Liver International

WILEY

Liver INTERNATIONAL

ORIGINAL ARTICLE

Liver Injury due to Intravenous Methylprednisolone in the Drug-Induced Liver Injury Network

Jawad Ahmad[1] | Yi-Ju Li[2] | Elizabeth Phillips[3] | Andrew Dellinger[2] | Paul H. Hayashi[4] | Naga Chalasani[5] | Robert J. Fontana[6] | David E. Kleiner[7] | Huiman X. Barnhart[8] | Jay H. Hoofnagle[9] | the Drug-Induced Liver Injury Network

[1]Recanati-Miller Transplantation Institute, Icahn School of Medicine at Mount Sinai, New York, New York, USA | [2]Department of Biostatistics and Bioinformatics, Duke School of Medicine, Durham, North Carolina, USA | [3]Vanderbilt University Medical Center, Nashville, Tennessee, USA | [4]Food and Drug Administration, Silver Spring, MD, USA | [5]Division of Gastroenterology and Hepatology, Indiana University, Indianapolis, Indiana, USA | [6]Division of Gastroenterology and Hepatology, University of Michigan, Ann Arbor, Michigan, USA | [7]Laboratory of Pathology, Intramural Division, National Cancer Institute, National Institutes of Health (NIH), Bethesda, Maryland, USA | [8]Duke Clinical Research Institute, Durham, North Carolina, USA | [9]Liver Disease Research Branch, Division of Digestive Diseases and Nutrition, National Institute of Diabetes and Digestive and Kidney Diseases (NIDDK), NIH, Bethesda, Maryland, USA

Correspondence: Jawad Ahmad (jawad.ahmad@mountsinai.org)

Received: 1 October 2024 | **Revised:** 23 December 2024 | **Accepted:** 31 December 2024

Handling Editor: Luca Valenti

Funding: This work was supported by National Institute of Diabetes and Digestive and Kidney Diseases.

Keywords: drug induced liver injury | HLA genotype associations | methylprednisolone | multiple sclerosis

ABSTRACT

Background and Aims: Short courses of intravenous (iv) methylprednisolone (MP) can cause drug induced liver injury (DILI). The aim of this study was to assess the clinical features and HLA associations of MP-related DILI enrolled in the US DILI Network (DILIN).

Methods: DILIN cases with MP as a suspected drug were reviewed. DILIN causality scoring was assigned on a 5-point scale (definite, highly likely, probable, possible, unlikely). All cases with MP causality scores of definite, highly likely or probable were analysed. HLA data from direct sequencing were analysed.

Results: Eleven cases of definite, highly likely, or probable MP DILI were identified. The median age was 48 years; 73% were female; median latency to onset was 30 days; 55% were jaundiced; and all had hepatocellular injury with one patient requiring transplantation. Nine of the 11 cases were in patients with multiple sclerosis (MS). Liver biopsies in 7 cases revealed mild acute hepatitis with/without cholestasis. HLA data demonstrated that *HLA-DRB1*15:01*, the primary HLA class II allele associated with MS was over-represented. *HLA-DQB1*06:02-HLA-DQA1*01:02* which is haplotypic with the *HLA-DRB1*15* haplotype was more common in the MP DILI cases compared to other DILI controls ($p = 0.03$) and to DILI controls exposed to MP ($p = 0.04$).

Conclusion: MP DILI is characterised by hepatocellular injury, short latency and generally rapid recovery. There was no independent HLA haplotype associated with MP DILI.

Abbreviations: AF, allele frequency; AIH, autoimmune hepatitis; Alk P, alkaline phosphatase; ALT, alanine aminotransferase; CF, carrier frequency; DILI, drug induced liver injury; DILIN, drug Induced liver Injury Network; HiC, high confidence; iv, intravenous; MP, methylprednisolone; MS, multiple sclerosis; NIDDK, National Institute of Diabetes and Digestive and Kidney Diseases; NIH, National Institutes of Health.

© 2025 John Wiley & Sons A/S. Published by John Wiley & Sons Ltd.

Summary

- Intravenous methylprednisolone (MP) can cause liver injury, particularly when used in patients with multiple sclerosis (MS).
- The injury can be severe with more than half the patients developing jaundice.
- There were no genetic risk factors associated with MP use beyond the known genetic risk factors for MS.

1 | Introduction

Intravenous (iv) methylprednisolone (MP) is a potent anti-inflammatory agent used to treat a variety of immune-mediated diseases including multiple sclerosis (MS) and Graves ophthalmopathy. It has a rapid onset of action and is almost completely excreted within 12 h [1]. Typically, iv MP is administered 0.5–1 g daily for 2–3 days until the patient's condition stabilises and then continued at a lower dose or converted to oral prednisolone or prednisone. Lower iv daily doses of 40–80 mg are routinely used in patients with inflammatory bowel disease and asthma requiring hospitalisation.

In patients with MS, national guidelines recommend iv MP 1 g daily for 3–5 days for patients with a relapse or exacerbation of disease in whom oral corticosteroids have failed or hospitalisation is required [2]. Idiosyncratic liver injury following MP administration has been reported with a similar presentation as autoimmune hepatitis (AIH)- a disease with known underlying HLA associations and which is also routinely treated with corticosteroids [3].

The Drug-Induced Liver Injury Network (DILIN) is a National Institutes of Health (NIH)-funded multicenter observational cohort study that has been enrolling patients with suspected DILI in the United States since 2004 [4, 5]. Because DILI is a diagnosis of exclusion, patients who have a temporal exposure to a drug or herbal and dietary supplement (HDS) undergo a thorough evaluation with laboratory data and imaging. Causality assessment is performed by expert review of each case after exclusion of competing causes and 6 months of follow-up. As the literature on DILI has advanced over the last 2 decades, the clinical phenotype of liver injury attributed to iv MP particularly in patients with MS or Graves' ophthalmopathy has been reported [3, 6–11]. The primary objective of this present study was to identify the clinical, histological, and genetic characteristics of cases of DILI attributed to iv MP enrolled in DILIN from 2004 to 2022. We also reviewed the available literature on other cases of iv MP hepatotoxicity to provide summary data and guidance to practicing clinicians.

2 | Methods

A detailed description of the DILIN study design has been previously published [4]. The DILIN prospective study was approved by the Institutional Review Boards at each clinical site and data-coordinating center and by a central Data Safety and Monitoring Board appointed by the NIDDK. All enrolled subjects provided written informed consent. All authors had access to the study data, reviewed, and approved the final manuscript.

Briefly, patients with suspected DILI are eligible who meet predefined laboratory criteria including elevations in aspartate aminotransferase (AST), alanine aminotransferase (ALT), or alkaline phosphatase (Alk P) levels with or without jaundice or coagulopathy. Liver biopsy, though not required for enrollment, is centrally reviewed by an expert pathologist whenever available. Prospective subjects are enrolled within 6 months of onset of injury and followed up at 6 months after enrollment. Patients with persistent liver injury at 6 months are considered to have chronicity and are asked to return annually for up to 4 years. Formal causality adjudication is undertaken at least 6 months after enrollment using expert opinion by three hepatologists independently [12]. The three reviewers come to a consensus opinion score which is voted upon by the full Causality Committee in cases of disagreement. The DILIN expert system employs a 5-point likelihood score: 1 (definite: ≥ 95% likelihood), 2 (highly likely: 75%–94% likelihood), 3 (probable: 50%–74% likelihood), 4 (possible: 25%–49% likelihood) or 5 (unlikely: < 25% likelihood). Scores of 1, 2 and 3 are considered high confidence (HiC) cases, while scores of 4 and 5 are considered possibly or unlikely DILI and an alternative diagnosis is determined. In cases in which more than one agent is implicated, an overall causality score is assigned, and separate causality scores are assigned to each suspected drug, one being assigned the primary cause. No more than 3 suspect drugs are allowed to be listed as possibly implicated, but all drugs taken within 2 months of onset were recorded as concomitant medications.

The current study focusing upon MP involved two stages. Initially patients enrolled into the DILIN where the liver injury was deemed at least possibly related to MP (i.e. scores 1–4) were reassessed. In the second stage, all cases in which MP was listed as a concomitant drug (i.e. not originally implicated as causal) were reassessed by two investigators independently (JA, JHH). All cases that the two investigators considered as 'possibly' related to MP were then re-adjudicated by the full Causality Committee.

HLA sequencing was performed on all DILIN cases using the Illumina MiSeq platform at the Vanderbilt University Medical Center as previously described [13]. Since many of the HiC MP DILI cases occurred in MS patients, the HLA associations may have been related to MS rather than a risk of DILI related to MP. Hence, to compare HLA allelic associations with the HiC MP DILI cases we looked at three control groups. Firstly, HiC cases of DILI attributed to another medication but who had been exposed to MP within the previous 2 months and adjudicated as unlikely to be MP DILI (MP exposure controls). Secondly, patients with MS who developed HiC DILI attributed to another medication other than MP (MS disease controls). Thirdly, HiC cases of DILI attributed to other conventional medications (excluding those due to HDS) who were not exposed to MP and did not have MS (DILI controls).

2.1 | Statistical Analysis

Summary statistics were computed for all MP implicated cases and DILI cases not caused by MP occurring in patients with MS (the MS controls). Due to the limited number of MP cases,

direct allele frequency (AF) difference between MP cases and each comparison group was tested by Fisher's exact tests. As most MP cases also had MS, the HLA allele associations of HiC DILI cases with MS were compared to those associated with other DILI cases without MP and MS. Multivariable logistic regression was performed to test HLA allelic association with MS DILI after adjusting for age and the first principal component (PC) for the potential impact from population stratification. PCs were derived from the genome-wide genotype data in the DILIN cohort as previously described [13]. To correct for multiple testing, the Qvalue, one of the false discovery rate (FDR) methods, was computed for each HLA allele using the QVALUE program [14]. Haplotypes for the combination of HLA alleles of interest were explored by the Cobygram software, and haplotype frequency was compared between the HiC MS DILI group and the control groups. Finally, the three previously reported genetic variants related to DILI in DILIN, rs2476601 in PTPN22 [15], the GG genotype of rs1363907 in ERAP2 [16], and rs61745685 in ERAP1 [17] were assessed for association with MP DILI.

3 | Results

Of the 2493 patients enrolled in the DILIN Prospective Study between 2004 and 2022, 11 were adjudicated as HiC MP-DILI cases (Table 1 and Table S1), 10 were possible MP-DILI, and 64 were exposed to MP but considered unlikely to be MP-DILI (Figure 1). Among the 11 HiC cases, two were definite, four highly likely, and five probable. Two HiC DILI cases initially had MP listed as a concomitant medication that upon re-review and re-adjudication was attributed to MP. All 11 had received iv MP at a dose of at least 1 g daily, nine for 3–5 days, one for 11 days and one intermittently over 150 days. The median age was 48 years, eight (73%) were female, eight European American, two African American, and one Asian. Nine patients were being treated for MS, one for a spinal cord contusion and one for an ulcerative colitis flare. The median latency (from drug start to onset of DILI) was 30 days (range 4–150 days). All patients had hepatocellular injury with usually rapid improvement. A 49-year-old female patient, however, without known underlying liver disease, developed severe hepatocellular injury (ALT 1874 U/L) with jaundice (total bilirubin 32.4 mg/dL) and synthetic dysfunction (INR 3.5) several weeks after receiving 3 days of iv MP 1 g for her MS flare. She did not improve, was listed as a status 1, and underwent successful liver transplantation with the explanted liver showing portal inflammation with increased plasma cells, bridging necrosis and parenychmal collapse. Autoantibodies were noted in a minority of patients. Liver biopsies in seven patients showed mild acute hepatitis with lobular and interface necroinflammation. Three cases had features of autoimmune hepatitis (AIH) with mild to moderate interface hepatitis. Three HiC cases were treated for the liver injury with tapering doses of oral prednisone with normalisation of liver tests within 5 weeks. One patient was also treated with ongoing azathioprine.

Of the 10 cases that were considered possibly related to MP, demographic data were similar to the HiC MP cases (Table S2). The dose of MP was unavailable in most cases, and four patients were being treated for MS. Five cases were adjudicated as HiC DILI but were attributed to another agent rather than MP. All 10 cases had a hepatocellular injury and three had jaundice. Eight patients recovered while two had residual evidence of liver injury at 6 months.

In the entire DILIN cohort of 2439 patients, 35 occurred in MS patients. Excluding 9 cases attributed to MP and 5 cases that were judged to be only possibly or unlikely DILI, 21 were adjudicated as having HiC DILI due to other drugs (MS disease

TABLE 1 | Clinical characteristics of 11 high confidence methylprednisolone DILI cases in the DILIN prospective cohort from 2004 to 2022.

Characteristic	Median or number	Range or %
Age (years)	48	18–69
Female sex (*N*)	8	73%
Non-Hispanic White (*N*)	8	73%
BMI (kg/m^2)	26.8	21.4–49.3
Multiple sclerosis (*N*)	9	82%
Symptoms (*N*)	6	55%
Rash (*N*)	1	11%
Eosinophilia > 500/μL (*N*)	1	11%
Hospitalised (*N*)	10	91%
Duration of treatment (days)	5	3–150
Latency to DILI onset (days)	30	4–150
Initial *R* value	16.5	5.0–35.6
Initial ALT (U/L)	643	228–2669
Peak ALT (U/L)	1168	228–2669
Initial total bilirubin (mg/dL)	1.5	0.3–31.4
Peak total bilirubin (mg/dL)	3.2	0.4–31.4
Peak bilirubin ≥ 2.5 mg/dL	6	55%
Liver biopsy (*N*)	7	64%
ANA positive (*N*)	4	36%
SMA positive (*N*)	2	18%
Ig > 1500 mg/dL (*N* = 7)	4	57%
Days to > 50% decrease from peak ALT	19	3–36
Days to > 50% decrease from peak total bilirubin	18	14–33
Days to recovery (*N* = 10)	65	30–186
Oral corticosteroid therapy for injury (*N*)	3	27%
Recovered (*N*)	10	91%
Chronic liver injury (*N*)	0	0%
Fatal/transplant (*N*)	1	9%

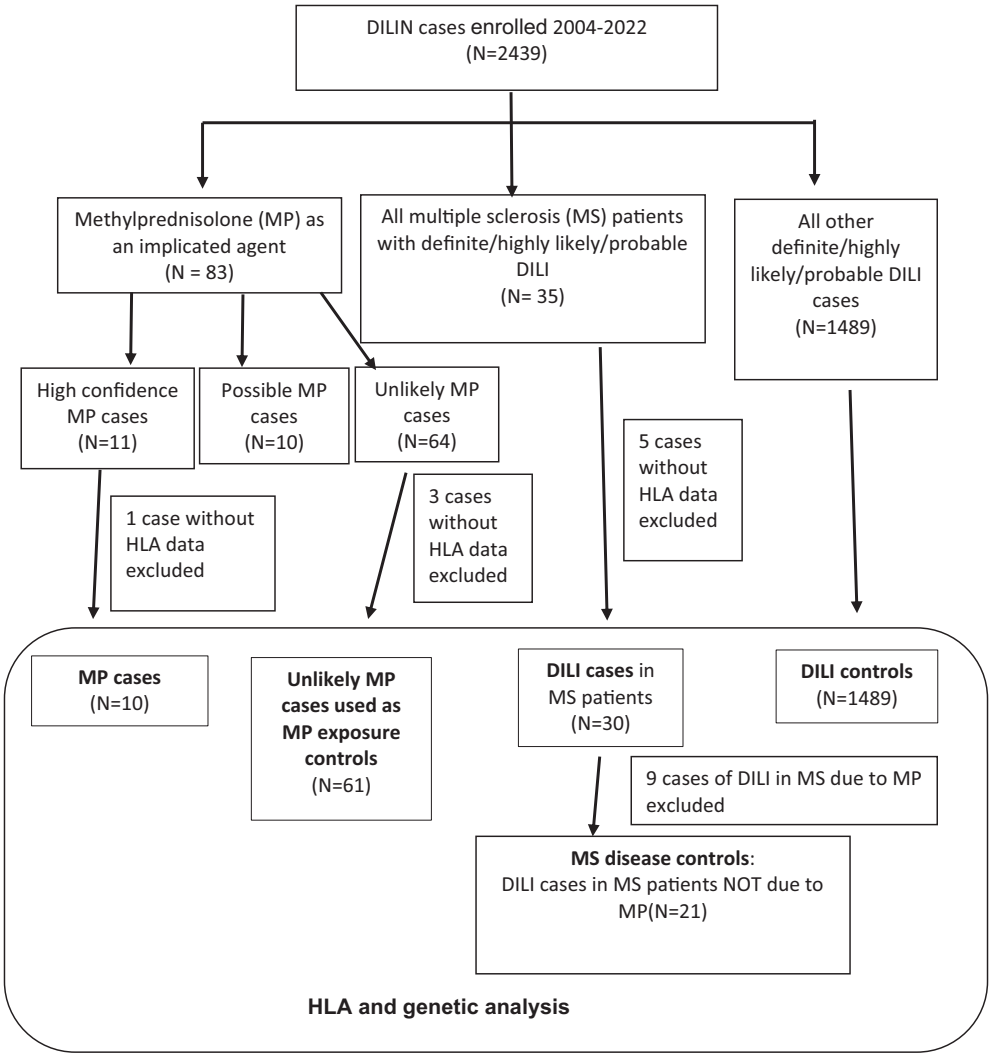


FIGURE 1 | Consort diagram of patients included in the study are shown.

controls) (Table S3). Of the 21, 13 were attributed to drugs being used to treat MS, including 11 due to interferon beta, one to dimethyl fumarate, and one to natalizumab. In the 8 remaining MS patients, the injury was attributed to nitrofurantoin ($N=2$) and one each from amoxicillin/clavulanate, oxaprozin, ribociclib, carbamazepine, atorvastatin, and nivolumab.

HLA data were available in most cases and controls (Table 2 and Table S4). Three class II alleles; *HLA-DQB1*06:02*, *HLA*DQA1*01:02*, and *HLA-DRB1*15:01*, were significantly more frequent in HiC MP DILI cases than in MP exposure and DILI controls. These three alleles are associated with MS [18]. They have also been associated with protection from type I diabetes although the greatest effect comes from HLA-DQB1*06:02 [19]. Regarding MP DILI, among these three HLA alleles, *HLA-DQB1*06:02* was most significant with an AF of 0.40 (carrier frequency, CF =70%), which is higher than estimated from USA population databases, 0.12 for European, 0.20 for African, and 0.04 for Asian-Americans (allelefrequencies.net). *HLA*DQA1*01:02* ranked as the second most significant association with MP DILI with an AF of 0.45 (and CF of 80%), higher than the frequencies in US population databases (0.23 in European Americans). The third strongest HLA genotype association with the MP cases was *HLA-DRB1*15:01*, a well-recognised HLA class II allele associated with MS. This allele was found in 5 of the 10 MP cases, all of whom were heterozygotes (AF = 0.25) and had MS. A similar AF was also observed in MS disease (non-MP DILI) controls (AF = 0.24). In contrast, lower AF of this allele was observed in the DILI controls (AF = 0.13) and MP exposure controls (AF = 0.11), which are a similar rate to those in the US Non-Hispanic White population (AF = 0.11).

These three class II alleles identified for MP DILI also form a haplotype called 'DR15 haplotype' (*DRB1*15:01-DQA1*01:02-DQB1*06:02*), which is a known primary HLA haplotype risk factor for MS [18]. The visualisation of the DR15 haplotype is depicted in Figure 2, which shows the difference in haplotype frequency between MP DILI cases and two non-MS comparison groups. The DR15 haplotype was present in half of MP DILI cases (one case being homozygous), leading to a higher haplotype frequency as compared to DILI controls (Table 2). In contrast, there was no difference in the haplotype frequency between the MP cases and the MS disease controls (haplotype frequency: 0.30 vs. 0.24, $p=0.75$).

The two HLA alleles, *HLA-DRB*03:01* and *DRB*04:01*, known to be associated with spontaneous AIH were not overrepresented

TABLE 2 | Results of HLA alleles and DR15 haplotype association with MP DILI with comparison to other DILI cases without MP or MS and unlikely MP DILI cases.

Allele/ Haplotype	MP DILI cases ($n=10$)		Non-MP, non-MS DILI controls ($n=1489$)			MP exposure controls ($n=61$)			MS disease controls ($n=21$)		
	CF	AF	CF	AF	Fisher P	CF	AF	Fisher P	CF	AF	Fisher P
DQB1*06:02	0.70	0.40	0.27	0.15	0.01	0.21	0.13	0.01	0.52	0.29	0.40
DQA1*01:02	0.80	0.45	0.37	0.22	0.02	0.36	0.20	0.02	0.52	0.29	0.26
DRB1*15:01	0.50	0.30	0.24	0.13	0.04	0.21	0.11	0.04	0.48	0.24	0.75
DR15 haplotype	0.50	0.30	0.22	0.12	0.03	0.21	0.11	0.04	0.48	0.24	0.75
AIH associated HLA risk alleles											
DRB1*03:01	0.1	0.05	0.21	0.12	0.72	0.28	0.14	0.47	0.19	0.12	0.66
DRB1*04:01[a]	0	0	0.11	0.06	—	0.05	0.02	—	0.10	0.05	—
Other DILI risk alleles											
PTPN22: rs2476601	0.20	0.10	0.19	0.10	> 0.99	0.15	0.07	0.65	0.24	0.12	> 0.99
ERAP1: rs62376414	0.30	0.20	0.17	0.09	0.10	0.15	0.07	0.09	0.05	0.02	0.03
ERAP2: rs1363907[b]	0.40	—	0.39	—	> 0.99	0.31	—	0.72	0.33	—	> 0.99

[a]Because DRB1*04:01 was not present in our MP DILI cases, association tests were not performed.
[b]GG genotype.

in HiC MP cases and MS disease controls as compared to other DILI controls (e.g. *DRB1*03:01* AF = 0.05 vs. 0.12; *DRB1*04:01* AF = 0 and 0.05) (Table 2). The frequencies of these alleles in the MS disease controls (0.12 for DRB1*03:01 and 0.05 for DRB1*04:01) were similar to those in Non-Hispanic White control populations (*DRB1*03:01* AF = 0.12 and *DRB1*04:01* AF = 0.09: from allellefrequencies.net). Finally, the target variants in PTPN22, ERAP1 and ERAP2 were not associated with MP DILI when compared to DILI controls and MP exposure controls. However, the ERAP1 rs62376414 showed nominal significant higher AF in HiC MP cases than in MS disease controls (AF: 0.20 vs. 0.02, $p = 0.03$) (Table 2).

4 | Discussion

Idiosyncratic DILI from iv MP has been increasingly reported over the last 20 years [3, 6–11] typically occurring in patients with MS or Graves' disease who frequently receive 0.5–1 g daily for 3–5 days or more. Of the 11 HiC DILI cases due to MP seen in DILIN, nine occurred in MS patients but none were associated with Graves' disease. The clinical presentation was very consistent, with a rapid onset of severe acute hepatocellular injury with or without jaundice arising within a few days to weeks after iv MP treatment for a flare of MS. Autoimmune serologies were positive in a minority of patients and the liver histology demonstrated varying degrees of an acute hepatitis, with features of AIH in some patients. This association seems paradoxical as corticosteroids are used to treat de novo AIH and drug-induced AIH. However, an immune mediated hyper-reactivity via rebound or reconstitution after MP is stopped or tapered may be occurring in susceptible patients [11]. One case developed acute hepatic failure requiring liver transplantation while almost all the remaining cases had self-limited hepatitis without the need for long-term immunosuppressive therapy.

Prospective data in MS patients treated with pulsed iv MP suggests that liver injury is not infrequent. Among 175 MS patients given iv MP at a dose of 1 g daily for 5 days, 15 (8.6%) patients developed liver injury, four with jaundice. Case adjudication suggested MP-DILI in three patients and de novo AIH in another three [3]. The current data from DILIN did not suggest coincidental AIH as HLA alleles of AIH were not over-represented although the sample size was small.

Recent studies with liver biopsy have also suggested MP liver injury is due to idiosyncratic DILI rather than sporadic AIH, particularly because the injury was self-limited and spontaneously resolved without need for long-term immunosuppression [6, 7]. In the French pharmacovigilance database, 97 MP-DILI cases were analysed with similar findings as the current study with a mild to moderate hepatocellular injury with quick resolution [7]. Patients with MS were again over-represented, but there were also patients on MP for other autoimmune diseases and 20% developed DILI from oral corticosteroids. In the current study, 10 patients recovered completely but one patient needed liver transplantation. Interestingly this patient had an episode of acute hepatitis 12 years prior, not recognised as DILI but treated with oral corticosteroids (without treatment in the interim), suggesting that the current episode was an inadvertent rechallenge, a phenomenon seen in 10 of 13 MP-DILI patients in the French pharmacovigilance database [7]. Advanced fibrosis over several years is also possible with repeated exposure to iv MP as noted in an MS patient that improved after withdrawal of corticosteroids [20].

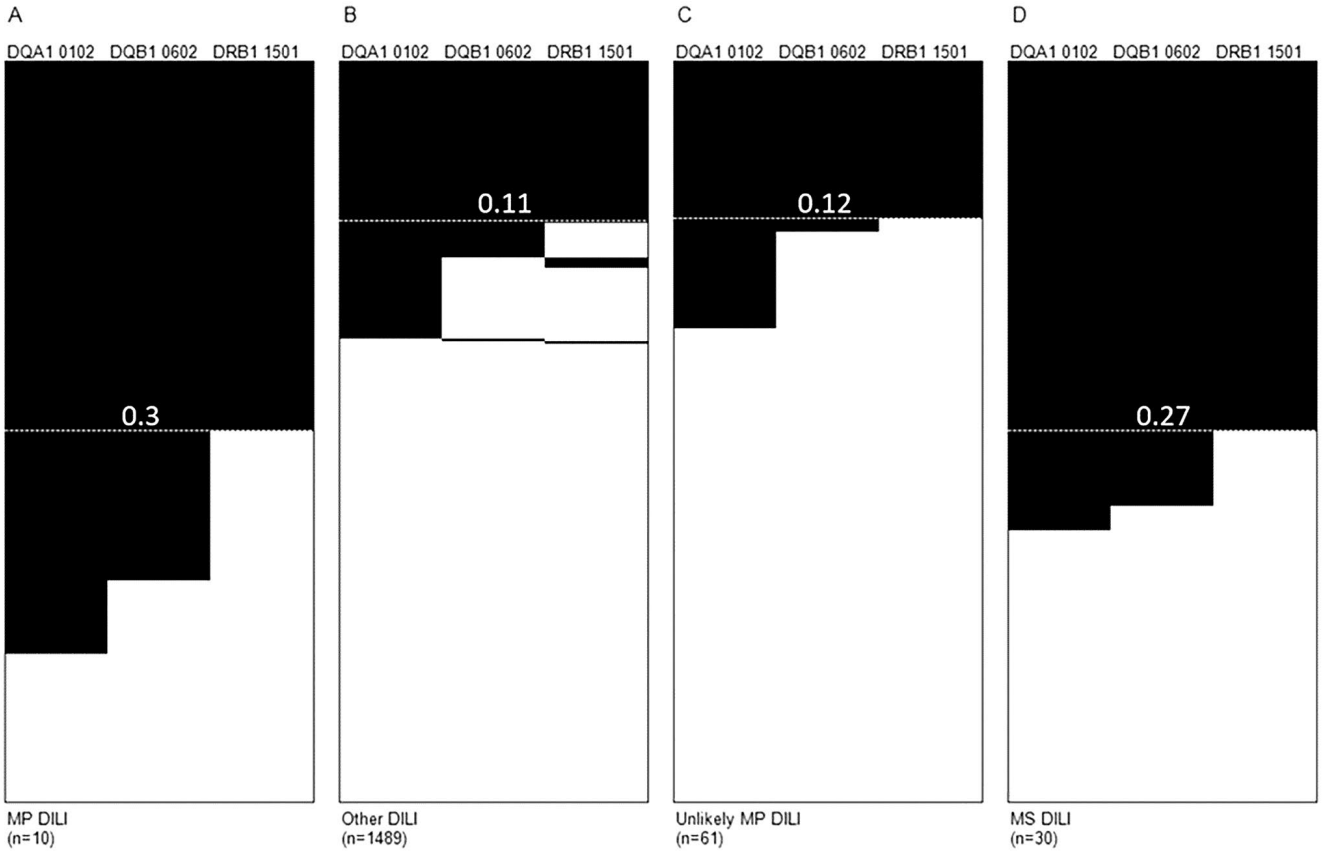


FIGURE 2 | Frequencies of HLA haplotypes derived from different combinations of DRB1*15:01, DQA1*01:02, DQB1*06:02 alleles in MP DILI cases and the three control groups: DILI, MP exposure and MS disease control groups. The black colour indicates the present of the allele. The vertical axis indicates the frequency of each allele or haplotype. The dashed line annotates DR15 (DRB1*15:01-DQA1*01:02-DQB1*06:02) haplotype with its haplotype frequency showing above. The DR15 haplotype frequency is similar in MP DILI cases and MS disease control groups but lower in the DILI controls and MP exposure controls.

All the HiC MP cases with MS had been exposed to doses of iv MP of at least 1 g per infusion, a similar dose to that used in Graves' disease. A study of more than 1000 consecutive patients with Graves' ophthalmopathy treated with similar doses of iv corticosteroids noted a significantly increased risk of liver injury in older patients (> 53 years) and in doses > 0.8 g per infusion [8]. Similarly, various iv MP regimens caused a dose-dependent effect on ALT levels in 49 patients with Graves' orbitopathy [9]. By using a lower dose of iv corticosteroids and adding oral prednisone to prevent a rebound AIH in patients with elevated ALT, a lower risk of severe liver injury was noted [10].

The mechanism of liver injury associated with iv MP is unclear as is the predilection to affect patients with MS. Although development of MS is strongly associated with EBV infection [21], there was no clinical evidence of adenopathy or rash in our patients suggestive of EBV hepatitis. Furthermore, testing for EBV infection was negative and the clinical presentation and pathological findings are more like AIH. Seven of the 11 HiC patients had liver biopsies and histologic features of AIH were seen in three patients with three patients treated with tapering oral prednisone for the liver injury, one of whom was continued on azathioprine. Similar features were seen in a recent report of eight patients (most with MS) who developed DILI after MP administration where liver biopsies all showed some degree of interface hepatitis [22]. In contrast to the hepatotoxicity of high dose iv amiodarone that has been attributed to the vehicle additive of polysorbate, it is unlikely that iv MP hepatotoxicity is mediated by a vehicle additive since the buffers of sodium succinate and sodium phosphate and sucrose are endogenous molecular species [23].

HLA alleles play a significant role in the susceptibility of immune-mediated adverse drug reactions [24]. Multiple HLA associations with DILI have been reported such as HLA-A*33:01 with terbinafine [25], HLA-B*35:02 with minocycline [26], HLA-DRB1*15:01 with amoxicillin clavulanic acid [27], and DRB1*16:01/DQB1*05:02 with flupirtine-DILI among others [28]. Some HLA alleles are associated with the risk of DILI across several drugs, particularly HLA-B*35:01, seen with DILI due to trimethoprim-sulfamethoxazole [13], green tea extract [29], *Polygonum multiflorum* [30], and Garcinia cambogia [31]. It should be remembered that many of these studies had a limited number of cases so designating specific HLA polymorphisms as risk alleles for DILI based solely on AF comparisons would require further studies and a validation cohort. The carrier frequency of HLA alleles in the general population is very variable and the incidence of DILI, even with well recognised hepatotoxic drugs, is too low to recommend testing for HLA alleles before prescribing a medication. However, testing for a drug-specific HLA risk allele may help in establishing a diagnosis of DILI [32].

TABLE 3 | Selected published series of iv MP associated liver injury.

	Current study 2023[a]	Nociti 2018	Kimura 2020	Allgeier 2022	Cottin 2020	Sisti 2015
DILI cases	11	6	8	13	77	14
Median age/years (range)	48 (18–69)	28 (19–59)	37 (28–49)	39 (20–74)	45.7	55 (30–78)
Female	73%	83%	100%	92%	59%	79%
MS	82%	100%	100%	92%	27%	
Graves						100%
Other diseases	18%			8%	73%	
Median peak ALT/U/L (range)	1168 (228–2669)	931 (778–2956)	912 (170–3720)	1431 (336–2667)	NA (79% hepatocellular injury)	NA (ALT > 300)
Median peak bilirubin/mg/dL (range)	3.2 (0.4–31.4)	1.5 (1.3–10.8)	1.15 (0.4–21.6)	10 (0.8–29.7)	NA	NA
Jaundice	55%	17%	25%	62%	34%	NA
ANA and/or SMA positive	45%	33%	0%	92%	NA	NA
Liver biopsy	67%	83%	88%	77%	17%	NA
% Fatal/liver txp	9%	Not reported	Not reported	Not reported	Not reported	Not reported

[a]Only study with genetic analyses reported.

The HLA analysis identified three HLA alleles, *HLA-DQB1*06:02*, *HLA-DQA1*01:02*, and *DRB1*15:01* as well as the DR15 haplotype formed by these three alleles as potential susceptibility HLA alleles for MP-DILI. The *DRB1*15:01* allele and DR15 are known risk HLA allele and haplotypes for MS in patients of European descent [33]. As 9 of 10 MP DILI cases with HLA data had MS, the HLA alleles and DR15 haplotype identified were more likely due to the underlying MS rather than an association with MP-DILI. These data highlight the potential for confounding of interpretation of genetic data for risk of DILI by the underlying disease being treated.

The represented SNPs in PTPN22, ERAP1, and ERAP2 previously identified for other drug specific DILI in DILIN showed no association with MP DILI. However, the SNP rs62376414 in ERAP1 showed more prevalence in the 10 MP cases than the 21 MS disease controls (AF: 0.20 vs. 0.02), which may be an indicator to differentiate MP effect from MS effects in those with DILI. However, the number of cases was small and further studies are needed to validate this finding.

A comparison of the current study to other selected series of iv MP liver injury is shown in Table 3, highlighting very similar clinical features and its predominance in MS patients. Although other authors suggest this could be AIH, the data in the current study demonstrated a low incidence of autoantibodies and lack of known HLA alleles associated with AIH.

There are some limitations to this study. Although the data was collected prospectively, recognition of drugs associated with DILI has changed over time and accurate documentation of MP usage as an implicated agent may have been lacking. Eight of the 11 HiC MP cases were enrolled in the last 10 years, compared to only three in the first 10 years of DILIN. Non-Hispanic White participants are over-represented in DILIN and recent studies have demonstrated that there are significant racial differences in the risk of MS, partially due to conserved extended haplotypes [34]; and DILI due to some classes of drugs such as anti-epileptics [35].

In conclusion, MP DILI is characterised by hepatocellular injury with or without jaundice, short latency, and usually rapid recovery, although fatal MP DILI can rarely occur. In DILIN, MP DILI was seen largely in MS patients and the HLA haplotypes associated with an increased risk of MS likely represented an association with the treated patient population rather than a distinct DILI risk. The observation that nearly all cases in this series and those reported in the literature arose after administration of 0.8–1 g per day for at least 3–5 days suggests that clinicians using these drugs should be aware for this potential adverse event and have a low threshold for monitoring liver tests in patients who develop new symptoms after iv infusion.

Author Contributions

All authors contributed to the collection of clinical data, data analysis, and initial and final drafting of the manuscript.

Acknowledgements

Research reported in this publication was supported by the National Institute of Diabetes and Digestive and Kidney Diseases (NIDDK) of the National Institutes of Health under award numbers

U01DK065211 (Indiana University), U01DK065184 (University of Michigan), U01DK065201 (University of North Carolina-Chapel Hill), U01DK083020 (University of Southern California), U01DK083027 (Thomas Jefferson University/Albert Einstein Medical Center), U01DK100928 (Icahn School of Medicine at Mount Sinai), and U24DK065176 (Duke University). Additional support is provided by the intramural programs of the NIDDK and National Cancer Institute. The content and opinions expressed in this article are solely the responsibility of the authors and do not necessarily represent the official views of the National Institutes of Health.

Ethics Statement

DILIN prospective study was approved by the Institutional Review Boards at each clinical site and data-coordinating center and by a central Data Safety and Monitoring Board appointed by the NIDDK.

Consent

All enrolled subjects provided written informed consent.

Conflicts of Interest

JA, YJL, EP, AD, RJF, DEK, HXB, JHH: No conflict of interest to disclose. No conflicts of interests for this paper for NC. For full disclosure, Dr. Chalasani (in preceding 12 months) had paid consulting for Madrigal, Zydus, Merck, Pfizer, Altimmune, GSK, Ipsen, and Foresite in the NASH and DILI areas. He reports research support from Exact Sciences and DSM. He has equity in Avant Sante, a contract research organisation.

Data Availability Statement

Research data including liver biopsy material were collected as part of participants' standard clinical care and are privacy protected for patient confidentiality.

References

1. https://www.accessdata.fda.gov/drugsatfda_docs/label/2011/011856s103s104lbl.pdf, accessed June 30, 2024.

2. https://www.nice.org.uk/guidance/ng220, accessed June 30, 2024.

3. V. Nociti, M. Biolato, C. De Fino, et al., "Liver Injury After Pulsed Methylprednisolone Therapy in Multiple Sclerosis Patients," *Brain and Behavior: A Cognitive Neuroscience Perspective* 8 (2018): e00968.

4. R. J. Fontana, P. B. Watkins, H. L. Bonkovsky, et al., "Drug-Induced Liver Injury Network (DILIN) Prospective Study: Rationale, Design and Conduct," *Drug Safety* 32 (2009): 55–68.

5. N. Chalasani, H. L. Bonkovsky, R. Fontana, et al., "Features and Outcomes of 899 Patients With Drug-Induced Liver Injury: The DILIN Prospective Study," *Gastroenterology* 148 (2015): 1340–1352.

6. H. Kimura, A. Takeda, T. Kikukawa, et al., "Liver Injury After Methylprednisolone Pulse Therapy in Multiple Sclerosis Is Usually due to Idiosyncratic Drug-Induced Toxicity Rather Than Autoimmune Hepatitis," *Multiple Sclerosis and Related Disorders* 42 (2020): 102065.

7. J. Cottin, S. Pierre, V. Pizzoglio, et al., "Methylprednisolone-Related Liver Injury: A Descriptive Study Using the French Pharmacovigilance Database," *Clinics and Research in Hepatology and Gastroenterology* 44 (2020): 662–673.

8. E. Sisti, B. Coco, F. Menconi, et al., "Age and Dose Are Major Risk Factors for Liver Damage Associated With Intravenous Glucocorticoid Pulse Therapy for Graves' Orbitopathy," *Thyroid* 25 (2015): 846–850.

9. P. Miśkiewicz, A. Jankowska, K. Brodzińska, et al., "Influence of Methylprednisolone Pulse Therapy on Liver Function in Patients With Graves' Orbitopathy," *International Journal of Endocrinology* 21 (2018): 1978590.

10. M. Moleti, G. Giuffrida, G. Sturniolo, et al., "Acute Liver Damage Following Intravenous Glucocorticoid Treatment for Graves' Ophthalmopathy," *Endocrine* 54 (2016): 259–268.

11. M. E. Zoubek, J. Pinazo-Bandera, A. Ortega-Alonso, et al., "Liver Injury After Methylprednisolone Pulses: A Disputable Cause of Hepatotoxicity. A Case Series and Literature Review," *United European Gastroenterologisches Journal* 7 (2019): 825–837.

12. D. C. Rockey, L. B. Seeff, J. Rochon, et al., "Causality Assessment in Drug-Induced Liver Injury Using a Structured Expert Opinion Process: Comparison to the Roussel-Uclaf Causality Assessment Method," *Hepatology* 51 (2010): 2117–2126.

13. Y. J. Li, E. J. Phillips, A. Dellinger, et al., "Human Leukocyte Antigen B*14:01 and B*35:01 Are Associated With Trimethoprim-Sulfamethoxazole Induced Liver Injury," *Hepatology* 73 (2021): 268–281.

14. J. D. Storey and R. Tibshirani, "Statistical Significance for Genome-wide Studies," *Proceedings of the National Academy of Sciences of the United States of America* 100 (2003): 9440–9445.

15. E. T. Cirulli, P. Nicoletti, K. Abramson, et al., "A Missense Variant in PTPN22 Is a Risk Factor for Drug-Induced Liver Injury," *Gastroenterology* 156 (2019): 1707–1716.

16. P. Nicoletti, A. Dellinger, Y. J. Li, et al., "Identification of Reduced ERAP2 Expression and a Novel HLA Allele as Components of a Risk Score for Susceptibility to Liver Injury due to Amoxicillin-Clavulanate," *Gastroenterology* 164 (2023): 454–466.

17. R. J. Fontana, Y. J. Li, R. Vuppalanchi, et al., "ERAP-1 and ERAP-2 Variants in Liver Injury After COVID-19 mRNA Vaccination: A US Multicenter Study," *American Journal of Gastroenterology* 119 (2024): 1496–1505.

18. J. A. Hollenbach and J. R. Oksenberg, "The Immunogenetics of Multiple Sclerosis: A Comprehensive Review," *Journal of Autoimmunity* 64 (2015): 13–25.

19. K. M. Simmons, A. M. Mitchell, A. A. Alkanani, et al., "Failed Genetic Protection: Type 1 Diabetes in the Presence of HLA-DQB1*06:02," *Diabetes* 69 (2020): 1763–1769.

20. E. Grilli, V. Galati, N. Petrosillo, et al., "Incomplete Septal Cirrhosis After High-Dose Methylprednisolone Therapy and Regression of Liver Injury," *Liver International* 35 (2015): 674–676.

21. F. Aloisi, G. Giovannoni, and M. Salvetti, "Epstein-Barr Virus as a Cause of Multiple Sclerosis: Opportunities for Prevention and Therapy," *Lancet Neurology* 22 (2023): 338–349.

22. J. Allgeier, S. Weber, R. Todorova, et al., "Acute Liver Injury Following Methylprednisolone Pulse Therapy: 13 Cases From a Prospectively Collected Cohort," *European Journal of Gastroenterology & Hepatology* 34 (2022): 457–461.

23. A. Rhodes, J. B. Eastwood, and S. A. Smith, "Early Acute Hepatitis With Parenteral Amiodarone: A Toxic Effect of the Vehicle?," *Gut* 34 (1993): 565–566.

24. P. Deshpande, R. J. Hertzman, A. M. Palubinsky, et al., "Immunopharmacogenomics: Mechanisms of HLA-Associated Drug Reactions," *Clinical Pharmacology and Therapeutics* 110 (2021): 607–615.

25. R. J. Fontana, E. T. Cirulli, J. Gu, et al., "The Role of HLA-A*33:01 in Patients With Cholestatic Hepatitis Attributed to Terbinafine," *Journal of Hepatology* 69 (2018): 1317–1325.

26. T. J. Urban, P. Nicoletti, N. Chalasani, et al., "Minocycline Hepatotoxicity: Clinical Characterization and Identification of HLA-B *35:02 as a Risk Factor," *Journal of Hepatology* 67 (2017): 137–144.

27. M. I. Lucena, M. Molokhia, Y. Shen, et al., "Susceptibility to Amoxicillin-Clavulanate-Induced Liver Injury Is Influenced by

Multiple HLA Class I and II Alleles," *Gastroenterology* 141 (2011): 338–347.

28. P. Nicoletti, A. N. Werk, A. Sawle, et al., "HLA-DRB1*16: 01-DQB1*05: 02 Is a Novel Genetic Risk Factor for Flupirtine-Induced Liver Injury," *Pharmacogenetics and Genomics* 26 (2016): 218–224.

29. J. H. Hoofnagle, H. L. Bonkovsky, E. J. Phillips, et al., "HLA-B*35:01 and Green Tea-Induced Liver Injury," *Hepatology* 73 (2021): 2484–2493.

30. C. Li, T. Rao, X. Chen, et al., "HLA-B*35:01 Allele Is a Potential Biomarker for Predicting *Polygonum multiflorum*-Induced Liver Injury in Humans," *Hepatology* 70 (2019): 346–357.

31. R. Vuppalanchi, H. L. Bonkovsky, J. Ahmad, et al., "Garcinia Cambogia, Either Alone or in Combination With Green Tea, Causes Moderate to Severe Liver Injury," *Clinical Gastroenterology and Hepatology* 20 (2022): e1416–e1425.

32. R. J. Fontana, E. S. Bjornsson, R. Reddy, et al., "The Evolving Profile of Idiosyncratic Drug-Induced Liver Injury," *Clinical Gastroenterology and Hepatology* 21 (2023): 2088–2099.

33. International Multiple Sclerosis Genetics Consortium, Wellcome Trust Case Control Consortium 2, S. Sawcer, et al., "Genetic Risk and a Primary Role for Cell-Mediated Immune Mechanisms in Multiple Sclerosis," *Nature* 476 (2011): 214–219.

34. D. S. Goodin, J. R. Oksenberg, V. Douillard, et al., "Genetic Susceptibility to Multiple Sclerosis in African Americans," *PLoS One* 16 (2021): e0254945.

35. N. Chalasani, H. L. Bonkovsky, J. G. Stine, et al., "Clinical Characteristics of Antiepileptic-Induced Liver Injury in Patients From the DILIN Prospective Study," *Journal of Hepatology* 76 (2022): 832–840.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.