Multifunctional Effects of a Small-Molecule STAT3 Inhibitor on NASH and Hepatocellular Carcinoma in Mice

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Abstract

Purpose: The incidence of hepatocellular carcinoma is increasing in the United States, and liver cancer is the second leading cause of cancer-related mortality worldwide. Nonalcoholic steatohepatitis (NASH) is becoming an important risk for hepatocellular carcinoma, and most patients with hepatocellular carcinoma have underlying liver cirrhosis and compromised liver function, which limit treatment options. Thus, novel therapeutic strategies to prevent or treat hepatocellular carcinoma in the context of NASH and cirrhosis are urgently needed.

Experimental Design: Constitutive activation of STAT3 is frequently detected in hepatocarcinoma tumors. STAT3 signaling plays a pivotal role in hepatocarcinoma survival, growth, angiogenesis, and metastasis. We identified C188-9, a novel small-molecule STAT3 inhibitor using computer-aided rational drug design. In this study, we evaluated the therapeutic potential of C188-9 for hepatocellular carcinoma treatment and prevention.

Results: C188-9 showed antitumor activity in vitro in three hepatocellular carcinoma cell lines. In mice with hepatocyte-specific deletion of Pten (HepPten−/− mice), C188-9 treatment blocked hepatocellular carcinoma tumor growth, reduced tumor development, and reduced liver steatosis, inflammation, and bile ductular reactions, resulting in improvement of the pathological lesions of NASH. Remarkably, C188-9 also greatly reduced liver injury in these mice as measured by serum aspartate aminotransferase and alanine transaminase levels. Analysis of gene expression showed that C188-9 treatment of HepPten−/− mice resulted in inhibition of signaling pathways downstream of STAT3, STAT1, TREM-1, and Toll-like receptors. In contrast, C188-9 treatment increased liver specification and differentiation gene pathways.

Conclusions: Our results suggest that C188-9 should be evaluated further for the treatment and/or prevention of hepatocellular carcinoma. Clin Cancer Res; 23(18); 5537–46. ©2017 AACR.

Introduction

Hepatocellular carcinoma is the second most common cause of cancer-related deaths worldwide (1). Although the highest rates of liver cancer are found in certain areas of Asia and Africa, liver cancer incidence and mortality rates are increasing strikingly in western countries, including the United States (2, 3). Liver cirrhosis due to hepatitis B virus, hepatitis C virus, high alcohol consumption or nonalcoholic steatohepatitis (NASH) are the main risk factors associated with hepatocellular carcinoma; most patients with hepatocellular carcinoma have compromised liver function, which limits treatment options. Hepatocellular carcinoma is a complex and highly heterogeneous disease with a large spectrum of genomic alterations and aberrant activation of cell signaling pathways (4–6). Currently, effective treatment options for hepatocellular carcinoma are limited. Surgical resection or transplantation represent the only potentially curative therapies for hepatocellular carcinoma, but most patients are diagnosed at an advanced stage and are not candidates for these approaches. Thus, there is a pressing need for the development of novel approaches to treat and prevent hepatocellular carcinoma (7, 8).

The pivotal role of STAT3 in cancer development and progression in many human cancers has led to intense efforts to identify small molecules and other strategies for targeting STAT3 (9–11). STAT3 is a transcription factor that regulates cell proliferation and survival as well as immune responses associated with cancer development and progression including hepatocellular carcinoma. Nearly 60% of human hepatocellular carcinoma exhibit activated nuclear STAT3 and STAT3 activation is associated with a poor prognosis (12, 13). The critical role of STAT3 as a regulator of liver cancer development and progression was demonstrated in mice (13, 14). STAT3 has also been linked to liver inflammation, injury, and regeneration and to the activation of hepatic stellate cells (15–17).
Translational Relevance
The incidence of hepatocellular carcinoma is increasing in the United States and is the second leading cause of cancer-related mortality worldwide. Nonalcoholic steatohepatitis (NASH) is becoming an important risk for hepatocellular carcinoma, and most patients with hepatocellular carcinoma have underlying liver cirrhosis and compromised liver function, which limit treatment options. Thus, novel therapeutic strategies to prevent or treat hepatocellular carcinoma in the context of NASH and cirrhosis are urgently needed. This study identified the novel small-molecule C188-9 as a highly promising therapeutic drug for treatment and prevention of hepatocellular carcinoma. C188-9 showed not only preventive and antitumor activity but also significant reduced pathologic lesions of NASH and hepatocellular injury, with an overall improvement of liver functions. This dual effect of C188-9 may be highly beneficial to patients with hepatocellular carcinoma with NASH or liver cirrhosis. A phase 1 trial will be initiated later this year to examine the potential of C188-9 treatment in patients with hepatocellular carcinoma.

In a drug development program involving virtual ligand screening, two-dimensional (2-D) similarity screening, 3-D pharmacophore analysis, and SAR-based medicinal chemistry, we identified C188-9 as a potent small-molecule that targets the Src-homology (SH) 2 domain of STAT3 (18–21). C188-9 inhibited growth and survival of several cancer cell lines in vitro, including breast cancer (18), acute myeloid leukemia (19), head and neck squamous cell carcinoma (20) and non–small cell lung cancer (21). To test the effects of C188-9 on hepatocellular carcinoma and underlying liver disease, we herein used mice with hepatocyte-specific deletion of Pten (Hep^Pten−/− mice). These mice present with hepatomegaly and develop liver disease marked by steatosis, inflammation, and fibrosis characteristic of NASH, which progresses to development of hepatocellular carcinoma (22–25). This is a highly relevant model for preclinical studies of hepatocellular carcinoma in the context of steatosis, fibrosis or NASH (26, 27).

Materials and Methods
Cell culture and MTT viability assays
Human hepatoma cell lines HuH7 (ATCC), and PLC/PRF/5 and hepatoblastoma cell line HepG2 (ATCC) were grown in DMEM (Invitrogen) supplemented with 10% FBS, 100 units/mL penicillin, and 100 μg/mL streptomycin. The hepatic epithelial cells THLE3 (ATCC) were grown and maintained in BEGM+ (Lonza/Clonetics Corp.) but cultured in complete DMEM when assays were performed. For cell viability assays, cells were treated in 96-well plates in medium ± C188-9 (StemMed, Ltd.) for 48 hours and subjected to MTT assays. Briefly, cells were incubated with 0.5 mg/mL of the MTT solution (Sigma) for 2 hours and cell viability was measured by optical density (OD) at 590 nm (SpectraMax Plus 384 Microplate Reader, Molecular Devices). Experiments were performed in triplicate and used for IC50 calculation using GraphPad software.

Mouse treatment and MR imaging
The study was approved by our Institutional Animal Care and Use Committee (IACUC). C57BL/6 mice carrying Pten conditional knockout alleles were crossed with an Albumin (Alb)-Cre-transgenic mouse. For this model, control animals are Pten(fl/fl)Alb-loxP/loxPAlb-cre−/−, whereas the experimental mice are Pten(fl/fl)Alb-loxP/loxPAlb-cre−+/−. For in vivo treatment, C188-9 was dissolved in DMSO, and hepatic Pten null mice (Hep^Pten−/− mice; 11 month-old) received C188-9 (100 mg/kg) or vehicle (DMSO) by intraperitoneal injection daily for 4 weeks. Each treatment group included 9 to 12 mice. In a separate prevention study, Hep^Pten−/− mice (8 months old) received C188-9 (50 mg/kg) or DMSO by intraperitoneal injection daily for 4 weeks. MRI was performed at the beginning of treatment and repeated after 2 and 4 weeks, on a four-channel, 7T dedicated small animal scanner (Bruker Biospin MRI). For tumor detection, a rapid acquisition with relaxation enhancement (RARE) sequence was used in the coronal and axial planes with a 0.25-mm slice thickness and with the number of slices sufficient to cover the entire liver. For respiration monitoring, a pressure-sensitive pad was placed on the animal bed directly underneath the animal. The compression and decompression of the pad were measured, and the generated signal was finally fed to the MRI scanner.

Liver histopathology, IHC, and liver function assays
ACULC-endorsed euthanasia by CO2 was performed followed by necropsy at which time, liver and tumor tissues were collected and snap-frozen in liquid nitrogen or fixed in 10% neutral buffered formalin and paraffin embedded (FFPE). The snap-frozen tissues were pulverized for RNA or protein extraction. FFPE tissues were sectioned in 4-μm-thick histologic sections that were stained with hematoxylin and eosin (H&E) or Masson’s trichrome staining. Histopathologic analysis was performed blindly by a liver pathologist. A NAFLD Activity Score (NAS) was described for scoring liver biopsies in patients with steatosis/steatohepatitis (28). In most cases of human NASH, the majority of the steatosis is of the macrovesicular type. Although focal areas of microvesicular steatosis can be seen, this is not a common component of the steatosis in human disease. In contrast, some mouse models of NASH, including the Hep^Pten−/− model, have mixed macrovesicular and microvesicular steatosis. We therefore used a modified NAFLD activity score (mNAS) to include both macrovesicular and microvesicular steatosis grades, calculated as an unweighted sum of the grading scores of macrosteatosis (0–3), microsteatosis (0–3), grade of lobular inflammation (0–3), and presence of ballooning (0–2). Bile ductular reaction was assessed on a 1 to 4 scale. Blood samples were also taken at necropsy and processed for serum collection. Serum aspartate aminotransferase (AST) and alanine transaminase (ALT) activities were determined using ACE AXCEL clinical chemistry system (Diagnostic Technologies) according to the manufacturer’s instructions. Standard controls were run before each determination, and the values obtained for the biochemical parameter were within the expected ranges. HIC staining for Ki67 was performed using vehicle- and C188-9-treated tumor slides. Slides were scanned and analyzed using Aperio ImageScope software. The proliferation index was determined by calculating the average percentage of Ki67 tumor positive cells.

RNA sequencing and differentially expressed gene analysis
Total RNA was isolated from liver and tumors of the study mice. Following second-strand cDNA synthesis, end repair, adaptor ligation, and PCR amplification, the enriched cDNA
libraries were sequenced using Illumina HiSeq 3000. Libraries were run using 30-base-pair single-end reads on Illumina HiSeq 3000 System. Sequence files were generated in FASTQ format, and reads were mapped to mouse genome mm10 and then aligned by TopHat2 (29). Gene expression levels were quantified using Cufflinks (version 1.0.3) in the FPKM unit (fragments per kilobase of exon per million fragments mapped) together with confidence intervals. Cufflinks ran in the default parameters except that the annotated gene set was supplied using the -G option. Subsequently, the empirical analysis of digital gene expression data in R (edgeR) tool was utilized to detect the differentially expressed genes (DEG) after filtering out genes with counts per million (CPM) under 10 in all samples. CPM values were scaled by the total number of fragments. The multiple comparison P values were adjusted by using Benjamini–Hochberg method, providing a P value cutoff for significance controlled by the FDR. DEGs were selected using the following criteria: FDR < 0.05 and fold change > 1.5. The heat map of DEGs was generated using Pearson correlation and Ward distance in R and CPM values. DEGs were further analyzed using the ingenuity pathway analysis (IPA) software (Ingenuity Systems; http://www.ingenuity.com). IPA identifies putative networks, biological functions, and canonical pathways overrepresented among the DEGs.

Results

C188-9 reduced hepatoma cell viability

To evaluate the potential of C188-9 as a therapeutic strategy for hepatocellular carcinoma, we first examined the effect of C188-9, a potent, nontoxic, inhibitor of STAT3, on the viability of the hepatoma cell lines Huh7 and PLC/PRF/5 and the hepatoblast-derived cells HepG2. All three cell lines had increased activated STAT3 (2-fold), when compared to the normal hepatic epithelial cells THLE3 (Fig. 1A). We then treated them with C188-9 at serial concentrations ranging from 0.19 to 100 μmol/L for 48 hours under anchorage-dependent condition. C188-9 reduced cell viability of all three cell lines with IC50 values of 11.27, 10.19, and 11.83 μmol/L for Huh7, PLC/PRF/5, and HepG2, respectively (Fig. 1B). Finally, we confirmed the inhibition of pSTAT3 levels in these cells upon C188-9 treatment. At 10 μmol/L, pSTAT3 levels were reduced by 25.4%, 25.1%, and 13.2% and at 30 μmol/L, pSTAT3 levels were reduced by 43.9%, 66.5%, and 81.1%, in Huh7, PLC/PRF/5, and HepG2 cells, respectively (Fig. 1C).

C188-9 treatment resulted in tumor growth arrest in mice with hepatic deletion of Pten

We then evaluated the effect of targeting STAT3 in vivo, using the HepPten−/− mouse model. We treated 11-month-old HepPten−/− male mice for 4 weeks, with daily intraperitoneal injections of C188-9 or vehicle. All treated mice had developed tumors prior to treatment as confirmed by MRI. MRI imaging showed continuous tumor growth increase in vehicle-treated mice, but arrest of tumor growth in C188-9-treated mice (Fig. 2A). Indeed, although the average tumor growth rate in the vehicle group was 2.06-fold over 14 days, the average tumor growth rate was 1.16-fold in the C188-9-treated group (P < 0.001; Fig. 2B). The tumor growth arrest induced by C188-9 treatment was further confirmed by comparing the average tumor volume determined by MRI in both groups prior to treatment (119.02 and 92.64 mm3 for vehicle- and C188-9-treated mice, respectively; P = ns) and at the end of treatment (249.02 and 106.48 mm3 for vehicle- and C188-9-treated mice, respectively; P = 0.04; Fig. 2C). Necropsy results showed that although 70% of the tumors collected at time of necropsy from the vehicle group were >100 mm3, only 24.85% of the tumors in C188-9-treated mice were >100 mm3 (P = 0.02; Fig. 2D). Necropsy results also showed a significant reduction of liver to body weight ratio in C188-9-treated group compared to vehicle-treated mice (P = 0.02), further supporting the reduction of tumor growth upon C188-9 treatment (Fig. 2E). Finally, blinded analysis of all tumors by a pathologist showed that C188-9 treatment resulted in decreased percentage of carcinomas upon C188-9 treatment (from 92.87% to 86.67%) and concomitant increased percentage of adenomas (from 7.13% to 13.33%), indicating that tumor malignancy progression was inhibited upon C188-9 treatment (Fig. 2F).

C188-9 treatment improves NASH and liver function

Because HepPten−/− mice develop NASH prior to hepatocellular carcinoma, we also evaluated the effect of C188-9 treatment on this underlying liver pathology. The liver parenchyma in the vehicle-treated mice showed diffuse mixed macro- and microsteatosis extending from zones 1 to 3 (Fig. 3A, a and b). In contrast, the C188-9-treated mice showed minimal steatosis, with only a few small foci of steatosis observed in the centrilobular area (Fig. 3A, arrows in c). As shown in Fig. 3B, steatosis scoring further
confirmed that C188-9 treatment resulted in a decrease in hepatic steatosis for both macrovesicular and microvesicular steatosis (2.7 ± 0.2 vs. 0.8 ± 0.2 and 2.7 ± 0.2 vs. 0.3 ± 0.2, respectively, \( P < 0.001 \) for both). In line with the effect of C188-9 on reducing the steatosis, ballooning of hepatocytes and inflammation were also significantly decreased in mice treated with C188-9 compared to vehicle-treated mice (1.8 ± 0.2 vs. 0.4 ± 0.2; \( P = 0.002 \) and 2 vs. 1 ± 0.3; \( P = 0.016 \)). Using an mNAS to include both macrovesicular and microvesicular steatosis grades, we observed an overall inhibition of NASH and reversion to a phenotype with milder pathology upon C188-9 treatment (9.2 ± 0.3 vs. 2.4 ± 0.7; \( P < 0.001 \); Fig. 3B). The vehicle-treated mice also showed frequent areas of prominent bile ductular reaction with peribiliary neutrophilic inflammation (Fig. 3A, a and b). In contrast, most of the C188-9-treated mice appeared similar to untreated control mice, with the exception of rare focal bile ductular reactions, which had less associated inflammation and were significantly smaller in size when compared to those observed in the vehicle group (Fig. 3A, c and d). The bile ductular reaction scores were significantly reduced upon C188-9 treatment (2 vs. 0.6 ± 0.8; \( P = 0.004 \); Fig. 3C). In addition, C188-9 treatment significantly reduced fibrosis in these areas, measured by Masson's trichrome staining, from 8.77% to 3.07% (\( P < 0.001 \); Fig. A, panels a–d and 3D ). Most remarkably and in agreement with NASH improvement, serum biochemical analysis showed a significant reduction of hepatocellular injury upon C188-9 treatment as ALT and AST

\[ \text{ALT} \]
levels decreased upon C188-9 treatment, from 434 to 165.43 IU/L ($P = 0.003$) and from 350 to 182.57 IU/L ($P = 0.004$), respectively (Fig. 3E), reaching near to normal values.

C188-9 treatment reduces tumor development $\text{in vivo}$

Because of the effects of C188-9 on NASH severity, we evaluated the effect of C188-9 on tumor development in the Hep$\text{Pten}^\text{-/-}$ mice. Mice without tumors as determined by MRI, were treated with C188-9 or vehicle and tumor development was monitored over a 4-week period by MRI. At the end of treatment, the average tumor size (6.24 $\pm$ 3.02 mm$^3$ vs. 25.25 $\pm$ 10.6 mm$^3$; $P = 0.05$) and average tumor burden (9.36 $\pm$ 5.67 mm$^3$ vs. 38.18 $\pm$ 17.76 mm$^3$) were lower in C188-9 treated mice compared to the vehicle group (Fig. 4), demonstrating that treatment of C188-9 reduces tumor development in Hep$\text{Pten}^\text{-/-}$ mice.

Gene expression changes upon C188-9 treatment in tumors and adjacent liver in Hep$\text{Pten}^\text{-/-}$ mice

To identify the mechanism of C188-9 effect $\text{in vivo}$, we measured mRNA expression using RNA-sequencing in both liver and tumors from C188-9-treated group and vehicle group. Using $P$ value <0.05 and fold change >1.5, we identified 606 upregulated and 870 downregulated genes in liver and 478 upregulated and 172 downregulated genes in tumors, upon C188-9 treatment. Among these genes, 144 genes were commonly upregulated and 96 genes were commonly downregulated in both liver and tumor (Fig. 5A). Hierarchical clustering based on these DEGs distinguished four main clusters corresponding to vehicle liver, vehicle tumor, C188-9 tumor and C188-9 liver, with the widest separation being between vehicle liver and C188-9 liver. The clustering analysis demonstrated that all mice responded similarly to C188-9 treatment and that the effects on gene expression were largely specific to the liver or the tumor, with the largest effect being observed in liver (Fig. 5B).

We performed IPA for all DEGs significantly downregulated or upregulated or in liver, in tumor, or in both. The top biological functions and canonical pathways that were downregulated by C188-9 were TREM1 signaling, role of pattern recognition receptors in recognition of bacteria and viruses in liver; cellular growth and cell death and survival in tumor; mitotic role of polo-like
kinase, and interferon signaling in both liver and tumor (Supplementary Table S2). IPA analysis identified STAT3 as the main upstream regulator of the downregulated DEGs. Inhibition of STAT3 activity upon C188-9 treatment was confirmed by measuring pY-STAT3 levels. pY-STAT3 levels were increased in tumors compared to liver in the vehicle group ($P = 0.02$) confirming the activation of STAT3 in hepatocellular carcinoma in HepPten mice. C188-9 treatment resulted in a reduction of pY-STAT3 levels in tumors to levels similar to those observed in vehicle-treated tumors ($P = 0.014$; Supplementary Fig. S1). TGFβ1 and IFNγ were also identified as upstream regulators in liver. In agreement, IFNγ-inducible genes and toll like receptors were overrepresented among the downregulated DEGs. A large number of profibrotic and tumor promoter genes were also found downregulated in liver and tumor (Supplementary Table S2). The effect on IFNγ-inducible genes suggested that STAT1 activity could also be
inhibited upon C188-9 treatment in Hep\(^{\text{Pten}}\)\(^{-}\) tumors. Indeed, pY-STAT1 levels were decreased upon C188-9 treatment in tumors in Hep\(^{\text{Pten}}\)\(^{-}\) mice (\(P = 0.002\); Supplementary Fig. S1). The top biological functions and canonical pathways that were upregulated by C188-9 were FXR/RXR activation, estrogen biosynthesis and cholesterol biosynthesis in liver; granulocyte adhesion in tumor; LXR/RXR activation in both liver and tumor (Supplementary Table S3). Interestingly, Hnf4a, a major hepatocytic differentiation transcription factor, was identified as the main upstream regulator in liver, and other liver specification and differentiation genes were also upregulated such as Acox2 in liver and Hnf3a and aldolase C in tumor. A large number of cytochrome P450 genes were upregulated in both liver and tumor. Other genes associated with inhibition of fibrosis and tumor suppression in liver were also identified (Supplementary Table S3). We also randomly selected five genes from the list of DEGs, for validation by qRT-PCR. RNA sequencing data were validated by qRT-PCR for the downregulated genes CENPF, CD34, and HMMR, and the upregulated genes CD163 and CYP1A1 (Supplementary Fig. S2).

C188-9 treatment inhibits cell proliferation \textit{in vivo} and is associated with reduction in circulating inflammatory chemokines

Gene expression analysis identified Ki67 as a gene commonly downregulated in both liver and tumor upon C188-9 treatment in Hep\(^{\text{Pten}}\)\(^{-}\) mice. Sections from vehicle and C188-9 treated tumor were stained with Ki67 antibody, and the percentages of Ki67-positive cells were calculated. As shown in Fig. 6A, C188-9 treated...
group exhibited less staining for Ki67, when compared with the vehicle treated group (15.5 ± 1.9 vs. 8.4 ± 0.7; P < 0.001). Because inflammation was reduced based on histology analysis and because several inflammatory cytokines and chemokines were found modulated by C188-9 in gene expression analysis, we measured a panel of cytokines/chemokines in serum collected from the mice treated with either vehicle or C188-9. CXCL9 and CXCL10 levels were found to be dramatically decreased in C188-9-treated mice (364.6 ± 75.2 pg/mL vs. 159.9 ± 30.6 pg/mL, P = 0.01 and 455.1 ± 66.7 pg/mL vs. 234.0 ± 87.7 pg/mL, P = 0.05, respectively; Fig. 6B).

Discussion

Although causal roles for STAT3 in hepatic tumorigenesis have been proposed (32), the importance of STAT3 in hepatocellular carcinoma preconditions, such as liver fibrosis or NASH, has received far less attention, aside from two studies suggesting that STAT3 inhibition mediates the antifibrotic effect of sorafenib (33) and that STAT3 signaling is activated in NAFLD (34). Herein, we used a clinically relevant model of NASH-associated hepatocellular carcinoma to evaluate the therapeutic potential of C188-9, a small molecule inhibitor of STAT3. C188-9 binds to the SH2 domain of STAT3 and blocks its recruitment to the kinase-containing receptor complexes, its tyrosine phosphorylation, and its homodimerization. STAT3 activation can lead to tumorigenesis in diverse type of cancers (18–21). We demonstrated that C188-9 had beneficial effects on both hepatic tumor and NASH in liver, with blockage of tumor growth and progression, prevention of tumor development, reduction of steatosis, inflammation, and hepatocellular ballooning, resulting in NASH reversion, and reduction of bile ductular reaction and associated fibrosis. Evaluation of C188-9 treatment on additional models of hepatocellular carcinoma and NASH will be needed to demonstrate that the effects reported in this study are independent of hepatic PTEN loss. Future studies aimed at further characterizing STAT3 activation in human NASH-hepatocellular carcinomas are also warranted.

Genomic analysis identified a main inhibitory effect on immune response including downregulation of TREM-1 signaling and reduced expression of Toll-like receptors (TLR) and interferon-inducible genes. It was previously reported that the proinflammatory myeloid cell receptor TREM-1 controls development of hepatocellular carcinoma (35) and that TREM-1 expression in hepatic stellate cells is a prognostic marker for hepatitis B-related hepatocellular carcinoma (36). TLRs are pattern recognition receptors that sense and respond to microbial pathogens and damage-associated molecular patterns by facilitating inflammation (37). TLR are present on host immune cells, especially macrophages and dendritic cells, but also on epithelial cells (38). STAT3 is an important regulator of TLR2 and TLR4 activity and a mediator of TLR4 and TLR9 signaling (39–42). TLR3/4/9-mediated inflammatory responses are an important contributor of chronic inflammation-associated hepatocellular carcinoma (43). The reduction of TLRs in C188-9-treated HepPatm mice may contribute to the concomitant reduction in inflammation measured by histology and in reduced levels of inflammatory cytokines in serum of these mice and in the overall reduction of NASH severity. TLR2, TLR4, and TLR9 has been implicated in the development of ASH, NASH, liver fibrosis, and hepatocellular...
carcinoma and increased TLRs is involved in increased inflammation in these chronic liver disease (44–47). Whether the observed reduction in TLRs in liver and tumor upon C188-9 treatment corresponds to a reduction in immune cell infiltration or a reduced expression on epithelial cells or both requires further evaluation. A comprehensive immune profiling follow-up study aimed at identifying the immune cell populations affected by C188-9 treatment in the Hep/Pten− model would be highly relevant. Such populations include Th2 and Th17 cells: STAT3 drives development of Th17 cells and cytokine production by Th2 and Th17 cells and we have recently reported that C188-9 prevents the accumulation of Th2 and Th17 cells in a murine asthma model (48).

In contrast, the Farnesoid X receptor (FXR) signaling pathway was activated upon C188-9 treatment. FXR is highly expressed in liver and has an important role in protecting against hepatocellular carcinoma by inhibiting cell growth and inducing cell cycle arrest at G1 phase (49). Genomic analysis also identified HNF4a, a major hepatocytic transcription factor, as the main upstream regulator in liver and other liver specification genes upregulated in liver and tumor, suggesting that C188-9-induced hepatocytic differentiation in both liver and tumor. We recently showed that induction of hepatocytic differentiation in the Hep/Pten− model inhibits tumor growth, reduced liver fibrosis and prevented tumor development (7). Therefore, the improved differentiation status of hepatic cells may contribute to the therapeutic effect of C188-9 treatment on tumor and liver and the observed improvement in liver injury tests.

C188-9 has been shown to have inhibitory effects on STAT1 in prior studies involving head and neck squamous cell carcinoma (20). Although we identified STAT3 as the main upstream regulator targeted by C188-9 treatment in both liver and tumor, the significant overrepresentation of interferon-inducible genes among the C188-9-dependent downregulated genes, suggested that STAT1 activity was also inhibited. C188-9-induced inhibition of STAT1 activity was indeed confirmed in both liver and hepatic tumors. The differential contribution of inhibition of STAT1 versus STAT3 to the C188-9 treatment effects in Hep/Pten− model will be further investigated in follow-up studies.

In conclusion, this study identified the novel small-molecule C188-9 as a highly promising therapeutic drug for treatment and prevention of hepatocellular carcinoma. C188-9 showed not only preventive and antitumor activity but also significant reduced pathologic lesions of NASH and hepatocellular injury, with an overall improvement of liver functions. This dual effect of C188-9 may be highly beneficial to patients with hepatocellular carcinoma with NASH or liver cirrhosis. A phase 1 trial will be initiated later this year to examine the potential of C188-9 treatment in patients with hepatocellular carcinoma.

Disclosure of Potential Conflicts of Interest

D.J. Tweardy is an employee of and holds ownership interest (including patents) in SemMed, Ltd. No potential conflicts of interest were disclosed by the other authors.

Authors’ Contributions

Conception and design: D.J. Tweardy, L. Beretta

Development of methodology: D.J. Tweardy

Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): H. Shen, M. Gagea, T.K. Eckols, L. Beretta


Writing, review, and/or revision of the manuscript: K.H. Jung, W. Yoo, H.L. Stevenson, D. Deshpande, M. Gagea, U. Bharadwaj, D.J. Tweardy, L. Beretta

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References


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