 DOI: https://doi.org/10.5114/ceji/214592

Interactions of infection history with vaccine immune responses in pediatric patients with Kawasaki disease

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Abstract

Introduction: *We aimed to assess the influence of infection history in pediatric patients with Kawasaki disease (KD) on vaccine immune responses in the convalescence stage.*

Material and methods: *In this study, a total of 298 pediatric patients who were diagnosed with KD between January 2021 and December 2024 and completed follow-up were included. They were assigned to a high infection burden group (n = 152) and a low infection burden group (n = 146). All pediatric patients underwent immunization with measles-mumps-rubella (MMR), hepatitis B, or varicella vaccine at least 11 months after treatment with intravenous immunoglobulin, and completed serological tests within 1-3 months after vaccination. Antibody levels were measured via enzyme-linked immunosorbent assay, and the positive conversion rates and geometric mean titers (GMTs) were calculated.*

Results: *Compared with the low infection burden group, the high infection burden group had a significantly lower positive conversion rate (82.2% vs. 93.2%, p = 0.006) and GMT (320 IU/ml vs. 540 IU/ml, p = 0.010) of measles antibody. High infection burden was independently associated with a higher likelihood of immunization failure in multivariate logistic regression analysis (odds ratio [OR] = 2.35, 95% confidence interval [CI]: 1.20-4.62, p = 0.013). Quartile-stratified analysis indicated that the measles antibody level declined significantly with increasing infection frequency (p for trend = 0.003).*

Conclusions: *A history of high infection burden was associated with lower vaccine-induced immune responses. In particular, frequent respiratory tract infection can significantly weaken the vaccine-induced immune responses in the convalescence stage.*

Key words: *seroconversion, antibody titer, IVIG, respiratory infections, post-vaccination immunity.*

(Cent Eur J Immunol 2026; 51 (4): 1-8)

Introduction

Defined as an acute, self-limited systemic vasculitis of unknown etiology, Kawasaki disease (KD) has been currently recognized as the leading cause of acquired heart disease in children in developed countries [1]. The typical pathological changes of KD involve the inflammation of small- and medium-sized blood vessels and abnormal activation of the immune system, and some pediatric patients are likely to develop coronary arterial lesions, giving rise to long-term cardiovascular risks [2]. Although the etiology of KD remains unclear, epidemiological studies have indicated that the onset of KD is closely associated with infection triggers, with seasonal and district clustering features [3]. Multiple viral and bacterial infections are considered potential triggers of KD, and a dose-dependent relationship between the frequency of prior infection events and KD occurrence has been demonstrated in a study [4]. Evidence suggests that pediatric patients with KD may have experienced abnormal immune regulation or subtle immune deficiency prior to onset.

At the immunological level, the acute phase of KD is accompanied by significant immune dysfunction, including imbalance of T-cell subsets and overexpression of inflammatory factors [5]. Some pediatric patients may have a background of host susceptibility, presenting a bias in immune function during their responses to infections [6]. This not only contributes to the explanation of the relationship between KD and infection but also raises concerns about whether the long-term immune function is affected. On the other hand, intravenous immunoglobulin (IVIG) as the standard treatment protocol for KD can interfere with the immunogenicity of vaccines. Therefore, it is recommended in guidelines that pediatric patients should receive immunization with live vaccines such as measles-mumps-rubella (MMR) and varicella at least 11 months after IVIG treatment [7, 8]. However, despite the evidence that infections can induce KD and that IVIG

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Submitted: 13.10.2025, Accepted: 22.11.2025

can affect vaccination timing [9, 10], systematic studies on whether the infection history in pediatric patients with KD influences their immune responses to routine vaccination after convalescence have been scarce.

Consequently, it was hypothesized in this study that pediatric patients with a higher frequency of infections before diagnosis of KD may exhibit weakened humoral immune responses to routine vaccination after convalescence, which may elevate the risk of immunization failure. To test this hypothesis, a single-center retrospective cohort study was conducted to systematically evaluate the association between infection history and vaccine immune responses. This study aimed to examine the interaction mechanism between infection history and vaccine responses in pediatric patients with KD, thus providing evidence-based guidance on vaccination management and long-term protection strategies for these patients.

Material and methods

Sample size estimation

The positive conversion rate of measles antibody was determined as the primary outcome in this study. Based on data from previous studies and a pilot investigation by this center, the predicted difference in the positive conversion rate between a high infection burden group and a low infection burden group was approximately 10%. With two-tailed $\alpha = 0.05$ and testing power = 80%, about 130 subjects per group were required. Considering a 10% loss of data, the final target sample size was set at 290 subjects and above. In total, 356 subjects were screened for this study. Ultimately, 298 subjects were enrolled and completed follow-up, meeting the requirements for statistical analysis. The study was approved by the ethics committee of our hospital and performed strictly according to the Declaration of Helsinki.

Study design and subjects

In this single-center retrospective cohort study, the subjects were recruited from pediatric patients definitely diagnosed with KD in the hospital during January 2021 and December 2024 according to the criteria of the American Heart Association and jointly confirmed by specialists in pediatric rheumatic immunology and cardiology [11].

Inclusion and exclusion criteria

Inclusion criteria: 1) diagnosis of KD according to the American Heart Association scientific statement [12]; 2) availability of complete electronic medical records, including the infection history, immunization records, and serological test results within 12 months before KD onset; 3) completion of immunization with target vaccines (MMR, hepatitis B, and varicella) after convalescence and at 11 months after IVIG treatment; 4) completion of antibody detection at 1-3 months following vaccination.

Exclusion criteria: 1) pediatric patients with known primary or secondary immune deficiency; 2) those receiving long-term treatment with immunosuppressive drugs for other diseases; 3) those with missing key data (infection history, vaccination history, antibody detection results, etc.).

Grouping methods

The pediatric patients were grouped based on the number of infections occurring in 12 months before KD diagnosis. Specifically, through retrieving electronic medical records, infection events covering upper respiratory tract infection, lower respiratory tract infection, gastrointestinal tract infection, and skin/soft tissue infection in the year prior to diagnosis were documented for each pediatric patient, with the total number of infections recorded. All infection events were verified using electronic medical records. An infection was counted only when documented by a physician diagnosis in outpatient or inpatient records, supported by clinical symptoms and, when available, laboratory or imaging findings. Parent-reported symptoms without medical evaluation were not included. Then the median number of infections across the cohort was determined as the critical value to allocate the pediatric patients to a high infection burden group (number of infections ≥ median, $n = 152$) and a low infection burden group (number of infections < median, $n = 146$). The grouping method was pre-established before database locking to ensure roughly balanced sample sizes between groups.

Follow-up and immunological detection

All pediatric patients received routine vaccination (MMR, hepatitis B, or varicella) at the immunization clinic more than 11 months after IVIG treatment to prevent IVIG from interfering with vaccine responses. All vaccinations were administered strictly in accordance with the National Immunization Program of China and the recommendations for post-IVIG immunization in Kawasaki disease. No deviations from the recommended vaccine types or schedules were documented among any of the enrolled children. On the day of vaccination, a follow-up record was established by the study nurse, and 2-3 ml of venous blood was collected during outpatient follow-up at 1-3 months after vaccination. If blood collection could not be completed on schedule, it was performed at 12 weeks following vaccination. Loss to follow-up was defined as failure to complete tests after week 16 and loss of contact for all three follow-ups.

All the separated serum samples were stored at –80°C and collectively delivered to the Department of Clinical Laboratory for testing using an enzyme-linked immunosorbent assay kit (Thermo Fisher Scientific, USA) in strict accordance with the manufacturer's instructions. Each

sample was measured repeatedly. To ensure blinding, laboratory personnel were not provided with any clinical information, grouping status, or infection history of the participants. Serum samples were labeled with anonymized codes generated by an independent data manager before batch testing, and the linkage file was inaccessible to laboratory staff. The results of antibody detection were automatically input into the laboratory information system of the hospital; they were imported into the research database after cross-validation against the electronic medical records and local immunization information system, thereby ensuring data integrity and accuracy.

Outcome measures

Primary outcome

The primary outcome of this study was the positive conversion rate of measles antibody, namely, whether the pediatric patients successfully developed protective antibodies against measles following MMR vaccination after recovering from KD. Serum immunoglobulin G (IgG) level against measles was measured after blood sampling at 1-3 months after vaccination. A level ≥ 200 mIU/ml was defined as positive (i.e., acquisition of protective immunity), while a level < 200 mIU/ml was considered negative [13]. The difference in positive conversion rate between the two groups was reported as a percentage (number of positive cases/total number of vaccinated cases × 100%).

Secondary outcome

The secondary outcome was the geometric mean titer (GMT) of serum antibody levels in pediatric patients following vaccination. The original values of antibody titer typically presented skewed distribution; means were first calculated after natural logarithmic transformation, and then GMT was obtained through anti-logarithmic transformation, followed by calculation of the 95% confidence interval (CI). GMT reflects the difference in the intensity of post-vaccination immune response between the two groups, with a higher GMT representing a stronger humoral immune response [14].

Exploratory outcomes

To further validate the generalizability of the results, antibody responses following hepatitis B and varicella vaccination were also determined as the exploratory outcomes in this study, with positivity determination and GMT calculation performed using the same methodology. Hepatitis B antibody was positive with anti-HBs ≥ 10 mIU/ml, and varicella antibody was positive with IgG ≥ 100 mIU/ml [15, 16].

Multivariate logistic regression analysis

A multivariate logistic regression model was constructed on the basis of intergroup comparisons, with positive conversion of measles antibody defined as the dependent variable. Confounders were selected a priori according to clinical relevance and previous evidence [17, 18]. Age and gender were included as essential demographic variables, whereas KD classification (complete/incomplete), IVIG responsiveness (yes/no), and coronary artery involvement (yes/no) were incorporated because they reflect disease severity, immune status, and coronary risk. All covariates were entered simultaneously into the multivariable model. In the master model, high infection burden served as the main exposure variable, and adjusted odds ratios (ORs) with 95% CIs were calculated.

To further investigate the influence of infection types on immune responses, a multivariate logistic regression model with respiratory tract infection as the exposure indicator was established. Respiratory tract infection was defined according to outpatient/emergency visits and hospitalization records within 12 months before KD diagnosis, with ICD-10 codes J00-J06, J09-J18, and J20-J22 incorporated. Two visits with an interval of < 14 days were recorded as a single event. A frequent respiratory tract infection group and a non-frequent group were defined based on the cohort median of respiratory infection episodes within the 12 months prior to KD diagnosis. Frequent respiratory tract infection was defined as a number of documented respiratory infections equal to or above the cohort median, whereas non-frequent infection was defined as a number below this threshold. Based on this definition, 148 children were assigned to the frequent respiratory infection group and 150 to the non-frequent group.

Dose-response relationship analysis

To evaluate the dose-response relationship between the number of infections and antibody titers, the pediatric patients were stratified by quartiles of the number of infections, and the corresponding positive conversion rate and GMT of measles antibody were calculated. Additionally, the linear change along with the increasing infection frequency was analyzed using the Cochran-Armitage trend test.

Interaction analysis

In this study, KD classification (complete vs. incomplete) was selected as a potential effect modifier. Statistically, an interaction term infection burden × KD classification was introduced into the multivariate logistic regression model, and covariates including age, gender, IVIG responsiveness, and coronary artery involvement were adjusted simultaneously, to examine whether the impact of infection burden on immune responses differs across KD classification. Additionally, stratified analyses were conducted to visually demonstrate the interaction, and the correlations between high/low infection burden and immunization fail-

Table 1. Baseline characteristics of pediatric patients in high and low infection burden groups

Characteristic	High infection burden group (n = 152)	Low infection burden group (n = 146)	Statistical value	p
Age (years), mean ±SD	3.4 ±1.2	3.6 ±1.4	t = –1.09	0.28
Male, n (%)	62 (40.8)	60 (41.1)	χ^2 = 0.00	0.95
Complete KD, n (%)	120 (78.9)	116 (79.5)	χ^2 = 0.02	0.88
CRP (mg/l), median (IQR)	62 (35-97)	59 (33-95)	Z = –0.72	0.47
Platelet count (×10^9/l), mean ±SD	420 ±102	415 ±96	t = 0.51	0.61
IVIG non-responsiveness, n (%)	18 (11.8)	15 (10.3)	χ^2 = 0.13	0.72
Coronary artery involvement, n (%)	12 (7.9)	10 (6.8)	χ^2 = 0.11	0.74

ure in pediatric patients with complete and incomplete KD were calculated separately.

Statistical analysis

SPSS 26.0 software was employed to process all data. The Shapiro-Wilk test was applied to assess the normality of continuous variables. Normally distributed continuous variables were expressed as mean ± standard deviation and compared between groups using the independent-samples t-test. Continuous variables not following a normal distribution were presented as median (interquartile range [IQR]) and analyzed using the Mann-Whitney U-test. Categorical variables were presented as frequency and percentage, and compared between groups using the chi-square test or Fisher's exact test. Blinding was also maintained during data extraction and statistical analysis. Data extraction was performed by trained research staff using anonymized records in which group labels were masked. Statistical analyses were conducted on a de-identified dataset in which grouping information was encoded and only revealed after completion of primary analyses.

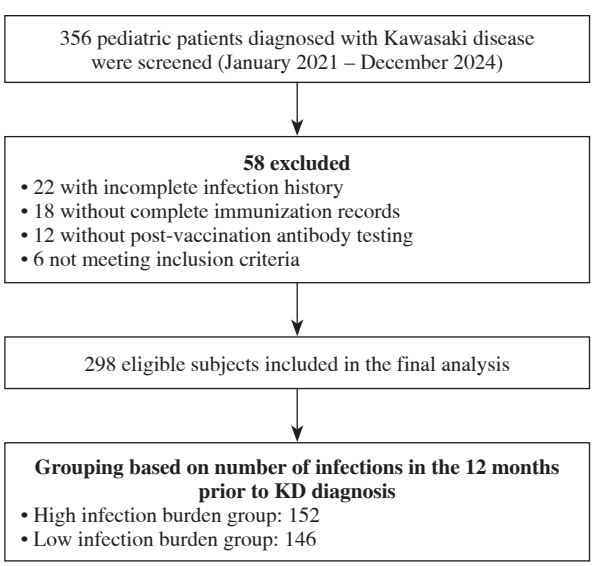

Fig. 1. Flowchart of subject enrollment

Results

Baseline characteristics of cases

There were no statistically significant differences in demographic characteristics, KD classification, laboratory indicators, and IVIG treatment status between the high and low infection burden groups (Table 1). A total of 356 pediatric patients diagnosed with Kawasaki disease were screened, of whom 58 were excluded for predefined reasons. Finally, 298 eligible subjects were included in the analysis. The enrollment process is shown in Figure 1.

Vaccine immune responses

Following MMR vaccination, the positive conversion rate of measles antibodies was significantly lower in the high infection burden group than in the low infection burden group (82.2% vs. 93.2%, p = 0.006). Regarding the an-

Table 2. Vaccine immune responses of pediatric patients in high and low infection burden groups

Indicator	High infection burden group (n = 152)	Low infection burden group (n = 146)	Statistical value	p
Positive measles antibody conversion rate (%)	82.2	93.2	χ^2 = 7.58	0.006
GMT of measles antibodies (IU/ml)	320 (95% CI: 280-365)	540 (95% CI: 490-595)	t = –2.59	0.010
Positive hepatitis B antibody conversion rate (%)	88.6	92.4	χ^2 = 1.36	0.24
Positive varicella antibody conversion rate (%)	79.5	87.0	χ^2 = 2.89	0.09

tibody titers, the high infection burden group had a lower GMT than the low infection burden group (320 IU/ml vs. 540 IU/ml, $p = 0.01$) (Table 2).

Multivariate analysis of infection history and immunization failure

According to the multivariate logistic regression analysis with failed positive measles antibody conversion as the dependent variable, high infection burden was confirmed as an independent risk factor for immunization failure. Compared with that in the low infection burden group, the risk of immunization failure was more than twice as high in the high infection burden group (OR = 2.35, 95% CI: 1.20-4.62, $p = 0.013$). This association remained statistically significant after adjusting for age, gender, clinical classification of KD, IVIG responsiveness, coronary artery involvement, and other potential confounding factors. No significant association was observed between other covariates (age, gender, KD classification, IVIG non-responsiveness, and coronary artery involvement) and immunization failure (Table 3).

Dependent variable: Measles antibody level below the protective threshold (0 = No, 1 = Yes). Independent variables: High infection burden (≥ median) + covariates (age, gender, clinical classification of KD, IVIG responsiveness, and coronary artery involvement). Variance inflation factor (VIF) < 2.0 for all variables.

In the subsequently established infection type model, frequent respiratory tract infection displayed a significant association with immunization failure. The risk of immunization failure in the pediatric patients with frequent respiratory tract infection was approximately 2.8 times that of the non-frequent group (OR = 2.80, 95% CI: 1.35-5.80, $p = 0.005$). This result was still of statistical significance even after adjusting for age, gender, clinical classification of KD, IVIG responsiveness, and coronary artery involvement. In contrast, none of the other covariates demonstrated significant effects in the model (Table 4).

Dependent variable: Measles antibody level below the protective threshold (0 = No, 1 = Yes). Independent variables: "frequent respiratory tract infection" as the exposure indicator (not co-existing with "high infection burden" in the same model) + identical set of covariates. VIF < 2.0 for all variables.

Dose-response relationship between infection frequency and immune response

Furthermore, the relationship between the number of infections and the titer of antibodies against measles was explored using quartile-stratified analysis, which revealed that the antibody level showed a significant downward trend with the increase of infection frequency (p for trend = 0.003) (Fig. 2).

Interaction effects of KD classification

Stratified analysis revealed a stronger association between high infection burden and lower immune responses in pediatric patients with complete KD, and the positive measles antibody conversion rate was significantly lower than that in the low infection burden group (80.5% vs.

Table 3. Multivariate logistic regression of factors associated with immunization failure (failure of positive conversion) following MMR vaccination (master model: total infection burden)

Variable	Comparison/coding	Adjusted OR (95% CI)	*p*
High infection burden	vs. low infection burden	2.35 (1.20-4.62)	0.013
Age (every one year of increased age)	Continuous variable	0.93 (0.78-1.11)	0.42
Male	vs. female	1.06 (0.56-2.03)	0.86
Complete KD	vs. incomplete KD	1.31 (0.64-2.69)	0.46
IVIG non-responsiveness	vs. responsiveness	1.58 (0.70-3.52)	0.27
Coronary artery involvement	vs. non-involvement	1.44 (0.56-3.68)	0.44

Table 4. Multivariate logistic regression of association between frequent respiratory tract infection and immunization failure (type model)

Variable	Comparison/coding	Adjusted OR (95% CI)	*p*
Frequent respiratory tract infection	vs. non-frequent	2.80 (1.35-5.80)	0.005
Age (every one year of increased age)	Continuous variable	0.94 (0.79-1.12)	0.50
Male	vs. female	1.04 (0.55-1.99)	0.89
Complete KD	vs. incomplete KD	1.28 (0.62-2.63)	0.50
IVIG non-responsiveness	vs. responsiveness	1.64 (0.73-3.67)	0.23
Coronary artery involvement	vs. non-involvement	1.37 (0.54-3.47)	0.51

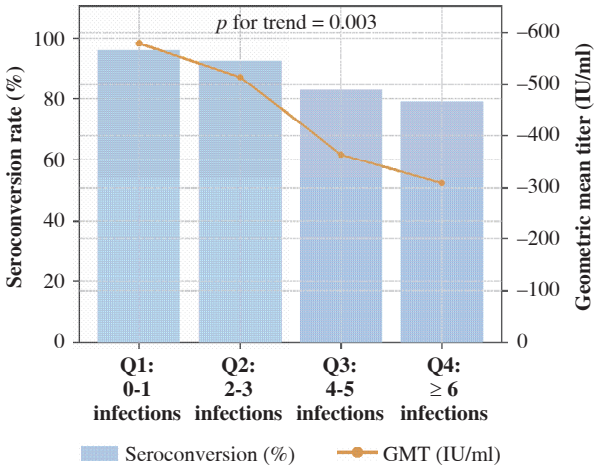

Fig. 2. Dose-response relationship between infection frequency and immune response of measles antibody. The pediatric patients were grouped by quartiles of the number of infections to compare the measles antibody responses across different infection levels. Blue bar charts indicate the positive measles antibody conversion rate (%) in each group, and orange line charts represent GMTs (IU/ml). In Cochran-Armitage trend test, p for trend = 0.003

94.2%, $p = 0.004$). However, no significant difference was observed between the two groups in pediatric patients with incomplete KD (difference in positive conversion rate, $p = 0.18$). Incorporating the interaction term into the multivariate logistic regression model revealed a significant infection burden × KD classification interaction (p for interaction < 0.05), suggesting that KD classification modifies the relationship between infection history and immune response. Specifically, the negative effect of frequent infection on immune response primarily occurred in pediatric patients with complete KD and was attenuated in those with incomplete KD.

Discussion

This study conducted a systematic analysis on vaccine immune responses in pediatric patients with KD in the convalescence stage. The results demonstrated that a history of high infection burden markedly reduced the positive conversion rate and GMT of measles antibodies, and this effect was stronger in pediatric patients with frequent respiratory tract infection. Interaction analysis further indicated that the pediatric patients with complete KD had a stronger negative association. These findings fill the gap in existing literature on pediatric patients with KD and provide new perspectives for immune monitoring and vaccination strategies. Previous studies have also shown that children with KD who received high-dose IVIG may exhibit reduced serologic responses to measles-containing vaccines. Cardenas-Brown *et al*. identified suboptimal timing and reduced serologic responses to MMR/MMRV vaccination after IVIG treatment in KD patients [8], while two recent studies confirmed that post-IVIG vaccination may be associated with lower seroconversion rates and delayed immune recovery in this population [19, 20]. These observations align with our findings and further support the notion that altered immune recovery following IVIG may contribute to reduced measles antibody responses in susceptible KD subgroups.

The principal findings of this study align to some extent with recent research results concerning the relationship between virus exposure history and vaccine response. The study of Li *et al.* on animal models demonstrated that continuous viral exposure in the early life cycle could impair the vaccine-induced specific antibody responses, which might be mediated by altering the immune environment or micro-ecological structure in hosts [21]. Meanwhile, Xie *et al.* found in their study on the efficacy of influenza and SARS-CoV-2 vaccines that immunoblot or repeated infection potentially interfered with immune responses and decreased the efficacy of vaccines [22]. These mechanistic studies provide theoretical support for the association between infection burden and weakened immune responses observed from the participants. In addition, Sullivan *et al.* reported that repeated vaccination might reduce immunogenicity in populations inoculated with influenza vaccine, suggesting a potential shared mechanism with the reduced GMT in the high infection burden group in this study [23].

In subgroup analyses, the pediatric patients with frequent respiratory tract infection were found to be more prone to immunization failure. Respiratory tract infection may pose a more direct impact on the mucosal immune system or induce long-term changes in systemic inflammation or immunoregulatory pathways, thereby increasing the probability of compromising the vaccine-induced B cell memory or antibody generation [24]. This finding is consistent with existing literature on the interaction between numerous respiratory viruses and the immune system [25, 26].

Regarding the interaction of KD classification, this study demonstrated that the pediatric patients with complete KD experienced a stronger negative effect of high infection burden on immune responses, whereas those with incomplete KD exhibited no significant difference. It suggests that the clinical phenotype of KD may act as an effect modifier. Complete KD may be accompanied by stronger immune activation and inflammatory responses, and the comorbidity with high infection burden may cause a greater cumulative impact on the immune system, leading to more evident attenuation of vaccine responses [18]. Similar findings have been reported in the context of other diseases. For example, external factors (such as infection history, nutritional status, and inflammation level) have greater influences on vaccine responses in some subgroups

with high inflammation levels or abnormal fundamental immunity [27, 28]. The interaction analysis not only holds biological plausibility but also enhances the novelty and practicability of our study in the KD population.

However, several limitations should be acknowledged. The infection records may contain inaccuracies due to the retrospective design. Although multiple confounding factors were adjusted for, unmeasured variables may still have influenced the results. In addition, as an observational study, the findings indicate associations rather than causal relationships and should be interpreted with caution. Moreover, the data were derived from a single tertiary center in China, where vaccination schedules, healthcare access, and infection patterns may differ from other regions or healthcare systems, which may limit the generalizability of the findings. Validation in multicenter or international cohorts is therefore warranted.

Conclusions

In conclusion, this study offers a new perspective on vaccination strategies for pediatric patients with KD. The infection history may not only be related to KD onset but may also represent an important background characteristic associated with immune patterns in the convalescence stage. In the future, these associations should be validated in larger populations through prospective designs, and immunological mechanisms can be additionally explored to develop more accurate immunization and monitoring protocols for pediatric patients with KD.

Funding

This research received no external funding.

Disclosures

This study was approved by the ethics committee of Shunyi Maternal and Children's Hospital of Beijing Children's Hospital. All procedures complied with the Declaration of Helsinki principles, and written informed consent was obtained from all subjects.

The author declares no conflict of interest.

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