CSF1 Restores Innate Immunity Following Liver Injury in Mice and Serum Levels Indicate Outcomes of Patients With Acute Liver Failure

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Title: CSF1 Restores Innate Immunity Following Liver Injury in Mice and Serum Levels Indicate Outcomes of Patients With Acute Liver Failure

Short Title: CSF1 indicates outcome in liver failure

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Abbreviations: CSF1: colony stimulating factor 1; CSF1R: CSF1 receptor; HMGB1: high mobility group protein 1; PH: partial hepatectomy

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Stutchfield BM, Hume DA, Wigmore SJ and Forbes SJ obtained funding; Mackinnon AC, Bain CC, Jenkins SJ, Mowat A.Mcl, Wojtacha D, Man TY produced experimental data and/or key materials

Conflict of interest statement: A patent application has been filed by the University of Edinburgh for CSF1 based therapeutics in the treatment of liver disease. BM Stutchfield, DJ Gow, DA Hume and SJ Forbes are listed as co-inventors. No other author disclosures.
Abstract

Background & Aims: Liver regeneration requires functional liver macrophages, which provide an immune barrier that is compromised following liver injury. Numbers of liver macrophages are controlled by macrophage colony stimulating factor (CSF1). We examined the prognostic significance of serum level of CSF1 in patients with acute liver injury and studied its effects in mice.

Methods: We measured levels of CSF1 in serum samples collected from 55 patients who underwent partial hepatectomy at the Royal Infirmary Edinburgh between December 2012 and October 2013, as well as from 78 patients with acetaminophen-induced acute liver failure admitted to the Royal Infirmary Edinburgh or the University of Kansas Medical Centre. We studied the effects of increased levels of CSF1 in uninjured mice that express wild-type CSF1 receptor or a constitutive or inducible CSF1 receptor reporter, as well as in Ccr2−/− mice; we performed fate-tracing experiments using bone marrow chimera. We gave CSF1-Fc to mice following partial hepatectomy and acetaminophen intoxication, and measured regenerative parameters and innate immunity by clearance of fluorescent microbeads and bacterial particles.

Results: Serum levels of CSF1 increased in patients undergoing liver surgery in proportion to the extent of liver resected. In patients with acetaminophen-induced acute liver failure, low serum level of CSF1 was associated with increased mortality. In mice, administration of CSF1-Fc promoted hepatic macrophage accumulation via proliferation of resident macrophages and recruitment of monocytes. CSF1-Fc also promoted trans-differentiation of infiltrating monocytes into cells with a hepatic macrophage phenotype. CSF1-Fc increased innate immunity in mice following partial hepatectomy or acetaminophen-induced injury, with resident hepatic macrophage the main effector cell.

Conclusions: Serum CSF1 appears to be a prognostic marker for patients with acute liver injury. CSF1 might be developed as a therapeutic agent to restore innate immune function following liver injury.

Keywords: drug-induced liver damage; clearance; immune response; M-CSF
Introduction

The liver provides an essential immune barrier against gut-derived pathogens entering the portal circulation\(^1\). While surgical removal of liver tissue (partial hepatectomy) results in rapid compensatory upregulation of metabolic function, the liver’s innate immune capacity is markedly impaired\(^2,3\). Acute toxic liver injury leads to widespread hepatocyte necrosis and compromises barrier function\(^4\). Changes in gut wall integrity associated with liver failure facilitate the translocation of gut-derived pathogens\(^5\). Consequently, sepsis is common in patients with liver failure and is strongly-associated with high mortality rates\(^6,7\). Liver transplantation is the only effective therapy for life-threatening liver failure but active sepsis is contraindicated in transplantation.

Hepatic macrophages mediate hepatic innate immune defence and promote hepatocyte proliferation following liver injury\(^8,9\). Tissue macrophage numbers are controlled during development, and in the steady state, by macrophage colony stimulating factor (CSF1), which acts through a tyrosine kinase receptor, CSF1R\(^10,11\). Csf1\(^-\) deficient mice (op/op) have few tissue macrophages and impaired liver regeneration following partial hepatectomy\(^12\). Hepatic macrophages control circulating CSF1 levels via receptor-mediated endocytosis through CSF1R\(^13\). In humans following living donor partial hepatectomy, elevated circulating CSF1 is associated with more rapid liver regrowth\(^14\). In acute toxic liver injury models, monocyte-derived macrophage recruitment is required for necrotic tissue resorption\(^15\). In human acute liver injury, hepatic macrophages are implicated in tissue repair and low monocyte counts are associated with mortality\(^16,17\). Based upon these findings there is a strong rationale for exploring the potential of macrophage-based therapeutics to improve outcomes following acute liver injury.

Here we demonstrate that high serum CSF1 is associated with survival in patients with ALF and outperforms previous markers of outcome in terms of discriminative ability. We demonstrate that CSF1 administration in animal disease models promotes rapid recovery of innate immune function and hence has therapeutic potential in human liver failure.
Materials and Methods

Human Work

Ethical approval was obtained from the South East Scotland Research Ethics Committee (2) for patients undergoing PH at the Hepatobiliary Unit, Royal Infirmary Edinburgh, between December 2012 and October 2013. Liver failure was defined according to Schindl et al.\(^7\). For the acetaminophen induced acute liver failure (ALF) cohort, ethical approval was granted by the local human research ethics committee and informed consent obtained from all patients, or next of kin, before study entry. This study builds on previous analysis of this patient cohort by Antoine et al.\(^18\), representing 78 adult patients admitted to the Royal Infirmary Edinburgh, UK or the University of Kansas Medical Centre, USA with acute liver injury. Serial patient samples from a second patient cohort were collected at admission to hospital (as opposed to admission to the specialist liver centre with acute liver failure)\(^18\). Details of serum analyses are provided in the supplementary methods. Primary hepatocytes were isolated from human liver tissue obtained from liver resection specimens immediately following surgery, with full informed consent and ethical approval from the relevant authorities (National Research Ethics Service REC reference: 11/NW/0327). See Supplementary Methods for assay details.

Animal experiments

Animal procedures were approved by the relevant institutional ethics committee (Albert Einstein College of Medicine, USA, University of Edinburgh, UK, and the University of Glasgow, UK) and adhered to the Animals (Scientific Procedures) Act 1986, UK and NIH guide for the Care of Laboratory Animals, USA. 8 -12 week male mice were used. \(CCR2^{-/-},\text{C57Bl/6}\) and MacGreen mice (\(Tg(Csf1R-GFP)_{\text{Hume}}\)) were bred and maintained under specific pathogen-free conditions. \(Tg(Csf1r-Mer2iCre)_{\text{jwp}}\) were crossed to Rosa floxed stop tomato red and lineage tracing experiments performed as described\(^20\). Fate tracing bone marrow-derived monocytes was performed using a mouse chimera as previously described\(^21\). Wild type \(\text{C57BL/6}\) mice were obtained from Charles River. Mice were randomly distributed and maintained on 12-hr light-dark cycle with feed \textit{ad libitum}. 2/3 partial hepatectomy was performed as previously described\(^22\). Acetaminophen intoxication involved intraperitoneal
administration of 350mg/kg acetaminophen (Sigma Aldrich)\textsuperscript{23}. Treatment group received 0.75mcg/g CSF1-Fc, prepared as described previously\textsuperscript{24} (control: PBS) administered subcutaneously immediately following partial hepatectomy or 12 hours following acetaminophen intoxication and subsequently every 24 hours for up to three further doses. Reagents and methodology for immunohistochemistry, flow cytometry, quantification of mRNA, phagocytosis assay and serum analyses are provided in the supplementary methods.

Hepatocyte toxicity and metabolic assays
Details of human and mouse hepatocyte toxicity and metabolic assays are provided in the Supplementary Methods.

Statistics
Statistical analysis was performed on Graphpad Prism V6.0, except logistic regression analyses which were conducted in \textit{R}\textsuperscript{25}. All data are presented as mean +/- standard error of the mean unless otherwise stated. Two tailed Student’s \textit{t} test are used where appropriate to analyse parametric data. One-way and Two way ANOVA with Bonferroni adjustment are stated when used. Human serum analyses and development of the logistic regression models were completed by a qualified statistician. Level of significance was set at \( p < 0.05 \) for all analyses (figures *\( p < 0.05 \), **\( p < 0.01 \), ***\( p < 0.001 \), ****\( p < 0.0001 \)).

Results

\textbf{Serum CSF1 rises according to extent of partial hepatectomy and is associated with survival in acute liver failure}

In a cohort of 55 patients undergoing up to 75\% PH (cohort details: Supplementary Figure 1A) serum CSF1 was significantly elevated compared to healthy controls. There was a small reduction at day 1 post surgery followed by a marked increase in CSF1 level by postoperative day 3 (Figure 1A). There was no correlation between serum CSF1 level and blood loss (Supplementary Figure 1B). The initial
fall in serum CSF1 level may be due to removal of tumour cells, which secrete CSF1. We hypothesized that the subsequent rise in serum CSF1 level might be produced by proliferating hepatocytes. Due to the risks associated with liver biopsy in humans, we examined a mouse model of 2/3 PH CSF1 mRNA was unchanged following PH (Supplementary Figure 1C). In the patient cohort the CSF1 increase was related to the extent of resection (Figure 1B). Two patients developed postoperative liver failure and both had serum CSF1 levels below the 25th percentile (Figure 1C; clinical details in Supplementary Figure 1D).

We sampled serum from a large patient cohort with established acetaminophen-induced ALF on arrival at the specialist centre (cohort details: Supplementary Figure 2A). Assessment of ALF and requirement for liver transplantation is currently based on the validated modified King’s College Hospital (KCH) criteria which reflect poor clinical condition and likelihood of death. Low serum CSF1 was significantly associated with patient deterioration to KCH criteria (Supplementary Figure 2B and C), and subsequent death or liver transplantation (Figure 2A). Regardless of final outcome, those patients with a Systemic Inflammatory Response Score (SIRS) >2 had a significantly lower CSF1 level (Supplementary Figure 2D). Serial samples in a separate patient cohort (details Supplementary Figure 2E), followed from first presentation to hospital, showed serum CSF1 levels continued to increase in patients whose liver regenerated, whereas CSF1 levels fell in those who deteriorated (Figure 2B). In the livers removed from transplant recipients, CSF1 was detected in hepatocytes and non-parenchymal cells (Supplementary Figure 2E). Given the risks of liver biopsy, we used the mouse model to assess hepatic CSF1 gene expression. In contrast to PH, hepatic CSF1 mRNA expression increased significantly following acetaminophen intoxication peaking at Day 2 (Supplementary Figure 2F).

The current best available prognostic biomarker in ALF is serum acetyl-HMGB1 (high mobility group box-1). This DAMP (damage associated molecular patterns) is released from necrotic tissue and by activated immune cells in response to injury. We assessed the discriminative ability of acetyl-
HMGB1, alongside CSF1 and also established clinical measures including bilirubin, prothrombin time and ALT level using the receiver operator characteristic (ROC) curve (Figure 2C). Serum CSF1 and acetyl-HMGB1 demonstrate similar profiles, whereas bilirubin, PT, ALT and APACHEII score were of limited value. There was an inverse correlation between CSF1 and acetyl-HMGB1 (Figure 2D). When combined in a logistic regression model, only CSF1 showed significance (Figure 2E; Supplementary Figure 2F), indicating that serum CSF1 level was a better predictor of outcome than acetyl-HMGB1 (Supplementary Figure 2G and H). Figure 2F provides example CSF1 values with risk of death based on the ‘CSF1 alone’ model.

**Sustained CSF1R stimulation induces hepatic enlargement involving macrophage accumulation in mice**

The association of low serum CSF1 with poor prognosis in ALF provides a rationale for therapeutic use. Some studies report that CSF1R is expressed outside the macrophage lineage\(^{29,30}\). We therefore examined CSF1R expression using MacGreen mice, where eGFP is under the control of the Csf1r promoter\(^{19}\). Multiphoton ex vivo imaging of liver confirmed CSF1R expression limited to cells with tissue macrophage morphology (Figure 3A). To confirm this, we crossed Csf1r-Mer-Cre-Mer to Rosa26-LSL-dTom reporter mice to allow tamoxifen-induced labelling of CSF1R\(^{+}\) cells, as previously described\(^{20}\). Co-localisation of the pan-macrophage marker F4/80 confirmed that all dTomato\(^{+}\) cells (CSF1R\(^{+}\)) cells belonged to the macrophage lineage (Figure 3B). These data are supported by expression profiling from the FANTOM5 consortium that show no detectable CSF1R mRNA in hepatocytes isolated from control, or regenerating, mouse liver or isolated human hepatocytes\(^{31}\).

To assess the therapeutic potential of CSF1, we used the CSF1-Fc fusion protein, which overcomes the short half-life of CSF1 protein in vivo\(^{24}\). CSF1-Fc treatment of mice promoted hepatic macrophage accumulation but the mechanisms were unclear\(^{24,32}\). Six hours following CSF1-Fc administration to uninjured mice there was a marked upregulation of hepatic chemokines, particularly CCL2, CCL7 and CCL12, which are ligands for the CCR2 receptor and highly expressed by classical (Ly6C\(^{+}\)) blood...
monocytes (Figure 3C; array details Supplementary Figure 3A). After 4 days of CSF1-Fc treatment 20% of the liver was composed of F4/80+ macrophages compared to 2% in steady state (Fig 3D). This macrophage accumulation initiated hepatocyte proliferation at day 4. Mechanisms of hepatocyte proliferation are multifactorial with an upregulation of many cytokines and chemokines associated with the inflammatory response. Despite the induction of pro-inflammatory cytokine mRNA in the liver, serum ALT and AST were reduced with CSF1-Fc treatment, while bilirubin was unchanged (Fig 3F) and there was no hepatocyte apoptosis (Supplementary Fig 3B). The spleen increased in size although weight of other organs did not change (Supplementary Fig 3C and 3D).

**Macrophage accumulation involves in situ proliferation and CCR2-related infiltration**

Infiltrating monocyte-derived macrophages and tissue resident macrophages can be distinguished by relative expression of F4/80 and CD11b and may remain distinctly-regulated entities in steady state liver and following acetaminophen-induced injury. Following CSF1-Fc treatment, there was a two-fold increase in cells with a resident hepatic macrophage phenotype (F4/80hiCD11blo) and over a five-fold increase in the monocyte-derived infiltrating macrophages (F4/80hiCD11bhi cells), consisting predominantly of Ly6C hi monocytes (Figure 4A). Both F4/80hiCD11blo and F4/80hiCD11bhi cells proliferated markedly in situ following CSF1-Fc administration (Figure 4B; Supplementary Figure 4A and B). Liver macrophages in the treated livers were fate-mapped using tissue-protected bone marrow chimeric mice, where only the hind legs of recipient CD45.1+CD45.2+ animals were irradiated before engraftment of congenic CD45.1+ bone marrow. In these animals, F4/80hiCD11bhi macrophages and blood monocytes exhibited equivalent donor chimerism (Figure 4C). In PBS treated animals F4/80hiCD11blo cells remained almost exclusively of host origin, consistent with their proposed tissue origin. However, following CSF1-Fc treatment, approximately 20% of the F4/80hiCD11blo cells were derived from recruited cells. Thus, the increase in liver macrophages resulted from infiltration of monocytes, proliferation of infiltrating and resident cells as well as a minor role for differentiation of infiltrating macrophages into a resident macrophage phenotype. The only other cell population that increased significantly was eosinophils (Supplementary Figure 4C), which may have responded to
eosinophil chemoattractants CCL3, 4, 7 and 12, detected 6 hours following CSF1-Fc administration (Figure 3C).

Ligands for the CCR2 receptor, which are potent monocyte chemoattractants, were upregulated early after CSF1-Fc administration (Figure 3A). To examine the role of recruited monocytes, we tested CSF1-Fc administration on Ccr2−/− mice, hypothesizing that the mobilization and recruitment of infiltrating F4/80lo CD11bhi macrophages would be prevented since Ly6Chi monocytes are thought to depend upon CCR2 signals for release from the bone marrow and extravasation into inflamed tissues15, 36. Surprisingly Ccr2−/− mice developed a pronounced Ly6Chi monocytosis following CSF1-Fc administration, indicating that CSF1 can overcome the CCR2 requirement for marrow release (Supplementary Figure 4D). Nevertheless, CSF1-Fc driven hepatic engraftment by infiltrating macrophages was reduced by CCR2 deficiency (Figure 4D). Accumulation of resident F4/80loCD11bhi macrophages was largely unaffected, consistent with local proliferation being the major means of expansion. The increase in eosinophils was unaffected by CCR2 deficiency. CSF1-Fc treatment increased hepatic neutrophils in CCR2 deficiency (Supplementary Figure 4E), probably due to the deficit in infiltrating monocytes which regulate neutrophil activity35. Importantly, CCR2 deficiency prevented the increase in liver to body weight ratio observed in wild type mice following CSF1-Fc administration (Figure 4C). Although F4/80lo/CD11bhi macrophages are not completely dependent on CCR2 for mobilisation and trafficking to tissues, the data suggest the action of CSF1-Fc on monocyte-derived rather than resident macrophages is the critical step promoting hepatic enlargement.

**CSF1-Fc treatment accelerates recovery of innate immune capacity following partial hepatectomy**

Patient survival depends upon the rapid restoration of liver macrophage functions to clear pathogenic material. We therefore tested the effect of CSF1-Fc upon innate immune function in injury models. CSF1-Fc administration increased liver size over controls at 4 days following PH (Figure 5A).
Hepatocyte staining (CYPD2) per unit area (Supplementary Figure 5A) was reduced following CSF1-Fc treatment, indicating the increased size was due to increased non-parenchymal cell accumulation. Peak hepatocyte proliferation (Day 2) was not increased by CSF1-Fc treatment (Figure 5B), although at later time points the macrophage accumulation did promote increased hepatocyte proliferation compared to controls. To confirm the role of endogenous CSF1 signalling, implied from studies of op/op mice, we treated with a CSF1R kinase inhibitor (GW2580) or a blocking antibody against the CSF1 receptor (AFS98). Both treatments reduced hepatocyte proliferation (Supplementary Figure 5b) and affected the expression of macrophage related cytokine and matrix remodelling genes associated with regeneration (Supplementary Figure 5C and 5D).

Following PH, macrophages accumulated more rapidly in the liver of CSF1-Fc treated mice, involving both monocyte derived infiltration and proliferation (Figure 5C). There was a corresponding elevation in genes encoding phagocytic receptors, such as MARCO (macrophage receptor with collagenous structure) and MSR1 (macrophage scavenger receptor 1, with a reciprocal reduction following CSF1 blockade (Figure 5D). To assess the impact on clearance of insoluble material and bacteria-derived particles, we injected fluorescent-labelled latex microbeads intravascularly. These were rapidly and selectively taken up by liver phagocytes. There was minimal uptake by the spleen, lung, kidney, brain, and circulating cellular populations (Supplementary Figure 5E-G). Multiphoton imaging of the Csf1r-eGFP mouse liver confirmed that microbeads were phagocytosed by hepatic macrophages with CSF1-Fc treatment causing enhanced clearance from the circulation (Figure 5E). Ex vivo whole organ fluorescence imaging indicated this enhanced clearance capacity was clearly due to liver uptake (Figure 5F). To extend these findings to potential pathogens, we used pH sensitive E. coli bioparticles which fluoresce when taken up into acidified vesicles and injected these into the portal vein (Figure 6A). CSF1-Fc treatment increased both internalisation capacity and the absolute yield of positive cells (Figure 6B). Relatively few infiltrating monocyte-derived cells (F4/80<sup>lo</sup> CD11b<sup>hi</sup>) internalised the labelled E.coli, but CSF1-Fc treatment again increased the clearance capacity (Figure 6C). The Ly6C<sup>lo</sup> monocyte population consistently showed a greater propensity for phagocytosis compared to the Ly6C<sup>hi</sup> population based on percentage of the populations phagocytosing the E.coli particles both in the control
and CSF1-Fc treated groups (Figure 6C). The resident F4/80<sup>hi</sup> CD11b<sup>lo</sup> cells remained the dominant phagocyte in the liver (Figure 6D).

**The impact of CSF1-Fc on acetaminophen toxicity**

The predictive value of serum CSF1 levels in patients with ALF, and the ability of CSF1-Fc to promote regeneration and improve clearance functions, suggests therapeutic potential in acetaminophen toxicity. Macrophage accumulation, proliferation of resident macrophages and infiltration of monocyte-derived macrophages is essential for recovery and subsequent regeneration following acetaminophen administration to mice<sup>16, 35</sup>. Enhanced macrophage accumulation could facilitate recovery by rapidly clearing necrotic debris and restoring hepatic immune function. We treated mice with CSF1-Fc 12 hours following acetaminophen intoxication, the point of maximal injury<sup>39</sup>. CSF1-Fc treatment expanded the macrophage compartment and increased liver weight to body weight ratio (Figure 7A). CSF1-Fc increased macrophage accumulation at the area of necrosis (Figure 7B), without significantly increasing the affected area (Supplementary Figure 6A). In control treated animals there was a predominance of infiltrating monocytes relative to resident hepatic macrophages as previously described<sup>15</sup>, and both these populations were boosted by CSF1-Fc (Supplementary Figure 6B). Expression of mRNA for clearance receptors MARCO and MSR was enhanced in the livers of CSF1-Fc treated animals (Figure 7C), associated with an increase in the phagocytic capacity of the liver detected using injected microbeads (Figure 7D). Despite the profound macrophage changes in the liver, serum cytokines were unaffected by CSF1-Fc treatment (Supplementary Figure 6C). Increased macrophage recruitment did not produce additional injury. Serum injury markers (ALT, Alk phos) decreased in CSF1-Fc treated mice, with reciprocal change following CSF1R blockade (Figure 7E; Supplementary 7F and G). These findings most likely reflect changes in the clearance of these enzymes by hepatic macrophages<sup>40</sup> (Figure 7C). Serum albumin was reduced by CSF1-Fc treatment, likely a reflection of the pro-inflammatory state given hepatic albumin gene expression was unchanged from control (Supplementary Figure 6D). Serum total protein was also unchanged (Supplementary Figure 6E). To further explore potential direct effects of CSF1-Fc on hepatocytes we assessed hepatocyte
viability and performed metabolic assays, which demonstrated no direct effect of CSF1-Fc on either mouse or human hepatocytes (Supplementary Figure 7A and B). Further, following acetaminophen intoxication in mice, there was no change in cytochrome p-450 activity assessed by CYP2E1 expression with CSF1-Fc treatment (Supplementary Figure 7C).

Discussion

We have demonstrated a clear association between reduced serum CSF1 level and poor outcome in acute liver failure in humans. CSF1-Fc treatment produced hepatic macrophage accumulation through in situ macrophage proliferation and recruitment of monocyte-derived cells in mouse models. Resident macrophages in the mouse are largely maintained through self-renewal. Fate mapping of hematopoietic cells indicated that CSF1-Fc can also drive conversion of circulating monocytes to cells of a resident macrophage phenotype. This novel finding demonstrates the plasticity in the resident and infiltrating macrophage compartments and provides new evidence that bone marrow derived macrophages can contribute to the resident macrophage population given appropriate stimuli.

CSF1-Fc driven hepatic macrophage accumulation enhanced innate immune capacity in mouse models of liver injury. Following PH, the therapeutic requirement to optimise liver function and boost regeneration must be weighed against the potential to promote cancer recurrence. Malignant tumours can themselves produce CSF1 which mediates macrophage accumulation, supporting tumour growth. Indeed, our series of preoperative patients with cancer in situ had elevated serum CSF1. However, effective elimination of circulating tumour cells, which are indicative of recurrence, requires hepatic macrophages which depend upon CSF1. The ability to enhance the innate immune capacity of the liver by increasing hepatic macrophage density may be valuable from an antimicrobial standpoint and may theoretically reduce cancer recurrence rates which can reach 60%.

ALF represents a different clinical challenge to PH. The low serum CSF1 in those who required liver transplantation or died in our patient cohort is consistent with the monocytopenia described in ALF,
particularly given the persistence of monocyte precursors in the bone marrow. Monocytes express low levels of HLA-DR in ALF which can impair the response to sepsis. Together with our results, these findings indicate that supplementary CSF1 therapy in the setting of low serum CSF1 might facilitate recovery by increasing monocyte numbers, induce a pro-regenerative macrophage phenotype, increase monocyte HLA-DR expression and enhance phagocytic capacity. Multiorgan involvement is characteristic of clinical deterioration in ALF and previous reports implicating CSF1 signalling in recovery following both kidney and brain injury highlight potential wider benefits of this strategy.

The ability to predict patient deterioration, using a marker such as CSF1, prior to meeting the current clinical criteria for transplantation (King’s College Hospital criteria) could facilitate the earlier stratification of patients with the greatest need. It would be interesting to study the role of CSF1 in acute-on-chronic liver failure, where innate immunity may be impaired.

There is mounting evidence for a CSF1 – CCR2 axis in monocyte recruitment with the induction of these factors following acute hepatic injury. The chemokine signalling induced in the liver following CSF1-Fc administration was not restricted to the CCR2 receptor, and monocyte extravasation into the liver parenchyma was impaired, but not prevented by the CCR2 deficit, suggesting that CSF1-Fc either mobilises monocytes from other sources (e.g, the spleen) or overcomes the CCR2-dependence on bone marrow release.

In contrast to PH, where the increase in available CSF1 is related to reduced clearance, in acute liver toxicity hepatic CSF1 mRNA increased (Fig Suppl. Fig 2c). Evidence of local production was also seen in the liver of patients (Fig Suppl. Fig 2d). The increased local hepatic CSF1 production may drive macrophage accumulation during the early response to injury, when phagocytosis is essential to clear dying hepatocytes. As well as the improved clearance of insoluble and infective material to reduce the risk of sepsis, macrophages might also promote clearance of circulating tumour cells. Some of the earliest studies of CSF1 treatment demonstrated an impact on tumour metastasis. CSF1-Fc has already
been shown to be safe in pigs\textsuperscript{24} and the native protein was previously tested by continuous infusion in human phase 1 trials and was well-tolerated\textsuperscript{47}.

In summary, we have shown that elevated serum CSF1 is an important response to liver injury, and impairment of this response is associated with poor outcome in acute liver failure. Serum CSF1 response following liver injury could be used to stratify patients according to severity and to identify candidates for CSF1 therapy.
Figure Legends

Figure 1: Serum CSF1 increases following partial hepatectomy in humans according to extent of resection
(a) Serum CSF1 in healthy volunteers and patients undergoing partial hepatectomy to remove cancer. (b) Mean serum CSF1 categorised according to extent of resection. (c) Box and whisker plots showing minimum to maximum values with patients developing postoperative liver failure overlaid with red dots.

Figure 2: High serum CSF1 level is associated with survival in acute liver failure in humans
(a) Serum CSF1 level in healthy volunteers and in patients following acetaminophen intoxication on arrival to a specialist liver unit (survived n=47; Died/Liver transplantation n=31). (b) Serial CSF1 samples of patients on first presentation to hospital following acetaminophen intoxication (n=10/group). (c) Receiver operator characteristic curve for serum CSF1, acetyl-HMGB1 (aHMGB1), prothrombin time (PT), ALT (alanine aminotransferase), bilirubin and APACHEII score with areas under curve (AUC value) for patients who subsequently survived or died/required liver transplantation. (d) Dot plot of serum CSF1 level versus log(serum acetyl-HMGB1) on presentation to the specialist liver centre (slope difference: F=0.15, p=0.70; Intercept difference: F=8.03, p=0.006). (e) Details of the combined logistic regression model. (f) Example serum values and predicted chance of death based on logistic regression involving CSF1 alone (Model 2).

Figure 3: Hepatic enlargement following CSF1R stimulation
(a) Representative multiphoton image of ex vivo liver (MacGreen mouse Tg(CSF1r-GFP)Hume) (b) Representative immunofluorescence images of Csf1r-Mer2iCreJWP x Rosa floxed stop tomato red following induction (c) Cytokine/Chemokine array of liver tissue 6 hours following CSF1-Fc treatment versus control (n=4/group). (d) Quantification of hepatic F4/80 immunohistochemistry in PBS control treated (n=8) and mice treated with CSF1-Fc for 2 or 4 days (n=4/group). (e) Quantification of hepatocyte proliferation in control treated mice and at Day 2 and Day 4 following CSF1-Fc administration (20 HPF/mouse). (f) Serum parameters following 4 days CSF1-Fc (grey, hollow circles) or PBS control (black, solid circles) treatment once daily (2-way repeated measures ANOVA with Bonferroni post hoc).
Figure 4: CSF1 receptor stimulation recruits monocytes and induces macrophage proliferation in uninjured mouse liver

(a) Number of hepatic macrophage populations (F480<sup>hi</sup>/CD11b<sup>lo</sup> and F480<sup>lo</sup>/CD11b<sup>hi</sup>) day 2 following CSF1-Fc administration (n=8/group) relative to mean of control group and representative Ly6C profile of F480<sup>hi</sup> (red) and F480<sup>lo</sup> (blue) populations. (b) Percentage of hepatic macrophage populations expressing markers of proliferation (Ki67 and BRDU) day 2 following CSF1-Fc administration relative to mean of control group. (c) Fate tracing bone marrow derived monocytes using chimeric mice demonstrating conversion of infiltrating cells to resident macrophage phenotype driven by CSF1-Fc. (% cells derived from blood monocytes is based on the ratio of chimerism in hepatic populations to chimerism in circulating blood monocytes) (d) Number of hepatic macrophage populations Day 2 following CSF1-Fc administration in WT and CCR2<sup>-/-</sup> mice (n=8/group) with representative Ly6C profile of F480<sup>hi</sup> (red) and F480<sup>lo</sup> (blue) populations (Solid = CCR2<sup>-/-</sup>; dotted line = WT) (e) Liver weight to body weight ratio following 2 days control (black) or CSF1-Fc administration (grey) in wild type and CCR2<sup>-/-</sup> mice (n=8/group).

Figure 5: CSF1-Fc enhances hepatic phagocytic capacity post partial hepatectomy in mice

(a) Liver weight to body weight ratio following partial hepatectomy (PH) with CSF1-Fc or control (n=8/group). (b) Ki67+ hepatocytes per HPF following PH (n=8/timepoint/group). (c) Number of resident (red) or infiltrating (blue) hepatic macrophage populations Day 2 following PH and CSF1-Fc administration. Representative dot plots of hepatic macrophage profile and representative Ly6C profile normalised to mode. (d) Hepatic gene expression of phagocytic markers MARCO (macrophage receptor with collagenous structure), MSR1 (macrophage scavenger receptor 1) and MR (mannose receptor) versus relevant control. (e) Multiphoton image of ex vivo Csf1r<sup>+</sup>eGFP mouse liver following injection of fluorescent microbeads and clearance from the circulation following sham or 2/3 PH with control or CSF1-Fc (n=6/group/timepoint)). (f) Net fluorescence liver, spleen, lung, kidney and brain Day 2 following PH and CSF1-Fc or control. (n=6 per group).

Figure 6: Contribution of hepatic phagocytes to clearance of pathogenic material

(a) Immunohistochemistry of hepatic macrophages (F4/80=green) following isolation by adherence and administration of E. coli bioparticles (pHrodo<sup>TM</sup>) (red). (b) Relative number and percentage of resident macrophages phagocytosing E. coli bioparticles (Phrodo). Representative density plots of phagocytic cells in the resident macrophage population. (c) Relative number of infiltrating macrophages phagocytosing E. coli
bioparticles compared to the mean of the control group with percentage of cells phagocytosing *E. coli* particles according to Ly6C expression status. (d) Pie charts illustrating proportion of phagocytic cells in the liver with bar chart showing absolute cell number comparison for resident and infiltrating macrophages, neutrophils and eosinophils.

**Figure 7: CSF1-Fc and acetaminophen intoxication in mice**

(a) Liver weight to body weight ratio with CSF1-Fc or control. (b) Representative immunohistochemistry F4/80 (red) and Ki67 (DAB) at Day 2 and Day 4 following acetaminophen with PBS control or CSF1-Fc. (c) Hepatic expression of phagocytosis associated genes following GW2580 (red), AFS98 (blue) or CSF1-Fc (grey) relative to mean of control group (vehicle, rat IgG2a, PBS respectively). (d) Net ex vivo liver fluorescence 15 minutes following injection of fluorescent beads. (e) Serum liver associated biochemistry tests at day 3 following acetaminophen intoxication and either GW2580 (red), AFS98 (blue) or CSF1-Fc (grey) compared to control (vehicle, rat IgG2a, PBS respectively).
References


Figure 1: Serum CSF1 increases following partial hepatectomy in humans according to extent of resection.
**Figure 2:** High serum CSF1 level is associated with survival in acute liver failure in humans.
Figure 3: Hepatic macrophage accumulation following CSF1-Fc administration
Figure 4: CSF1 receptor stimulation recruits monocytes and induces macrophage proliferation in uninjured mouse liver.
**Figure 5:** CSF1-Fc enhances hepatic phagocytic capacity post partial hepatectomy in mice
Figure 6: Contribution of hepatic phagocytes to clearance of pathogenic material
Figure 7: CSF1-Fc and acetaminophen intoxication in mice
<table>
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For healthy controls see Supplementary Figure 8

**Supplementary Figure 1:** Supporting details for partial hepatectomy in humans

---

**Gene expression relative to GAPDH**

**Time following partial hepatectomy in mice**
Supplementary Figure 1: Supporting details for partial hepatectomy in humans

(a) Details of patients undergoing partial hepatectomy categorised according to extent of resection (n=55). (b) Dot plot showing blood loss versus serum CSF1 (no relationship between these variables). (c) Details of patients developing postoperative liver failure (n=2). Blood loss according to extent of resection. (d) Hepatic CSF1 gene expression following partial hepatectomy in mice.
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**Systemic inflammatory response scoring (SIRS)**

One point for each of the following:

- Temperature >38°C or <36°C
- Heart rate > 90bpm
- Tachypnoea >20bpm
- White cell count <4000 cells/mm³ or > 12,000 cells/mm³

**Supplementary Figure 2:** Supporting details for acetaminophen intoxication in humans.
Gene expression relative to GAPDH

**Analysis of Deviance**

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**Deviance residuals**

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Time following partial hepatectomy in mice
Supplementary Figure 2: Supporting details for acetaminophen intoxication in humans.

(a) Details of acetaminophen intoxication patients presenting to the specialist liver unit with acute liver failure grouped according to survivors versus those who subsequently required liver transplantation or died (patient cohort and acetyl-HMGB1 values as per Antoine et al.\textsuperscript{24}; healthy control data also shown). (b) Serum CSF1 level in healthy volunteers and in patients following paracetamol intoxication on arrival to a specialist liver unit grouped according to whether patients subsequently deteriorated to meet the King’s college criteria or not (KCC no: n=45; KCC yes: n=33). (c) Receiver operator characteristic curves based on serum CSF1 level in patients according to King’s College Criteria and also patients who subsequently survived or died/required liver transplantation. (d) Serum CSF1 level according to systemic inflammatory response score (SIRS) on admission to the tertiary referral hospital with acute liver failure (NB. SIRS scores available for n=60). (e) Details of patients from first presentation to hospital following acetaminophen intoxication (n=10 per group; patients randomly selected from patient cohort as per Antoine et al.\textsuperscript{24}). (f) Immunohistochemistry for the CSF1 protein in explant liver following acetaminophen intoxication. (g) Hepatic CSF1 gene expression following acetaminophen intoxication in mice (One way ANOVA with Bonferroni post hoc). (h) Deviance residuals for logistic regression models. (i) Analysis of deviance comparing combined Log(acetyl-HMGB1) + CSF1 model (Model 1) and CSF1 alone (Model 2).
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Supplementary Figure 3: Continued.
Supplementary Figure 3: Supporting details for CSF1-Fc treatment of uninjured mice.

(a) Array data 6 hours following CSF1-Fc administration in uninjured mice (n=4/group). (b) TUNNEL immunohistochemistry following PBS control or CSF1-Fc administration (positive control DNAse treated section). (c) Organ weight relative to mean of control group following 2 days treatment with PBS control (black solid circles), or CSF1-Fc (grey hollow circles). (d) Representative F4/80 immunohistochemistry following 2 days treatment with PBS control or CSF1-Fc
Supplementary Figure 4: Supporting details for CSF1-Fc treatment of uninjured mice.

(a) Representative flow cytometry dot plot of BRDU and Ki67 expression in resident (red) and infiltrating (blue) macrophages. (b) Representative dual immunohistochemistry F4/80 (green) and BRDU or Ki67 (red) Day 2 following CSF1-Fc administration or control. (c) Number of hepatic dendritic cells (CD11c/MHCII +ve), eosinophils and neutrophils in control (black circles) and CSF1-Fc (grey circles) treated mice relative to mean of control group. (d) Number of Ly6C low, intermediate and high monocytes in wild type and Ccr2-/- mice following 2 days treatment with CSF1-Fc or PBS control (two way ANOVA with Bonferroni post hoc). (e) Number of hepatic dendritic cells (CD11c/MHCII +ve), eosinophils and neutrophils in control (black circles) and CSF1-Fc (grey circles) treated mice relative to mean of control group.
Supplementary Figure 5: continued.
Minimal uptake of microbeads by blood phagocytes at 1 and 15 minutes post microbead injection

Supplementary Figure 5: Supporting data for partial hepatectomy model

(a) Quantification CYPD2 immunofluorescence (red) per 20x HPF/mouse (control n=8; CSF1-Fc n=7; t test). (b) Number of mitotic figures and Ki67 positive hepatocytes per high powered field following partial hepatectomy and either GW2580, AFS98 or CSF1-Fc administration versus control (vehicle gavage, rat IgG2a, PBS; n=8/group; 2-way ANOVA comparing intervention with relevant control, Bonferroni post hoc). (c) Hepatic gene cytokine expression at Day 2 following partial hepatectomy and either GW2580, AFS98 or CSF1-Fc administration versus control (vehicle gavage, rat IgG2a, PBS; n=8/group; 2-way ANOVA comparing intervention with relevant control, Bonferroni post hoc). (d) Hepatic MMP and UPAR (urokinase plasminogen activator) gene expression Day 2 following partial hepatectomy and either GW2580, AFS98 or CSF1-Fc administration versus control (vehicle gavage, rat IgG2a, CSF1-Fc; n=8/group; 2-way ANOVA comparing intervention with relevant control, Bonferroni post hoc). (e) Exvivo fluorescent imaging of organs 1 minute following injection of fluorescent microbeads into the inferior vena cava. (f) Flow cytometry plots demonstrating bead and cell gating of blood samples following fluorescent microbead injection into the inferior vena cava. (g) Representative flow plots of blood sampled from the inferior vena cava at 1 minute and 15 minutes following injection of fluorescent microbeads into the circulation. Gating strategies including total fluorescent bead count ("Total beads") and bead count within blood cellular populations ("Cells+beads").
**Total cytokines/chemokines analysed:**
- G-CSF
- Eotaxin
- GM-CSF
- IFN-G
- IL-1α
- IL-1β
- IL-2
- IL-3
- IL-5
- IL-6
- IL-7
- IL-9
- IL-10
- IL-12 p40
- IL-12 p70
- LIF
- IL-13
- LIX
- IL-15
- IL-17
- IP-10
- KC
- MCP-1
- MIP-1α
- MIP-1β
- M-CSF
- MIP-2
- MIG
- RANTES
- VEGF
- TNF-a

(analyses below background not shown on histogram)
Supplementary Figure 6: Supporting details for acetaminophen intoxication in mice

(a) Quantification of area of necrosis and cellular infiltrate at Day 2, 3 and 4 following acetaminophen intoxication. (b) Hepatic macrophage phenotype D3 following acetaminophen administration (F4/80+/CD11b− = resident macrophage population; F4/80+/CD11b+ = infiltrating macrophage population. (c) Serum cytokine array Day 4 following partial heptectomy and either PBS control or CSF1-Fc treatment (2-way ANOVA and Bonferroni post hoc ns). (d) Hepatic albumin gene expression relative to GAPDH comparing control and CSF1-Fc treated mouse liver (n=8/group; t test ns). (e) Total protein concentration at D3. (f) Serum ALT following acetaminophen intoxication in control (dotted line) and CSF1-Fc treated (solid line) mice.
**Supplementary Figure 7:** No evidence of direct hepatocyte effects of CSF1-Fc

(a) MTS reduction assay, LDH leakage assay and GSH content on mouse hepatocytes exposed to APAP and increasing concentration of CSF1-Fc showing no dose related effect. (b) MTS reduction assay, LDH leakage assay and GSH content on human hepatocytes exposed to APAP and increasing concentration of CSF1-Fc showing no dose related effect. (c) Whole liver assessment of CYP2E1 expression relative to actin assessed via Western blot and mRNA day 3 post acetaminophen intoxication with control or CSF1-Fc treatment.
Supplementary Methods

Human serum samples

Serum samples were blinded and cytokine analysis completed in a random order. Serum CSF1 was analysed using the Meso Scale Discovery® CSF1 immunoassay and analysed on a Meso QuickPlex SQ120. Serum acetyl-HMGB1 was analysed by mass spectrometry.

Clinical scoring

King’s college criteria in the context of acetaminophen induced liver failure was defined as arterial pH<7.3, international normalized ration (INR) > 6.5, serum creatinine > 300 and the presence of encephalopathy. The Systemic Inflammatory Response Criteria (SIRS) were met when 2 or more of the following occurred: body temperature >38°C or < 36°C; heart rate >90 beats per minute; respiratory rate >20 breaths per minute; white blood cell count >12,000/cf mm or <4,000/cf mm². APACHE2 score was calculated as previously described.

Reagents

CSF1-Fc is a conjugate of porcine CSF1 with the Fc region of porcine IgG1A (43.82kD total) produced by Zoetis for D. Hume (UK patent application GB1303537.1). Porcine CSF1 is equally active in mice. The Fc conjugate provides increased circulating half-life. CSF1-Fc did not exhibit any endotoxin like activity in murine BM-derived macrophages. CSF1 receptor blockade was induced by the CSF1R tyrosine kinase inhibitor, GW2580 (160mg/kg suspended in 0.5% hydroxypropylmethylcellulose and 0.1% Tween 80, LC laboratories), or using the antibody AFS98 produced by Sudo et al. and provided by BioServ UK. CSF1-Fc, GW2580 and AFS98 were administered immediately following 2/3 partial hepatectomy or 12 hours following acetaminophen intoxication (point of maximal injury).
Collection of mouse tissues

Mice were culled via CO2 inhalation and following a midline laparotomy blood was aspirated from the inferior vena cava for serum analysis. Mice were perfused through the inferior vena cava and viscera excised and weighed. Viscera were either fixed in 4% formalin for immunohistochemistry, placed in RNA later® (Life Technologies), or placed in PBS for flow cytometry.

Immunohistochemistry

Three µm sections of formalin-fixed tissue were used for immunostains. Ki67, BRDU and CYPD2 required heat mediated antigen retrieval with 0.01M sodium citrate pH 6.0 for 10 minutes. Primary antibodies were used at the following dilutions: Ki67 (Leica) 1:500, BRDU (Abcam) 1:100, F4/80 (clone CI:A3-I, Biolegend) 1:100, CYPD2 (Abcam) 1:100. Appropriate secondary antibody was applied at a 1:250 dilution. Dual immunohistochemistry with F4/80 and BRDU or Ki67 was performed by first developing F4/80 using the Tyramide signal amplification system (PerkinElmer®) with subsequent heat mediated antigen retrieval followed by BRDU or Ki67 staining. Ki67 and F4/80 dual immunohistochemistry was also performed by developing F4/80 with an alkaline phosphatase substrate kit (red, Vector) and following heat mediated antigen retrieval Ki67 was developed with 3,30-diaminobenzidine (Dako). Stained slides were blinded and images taken on the Nikon Eclipse E600. For image quantification of F4/80 staining 20 non overlapping images were photographed at x200. The extent of DAB staining quantified using image analysis software (Adobe Photoshop CS6). For CYPD2 quantification images were quantified using image analysis software (Adobe Photoshop CS6). For Ki67 quantification 20 serial non overlapping images were photographed at x400 then hepatocytes identified by assessment of morphology.

Flow cytometry

Liver was digested in 2mg/ml collagenase D (Sigma Aldrich) at 37degC for 30minutes then passed through a 100µm filter. 7 minute 50G spin to remove hepatocytes. Further purification of nonparenchymal cells using 30% percoll® (Sigma) gradient. Cell stained with fixable viability dye eFluor 780® then incubated with Fc block (TruStainfcX™, Biolegend) prior to staining with CD45
(clone:30F11, AF700, Biolegend), F480 (clone:BM8, PE/Cy7, Biolegend), CD11b (clone:RM208, FITC, Invitrogen), Ly6C (clone:HK1.4, PerCP/Cy5.5, Biolegend), dump gate (PE: CD3 (clone:17A2, PE, Biolegend), CD19 (clone:6D5, PE, Biolegend), Siglec F (clone:E502440, PE, BD Biosciences), Ly6G (clone:IA8,PE, BD Biosciences). For proliferation assay cells were fixed and permeabilised using BD Pharminogen BRDU flow kit then stained with antiBRDU (FITC, BD Pharminogen) and Ki67 (eF660, eBioscience). Flow cytometry performed using the LSR Fortessa.

Quantification of Messenger RNA

Quantification of messenger RNA (mRNA) Levels by Real-Time Reverse-Transcription Polymerase

RNA extraction kits (Qiagen) were used to extract RNA from whole tissue. Predesigned validated primer sets for MARCO (macrophage receptor with collagenous structure), MSR1 (macrophage scavenging receptor 1), MR (mannose receptor), Il6, OSM (oncostatin M), TNF (tumour necrosis factor), IFNg (interferon gamma), Il10 and GAPDH were purchased from Qiagen (Qiagen Quantitect Primers). Quantitative real-time PCR was performed using Express SYBR Green (Qiagen, UK). Gene expression was calculated relative to GAPDH for each sample. Gene array at 6 hours following CSF1-Fc administration was performed using Cytokine and Chemokine array RT² Profiler PCR arrays and analysed using the online RT² profiler PCR Array Data Analysis (Version 3.5, Qiagen, UK) and presented by Volcano plot. Affymetrix Mouse gene 1.1 ST Array data were accessed from the Gene Expression Omnibus website and analysed using GEO2R with Benjamini & Hochberg (False discovery rate) correction applied to the entire data series.

Phagocytosis assay

Under 2% isofluorane anaesthesia the inferior vena cava was cannulated and 100µl of red fluorescent bead solution (1:5 Latex beads 1.0µm, fluorescent red, SIGMA-ALDRICH®) infused through the cannula (1:2 solution for assay following paracetamol injury). Ex vivo fluorescent quantification was performed at one minute following bead injection and 15mls 0.9% NaCl flush (see Supplementary Figure 5a). For assessment of bead clearance from the circulation 20mcl of blood was removed from the cannula every two minutes starting from 1 minute post injection for 15 minutes and immediately
fixed (300μl FACS-Lyse, BD Biosciences). After the 15 minute timepoint mice were perfused with 15mls 0.9% saline through the IVC cannula with portal vein outflow. Organs were then removed (Liver, spleen, lungs, kidney, brain) and imaged using a Kodak In-Vivo Multispectral FX image station (Excitation: 550nm; Emission: 600nm; Exposure 1 sec; f-stop 2.8). Subsequently blood samples were analysed using a LSR-Fortessa™ flow cytometer (BD Biosciences) with fluorescent beads detected on the blue channel (B695/40) by a 1 minute sample collection on low flow rate setting. Multiphoton imaging was performed using a Zeiss LSM7 MP with Coherent Chameleon Ti:Sa laser.

Mouse Serum Analyses

Serum biochemistry assays were performed using commercially available kits by a biochemist, including alanine aminotransferase (ALT; Alpha Laboratories), alkaline phosphatase (Alk phos; Roche Diagnostics), total bilirubin (bili; Alpha Laboratories Ltd), albumin (Alb; Alpha Laboratories). Total serum protein was analysed using the Bradford assay as previously described 8. Serum cytokines and chemokines were analysed using MILLIPLEX® mouse cytokine/chemokine array (Merck-Millipore) in collaboration with a Merck-Millipore biomarker specialist.

Hepatocyte metabolic and toxicity assays

Human and mouse hepatocytes were isolated from liver tissue as previously described 9, 10. Glutathione (GSH) depletion assay, MTS reduction assay and LDH leakage assay were performed on human and mouse hepatocytes as previously described 10.
References