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Variation in Early Anakinra Use and Short-Term Outcomes in Multisystem Inflammatory Syndrome in Children

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Objective. Evidence regarding effectiveness of interleukin-1 receptor antagonism in multisystem inflammatory syndrome in children (MIS-C) is lacking. We characterized variation in initial treatment with anakinra and evaluated cardiovascular outcomes associated with adding anakinra to standard initial therapy.

Methods. We conducted a retrospective cohort study of MIS-C cases in a US surveillance registry from November 2020 to December 2021. Day 0 was the first calendar day of immunomodulatory treatment. Factors associated with initial anakinra use (days 0–1) were identified. We compared cases in patients ages 2–20 years receiving intravenous immunoglobulin (IVIG) and glucocorticoids versus anakinra plus IVIG and/or glucocorticoids on days 0–1, using inverse probability weighting to balance disease severity. Primary outcomes were vasopressor requirement on day 3 and impaired left ventricular ejection fraction on days 3–4. The secondary outcome was 50% reduction in C-reactive protein on day 3.

Results. Among 1,516 MIS-C cases at 44 sites, 193 (13%) patients received anakinra alone or with other immunomodulators as initial treatment (range 0–74% by site). Site accounted for 59% of residual variance in anakinra use. After balancing disease severity, initial treatment with anakinra plus IVIG and/or glucocorticoids (n = 121) versus IVIG plus glucocorticoids (n = 389) was not associated with significant differences in vasopressor requirement (25.6% versus 20.1%, respectively; risk ratio [RR] 1.27 [95% confidence interval (95% CI) 0.88–1.84]), ventricular dysfunction (33.7% versus 25.7%, respectively; RR 1.31 [95% CI 0.98–1.75]), or C-reactive protein reduction.

Conclusion. We identified substantial variation in initial anakinra use in a real-world population of children with MIS-C, but no average short-term improvement in cardiovascular outcomes associated with early addition of anakinra to IVIG and/or glucocorticoids compared to IVIG and glucocorticoids alone.

INTRODUCTION

The primary drivers of morbidity in multisystem inflammatory syndrome in children (MIS-C) are features of distributive and cardiogenic shock. Evidence of aberrant cytokine signaling has prompted empiric use of cytokine inhibitors, of which the interleukin-1 receptor antagonist (IL-1Ra) anakinra is the most commonly used in the US (1,2). IL-1α/IL-1β signaling promotes

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secretion of C-reactive protein (CRP) and other acute-phase reactants, fever, lymphocyte proliferation, endothelial cell activation, and production of other cytokines, including IL-6 and tumor necrosis factor (TNF) (3). Thus, it is reasonable to hypothesize that IL-1 inhibition could improve cardiovascular outcomes of MIS-C by reducing vasoplegia and myocardial injury driven by dysregulated inflammation.

Published experience with anakinra use in children with MIS-C is limited primarily to single-center case series, which are subject to publication bias (4–9). In guidelines released by the American College of Rheumatology (ACR), there was moderate consensus that high-dose anakinra (>4 mg/kg/day) should be considered for MIS-C refractory to intravenous immunoglobulin (IVIG) and glucocorticoids in patients with features of macrophage activation syndrome (MAS) and in those with relative contraindications to standard therapy (10). An estimated 22% of MIS-C cases in the US from October 2020 to July 2021 were treated with cytokine inhibitors (11). In an international meta-analysis, the pooled proportion of children receiving cytokine inhibitors was 27%, but with considerable heterogeneity (12).

Despite empiric use of cytokine inhibitors in the management of MIS-C, there remains little data on their effectiveness to define optimal use, and thus there is potential for considerable practice variability. The objectives of this study were to describe variation in and factors associated with anakinra use in MIS-C across 44 pediatric hospitals in the US and to compare cardiovascular outcomes of initial treatment with anakinra plus IVIG and/or glucocorticoids versus IVIG plus glucocorticoids alone.

PATIENTS AND METHODS

Study design. This was a retrospective cohort study using the Overcoming COVID-19 registry, a US public health surveillance network for children and adolescents hospitalized with SARS–CoV-2–related illness that is funded by the Centers for Disease Control and Prevention (CDC). The surveillance protocol was approved by the central institutional review board at Boston Children's Hospital, determined to meet requirements for public health surveillance as defined in 45 CFR 46.102(i)(2), and granted a waiver of informed consent. Trained study personnel at each site abstracted medical record data into standardized case report forms.

Study population. All MIS-C cases meeting the CDC case definition from sites that contributed ≥10 cases from November 2020 through December 2021 were considered for inclusion (13). Cases were adjudicated by principal investigators at each site and the coordinating center. Documentation of a positive SARS–CoV-2 reverse transcriptase–polymerase chain reaction or antibody test was required. We excluded patients with prior systemic glucocorticoid use within 7 days prior to admission, baseline immunosuppressant use, or immune dysregulation disorders.

Treatment groups. We defined initial therapy as immunomodulatory treatments received on days 0–1, with day 0 being the first calendar day any immunomodulatory treatment was received and day 1 being the next calendar day, to ensure exposure assessment occurred over at least 24 hours. We first categorized all MIS-C cases according to whether patients received anakinra as initial therapy, either alone or in combination with other immunomodulators. We then categorized cases according to initial therapy with anakinra plus IVIG and/or glucocorticoids versus IVIG plus glucocorticoids. Glucocorticoid dosing was recorded with pulse doses defined as 10–30 mg/kg of intravenous methylprednisolone or equivalent. Because obesity may influence treatment and outcomes, we excluded children <2 years of age in whom standardized obesity classification is not possible.

Outcomes. To assess treatment variation, we calculated the proportion of cases treated with anakinra alone or in combination with immunomodulators on days 0–1, excluding patients that received TNF or IL-6 inhibitors on days 0–1. To compare initial therapies, primary outcomes included any vasopressor requirement on day 3 of treatment and reduced left ventricular ejection

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fraction (LVEF) <55% on days 3–4 of treatment. As only calendar day of treatment (not time) was available, day 3 was selected to ensure outcome assessment occurred >24 hours after the first dose of anakinra in the treated group, which coincided with the expected time course of improvement in cardiovascular function described in prior reports (14). A range of days 3–4 was used for the LVEF outcome assessment due to variable timing and frequency of echocardiograms, the earliest of which was analyzed. As a secondary outcome, we evaluated 50% reduction of baseline CRP levels by day 3.

Covariates. We considered demographics (age, sex, race and ethnicity, insurance type, and social vulnerability index); calendar period, categorized as the time period before Delta variant predominance (November 2020 to May 2021) versus the time period of Delta variant predominance (June 2021 to December 2021); other clinical characteristics (body mass index classification based on the CDC percentile-for-age data table for children ages 2–19 years and standard categories for adults >19 years, 1 or more underlying condition, and day of illness); and laboratory characteristics on admission (CRP, platelet count, neutrophil:lymphocyte ratio, albumin, ferritin, and creatinine). Impairment in estimated glomerular filtration rate (eGFR) was used to quantify renal dysfunction. We also assessed severity of illness indicators within the first 24 hours of admission, including positive pressure ventilation (noninvasive or invasive ventilation), intensive care unit admission, baseline LVEF <55%, and any vasopressor requirement. Vasopressor use was additionally tested as an ordinal variable classified by the pediatric Sequential Organ Failure Assessment (pSOFA) score (15). We considered patients requiring either invasive mechanical ventilation or vasopressors to have life-threatening illness.

Statistical analysis. To characterize treatment variation, we calculated the proportion of MIS-C cases that were treated with anakinra as initial therapy (days 0–1) by site. We used mixed effects logistic regression models to identify factors associated with receipt of anakinra, with a random intercept for site. Age, sex, and severity indicators were included a priori. Additional covariates were added using a forward selection procedure and retained based on likelihood ratio tests or evidence of confounding, defined as >10% change in other coefficients. Ferritin was categorized according to the cutoff (>684 ng/ml) in the 2016 classification criteria for MAS in systemic juvenile idiopathic arthritis (16). Patterns of missingness were assessed. Complete case analysis was employed in all primary analyses, except for ferritin, for which a missing category was included due to the large proportion of missing values (28%) and potential for non-random missingness (Supplementary Methods, available on the *Arthritis & Rheumatology* website at https://onlinelibrary.wiley.com/doi/10.1002/art.42495). The intraclass correlation coefficient was used to quantify residual variance accounted for by site. In a secondary analysis, we also estimated marginal (population average) effects of each factor on the likelihood of initial anakinra use via generalized estimating equations with an exchangeable correlation structure.

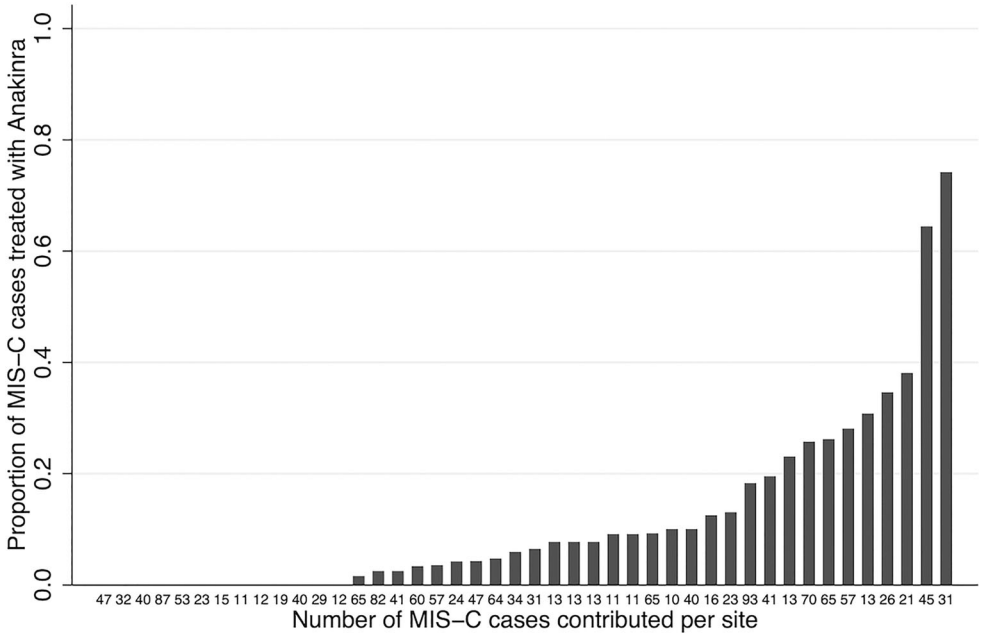

Figure 1. Bar graph representing the proportion of multisystem inflammatory syndrome in children (MIS-C) cases contributed by each site that were treated with anakinra alone or in combination with other immunomodulators as initial treatment on days 0–1, in ascending order. Each bar is labeled on the x-axis with the total number of MIS-C cases contributed by that site.

To compare treatment outcomes, we estimated risk ratios (RRs) using modified (robust) Poisson regression models with site-level random effects. To account for confounding by indication, we performed inverse probability of treatment weighting using propensity scores to balance covariates and indicators of disease severity at baseline across treatment groups (Supplementary Methods). Covariates were included in the propensity model based on clinical judgement, published literature (2,17), and identification of confounders or variables predictive of the outcome (18). To ensure cases had reasonable likelihood of receiving either treatment, we restricted comparator groups to the common (overlapping) region of the propensity distributions and trimmed extreme propensity scores (<10% probability of receiving either treatment) (19), prior to re-estimating propensity and inverse probability weights (20,21). Balance of covariates after inverse probability of treatment weighting was assessed using the standardized mean difference (SMD) and kernel density distribution plots. We tested further adjustment for pSOFA vasopressor scores and initial LVEF as a continuous measure in the weighted outcome models (22).

The primary analysis compared initial treatment with anakinra plus IVIG and/or glucocorticoids (anakinra group) versus IVIG plus glucocorticoids. In a secondary analysis, we restricted the anakinra group to those who received both IVIG and glucocorticoids, and also tested further adjustment for initial use of pulse dose intravenous methylprednisolone. With an estimated convenience sample of 120 anakinra-treated versus 360 non–anakinra treated cases and a 30–40% probability of each outcome, we calculated 80% power to detect a risk difference of 12–13% at a significance level of 0.05 in the absence of confounders (Mantel-Haenszel test).

We conducted several sensitivity analyses. To ensure results were robust to treatment of missing days 3–4 echocardiographic data, we compared estimates using complete case analysis to estimates using last observation carried forward. To evaluate the sensitivity of results to the chosen interval for outcome assessment, we shifted the vasopressor outcome by 1 calendar day in either direction. Furthermore, rather than restricting LVEF outcome assessment to days 3–4, we compared time to first normal LVEF ≥55% by treatment group among those with abnormal LVEF at treatment initiation using inverse probability of treatment weighting Cox proportional hazards regression, censoring observations at discharge. We also conducted propensity score matching using nearest neighbor caliper matching with replacement (k = 2; caliper width of 0.1). Last, we calculated E value bias statistics to evaluate the magnitude of unmeasured confounding necessary to change our conclusions. All statistical analyses were conducted using STATA version 16.0.

RESULTS

Variation in initial treatment patterns. Among 1,516 MIS-C patients from 44 sites, 193 (13%) patients received anakinra with or without other immunomodulators as initial therapy, 964 (64%) patients received IVIG plus glucocorticoids, 239 (16%) patients received IVIG alone, and a minority received glucocorticoids alone (4%) or no immunomodulators (4%). The 99 patients that received TNF inhibitors, almost exclusively from 2 sites, and 7 patients receiving tocilizumab were not analyzed further (Supplementary Table 1, https://onlinelibrary.wiley.com/doi/10.1002/art.42495). The vast majority (98%) of initial glucocorticoid administration was intravenous, most commonly with methylprednisolone (93%). The proportion of cases per site that

Table 1. Factors associated with receipt of anakinra in initial therapy for MIS-C*

	Adjusted OR (95% CI)	*P*
Age (years)	1.0 (0.9–1.0)	0.22
Female sex	0.7 (0.4–1.1)	0.10
Body mass index classification		
Healthy weight	–	–
Overweight	1.1 (0.6–2.3)	0.73
Obese	1.5 (0.9–2.6)	0.12
Social vulnerability index		
Lowest	–	–
Medium low	1.4 (0.7–2.8)	0.32
Medium high	1.9 (0.9–3.9)	0.08
Highest	1.7 (0.8–3.5)	0.17
Severity of illness indicators within 24 hours of admission		
Respiratory support		
None	–	–
Supplemental oxygen only	2.2 (1.2–3.9)	0.01
Noninvasive positive pressure ventilation	4.0 (1.2–14.0)	0.03
Invasive mechanical ventilation	8.9 (3.3–24.2)	<0.01
Any vasopressor requirement	2.3 (1.3–4.3)	0.01
Initial left ventricular ejection fraction <55%	1.4 (0.8–2.3)	0.24
Laboratory characteristics at admission		
Ferritin level		
≤684 ng/ml	–	–
>684 ng/ml	0.9 (0.5–1.5)	0.59
Missing	0.7 (0.3–1.3)	0.22
Estimated glomerular filtration rate		
Normal (≥90 ml/minute/1.73 m^2)	–	–
Mild–moderate impairment (45–89 ml/minute/1.73 m^2)	1.3 (0.7–2.4)	0.37
Moderate–severe impairment (<45 ml/minute/1.73 m^2)	2.6 (1.2–5.5)	0.02
Unknown/missing	0.9 (0.1–8.8)	0.96
Upper quartile of neutrophil:lymphocyte ratio	1.7 (1.0–2.8)	0.06
Platelet count (natural log)	0.7 (0.4–1.0)	0.07
Albumin	0.7 (0.4–1.1)	0.12

* Adjusted odds ratios (ORs) for the association with anakinra use as initial therapy determined from a mixed effects multivariable logistic regression model of 1,125 children ages ≥2 years with multisystem inflammatory syndrome in children (MIS-C) who had complete data available, with random intercept for site. Days of illness at presentation, presence of a preexisting condition, race and ethnicity, insurance status, alanine transaminase level, C-reactive protein, calendar period (before versus after Delta variant predominance), and intensive care unit admission were tested in the model and did not meet criteria for inclusion. 95% CI = 95% confidence interval.

were treated with anakinra as initial therapy varied between 0–74%, with a median of 6% (Figure 1), and was not associated with the number of cases contributed (ρ = 0.02, P = 0.92).

Of the 193 patients receiving anakinra as initial therapy, 161 (83%) patients received it with IVIG and glucocorticoids, 17 (9%) patients with IVIG only, 13 (7%) patients with glucocorticoids only, and 2 (1%) patients without other immunomodulators.

Of the 964 cases treated initially with IVIG plus glucocorticoids, 126 (13%) cases were subsequently treated with anakinra on day 2 or later (median day 2.5 [interquartile range (IQR) [2–4]) (Supplementary Table 1). The median initial dose of anakinra used in all cases was 4 mg/kg/day (range 0.2–20 mg/kg/day), with a median of 6 (IQR 4–9) total days of anakinra use, including use after hospital discharge.

Factors associated with anakinra as initial therapy in any combination with other immunomodulators. Indicators of illness severity, including respiratory support or vasopressors within 24 hours of admission as well as moderate-to-severe renal impairment (eGFR <45 ml/minute/1.73 m^2) were independently associated with anakinra use in any initial therapy (Table 1). The site of care accounted for 59% of residual variance after adjustment for individual characteristics, indicating substantial variation by site. The proportion of missing ferritin values also

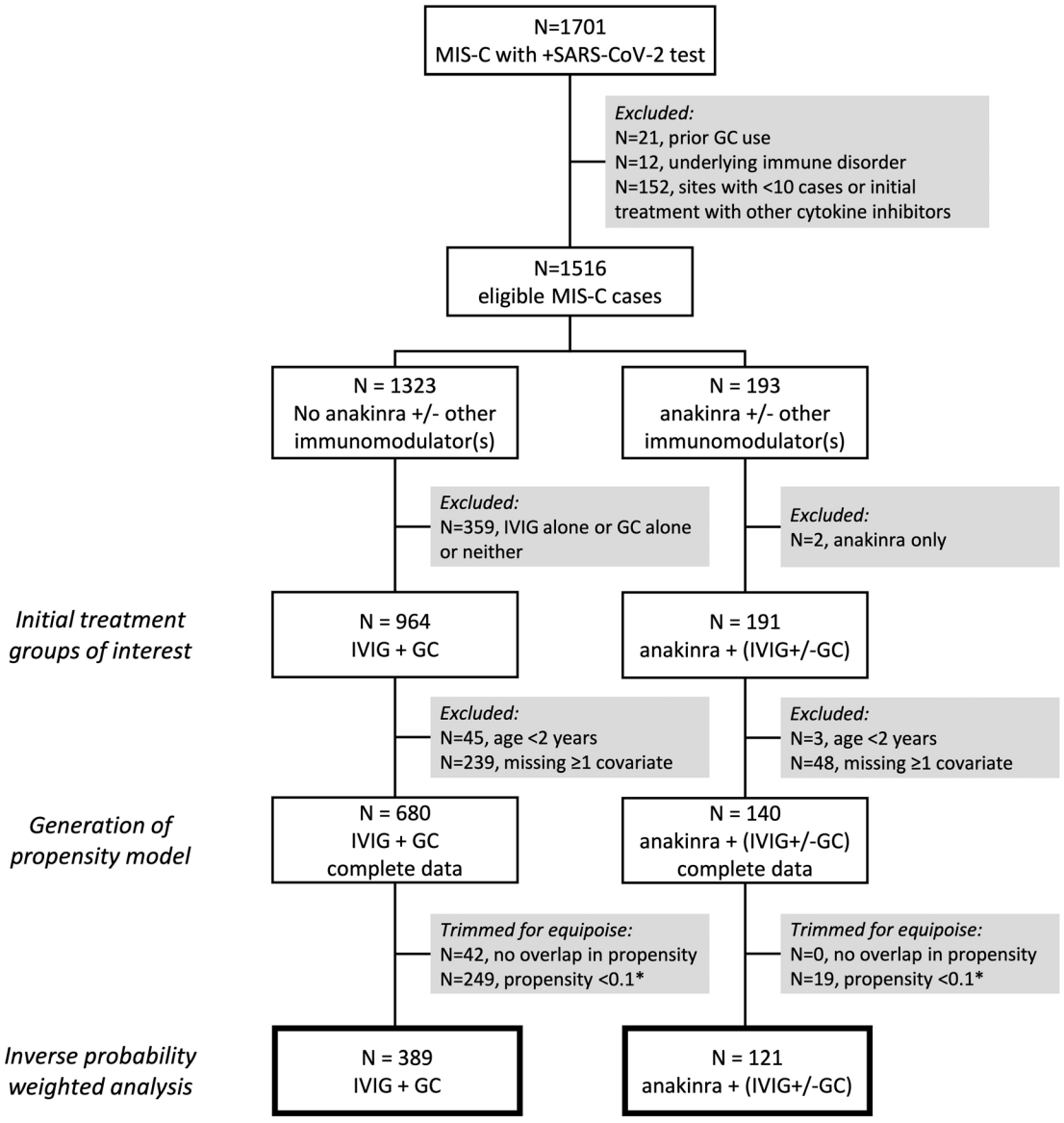

Figure 2. Flow diagram of selection criteria and sample sizes at each stage of the propensity weighted analysis. Boxes with thick borders indicate the final sample sizes in the inverse probability of treatment weighting estimates of the average treatment effect of anakinra plus intravenous immunoglobulin (IVIG) and/or glucocorticoids (GCs) compared to IVIG plus GC alone. * Cases with <10% predicted probability of receiving either treatment were removed to preserve clinical equipoise; in this cohort, only cases with <10% probability of receiving anakinra needed to be removed, as no cases had <10% probability of receiving only IVIG plus GC.

varied substantially by site (range 0–73%), but neither elevated nor missing ferritin was independently associated with anakinra use in initial therapy. Similarly, in the marginal model, baseline respiratory support and vasopressor requirement were significantly associated with anakinra use, but not ferritin (Supplementary Table 2, https://onlinelibrary.wiley.com/doi/10.1002/art.42495).

Outcomes associated with anakinra plus IVIG and/or glucocorticoids as initial therapy compared to IVIG plus glucocorticoids alone. A total of 820 observations with complete data were used to generate the propensity model, including 140 cases treated with anakinra plus IVIG and/or glucocorticoids on days 0–1 and 680 cases treated with IVIG plus glucocorticoids (Figure 2). Baseline characteristics and severity indicators in the propensity model prior to weighting are shown in Supplementary Table 3 (https://onlinelibrary.wiley.com/doi/10.1002/art.42495). There were no substantial differences in treatment assignment or baseline characteristics between included cases compared to those excluded for ≥1 missing covariate (Supplementary Table 4). Partial overlap in propensity scores was observed between treatment groups (Supplementary Figure 1). Restricting cases to the region of overlap resulted in loss of 42 cases from the IVIG plus glucocorticoid group only. Further trimming of cases with too low of a predicted probability (<10%) of receiving anakinra resulted in loss of 19 cases from the anakinra group and 249 cases from the IVIG plus glucocorticoid group, but no cases had to be trimmed for too low of a probability of receiving only IVIG plus glucocorticoids (Figure 2).

Covariate balance was achieved in the remaining 510 total cases (121 cases in the anakinra group versus 389 cases in the IVIG plus glucocorticoid group) after inverse probability weighting (Figure 3). In the weighted population, 85% of cases in both treatment groups had ≥1 severity indicator; 59% of cases in the anakinra group versus 58% of cases in the IVIG plus glucocorticoid group required invasive ventilation or vasopressor at baseline. Mean ± SD baseline LVEF was 54% ± 11–12% in both groups (Table 2). Among patients receiving glucocorticoids (n = 499), the median dose was 2 mg/kg/day methylprednisolone (IQR 1–8 mg/kg/day), of whom 24% were treated with pulse dose methylprednisolone. Inverse probability of treatment weighting and propensity score distributions are shown in Supplementary Figure 2 and Supplementary Figure 3, respectively, at https://onlinelibrary.wiley.com/doi/10.1002/art.42495.

Compared to initial therapy with IVIG and glucocorticoids, anakinra plus IVIG and/or glucocorticoids was not associated with significant differences between patients who received anakinra versus those who received IVIG plus glucocorticoids alone in the risk of vasopressor use on day 3 (25.6% versus 20.1%, respectively; RR 1.27 [95% confidence interval (95% CI) 0.88–1.84]) or left ventricular dysfunction on days 3–4 (33.7%

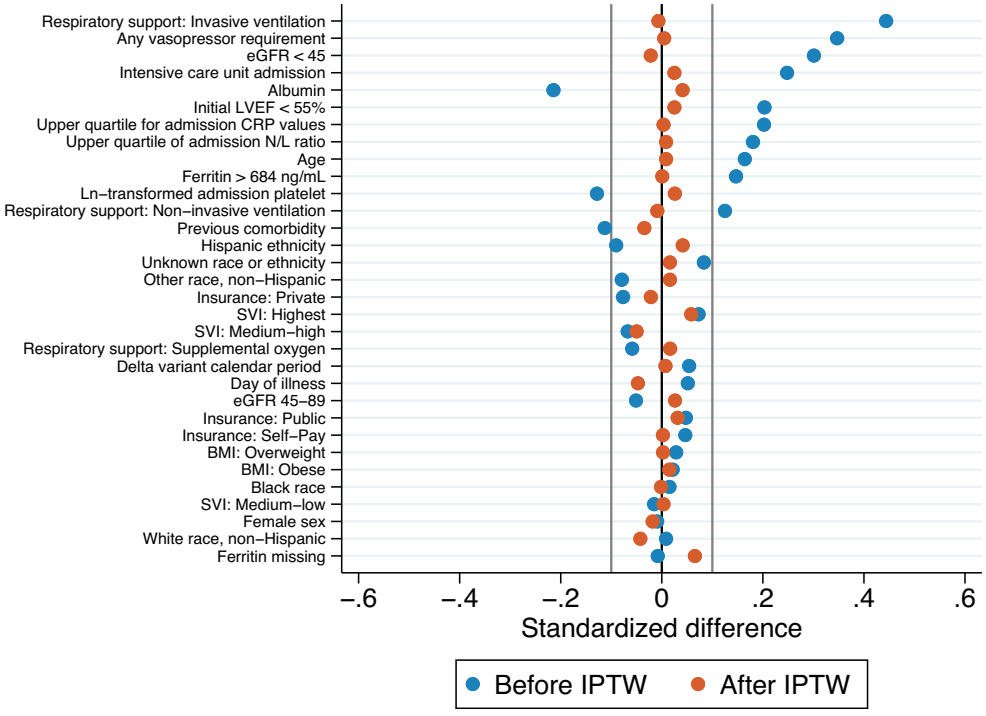

Figure 3. Standardized mean differences in individual covariates between the anakinra plus IVIG and/or glucocorticoid initial treatment group (n = 121) and the IVIG plus glucocorticoid initial treatment group (n = 389), before and after inverse probability of treatment weighting (IPTW). By convention, standardized differences <0.1 indicate adequate balance. eGFR = estimated glomerular filtration rate; LVEF = left ventricular ejection fraction; CRP = C-reactive protein; N/L ratio = neutrophil:lymphocyte ratio; SVI = social vulnerability index; BMI = body mass index.

Table 2. Distribution of baseline covariates before and after inverse probability weighting*

	Before weighting			After weighting		
	IVIG + GC (n = 389)	Anakinra + IVIG and/or GC (n = 121)	SMD	IVIG + GC (∑wt = 387.6)	Anakinra + IVIG and/or GC (∑wt = 122.7)	SMD
Age, mean ± SD years	9.9 ± 4.1	10.6 ± 4.1	0.17	10.1 ± 4.1	10.1 ± 4.1	0.01
Female sex	140 (36)	43 (36)	–0.01	139 (36)	43 (35)	–0.02
Delta variant predominance	234 (60)	76 (63)	0.05	237 (61)	75 (61)	0.01
Days of illness at admission, mean ± SD	4.9 ± 2.8	5.0 ± 3.0	0.05	4.9 ± 2.8	4.8 ± 3.0	–0.05
Days of illness at treatment day 0, mean ± SD†	5.5 ± 2.8	5.7 ± 2.9	0.06	5.6 ± 2.8	5.5 ± 2.9	–0.01
Race and ethnicity						
Asian or Pacific Islander	6 (2)	4 (3)	0.11	7 (2)	2 (1)	–0.02
Black, non-Hispanic	113 (29)	36 (30)	0.02	112 (29)	35 (29)	0.00
Hispanic ethnicity, any race	95 (24)	25 (21)	–0.09	92 (24)	31 (25)	0.04
Other race, non-Hispanic	11 (3)	2 (2)	–0.08	10 (3)	3 (3)	0.02
Unknown	21 (5)	9 (7)	0.08	25 (6)	8 (7)	0.02
White, non-Hispanic	143 (37)	45 (37)	0.01	142 (37)	42 (35)	–0.04
Insurance status						
Private	156 (40)	44 (36)	–0.08	152 (39)	47 (38)	–0.02
Self-Pay	7 (2)	3 (2)	0.05	8 (2)	3 (2)	0.00
Public	219 (56)	71 (59)	0.05	221 (57)	72 (59)	0.03
Unknown	7 (2)	3 (2)	0.05	7 (2)	1 (1)	–0.05
Social vulnerability index						
Lowest	79 (20)	25 (21)	0.01	79 (20)	24 (20)	–0.02
Medium low	99 (25)	30 (25)	–0.02	98 (25)	31 (26)	0.00
Medium high	108 (28)	30 (25)	–0.07	103 (26)	30 (24)	–0.05
Highest	103 (26)	36 (30)	0.07	108 (28)	37 (30)	0.06
Body mass index classification						
Healthy weight	188 (48)	56 (46)	–0.04	183 (47)	57 (46)	–0.02
Overweight	54 (14)	18 (15)	0.03	56 (14)	18 (14)	0.00
Obese	147 (38)	47 (39)	0.02	149 (39)	48 (39)	0.02
Previous comorbidity	152 (39)	54 (45)	–0.11	157 (41)	52 (42)	–0.03
Upper quartile for N/L ratio	130 (33)	51 (42)	0.18	138 (36)	44 (36)	0.01
Upper quartile for CRP	126 (32)	51 (42)	0.20	134 (35)	43 (35)	0.00
Platelet count, mean ± SD natural log	5.0 ± 0.5	4.9 ± 0.5	–0.13	5.0 ± 0.5	5.0 ± 0.5	0.03
Albumin, mean ± SD gm/dl	3.3 ± 0.6	3.1 ± 0.6	–0.21	3.2 ± 0.6	3.3 ± 0.6	0.04
Estimated glomerular filtration rate						
≥90 ml/minute/1.73 m^2	195 (50)	49 (40)	–0.19	186 (48)	59 (48)	–0.01
45–89 ml/minute/1.73 m^2	138 (35)	40 (33)	–0.05	137 (35)	45 (37)	0.03
<45 ml/minute/1.73 m^2	56 (14)	32 (26)	0.30	64 (17)	19 (16)	–0.02
Ferritin						
≤684 ng/ml	210 (54)	57 (47)	–0.14	203 (52)	61 (50)	–0.04
>684 ng/ml	133 (34)	50 (41)	0.15	138 (36)	44 (36)	0.00
Missing	46 (12)	14 (12)	–0.01	47 (12)	18 (14)	0.07
Severity of illness indicators within 24 hours of admission‡						
Respiratory support						
None	172 (44)	35 (29)	–0.32	159 (41)	50 (41)	–0.01
Supplemental oxygen	172 (44)	50 (41)	–0.06	170 (44)	55 (45)	0.02
Noninvasive ventilation	20 (5)	10 (8)	0.13	23 (6)	7 (6)	–0.01
Mechanical ventilation	25 (6)	26 (21)	0.44	37 (10)	11 (9)	–0.01
Any vasopressor requirement	212 (54)	86 (71)	0.25	225 (58)	72 (58)	0.03
Intensive care unit admission	289 (74)	102 (84)	0.35	298 (77)	96 (78)	0.00
Initial LVEF <55%	176 (45)	67 (55)	0.20	185 (48)	60 (49)	0.03
Initial LVEF (continuous), mean ± SD %§	55.0 ± 11.6	51.9 ± 11.2	–0.28	54.5 ± 11.9	53.9 ± 10.8	–0.05

* Distribution of covariates included in the propensity score model (except where indicated) before and after inverse probability weighting. Except where otherwise indicated, values are the number and unweighted or weighted percentage of patients. ∑wt = sum of weights; N/L ratio = neutrophil:lymphocyte ratio; CRP = C-reactive protein.
† Days of illness at treatment day 0 are shown to evaluate balance only; days of illness at admission timestamp rather than calendar day of treatment initiation was selected for inclusion in the propensity model.
‡ Before weighting, 325 (84%) patients in the intravenous immunoglobulin (IVIG) plus glucocorticoid (GC) group versus 110 (91%) patients in the anakinra group had ≥1 illness severity indicator (positive pressure ventilation, vasopressor requirement, intensive care unit admission, or impaired left ventricular ejection fraction [LVEF]) (standardized mean difference [SMD] 0.22). After weighting, 85% of patients in both treatment groups had ≥1 severity indicator (SMD –0.02).
§ Among 447 cases with quantitative measures of initial LVEF available. Means are shown to evaluate balance only; LVEF was not included as a continuous measure in the propensity model. Minimum values of LVEF were 20% in the IVIG plus GC group versus 22% in the anakinra-treated group before weighting.

versus 25.7%, respectively; RR 1.31 [95% CI 0.98–1.75]) in the weighted analyses (Figure 4). Additional adjustment in weighted outcome models for baseline LVEF as a continuous measure and pSOFA vasopressor score did not significantly change results. There was also no significant difference in CRP reduction by 50% by day 3 (Figure 4).

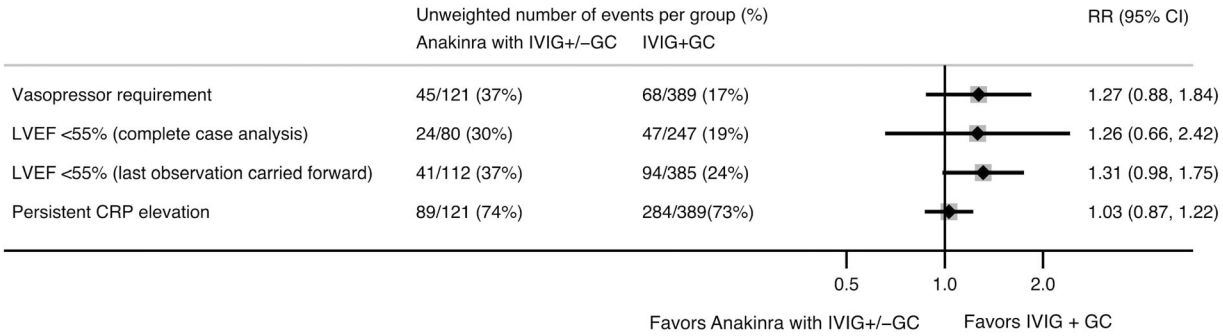

Figure 4. Risk ratios (RRs) of clinical outcomes in children with multisystem inflammatory syndrome in children (MIS-C) receiving anakinra as initial therapy with concomitant intravenous immunoglobulin (IVIG) and/or glucocorticoids (GCs) compared to children receiving IVIG plus GC alone, estimated using inverse probability of treatment weighting models with site-level random effects. Clinical outcomes were assessed on day 3 of treatment, except for left ventricular ejection fraction (LVEF), which was assessed on days 3–4, using either complete case analysis (N = 327 cases with LVEF recorded on days 3–4) or last observation carried forward (N = 497). The direction of the average treatment effect for C-reactive protein (CRP) is represented as failure to achieve 50% reduction in CRP from admission. 95% CI = 95% confidence interval.

Upon limiting the anakinra group to those who received concomitant initial treatment with both IVIG and glucocorticoids (n = 96), there was similarly no difference compared to those who received IVIG plus glucocorticoids (n = 310) in vasopressor requirement (RR 1.30 [95% CI 0.84–2.01]) or ventricular dysfunction (RR 1.34 [95% CI 0.96–1.85]). Further adjustment for initial use of pulse dose methylprednisolone (42% in anakinra group versus 23% in IVIG plus glucocorticoid group) yielded similar results (RR 1.30 [95% CI 0.85–1.98] for vasopressor use and RR 1.33 [95% CI 0.95–1.87] for ventricular dysfunction).

Among cases with abnormal LVEF at treatment initiation (n = 84 patients receiving anakinra plus IVIG and/or glucocorticoids; n = 191 patients receiving IVIG plus glucocorticoids), median time to first normal LVEF was 3 days (IQR 2–5 days; range 1–11 days). There was no significant difference in time to LVEF normalization in the anakinra group versus IVIG plus glucocorticoids alone (hazard ratio 0.78 [95% CI 0.52–1.17] for LVEF normalization after weighting). Uncensored individuals with prolonged LVEF recovery (≥6 days) in both the anakinra-treated (12 of 61 patients) and non–anakinra treated (16 of 135 patients) groups had lower initial LVEF (mean 43% versus 49%, respectively; $P < 0.01$), older age (mean 12.5 years versus 10.2 years, respectively; $P < 0.01$), and a higher frequency of severe renal impairment (39% versus 20%, respectively; $P < 0.01$). No other severity indicators or clinical features (obesity, ferritin, troponin [when available], sociodemographic characteristics) were associated with prolonged LVEF recovery.

Among patients treated initially with IVIG plus glucocorticoids, 42 (11%) of 389 patients received anakinra as rescue therapy on day 2 or later. Anakinra rescue therapy was associated with a higher frequency of positive pressure ventilation within 24 hours of admission compared to those initially treated with IVIG plus glucocorticoids who did not receive anakinra rescue treatment (21% versus 10%, respectively; $P = 0.03$) and higher baseline ferritin (median 599 ng/ml [IQR 420–1,325 ng/ml] versus 528 ng/ml [284–907 ng/ml], respectively; $P = 0.04$).

Sensitivity analyses. The likelihood of missing day 3 or 4 LVEF outcome data did not differ by treatment group, but baseline respiratory support was associated with greater completion of day 3 or 4 echocardiography (Supplementary Table 5, https://onlinelibrary.wiley.com/doi/10.1002/art.42495). Complete case analysis versus last observation carried forward yielded similar point estimates for ventricular dysfunction (Figure 4). Shifting vasopressor outcome assessment by 1 calendar day earlier or later did not change conclusions (data not shown). Similarly, the propensity matched analysis (n = 100 patients in the anakinra plus IVIG and/or glucocorticoid group versus n = 143 patients in the IVIG plus glucocorticoid group, representing 38 sites) did not demonstrate a significant association between anakinra use and outcomes of vasopressor requirement (RR 1.10 [95% CI 0.63–1.93]) or ventricular dysfunction (RR 1.25 [95% CI 0.77–2.03]). Assuming the true effect of anakinra is a 20% or 10% risk reduction, an unmeasured confounder would need to have a minimum strength of association on the risk ratio scale of 2.65 or 2.26, respectively, with both treatment and outcome to yield the null effect observed in the primary analysis of vasopressor use.

DISCUSSION

In this real-world epidemiologic study, there was substantial variation in the use of anakinra as initial treatment for MIS-C across pediatric centers in the US. Practice variation enabled identification of cases with reasonable likelihood to have received initial treatment with either anakinra plus standard therapy or IVIG and glucocorticoids alone. In these children with MIS-C, in which nearly 60% presented with life-threatening illness, we did not observe any significant associations between early anakinra use and short-term vasopressor requirement, ventricular dysfunction,

or CRP reduction to support routine addition of anakinra to initial therapy with IVIG or glucocorticoids.

Our findings contrast with a number of case series describing clinical improvement following early treatment with anakinra and good outcomes of early aggressive therapy for severe MIS-C cases, though no case series directly compared outcomes against standard therapy with IVIG and glucocorticoids (23). There may be several reasons for this observation. First, IVIG and glucocorticoids may be effective for controlling inflammation, such that we cannot detect effects of targeted therapies when used concurrently. Previous studies suggested that adding glucocorticoids to IVIG promotes faster recovery of cardiac function in MIS-C (2,24). Moreover, a recent study proposed IVIG targets activated neutrophils expressing IL-1β in MIS-C and the similar syndrome Kawasaki disease, providing a basis for efficacy of IVIG, although further validation is necessary (25). Second, it is possible that cardiovascular dysfunction and CRP elevation in MIS-C are driven by IL-1 to a lesser degree than in other hyperinflammatory states such as in MAS and Kawasaki disease. The distinct immune profiles of these conditions cautions against a one-size-fits-all approach to treatment (6,26). Conversely, recent studies in small groups of children with MIS-C and vaccine-induced myocarditis described a high prevalence of anti–IL-1Ra autoantibodies corresponding to reduced free IL-1Ra, which authors postulate may contribute to hyperinflammation (27,28). Thus, if anti–IL-1Ra autoantibodies contribute to MIS-C pathophysiology, it is possible that the average anakinra dose of 4 mg/kg/day in this study was insufficient to detect an effect. Larger doses up to 10 mg/kg/day have been reported in case series describing clinical benefit of anakinra for MIS-C (8,23). A greater understanding of the role of IL-1 and autoantibodies in MIS-C can inform the design of future studies of the effectiveness of IL-1 inhibition.

Current ACR guidelines recommend anakinra for treatment intensification but make no specific recommendations regarding initial treatment with anakinra, with the exception of MAS or contraindications to standard therapy (10). These recommendations were based largely on descriptive series (5,29,30), clinical experience of the expert panel, and extrapolation from experience using anakinra for other hyperinflammatory conditions, including IVIG-resistant Kawasaki disease (31). In our cohort, local practices sometimes diverged from ACR guidelines and favored early treatment with cytokine inhibitors, often in children with more life-threatening presentations and multiorgan dysfunction. The frequency of early anakinra use ranged from none at some sites to ~75% of patients at others, and nearly all TNF inhibitor use was accounted for by 2 sites, which may reflect ways in which institutions operationalized local multidisciplinary treatment standards, as previously described (23,32,33). While greater illness severity and local context were both important factors in the use of anakinra, we do not know whether specific clinical presentations such as fulminant myocardial dysfunction or suspected MAS prompted early anakinra use and how this differed by site. As many features of MAS overlap with MIS-C, it was not possible to classify a specific subgroup of patients with MAS in this registry. Of note, although race, ethnicity, and socioeconomic disadvantage have been associated with disproportionately higher rates of MIS-C (34,35), as well as more severe presentation (36), they were not significant predictors of early anakinra use to suggest that differential cytokine inhibitor use drives disparities in outcomes. Data from our epidemiologic study provide additional evidence to support current ACR recommendations to reserve cytokine inhibitors for treatment intensification in most hospitalized children with MIS-C. Per consensus guidelines, given the favorable safety profile of anakinra, empiric use in the setting of suspected MAS or refractory disease may be indicated, and our findings are not intended to supersede clinical judgement in this regard.

There are several remaining clinical questions our study could not answer. We lacked sufficient sample size to evaluate whether anakinra can supplant IVIG or glucocorticoids as initial treatment. This would be an important future direction, as fluid overload from IVIG in the setting of impaired cardiac function is of concern, and adverse effects of glucocorticoid use in MIS-C have been demonstrated (37), particularly in children with obesity. Obesity is prevalent in MIS-C and associated with worse outcomes (38); therefore, identifying optimal treatment strategies for children with comorbid obesity is necessary. Although it is unknown whether any patients receiving anakinra had relative contraindications to standard therapy, sensitivity analyses restricted to those receiving both IVIG and glucocorticoids suggest this does not explain our results. Secondly, we do not know if there is a subset of critically ill children that would benefit from early anakinra use or what doses may be required to achieve a clinical effect. Anakinra rescue therapy was administered to 11% of children who received IVIG and glucocorticoids initially, particularly to those requiring mechanical ventilation. Our study was not designed to evaluate rescue therapy or directly compare step-up to step-down approaches.

Strengths of our study include the large sample size and representation of pediatric hospitals across the US. However, there are several limitations related to the retrospective nature of this analysis and application of real-world data. Our results may not be wholly generalizable, as we had insufficient sample size to stratify by anakinra dose or by life-threatening features to assess heterogeneous treatment effects, including effect modification by level of baseline cardiac dysfunction. Additionally, our data reflect national practices and guidelines in the US and may not be generalizable to other countries (39). Laboratory data were missing in a substantial proportion of cases, particularly ferritin and troponin. Missingness may be non-random if ferritin was checked only for suspected MAS, which could bias estimates toward worse outcomes in the anakinra group. However, we balanced missing ferritin data across treatment groups to limit the potential impact of

this bias, and the substantial site variation in ferritin evaluation suggests that practice variability has an important role in evaluating ferritin level rather than suspicion of a specific pathophysiologic process.

An additional limitation of the surveillance registry is the inability to assess precise timing of therapies and response, as only calendar days were available. Similarly, cardiac enzymes and other measures of myocardial function (e.g., strain) were not captured sufficiently to assess fulminant myocardial injury and its relationship to anakinra usage or potential utility. With the observed effect estimates, we were likely underpowered to detect statistically significant differences. Despite the lower precision of our estimates in this setting, we believe that they are still informative, as accumulation of data from additional analyses in other cohorts would facilitate more precise pooled estimates (40). Last, it is important to emphasize this was a retrospective observational study; therefore, associations are hypothesis-generating and should be interpreted cautiously. Although inverse probability weighting is commonly used to address confounding by indication and several severity indicators were included to limit this bias, residual confounding remains a possibility. Mean baseline LVEF was slightly lower in the anakinra group compared to the IVIG plus glucocorticoid group (52% versus 55%, respectively), so while weighting achieved similar LVEF distributions in both treatment groups, other unmeasured indicators of cardiac injury may introduce confounding and could explain why our point estimates appeared to favor IVIG and glucocorticoids. However, any unmeasured confounder would need to have a rather large effect to explain our results.

In summary, we identified substantial variation in the use of anakinra as initial treatment for MIS-C in the setting of uncertain effectiveness and rapid development of local standards and treatment protocols. Our observational data do not provide evidence to support routine addition of anakinra to initial treatment with IVIG and glucocorticoids in most children hospitalized with MIS-C. Although the rare incidence of MIS-C impeded assessment of clinical efficacy in a randomized trial, retrospective analyses of real-world clinical experiences can inform future MIS-C treatment guidelines and comparative study designs. Additional understanding of the pathogenesis and treatment outcomes of MIS-C is needed to determine which rational therapies can augment or replace broadly immunomodulating agents and reduce their adverse effects. In addition, the role of targeted cytokine inhibition for patients with contraindications to broad immunomodulation or for those requiring adjunctive rescue therapy may warrant evaluation.

AUTHOR CONTRIBUTIONS

All authors were involved in drafting the article or revising it critically for important intellectual content. All authors approved the final version to be published. Dr. Chang had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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Acquisition of data. Young, Newhams, Kucukak, Crandall, Maddux, Rowan, Halasa, Harvey, Hobbs, Hall, Kong, Aguiar, Schuster, Fitzgerald, Singh, Wellnitz, Nofziger, Cvijanovich, Mack, Schwarz, Heidemann, Randoph.

Analysis and interpretation of data. Chang, Young, Muscal, Sexson Tejtel, Newburger, Zambrano, Campbell, Patel, Randolph, Son.

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