	0
No change	3	2	5	4
Worsening	0	0	0	2

SVR, sustained virologic response.

brosis of individual patients. Activity grade of all patients in both the SVR group and the non-SVR group improved or remained stable. Fibrosis stage was deteriorated in two of six patients in the non-SVR group, whereas no patients with an SVR showed worsening of fibrosis. There was no significant difference in histologic changes of both activity grade ($P=0.558$) and fibrosis stage ($P=0.211$) between the SVR and non-SVR groups during the short-term follow-up.

Safety and Tolerability

Six patients (18%) discontinued the treatment because of biliary complications (n=2), recurrent hepatocellular carcinoma (n=1), worsening of liver function (n=1), neutropenia (n=1), and human T-cell lymphotropic virus–associated myelopathy (n=1). The patient who discontinued the treatment because of worsening of liver function 9 months after starting the treatment was diagnosed with chronic rejection by liver biopsy 1 month after the discontinuation and died 2 months after the diagnosis. None of the 18 patients who received the extended treatment withdrew from the study. For the 28 patients who continued the treatment for 12 months or more, modification of the pegylated interferon or ribavirin dose was required in 22 patients (79%), reduction in the pegylated interferon dose was required in eight (29%), and reduction in the ribavirin dose was required in 21 (75%). During the extended treatment of the 18 patients, the ribavirin dose needed to be reduced for only three patients, and the pegylated interferon dose did not need to be reduced for any patient. Rate of the patients who required dose modifications of pegylated interferon and ribavirin was significantly higher in the non-SVR group than in the SVR group (Table 1).

DISCUSSION

In this study, an SVR rate of 50% was achieved using individualized extension of combination therapy with pegylated interferon α-2b and ribavirin for patients with recurrent hepatitis C genotype 1b after LDLT. This SVR rate was higher than that achieved in previous studies in which liver transplant recipients were treated for 12 months (*9–11*). Notably, only one patient relapsed in this study, indicating that individualized extension of treatment reduces the relapse rate and increases the SVR rate.

The virologic response during treatment is useful for predicting whether SVR will be achieved. In both transplant recipients and nontransplant patients, failure to achieve an early virologic response (EVR) to combination therapy, which was defined as a less than or equal to 2-log reduction in (partial EVR) or the complete absence of serum HCV RNA (complete EVR) at week 12 of therapy compared with the baseline level, most accurately predicts that SVR will not be achieved (*11*, *22*). For nontransplant patients who do not achieve complete EVR, treatment can be extended to 72 weeks instead of 48 weeks (*13*, *16*, *17*). In this study, complete EVR was achieved in only six patients. For the other 12 patients with delayed virologic responses, we believed it was desirable to extend the treatment to achieve SVR. However, it seems unlikely that a uniform duration of treatment can be defined, because virologic responses to combination therapy vary between transplant recipients who require frequent dose modifications and have high initial viral loads. In fact, in this study, there was a considerable variation in the time required for serum HCV RNA to become undetectable in different patients. Of the 18 patients who received the extended treatment, serum HCV RNA became undetectable within 12 weeks in six patients (33%), between 12 and 24 weeks in six patients (33%), between 24 and 36 weeks in three patients (17%), and after 36 weeks of treatment in three patients (17%). Therefore, individualized extension of the treatment would be the best strategy for these patients. The results of

individualized treatment of nontransplant patients with chronic hepatitis C were recently reported (*15*). Treatment for 44 weeks after serum HCV RNA became undetectable in nontransplant patients with chronic hepatitis C genotype 1 resulted in a significantly higher SVR rate than that in 48 weeks of standard therapy. Although the optimum duration of treatment for hepatitis C after liver transplantation is unknown, individualized treatment based on the time required for serum HCV RNA to become undetectable could help define the optimum duration.

Another issue involving antiviral therapy after transplantation is the tolerability of pegylated interferon and ribavirin. Dose reductions are frequent and drug discontinuation rates are higher in transplant patients than in nontransplant patients. In previous studies, 39% and 54% of patients received reduced doses of pegylated interferon and ribavirin, respectively, and the pooled weighted rate of treatment discontinuation was 26% (*11*). Therefore, treatment is often limited by poor tolerability and the frequent need for dose reductions and discontinuation (*10, 11*). In this study, 10 patients needed to discontinue treatment, but the reasons for this were not directly associated with the treatment in 9 of the 10 patients. All these patients were excluded within 12 months, showing that the extended protocol did not increase the incidence of major adverse events. Dose modifications were required for most patients, mainly because of cytopenia, but complications caused by cytopenia were not observed. Thus, the extended treatment did not affect the safety and tolerability of the therapy in this study.

In conclusion, individualized extension of combination therapy with pegylated interferon α-2b and ribavirin resulted in a high SVR rate and good tolerability. Further studies with a large number of patients are required to determine the efficacy and safety of this extended treatment regimen for recurrent hepatitis C after liver transplantation.

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Clinical features of biochemical cholestasis in patients with recurrent hepatitis C after living-donor liver transplantation

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SUMMARY. Recurrent hepatitis C after liver transplantation (HepC-LT) progresses faster than hepatitis C in non-transplant settings. Cholestasis has been suggested to be one characteristic of HepC-LT related to the rapid progression. We investigated the clinical features of biochemical cholestasis, which we defined as high serum concentrations of alkaline phosphatase and γ-glutamyl transpeptidase, in patients with recurrent hepatitis C after living-donor liver transplantation. Eighty patients were diagnosed with post-transplant recurrent hepatitis C after exclusion of other aetiologies of cholestasis by liver biopsy and imaging. The clinical features of biochemical cholestasis in the patients with HepC-LT, including histological changes, the efficacy of interferon therapy and helper T-cell (Th) subsets in the peripheral blood, were analysed. Fifty-five of the 80 patients with HepC-LT (69%) had evidence of biochemical cholestasis. Progression of liver fibrosis to stage F3 or F4 was significantly accelerated in patients with biochemical cholestasis compared with patients without cholestasis. The biochemical cholestasis in patients with HepC-LT improved after interferon therapy in 22 of 39 patients (56%) who showed a virological response to the therapy, suggesting that hepatitis C virus (HCV) caused the biochemical cholestasis in these patients. Patients with biochemical cholestasis who had a biochemical response to interferon therapy showed an increased Th1 responses in peripheral blood. In conclusion, biochemical cholestasis is the characteristic feature of HepC-LT and is related to progression of liver fibrosis. An increased Th1 response is associated with cholestasis caused by HCV after liver transplantation.

Keywords: hepatitis C, cholestasis, living-donor liver transplantation, Th1.

INTRODUCTION

Liver cirrhosis caused by hepatitis C virus (HCV) is the leading indication for liver transplantation in many countries. However, almost all patients who receive liver transplantation for HCV-related liver disease develop recurrent infection, and 70–90% of patients experience histologically proven recurrent hepatitis [1–6]. Progression of recurrent hepatitis C is often accelerated, and without appropriate antiviral therapy, 10–25% of patients develop cirrhosis within 5 years after transplantation, resulting in poorer prognosis for HCV-positive than HCV-negative recipients [7]. The median interval from transplantation to cirrhosis is 10 years compared with 20–40 years in non-transplant patients [8].

The progression of recurrent hepatitis C infection after liver transplantation (HepC-LT) is poorly understood. Established factors associated with this progression and graft survival after liver transplantation are recipient-related factors including age, sex, race and severity of illness before transplantation, donor age, treatment of rejection, time to recurrence, pre-transplant and early post-transplant HCV load and cytomegalovirus infection [9,10]. Recently, Iacob *et al.* [11] reported the presence of early cholestasis as an independent negative predictor of graft and patient survival and for the development of HCV-related cirrhosis in recipients with HCV.

In addition, a small number of patients with HCV infection after liver transplantation show the unique clinical feature

Abbreviations: ALP, alkaline phosphatase; ALT, alanine aminotransferase; CT, computerized tomography; ERCP, endoscopic retrograde cholangiopancreatography; FCH, fibrosing cholestatic hepatitis; γ-GTP, γ-glutamyl transpeptidase; HCV, hepatitis C virus; HepC-LT, hepatitis C after liver transplantation; HepC-NT, hepatitis C in non-transplant settings; LDLT, living-donor liver transplantation; MRCP, magnetic resonance cholangiopancreatography; PCR, polymerase chain reaction; Th, helper T-cell; VR, virological response.

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known as fibrosing cholestatic hepatitis (FCH) [12–14]. FCH is a progressive liver injury characterized by jaundice, high serum concentrations of alkaline phosphatase (ALP) and γ-glutamyl transpeptidase (γ-GTP), and very high serum HCV RNA levels. FCH progresses rapidly and leads to the development of cirrhosis and graft failure, sometimes within 1 year after liver transplantation. Histological findings are characterized by the presence of severe hepatocyte ballooning, intrahepatic cholestasis, pericellular and portal fibrosis, and ductular proliferation. Prognosis of FCH is poor, and antiviral therapy after the diagnosis of FCH has been reported not to improve the prognosis [15].

Even when patients do not have jaundice and intrahepatic cholestasis is not apparent in liver histology, we often encounter patients of HepC-LT with high serum concentrations of ALP and γ-GTP, which are enzymes associated with cholestasis. Elevation of ALP and/or γ-GTP in serum has been called biochemical cholestasis [16,17]. The biochemical cholestasis is rarely shown in the patients with hepatitis C in non-transplant settings (HepC-NT) [18]. Therefore, we hypothesized that biochemical cholestasis is related to the rapid progression of liver fibrosis in patients with HepC-LT. Clarification of the clinical features of the biochemical cholestasis may lead to the effective management for the patients with HepC-LT.

In this study, we retrospectively analysed the clinical features of biochemical cholestasis in the patients with HepC-LT after living-donor liver transplantation (LDLT), including the histological changes, the efficacy of interferon therapy and helper T-cell (Th) subsets in the peripheral blood.

MATERIALS AND METHODS

Patients

Between March 1999 and December 2007, 141 patients with HCV-related liver diseases underwent LDLT at Kyoto University [19]. Of these, 100 patients had been followed up for more than 6 months after LDLT in our hospital. Combination therapy with interferon and ribavirin ($n = 40$) [20] or peginterferon and ribavirin ($n = 40$) was given to 80 patients with recurrent hepatitis C between January 2001 and April 2007. The remaining 20 patients did not receive anti-viral therapy because of no histological recurrence of hepatitis C in the follow-up period. Eligibility for treatment was positive serum HCV RNA and histological evidence of recurrent hepatitis C. Exclusion criteria were a neutrophil count lower than 750/μL, a platelet count lower than 40 000/μL, a haemoglobin level of 9.0 g/dL or lower, or renal insufficiency. Other aetiologies of increased alanine aminotransferase (ALT) concentration, such as rejection and biliary obstruction, were excluded by liver biopsy and imaging, including ultrasonography, computerized tomography (CT), endoscopic retrograde cholangiopancreatography (ERCP) and/or magnetic resonance cholangiopancreatography (MRCP).

To provide a comparison group for these patients, we evaluated 103 consecutive patients with HepC-NT who received combination therapy with peginterferon plus ribavirin at Kyoto University between January 2005 and April 2007. Eligibility for the treatment was positive serum HCV RNA. Liver biopsy was not performed for most patients.

Treatment protocol

The basic treatment protocol between January 2001 and April 2004 for patients with recurrent hepatitis C after liver transplantation (HepC-LT) comprised three or six mega units of interferon-α-2b three times a week plus ribavirin at 400–800 mg/day orally for the first 6 months, followed by interferon monotherapy for 6 months [20]. Combination therapy with 1.5 μg/kg of peginterferon-α-2b plus ribavirin at 400–800 mg/day orally was given between May 2004 and April 2007.

Immunosuppression

The standard immunosuppression protocol comprised tacrolimus and low-dose steroid therapy. The target for whole blood tacrolimus lower level was 10–15 ng/mL during the first 2 weeks, 10 ng/mL thereafter and 5–8 ng/mL from the second month. Cyclosporine microemulsion was administered instead of tacrolimus to induce immunosuppression in three patients. Steroid therapy was initiated at a dose of 10 mg/kg before graft reperfusion, and then tapered down from 1 mg/kg/day on the first day to 0.3 mg/kg/day until the end of the first month, followed by 0.1 mg/kg/day to the end of the third month. After that, steroid administration was terminated. Mycophenolate mofetil or mizoribine was added for patients who experienced refractory rejection or required reduction in the tacrolimus dose because of adverse events.

Virological assays

The HCV genotype was determined by a genotyping system based on polymerase chain reaction (PCR) of the core region with genotype-specific PCR primers [21]. Serum HCV RNA load was evaluated by PCR using the Amplicor HCV assay (Cobas Amplicor HCV Monitor, Roche Molecular Systems, Pleasanton, CA, USA).

Th1 and Th2 cell assay

Th1 and Th2 cell percentages were measured before interferon therapy in 27 patients with recurrent HepC-LT. Th1, Th2 and Th0 cells in the human peripheral blood T-cell population were detected by intracellular cytokine staining and flow cytometric analysis [22,23]. Peripheral blood cells from patients were stimulated with phorbol myristate acetate (10 ng/mL) and ionomycin (1 μg/mL) for 4 h in the

presence of Brefeldin A (10 μg/mL; all from Sigma Chemical Co, St Louis, MO, USA). Cells were harvested and stained with phycoerythrin (PE)-cyanin-5-conjugated-anti-CD4 monoclonal antibody (Immunotech, Marseilles, France). The cells were fixed with 1% paraformaldehyde, permeabilized with FACS Permeabilizing Solution (Becton Dickinson, San Jose, CA, USA), and stained with FITC-conjugated-anti-IFN-γ and PE-conjugated-anti-IL-4 monoclonal antibodies (Becton Dickinson). Cytokine-producing CD4-positive cells were analysed on a FACS Calibur (BD Biosciences, San Jose, CA, USA). The percentages of cells in the gate of IFN-γ^+ IL-4$^-$ cells (Th1), IFN-γ^- IL4$^+$ cells (Th2), IFN-γ^+ IL-4$^+$ cells (double-positive Th0 or Th0-DP) and IFNγ^- IL-4$^-$ cells (double-negative Th0 or Th0-DN) were analysed.

Histological assessment

Liver biopsies were evaluated when patients showed an ALT concentration more than twice the normal upper limit or at yearly intervals with informed consent. Biopsy specimens were evaluated by a single pathologist (H.H.) with extensive experience in the pathology of liver transplantation. Necro-inflammatory activity (A0–A3) and fibrosis stage (F0–F4) were assessed using the METAVIR score [24,25].

Statistical analysis

Baseline characteristics and Th subsets were recorded and compared between disease types. For continuous variables that were nearly symmetrically distributed, mean values and standard deviations (SDs) are given, and these data were analysed by *t*-test and one-way analysis of variance. For non-normally distributed variables, medians and ranges are given, and the data were analysed by the Wilcoxon and Kruskal–Wallis tests. For categorical variables, counts are given, and the data analysed by chi-square test. The rates of patients who showed a progression of fibrosis to stage F3 or F4 after initiation of the interferon therapy were estimated using the Kaplan–Meier method and compared using log-rank tests. A P value <0.05 was considered significant.

RESULTS

Biochemical cholestasis in patients with recurrent hepatitis C after LDLT

Eighty patients were diagnosed with recurrent HepC-LT and other aetiologies of liver injury were excluded by liver histology and imaging. The blood concentration of ALP and γ-GTP, enzymes that reflect cholestasis, of the 80 patients with HepC-LT was significantly higher than those of 103 patients with HepC-NT before interferon therapy. The median ALP level was 485.5 IU/L (range 204–2977) in HepC-LT patients, compared with 259 IU/L (range 121–772) in the HepC-NT group ($P < 0.001$). The median γ-GTP level was 148.5 IU/L (range 15–1827) in the HepC-LT group, compared with 41 IU/L (range 12–399) in the HepC-NT group ($P < 0.001$). We defined biochemical cholestasis as an ALP concentration more than 1.2 times (more than 431 IU/L) or a γ-GTP concentration more than four times (more than 216 IU/L for men and 116 IU/L for women) the upper limit of normal, because <10% of the patients in the HepC-NT group satisfied these criteria, showing remarkable difference between the HepC-LT and HepC-NT groups (Fig. 1). Of the 80 patients with HepC-LT, 48 patients (60%) had an ALP concentration more than 1.2 times the upper limit of normal, whereas only 5% of the HepC-NT group had a high ALP concentration. Thirty seven patients with HepC-LT (46%) had a γ-GTP concentration more than four times the upper limit of normal, whereas 6% of HepC-NT patients had a high γ-GTP concentration. Taken together, 69% of the patients with HepC-LT (55 patients) showed either a high ALP concentration (>1.2 times normal) or high γ-GTP concentration (>4 times normal), whereas only 9% of the patients in the HepC-NT group had high values for one of these variables. These data clearly show that biochemical cholestasis is a characteristic of HepC-LT.

The cause of the biochemical cholestasis in patients with HepC-LT was examined again by imaging and liver histology, retrospectively. Imaging by ultrasonography, CT, ERCP or MRCP, or a combination, did not reveal any causes of mechanical cholestasis, such as biliary obstruction. Analysis of liver histology demonstrated intrahepatic cholestasis only in 12 of 55 patients (22%) with biochemical cholestasis and in seven of 25 patients (28%) without cholestasis. The

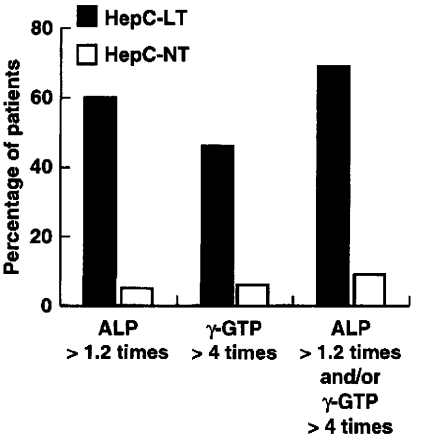

Fig. 1 Percentage of patients with biochemical cholestasis defined as increased serum alkaline phosphatase (ALP) concentration more than 1.2 times the upper limit of normal and/or gamma-glutamyl transpeptidase (γ-GTP) more than four times the upper limit of normal in patients with recurrent hepatitis C after liver transplantation (HepC-LT) or those with hepatitis C in non-transplant settings (HepC-NT).

prevalence and extension of liver steatosis also did not differ between patients with and without biochemical cholestasis. Steatosis, defined as more than 5% of hepatocytes with fat deposit on biopsy, was found in 22 of 55 patients (40%) with biochemical cholestasis, and in 11 of 25 patients (44%) without biochemical cholestasis. Thus, the major cause of biochemical cholestasis could not be determined by imaging or liver histology.

Progression of fibrosis in patients with biochemical cholestasis

As already mentioned, 55 (69%) of the 80 patients with HepC-LT showed biochemical cholestasis. These patients were classified into the cholestasis (Ch) group, and the remaining 25 patients (31%) were classified into the non-cholestasis (non-Ch) group. To evaluate the progression of liver injury in the Ch and non-Ch groups, we analysed the change in fibrosis stage by using the METAVIR score. The baseline fibrosis stages at diagnosis of recurrent hepatitis C did not differ between the Ch and non-Ch groups. The mean fibrosis stages were 0.95 in the Ch group (n = 55) and 1.06 in the non-Ch group (n = 25). We monitored the fibrosis stage by liver biopsy after initiation of interferon therapy at roughly yearly intervals. A liver biopsy was performed in 60 patients (75%) after the initiation of interferon therapy – including 43 in the Ch group (78%) and 17 in the non-Ch group (68%). The occurrence of fibrosis stage F3 or F4 in these 60 patients was assessed using Kaplan–Meier analysis (Fig. 2). No patient in the non-Ch group developed fibrosis stage F3 or F4, whereas 12 patients (28%) in the Ch group progressed to fibrosis stage F3 or F4 (P = 0.040, log-rank test). These data indicate that biochemical cholestasis was associated with the progression of fibrosis in the patients with HepC-LT.

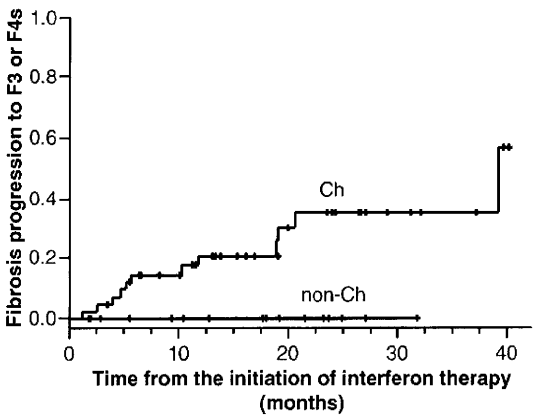

Fig. 2 Kaplan–Meier estimates of the rate of patients who showed progression of fibrosis to stage F3 or F4 (METAVIR score) after initiation of interferon therapy in patients with cholestasis (Ch) and without (non-Ch).

Effect of interferon therapy on biochemical cholestasis

To clarify the clinical characteristics of biochemical cholestasis in the patients with HepC-LT, we analysed the efficacy of interferon therapy in treating cholestasis (Fig. 3). Of the 55 Ch patients, 39 (71%) showed a virological response (VR) after interferon therapy, which was defined as a decrease in serum HCV RNA titre to <5 kIU/mL or a 2 $\log_{10}$ decrease. On the other hand, of the 25 non-Ch patients, 14 (56%) showed a VR following interferon therapy. When both ALP and γ-GTP concentrations decreased to the normal range or to less than half of the concentration before interferon therapy along with a reduced serum HCV RNA titre, cholestasis was assumed to be caused by HCV; we defined these patients as biochemical responders for cholestasis (Ch-VR-BR). Twenty two of the 39 (56%) virological responders with cholestasis satisfied these criteria and were classified into the Ch-VR-BR group. The biochemical cholestasis in the other 17 patients (44%) did not improve after interferon therapy despite a VR; these patients were classified into the Ch-VR-non-BR group. The lack of improvement indicated the presence of other mechanisms for development of cholestasis, although the imaging and histology could not

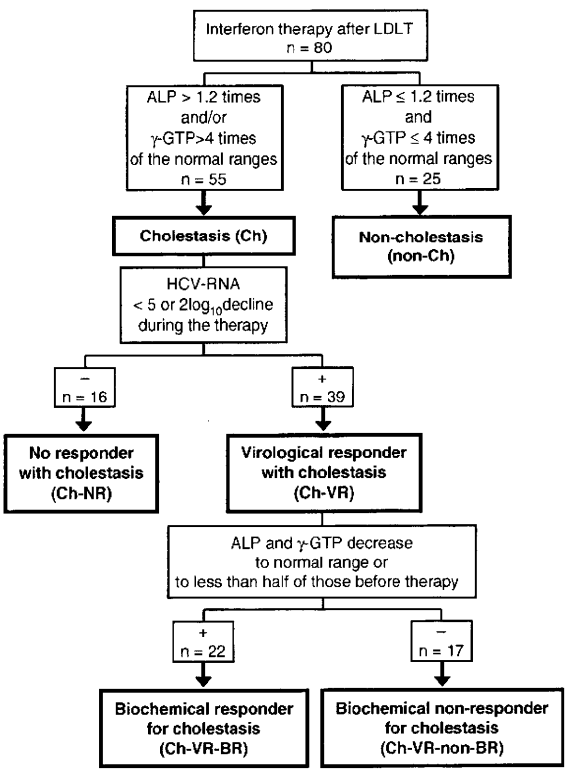

Fig. 3 Flow diagram showing the classification of patients with or without biochemical cholestasis, and the outcome of interferon therapy in patients with recurrent hepatitis C after liver transplantation. n = number of patients.

identify these causes before interferon therapy. However, after the initiation of interferon therapy, we found biliary obstruction in five patients and chronic rejection in three patients in the 17 patients with the Ch-VR-non-BR, suggesting that these conditions had caused the biochemical cholestasis. The causes of biochemical cholestasis in the remaining nine patients were unknown. Consequently, after excluding those eight patients, more than half of the cholestasis in patients with Ch-VR (22 patients of 31 patients) were interferon sensitive, indicating that cholestasis was attributed to HCV infection in the 22 patients. Based on the presence of biochemical cholestasis and the efficacy of interferon therapy, we classified the patients as shown in Fig. 3.

Increased Th1 responses in biochemical responders with cholestasis

Next, helper T-cell (Th) subsets of the peripheral blood were measured in the patients with HepC-LT by intracellular cytokine staining and flow cytometry, because Th responses are known to be an important factor for the progression of HepC-NT [26,27]. Peripheral blood cells were taken before interferon therapy from 18 patients with Ch, including nine patients with Ch-VR-BR, four with Ch-VR-non-BR and five with Ch-NR. Nine patients without cholestasis (non-Ch) were also analysed (Table 1). The percentage of Th1 cells and the Th1/Th2 ratio were significantly higher in the Ch than the non-Ch group ($P = 0.003$, *t*-test, and $P = 0.007$, Wilcoxon test respectively), suggesting that the increased Th1 response was associated with the cholestasis in the patients with HepC-LT. Then, to clarify the features of VR-Ch-BR that characterize cholestatic hepatitis caused by HCV, we compared the Th subsets among the Ch-VR-BR, Ch-VR-non-BR and non-Ch groups. As the Ch-NR group consisted of both HCV-related cholestasis and HCV-unrelated cholestasis, we excluded the Ch-NR group from the analysis. The percentage of Th1 cells was significantly higher in the Ch-VR-BR group than in Ch-VR-non-BR and non-Ch groups ($P = 0.001$, one-way analysis of variance). The percentage of Th0-DN cells in the Ch-VR-BR group was significantly lower than the other two groups ($P = 0.004$, Kruskal–Wallis test), but the percentages of Th2 cells and Th0-DP did not differ among the three groups, indicating pronounced differentiation of Th0-DN cells into Th1 cells in the Ch-VR-BR patients. Thus, this increased Th1 response in cholestatic patients with a biochemical response after interferon therapy suggests that cholestasis caused by HCV is associated with such a Th1 response.

DISCUSSION

In this study, we found that biochemical cholestasis, defined as a high ALP or γ-GTP concentration, was a characteristic feature of HepC-LT, and the biochemical cholestasis improved after interferon therapy in more than half of the patients. Differences of the clinical course between the HepC-LT and HepC-NT groups have been well documented. Rapid progression and poorer prognosis are well-known characteristics of HepC-LT compared with HepC-NT [8]. However, the differences in baseline characteristics have not been previously reported. Our data show that high ALP and/or γ-GTP concentration is a characteristic of HepC-LT that distinguishes it from the HepC-NT setting. This may not be surprising because several conditions related to transplantation, such as drug use, acute cellular rejection, chronic rejection, liver steatosis or biliary obstruction, result in cholestasis after liver transplantation. We excluded these conditions by liver histology and imaging, and then started interferon therapy for hepatitis C. Interestingly, after interferon therapy, the biochemical cholestasis improved in more than half of the patients in association with a reduction in

Table 1 Helper T-cell subsets in peripheral blood of patients with cholestasis (Ch) and without (non-Ch), and the three subgroups in the Ch group: biochemical responders for cholestasis (VR-Ch-BR), biochemical non-responders for cholestasis (VR-Ch-non-BR) in virological responders and virological non-responders (Ch-NR) before interferon therapy

	Ch				
	Total ($n = 18$)	Ch-VR-BR ($n = 9$)	Ch-VR-non-BR ($n = 4$)	Ch-NR ($n = 5$)	Non-Ch ($n = 9$)
Th1 (%)*	47.3‡ (13.1)	52.6▪ (11.9)	36.4 (11.6)	46.3 (12.6)	32.1 (6.5)
Th2 (%)*	1.28 (0.79)	1.41 (0.99)	1.20 (0.22)	1.12 (0.75)	1.86 (0.88)
Th0-DP (%)†	2.5 (0.7–14.9)	2.3 (0.7–14.9)	2.2 (1.6–2.5)	4.2 (2.4–7.6)	1.9 (0.8–7.4)
Th0-DN (%)†	46.2 (24.0–70.9)	44.6** (24–59.3)	62.3 (46–70.9)	41.2 (36.5–65.5)	60.9 (51.6–73.7)
Th1/Th2†	38.9§ (15.4–374)	38.8 (15.4–374)	25.3 (23.3–51.2)	42.6 (39.0–108.2)	16.9 (6.0–36.8)

Th0-DP, double-positive Th0; Th0-DN, double-negative Th0. *Mean (standard deviation). †Median (range). ‡Significantly higher than the non-Ch group ($P = 0.003$). §Significantly higher than the non-Ch group ($P = 0.007$). ▪Significantly higher than the Ch-VR-non-BR and the non-Ch groups ($P = 0.001$). **Significantly lower than the Ch-VR-non-BR and the non-Ch groups ($P = 0.004$).

HCV RNA titre, whereas no virological non-responder showed an improvement in biochemical cholestasis, indicating that the biochemical cholestasis was caused by HCV in many patients.

This study also demonstrated that the biochemical cholestasis in the patients with HepC-LT is associated with the progression of liver fibrosis. However, we still do not know whether the biochemical cholestasis is related to FCH. Fibrosis is accelerated in patients with biochemical cholestasis, but the liver histology in our patients did not show the features of FCH. In the 80 patients with HepC-LT in this study, only two (2.5%) were diagnosed as having FCH by liver histology. Both patients with FCH were in the Ch-NR group. Previous reports showed 7–15% incidence [12–14] of FCH in patients with HCV after liver transplantation. The lower incidence in our study might indicate that interferon therapy has a role in inhibiting the progression to FCH.

We found that biochemical cholestasis in patients with HepC-LT is characterized by Th1 predominance. We also demonstrated that virological responders to interferon therapy who showed improvement in cholestasis (Ch-VR-BR) had a higher Th1 response than those without improvement in cholestasis (Ch-VR-non-BR) or those without cholestasis (non-Ch), suggesting that a Th1/Th2 profile is associated with the pathophysiology of HCV-induced cholestasis after liver transplantation. The host immune response plays a critical role in both the control of HCV replication and liver injury [26,27]. In particular, the $CD4^+$ T-cell responses to HCV play a key role in the outcome of the infection, and an imbalance between Th1 and Th2 cytokines has been suggested as a factor influencing the activity and progression of hepatitis C [28–31]. Indeed, a correlation between dominant Th1 responses and progression of chronic hepatitis C has been reported [31], suggesting that the Th1 response plays a role in accelerating the disease. Thus, the increased Th1 response in patients with cholestasis may be associated with a more severe progression of fibrosis in patients with cholestasis than in those without after liver transplantation. Although the precise mechanism is unknown at present, our results indicate that the higher Th1 response may be a good marker for determining the cause of cholestasis and predicting the efficacy of interferon therapy in terms of cholestasis for patients with recurrent HepC-LT. Patients with a higher Th1/Th2 ratio may be good candidates for receiving interferon therapy.

In conclusion, biochemical cholestasis is a characteristic feature in patients with HepC-LT, which is associated with progression of fibrosis. The improvement of biochemical cholestasis following antiviral therapy appears to be important in preventing this progression. An increased Th1 response to HCV may contribute to the pathophysiology of cholestasis caused by HCV and the rapid progression of HepC-LT. Thus, manipulation of the T-cell response may be a promising therapeutic approach for preventing progression of HepC-LT.

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Article

The Ubiquitin Ligase Riplet Is Essential for RIG-I-Dependent Innate Immune Responses to RNA Virus Infection

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SUMMARY

RNA virus infection is recognized by the RIG-I-like receptors RIG-I and MDA5, which induce antiviral responses including the production of type I interferons (IFNs) and proinflammatory cytokines. RIG-I is regulated by Lys63-linked polyubiquitination, and three E3 ubiquitin ligases, RNF125, TRIM25, and Riplet, are reported to target RIG-I for ubiquitination. To examine the importance of Riplet in vivo, we generated Riplet-deficient mice. Fibroblasts, macrophages, and conventional dendritic cells from Riplet-deficient animals were defective for the production of IFN and other cytokines in response to infection with several RNA viruses. However, Riplet was dispensable for the production of IFN in response to B-DNA and DNA virus infection. Riplet deficiency abolished RIG-I activation during RNA virus infection, and the mutant mice were more susceptible to vesicular stomatitis virus infection than wild-type mice. These data indicate that Riplet is essential for regulating RIG-I-mediated innate immune response against RNA virus infection in vivo.

INTRODUCTION

RNA virus infection is initially recognized by RIG-I-like receptors, RIG-I and MDA5, which induce antiviral responses such as the production of type I interferons (IFNs) and proinflammatory cytokines (Yoneyama and Fujita, 2009; Takeuchi and Akira, 2010). Analyses of RIG-I and MDA5 knockout mice showed that RIG-I is essential for type I IFN production by mouse embryonic fibroblasts (MEFs), conventional dendritic cells (cDCs), and macrophages (Mfs) in response to RNA viruses such as vesicular stomatitis virus (VSV), influenza A virus (Flu), hepatitis C virus (HCV), Sendai virus (SeV), and Japanese encephalitis virus (JEV). MDA5 is critical in picornavirus infection (Kato et al., 2006; Saito et al., 2007). However, in plasmacytoid DCs (pDCs), loss of RIG-I has no effect on viral induction of IFNs, and TLR7 and MyD88 are required for inducing immune responses in these cells (Diebold et al., 2004; Kato et al., 2005; Kumar et al., 2006; Sun et al., 2006).

RIG-I consists of two N-terminal CARDs, a central DExD/H helicase domain, and a C-terminal repressor domain (CTD) (Yoneyama et al., 2004). Before viral infection, CTD of RIG-I suppresses N-terminal CARDs (Saito et al., 2007). When the CTD of RIG-I recognizes the 5′ triphosphate-double-stranded (ds) viral RNA, the conformation of the RIG-I protein changes, and the N-terminal CARD triggers interaction with its downstream partner IPS-1 (Hornung et al., 2006; Pichlmair et al., 2006; Saito et al., 2007; Cui et al., 2008; Takahasi et al., 2008; Rehwinkel et al., 2010). IPS-1 contains an N-terminal CARD that interacts with the tandem CARDs of RIG-I and a C-terminal transmembrane domain that localizes it to the mitochondrial outer membrane (Kawai et al., 2005; Meylan et al., 2005; Seth et al., 2005; Xu et al., 2005). IPS-1 activates TBK1 kinase, which mediates phosphorylation of IRF-3, leading to its dimerization and translocation into the nucleus (Kumar et al., 2006; Sun et al., 2006). The IRF-3 dimers, NF-κB, and AP-1 transcription factors activate type I IFN transcription (Honda et al., 2005). The secreted type I IFNs activates the IFNAR, which leads to phosphorylation and nuclear translocation of STAT1 (Akira et al., 2006; Honda et al., 2006).

RIG-I is regulated by ubiquitination. Three E3 ubiquitin ligases, RNF125, TRIM25, and Riplet, target RIG-I (Arimoto et al., 2007; Gack et al., 2007; Oshiumi et al., 2009). RNF125 functions as a negative regulator for RIG-I signaling and mediates Lys48-linked polyubiquitination of RIG-I, leading to protein degradation by the proteasome (Arimoto et al., 2007). On the other hand, TRIM25 and Riplet function as positive regulators for the signaling. TRIM25 mediates Lys63-linked polyubiquitination at Lys172 of RIG-I CARDs (Gack et al., 2007). Lys63-linked polyubiquitination induces interaction between RIG-I and IPS-1 CARDs, leading to the activation of signaling (Gack et al., 2007, 2008). However, there are several reports that describe other models. First, Zeng et al. developed an in vitro reconstitution system of the RIG-I pathway (Zeng et al., 2010). Using this system, they showed that Lys172 of RIG-I CARDs is required for binding to the Lys63-linked polyubiquitin chain (Zeng et al., 2010). They postulated that polyubiquitin binding and not ubiquitin modification is required for RIG-I activation (Zeng et al., 2010). In their model, unanchored polyubiquitin chains are responsible for RIG-I activation. However, they did not rule out the possibility that ubiquitination of some signaling proteins may contribute to RIG-I activation (Zeng et al., 2010). Second, Fujita T and his colleagues reported that residue 172 of mouse RIG-I is not Lys but Gln and human RIG-I K172R mutant was normally activated by SeV infection in RIG-I KO MEFs (Shigemoto et al., 2009).

The third ubiquitin ligase, Riplet, mediates Lys63-linked polyubiquitination of RIG-I CTD and CARDs (Gao et al., 2009; Oshiumi et al., 2009). This polyubiquitination promotes RIG-I activation and its antiviral activity in human cells (Horner and Gale, 2009; Nakhaei et al., 2009; Takeuchi and Akira, 2010; Yoneyama and Fujita, 2010); however, in vivo evidence is absent. Type I IFNs are mainly produced by DCs or Mf in vivo, and RIG-I is essential for type I IFN production in cDC and Mf (Kato et al., 2005; Sun et al., 2006; Kumagai et al., 2007). The role of Riplet in these cells also has not yet been examined. Both TRIM25 and Riplet proteins mediate Lys63-linked polyubiquitination of RIG-I, and thus Gao et al. suggested that Riplet may be a complementary factor of TRIM25 for RIG-I activation (Gao et al., 2009). Therefore, it is not known whether Riplet is essential for RIG-I activation. To address these issues, we generated Riplet knockout mice. Our analysis revealed that Riplet is essential for the RIG-I activation and innate immune responses against viral infection in vivo.

RESULTS

Ubiquitous Expression of Riplet mRNA

First, we examined mouse Riplet mRNA expression by quantitative PCR (qPCR), and found it to be ubiquitously expressed in various tissues, MEFs, bone marrow-derived DCs (BM-DCs), and Mf (BM-Mf) (Figure 1A, left panel). Furthermore, we have previously shown that human Riplet mRNA is expressed in various tissues. When we examined the expression of Riplet mRNA in human DCs, it was observed in human DCs as in HeLa cells (Figure 1A, right panel). These data indicate that Riplet is expressed in various tissues and cells that are able to produce type I IFNs.

Generation of Riplet-Deficient Mice

Previously, we have shown that Riplet is a positive regulator for RIG-I-mediated signaling, and it mediates Lys63-linked polyubiquitination of RIG-I. However, the functional role of Riplet in vivo remains unclear. To investigate the role of Riplet in vivo, we generated Riplet-deficient (*Riplet*$^{-/-}$) mice by homologous recombination of embryonic stem cells (ESCs) (Figure 1B). We confirmed the target disruption of Riplet without deletion outside the targeted region (Figure 1C, and see Figures S1A and S1B available online). Riplet mRNA expression was abolished in *Riplet*$^{-/-}$ cells (Figures 1E and 1F), and the knockout of Riplet did not affect the expression of other genes, such as RIG-I, MDA5, IPS-1, TICAM-1, TLR3, and TRIM25, which are involved in type I IFN production (Figure 1F). The mutant mice were born at the Mendelian ratio from *Riplet*$^{+/-}$ parents (Figure 1D), and they developed and bred normally. These mice displayed no apparent abnormalities up to 7 months of age. Mutations in the human Riplet/RNF135 gene cause the overgrowth syndrome (Douglas et al., 2007). We did not observe any overgrowth phenotypes in *Riplet*$^{+/-}$ and *Riplet*$^{-/-}$ mice. Next, we examined the composition of CD4-, CD8-, CD11c-, and/or PDCA1-positive cells in the spleen, and found no difference between wild-type and *Riplet*$^{-/-}$ mice (Figures S1C and S1D). Induction of cDC from BM in the presence of GM-CSF was also normal in *Riplet*$^{-/-}$ mice (Figure S1E). Therefore, the mouse Riplet gene is dispensable for development.

Riplet$^{-/-}$ Embryonic Fibroblasts Are Defective in Innate Immune Responses against RNA Viruses

Riplet is a positive regulator for RIG-I-mediated signaling. In mouse fibroblast, VSV and Flu are mainly recognized by RIG-I (Kato et al., 2006). Furthermore HCV 3′UTR RNA is also recognized by RIG-I (Saito et al., 2008). Therefore, we first examined the expression of type I IFNs, IFN-inducible gene IP-10, and Ccl5 in MEFs after HCV 3′UTR dsRNA transfection or infection with VSV or Flu. The induction of mRNA of IFN-α2, -β, IP-10, and Ccl5 in response to VSV or Flu was abrogated in *Riplet*$^{-/-}$ MEFs (Figures 2A–2D). In addition, transfection of low concentration of HCV 3′UTR dsRNA (0.05–0.2 μg/well) also failed to upregulate IFN-α2, -β, and IFN-inducible genes in *Riplet*$^{-/-}$ MEFs (Figures 2A–2D).

Single-stranded (ss) RNA, which is synthesized by T7 RNA polymerase in vitro, induced lower IFN-β expression than dsRNA (Figure S2A). The induction of IFN-β mRNA by HCV 3′UTR ssRNA was also abolished in *Riplet*$^{-/-}$ MEFs (Figure S2A). Although the induction of IFN-β mRNA in response to VSV infection was abrogated in *Riplet*$^{-/-}$ MEFs even at high (moi = 5) or low multiplicities of infection (moi = 0.2 or 1), the induction of IFN-β mRNA in response to high concentration of HCV dsRNA (0.8 μg/well) was detected in *Riplet*$^{-/-}$ MEFs (Figures S2C–S2K). Therefore, RIG-I does not require Riplet function in the presence of large amounts of naked viral RNA in the cytoplasmic region.

Recently, Onoguchi et al. reported that type III IFN, IFN-λ, induction was RIG-I dependent during viral infection (Onoguchi et al., 2007). The induction of IFN-λ mRNA in response to VSV was also abrogated in *Riplet*$^{-/-}$ MEFs (Figure S2B).

Next, we examined type I IFNs or IL-6 levels in culture supernatants after viral infection or HCV 3′UTR RNA transfection (low concentration condition). The production of IFN-α, -β, and IL-6 in culture supernatants was abrogated in *Riplet*$^{-/-}$ MEFs (Figures 3A–3C). Next, we analyzed the contribution of Riplet to the antiviral response. When MEFs were infected with VSV at various mois, cytopathic effects (CPEs) were more severe in *Riplet*$^{-/-}$ than in wild-type MEFs (Figure 3D). These results demonstrate that Riplet plays a critical role in the elimination of RNA virus infection by induction of IFN responses.

Riplet Is Dispensable for the Production of Type I IFN Induced by B-DNA and HSV-1 Infection

Cytoplasmic B-form double-stranded DNA (dsDNA) stimulates the cells to induce type I IFNs and IFN-inducible genes (Ishii et al., 2006). TBK1 is required for type I IFN induction by dsDNA (Ishii et al., 2008). Although immortalized MEFs require RIG-I for type I IFNs production by dsDNA stimulation, primary MEFs do not require IPS-1, which is a RIG-I adaptor, for type I IFNs production by dsDNA (Kumar et al., 2006; Chiu et al., 2009). We examined the expression of IFN-β and IP-10 mRNA by dsDNA stimulation in primary wild-type and *Riplet*$^{-/-}$ MEFs. IFN-β and IP-10 mRNA were detected in *Riplet*$^{-/-}$ MEFs by dsDNA transfection similar to that detected in wild-type MEFs (Figures 4A and 4B).

Next, we examined IFN-β mRNA expression during infection with DNA virus, HSV-1. Wild-type and *Riplet*$^{-/-}$ MEFs were infected with HSV-1, and IFN-β mRNA expression was examined by RT-qPCR. IFN-β expression in *Riplet*$^{-/-}$ MEFs was comparable to that in wild-type MEFs (Figure 4C). Taken together, these

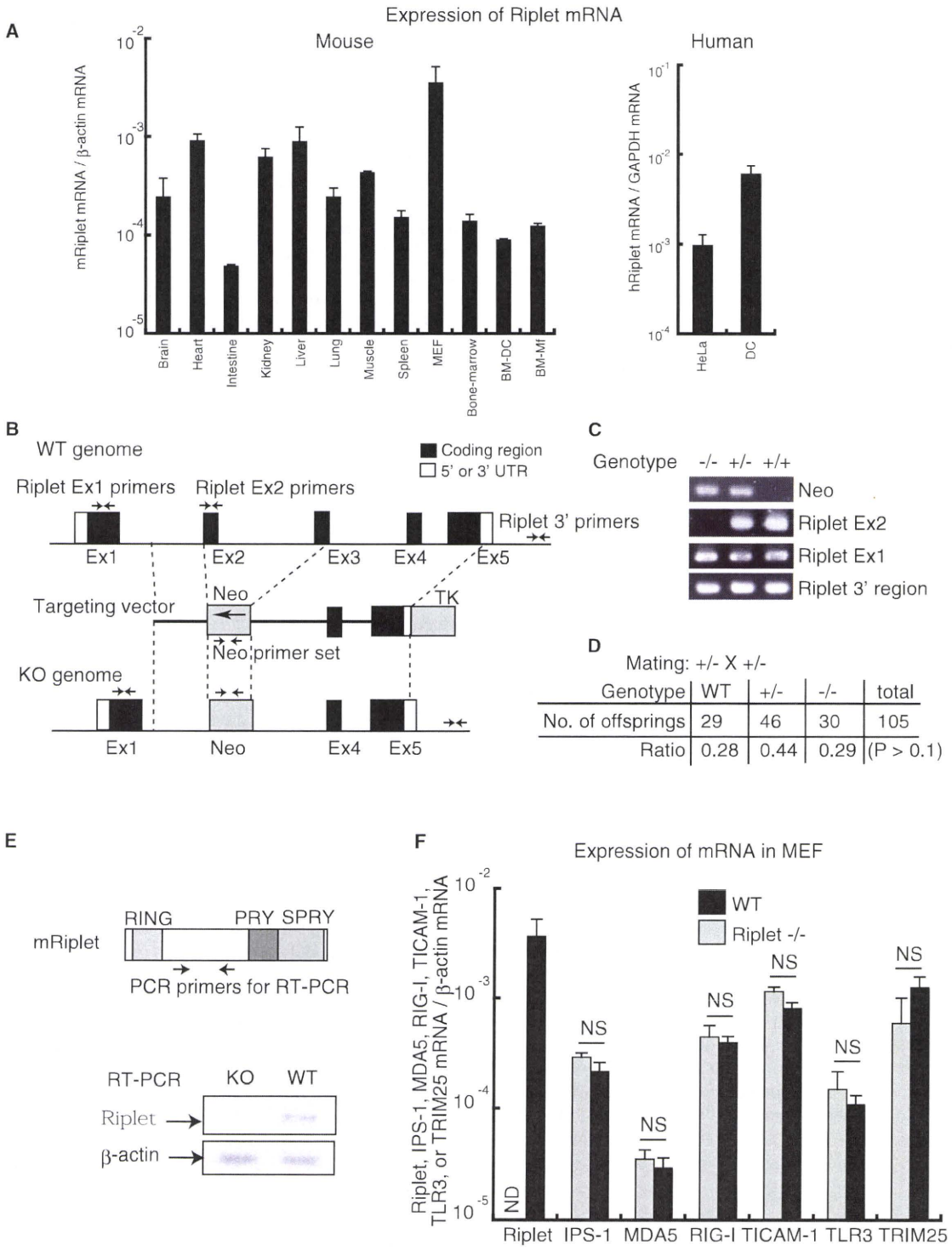

Figure 1. Targeted Disruption of the Murine Riplet Gene

(A) Riplet mRNA expression in mouse tissues and cells or human cells. RT-qPCR was performed to measure Riplet mRNA, and each sample was normalized to β-actin (mouse) or GAPDH (human). Data are shown as means ±SD and are representative of three independent experiments.

(B) Structure of the mouse Riplet gene, targeting vector, and disrupted gene. Closed boxes indicate the coding exon of Riplet, and hatched boxes indicate the Neo or TK gene coding region. The primer sets for PCR are shown by arrows.

data indicate that Riplet-dependent RIG-I activation is dispensable for type I IFN and IFN-inducible genes mRNA expression by cytoplasmic DNA in primary MEFs. This is consistent with previous studies reporting that the IPS-1-dependent pathway is dispensable for type I IFN production by cytoplasmic dsDNA stimulation (Kumar et al., 2006).

Riplet Is Essential for Triggering the RIG-I Signaling Pathway

We further examined the role of Riplet in RIG-I-mediated signaling during RNA virus infection. In RIG-I-mediated signaling, induction of type I IFNs and proinflammatory cytokines requires the activation of transcription factor IRF3. IRF3 is phosphorylated by TBK1 and IKK-ε. Phosphorylated IRF3 induces IFN-β gene expression. IFN-β produced subsequently stimulates the JAK-STAT pathway to amplify the responses. To determine the role of Riplet in signaling pathway activation, we analyzed IRF3 and STAT1 activations after VSV infection in *Riplet*$^{-/-}$ MEFs. VSV-induced dimerization of IRF3 and VSV- or Flu-induced pohsphorylation of STAT1 were abrogated in *Riplet*$^{-/-}$ MEFs (Figures 3E and 3F). These results demonstrate that Riplet is essential for activating the transcription factors that work early phase of RNA virus infection.

In the absence of viral infection, RIG-I CTD suppressed N-terminal CARDs (Saito et al., 2007). After viral infection, RIG-I CTD binds to viral RNA, leading to conformational changes (Saito et al., 2007). Later, RIG-I CARDs undergo TRIM25-mediated polyubiquitination and associate with IPS-1 CARD (Gack et al., 2007, 2008). When we tested the effect of Riplet on RIG-I activation, the full-length RIG-I protein with CTD failed to activate the IFN-β promoter in *Riplet*$^{-/-}$ MEFs (Figure 5A); however, promoter activation by the expression of RIG-I CARDs without CTD was normal in *Riplet*$^{-/-}$ MEFs (Figure 5B). These data indicate that Riplet is required for the activation of full-length RIG-I, but not for the activation of RIG-I CARDs without CTD. Next, we performed complementation assays. Immortalized *Riplet*$^{-/-}$ MEFs were transfected with an empty-, RIG-I-, or RIG-I-5KA mutant-expressing vector together with or without Riplet-expressing vector. The RIG-I-5KA mutant harbors mutations in five C-terminal Lys residues that are important for Riplet-mediated ubiquitination (Oshiumi et al., 2009). In the *Riplet*$^{-/-}$ cell line, RIG-I was not activated by HCV RNA stimulation, and Riplet expression led to the activation of wild-type RIG-I (Figure 5C). The deletion of the Riplet RING finger domain, which is the catalytic domain of ubiquitin ligase, abolished RIG-I activation (Figure 5D). Unlike wild-type RIG-I, Riplet expression failed to activate the RIG-I-5KA mutant protein (Figure 5C). The activations of wild-type and mutant RIG-I were correlated with its polyubiquitination (Figure S3A). Although the RNA binding activity was weakly reduced by the 5KA mutation, the pull-down assay showed that RIG-I-5KA mutant bound to dsRNA (Figure S3B). Next, we examined ligand-independent RIG-I activation by overexpression of Riplet. Overexpression of Riplet in HEK293 cells activated RIG-I in the absence of RIG-I ligand, such as viral RNA (Figure S3C). This ligand-independent activation of RIG-I by Riplet overexpression was also abolished by the 5KA mutation (Figure S3C). In addition, we examined the polyubiquitination of exogenously expressed RIG-I CTD fragment. Polyubiquitination of RIG-I CTD fragment was increased by overexpression of Riplet (Figure 5M), and was reduced by overexpression of the dominant-negative form of Riplet (Riplet DN) (Figure 5N). Polyubiquitination of RIG-I CTD fragment was not detected in Riplet-deficient cells (R3T cells); however, expression of Riplet led to polyubiquitination of RIG-I CTD fragment (Figure 5O). These data are consistent with our previous report (Oshiumi et al., 2009). Taken together, these data indicate that Riplet-dependent polyubiquitination of RIG-I is important for RIG-I activation.

Previously, we showed that Riplet is not involved in MDA5-mediated signaling. IFN-β promoter activation by MDA5 overexpression was normal in *Riplet*$^{-/-}$ MEFs (Figure 5E). Transfection of poly(I:C), which is recognized by MDA5, induced IFN-β, IL-6, and IP-10 expression in both wild-type and *Riplet*$^{-/-}$ MEFs (Figures 5F–5H). In addition, stimulation with lipopolysaccharide (LPS), which is a TLR4 ligand, normally induced expression of these cytokines in *Riplet*$^{-/-}$ MEFs (Figures 5I–5K). Furthermore, IL-6 production in culture medium in response to LPS was normal in *Riplet*$^{-/-}$ MEFs (Figure 5L). Taken together, these data indicate that Riplet is essential for the RIG-I-mediated type I IFN or IL-6 production upon viral infection in nonprofessional immune cells like fibroblasts, but is not required for MDA5- or TLR4-mediated signaling.

Riplet Is Required for Antiviral Innate Immune Responses in Conventional Dendritic Cells and Macrophages

We examined whether Riplet is required for the induction of type I IFN in DCs or Mf. DCs play a pivotal role in bridging innate and adaptive immune responses, and can be classified into cDCs and pDCs, the latter producing high levels of type I IFNs. Mfs also produce type I IFN. We induced cDCs from BM cells in the presence of GM-CSF (BM-DC). Twenty-four hours after VSV or Flu infection, cDCs of wild-type mice produced IFN-α, -β, and IL-6 (Figures 6A–6F). In contrast, the cDCs of *Riplet*$^{-/-}$ mice showed severely impaired IFN-α, -β, or IL-6 production during VSV or Flu infection (Figures 6A–6F). When the cDCs were stimulated with a TLR4 ligand, such as LPS, IFN-β or IL-6 production in *Riplet*$^{-/-}$ cDCs was almost normal (Figures S4A and S4B), indicating that Riplet is dispensable for LPS-induced cytokine production in cDCs.

Then we tested M-CSF-induced BM-Mf. Wild-type Mf produced IFN-α, -β, and IL-6 after VSV or Flu infection (Figures

(C) PCR of mouse tail. Genomic DNA was extracted from wild-type, *Riplet*$^{+/-}$, or *Riplet*$^{-/-}$ mice tails and PCR was performed using primers shown in (B).
(D) Genotype analyses of offspring from heterozygote intercrosses. Chi-square goodness-of-fit test indicated that deviation from Mendelian ratio was not statistically significant ($p > 0.1$).
(E) RT-PCR of MEFs. Total RNA from wild-type and *Riplet*$^{-/-}$ MEFs were extracted and subjected to RT-PCR to determine Riplet mRNA expression.
(F) Riplet, IPS-1 MDA5, RIG-I, TICAM-1, TLR3, and TRIM25 expression in MEFs. Total RNA from wild-type and *Riplet*$^{-/-}$ MEFs were extracted and subjected to RT-qPCR to determine mRNA expression. Expression of the indicated gene mRNA was normalized to β-actin mRNA expression. Data are shown as means ±SD and are representative of three independent experiments. "NS" indicates no statistically significant difference between the two samples.
See also Figure S1 and Table S1.