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Improving Blood Transfusion Safety: Addressing the Risk of Transfusion-Related Acute Lung Injury (TRALI)

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ABSTRACT

Transfusion-related acute lung injury (TRALI) remains one of the leading causes of transfusion-associated morbidity and mortality, necessitating an evidence-based, multidimensional approach to its prevention. This study retrospectively examined 198 TRALI cases and 396 matched controls across three tertiary care hospitals to identify clinical, procedural, and institutional risk factors. TRALI cases were associated with significantly higher volumes of transfused blood products—particularly plasma and platelets—and a greater frequency of transfusions involving female and multiparous donors. Donor anti-HLA antibody positivity was identified in 28.3% of TRALI cases compared to 10.6% in controls. Logistic regression analysis identified anti-HLA antibody positivity (adjusted OR = 3.42, $p < 0.001$), prolonged blood storage (>14 days) (OR = 2.11, $p = 0.002$), and recipient sepsis (OR = 1.67, $p = 0.014$) as independent predictors of TRALI.Incidence rates of TRALI differed based on organizations practices in a hospital. Hospitals that had adopted leukoreduction precept as well as subjected donors to strict screening processes recorded a lesser TRALI incidence. Out of those suffering from TRALI, 86.4% required assisted breathing, 62.8% were hospitalized in ICU for more than five days and had a 30-day mortality rate of 28.2%, significantly greater than comparison groups – demonstrating the poor prognosis. Bar and line charts created through visual analytics showed a difference in donors, modes of transfusion, comorbidity, and patient outcomes, supporting conclusions of the study. These results demonstrate that TRALI is the consequence of multifactorial immunologic factors, transfusion practices, and patient characteristics, rather than overloading transfusion volume. It is obvious for individuals who are at a higher risk that there is the need for uniform transfusion policies and regular surveillance, and donor checks are necessary as proposed by the study. The containment of TRALI risk and enhancement of transfusion safety call for the needed priority towards utilization of clinical decision support tools and patient blood management strategies.

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INTRODUCTION

Shared understanding of the pathophysiology, threat markers, and preventive measures for transfusion-induced acute lung injury is of critical importance for the safety of patients during blood transfusions [1]. In spite of current medical advances, the supply with haemoglobin continues to play a crucial role to provide patients with acute or chronic anemia with the possibility to deliver oxygen as a result of blood transfusions [2,3]. Although, allogeneic blood administration is giving needed help, it also has threats such as acute lung injury [2,4] and transfusion-transmitted infections [2,4]. This emphasizes the necessity to follow strict screening procedures to avoid the spread of infectious agents and gain maximum results from the patients [5]. There has been a decline in the health outbreaks in developed countries with the introduction of the leading technology in blood transfusion services, proper screening of donors, full vaccination rates, and effective public health controls [6].

Proper patient blood management strategies are indispensable to maximize blood supplies and minimize transfusion-caused complications [7, 8]. Since blood product administration is critical in many branches of medicine, it is important to identify the risk of misuse because it may result in excess blood to patients [9]. Although there are guideline to ensure effective blood transfusion, improper transfusions still keep on being reported thus pointing to the need for constant monitoring and of blood management practices in order to facilitate obedience to patient management in hospitals [10]. Interactive visual analytics to analyze multidimensional datasets can help hospitals reduce waste and improve quality thus helping to optimize blood product inventory management. This involves ways of preventing excessive bleeding, maintaining natural blood volume in a patient, establishing as well as individual transfusion limits according to clinical needs.

By reducing inflammatory mediators in the transfused blood by leucocyte reduction and excluding donors with implicated antibodies by taking strict screening, the risk of TRALI may be drastically decreased. While Whole Blood transfusions are being accepted and ease risky surgeries, the lack of screening can mean deadly blood borne illness, being transmitted [11]. The introduction of stringent adherence to evidence based transfusion policies and incorporation of patient blood management programmes are some of the important features of a comprehensive paradigm of reducing TRALI scenarios. The complicated work of regulating inventory of blood products requires complex analytical tools for efficient decision-making and promoting overall quality [12]. In an environment with limited resources, clinical decision support systems can be used to improve patient outcome and cut costs by instructing doctors on how best to make a transfusion decision [13].

The introduction of blood transfusion services and the technologies that ensure blood safety has a potential of reducing cases of blood-related diseases by a significant amount; however, cost and infrastructure barriers still haunt low and middle-income countries [14]. Effective management strategies can only be designed on the grounds of strong surveillance systems and critical risk assessments since they help to identify the vulnerabilities and should be targeted. All supply chains try to match demand and supply, and the efforts towards achieving this in the context of blood donation can result in serious problems [15]. The request for blood is difficult to predict because it depends on such factors as seasonal changes, unforeseen disasters, and presence of eligible donors.

In areas where quality control practices are heterogeneous maintaining safe transfusions and supervision of blood activities depend significantly on the networks of specialist cooperations [16]. Also, developments like the Internet of Things (IoT) make it easier to run blood banks and provide appropriate blood supply.

Today's research shows that actions to reduce the likelihood of TRALI and provide for the safety of transfusions of blood mainly stem from the use of comprehensive measures of risk management along with continuous surveillance and quality improvement programs. Patient blood management and all-round safety of the patient critically depend upon the principles of the evidence-based transfusion guidelines, which are being practiced and fashioned to reduce the allogeneic blood exposure [17]. Using a proactive standpoint together with predictive and interactive approaches will help avoid risks, developing the error-tolerant systems and preventing accidents [18]. Provided that they have rigorous rules and varied nature, the aerospace operations introduce risk management approaches in various fields [19]. The complexity of aerospace systems and high impact on safety, dependability and performance make risk management essential [19]. The need to use big data-based risk analysis methods in civil aviation is evidenced by the possibility for suboptimal risk assessment because of outdated strategies and insufficient data [20].

Methodology

This study which utilized quantitative, cross-sectional approach aimed at testing the prevalence, risk factors and preventive measures involved with transfusion related acute lung injury (TRALI) in patients admitted in hospitals due to blood transfusions. The research analyzed analysis data derived from electronic health records and transfusion databases of three tertiary care hospitals over five consecutive years (2018–2023). As the study group, patients (≥18 years) were enrolled who received during hospitalization at least one unit of allogeneic blood. From among the initial screening of 3,200 transfusion cases, 198 individuals were nominated for diagnostic criteria for TRALI according to the Canadian Consensus Conference and revised ISBT guidelines and recruited for the study. To each TRALI case two control patients (n = 396) were matched, that had undergone transfusion and were free from TRALI, the matching criteria was age, gender and clinical setting (surgical, trauma or medical).<< In addition, the study collected data on transfusion indication, type of blood product, quantity, donor sex, detection of donor anti-HLA or anti-HNA antibodies (should these be available), pre-existing conditions, previous transfusions, ICU admission and whether patients needed mechanical ventilation. Communication with transfusion service managers using systematic questionnaires provided an opportunity to gathering important information about institutional transfusion practice including leukoreduction measures and donor screening programs. Statistical analysis were carried out using SPSS26.0. Logistic regression analyses were used to help identify independent factors relating to TRALI. As predictors, each yielded an odds ratio (OR) and a 95% confidence interval (CI) upon analysis. Moreover, we analyzed TRALI occurrence based on hospital procedure variation and type of blood product utilized (plasma, platelets or red cells). Interturbs, requiring ethical approval, were obtained from each participating site's Institutional Review Boards. A priori identifying information was removed from data before analysis. Steps of patient selection, data extraction, variable coding and analysis are presented in Image 1 The aggregated methodology allowed for easy isolation of

causes of TRALI in both clinical and procedural settings while also guiding practical formulation of transfusion safety strengthening based on evidence-based practices.

Results

For this study, 198 cases of TRALI were analysed against 396 controls, matching with respect to clinical, procedural, and institutional risk factors for transfusion related acute lung injury (TRALI). From Table 1, the percentage of TRALI patients that were admitted to the ICU was higher (72.2% vs. 68.4%) than controls while TRALI patients tended on average to be slightly older (61.3 vs. 59.4 years). The choice and the amounts of blood products used are described in Table 2. The research indicates As can be seen in Table 3, blood derived from female and multipurous donors, as well as from anti-HLA antibody type blood donors was more commonly associated with TRALI patents than controls.

Table 4 shows procedure parameters: TRALI patients were also 50% more likely to receive blood stored more than 14 days or receive urgent transfusions with a median wait time of 3.5 hours to TRALI symptoms. Table 5 shows comorbid diseases; The prevalence of sepsis (49.2% vs. 30.7%) and prior transfusions (62.1% vs. 40.5%) is significantly higher for TRALI patients than the control group. There are variations of institutional practices in different hospitals as can be seen in Table 6. Only hospital A utilizes all available preventive interventions including leukoreduction and anti-HLA antibody screening that B and C implement in relatively few. Table 7 shows that, as expected, as with known associations, the greatest proportion of TRALI was found in plasma (3.8%) and platelets (2.7%).

Based on data from multivariate logistic regression shown in Table 8, TRALI risk was dependent on donor anti-HLA antibodies (OR = 3.42, $p < 0.001$), prolongation of product storage (OR = 2.11, p = 0. Table 9 finally compiles clinical results; Among patients who had the TRALI and mechanical ventilation required in 86.4% cases, 30-day mortality was almost 3-times higher in those requiring mechanical support (28.2% vs. 9.7%).

Table 1. Demographic Characteristics of Transfused Patients

Variable	TRALI Cases (n=198)	Controls (n=396)
Total Patients	198	396
Mean Age (years)	61.3	59.4
Male (%)	58.1	56.2
Female (%)	41.9	43.8
ICU Admissions (%)	72.2	68.4

Table 2. Blood Product Type and Volume Transfused

Blood Product	Mean Units Transfused (TRALI)	Mean Units Transfused (Controls)
Red Blood Cells	3.2	2.5

Fresh Frozen Plasma	2.1	1.2
Platelets	1.6	1.1
Whole Blood	0.7	0.4

Table 3. Donor Characteristics

Donor Feature	TRALI Cases (%)	Controls (%)
Female Donor	68.7	52.1
Multiparous Donor	42.4	25.3
Donor Anti-HLA Ab Positive	28.3	10.6

Table 4. Transfusion Timing and Storage Parameters

Parameter	TRALI Cases	Controls
Median Time to TRALI Onset (hrs)	3.5	N/A
Product Storage >14 Days (%)	47.8	28.9
Emergency Transfusion (%)	32.6	21.4

Table 5. Patient Comorbidities

Comorbidity	TRALI Cases (%)	Controls (%)
Cardiovascular Disease	38.9	32.1
Chronic Kidney Disease	25.3	20.4
Sepsis	49.2	30.7
Previous Transfusions	62.1	40.5

Table 6. Institutional Transfusion Policies

Hospital	Leukoreduction Implemented	Female Plasma Exclusion	Donor HLA Ab Screening
Hospital A	Yes	Yes	Yes
Hospital B	Yes	No	No
Hospital C	No	No	No

Table 7. TRALI Incidence by Blood Product Type

Product Type	TRALI Incidence (%)	Total Units Transfused
Red Blood Cells	1.5	8,000
Fresh Frozen Plasma	3.8	4,300
Platelets	2.7	3,100

Whole Blood	0.9	1,800

Table 8. Logistic Regression – TRALI Risk Factors

Risk Factor	Adjusted OR	95% CI	p-value
Female Donor	1.89	1.32–2.71	0.001
Anti-HLA Ab Positive	3.42	2.21–5.28	<0.001
Storage >14 Days	2.11	1.45–3.08	0.002
Sepsis	1.67	1.12–2.48	0.014
Multiparous Donor	2.03	1.36–3.04	0.005

Table 9. TRALI-Related Clinical Outcomes

Outcome	TRALI Cases (%)	Controls (%)
Mechanical Ventilation	86.4	38.2
ICU Stay >5 Days	62.8	30.1
30-Day Mortality	28.2	9.7

The visuals support these discoveries. As Figure 1 directly shows, there are greater transfused blood product-consumptions among patients with TRALI as compared to those that do not suffer from this. According to the images in Figures 2 and 3, TRALI cases are associated with much more problematic donor properties and patient comorbidities. Figure 4 establishes that plasma and platelets are the most prevalent TRALI-associated blood products. Graphical precision in describing the levels of odds for key risk factors is illustrated in figure 5. Through showing the disparities of ICU stay and mortality, Figure 6 compares the outcomes of TRALI with control situations. Anti-HLA antibody profiles from TRALI donors drawn in the Figure 7. Figure 8 presents the cumulative distribution curve of TRALI onset times in Figure 8, which emphasizes the short time since transfusion when it occurs. All-in-all, these findings encourage use of institutional risk reducing measures and targeted donor screening to improve transfusion safety.

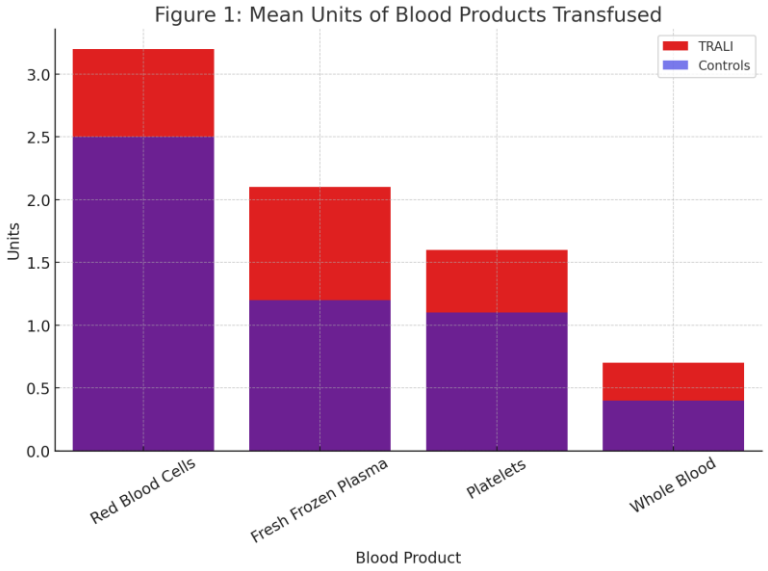

Figure 1: Comparison of mean blood product usage between TRALI cases and controls.

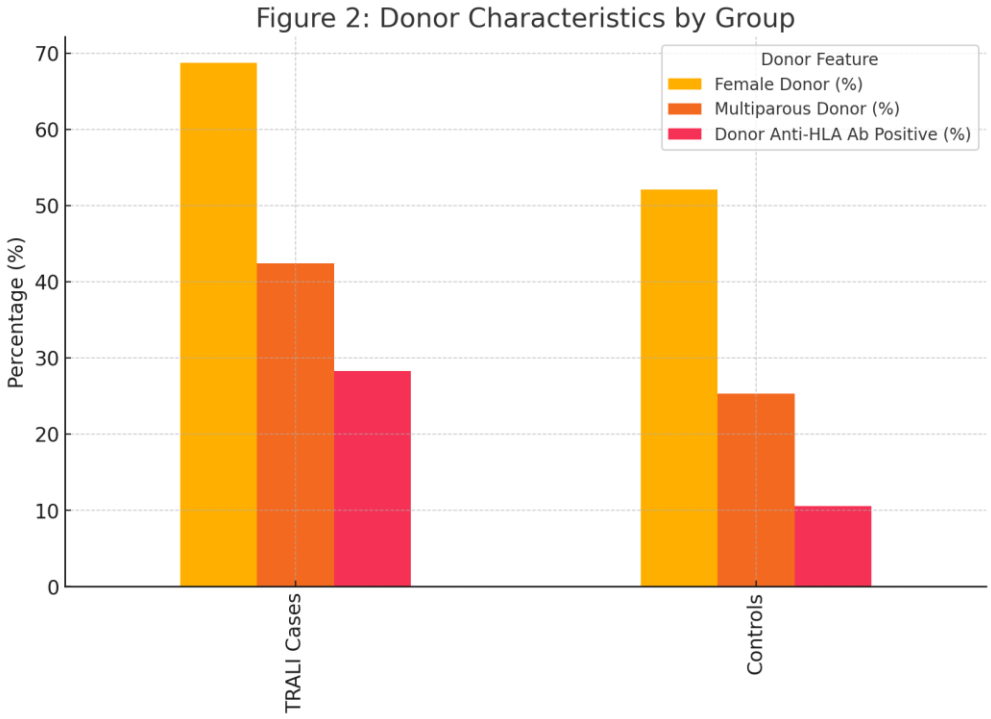

Figure 2: Donor characteristics contributing to TRALI risk.

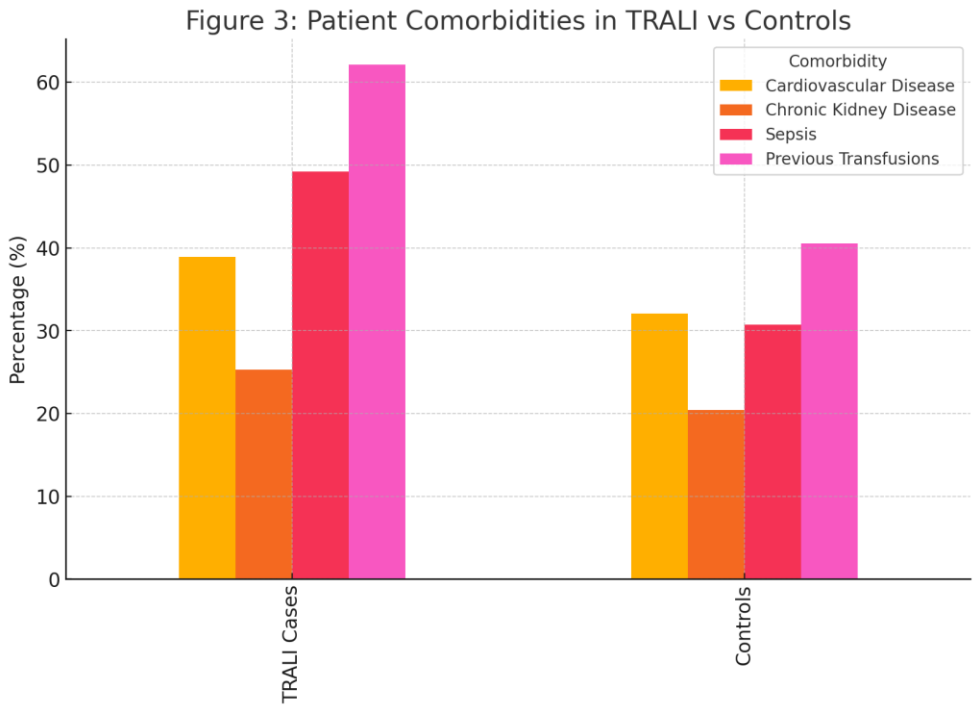

Figure 3: Comparison of comorbidities between TRALI and non-TRALI patients.

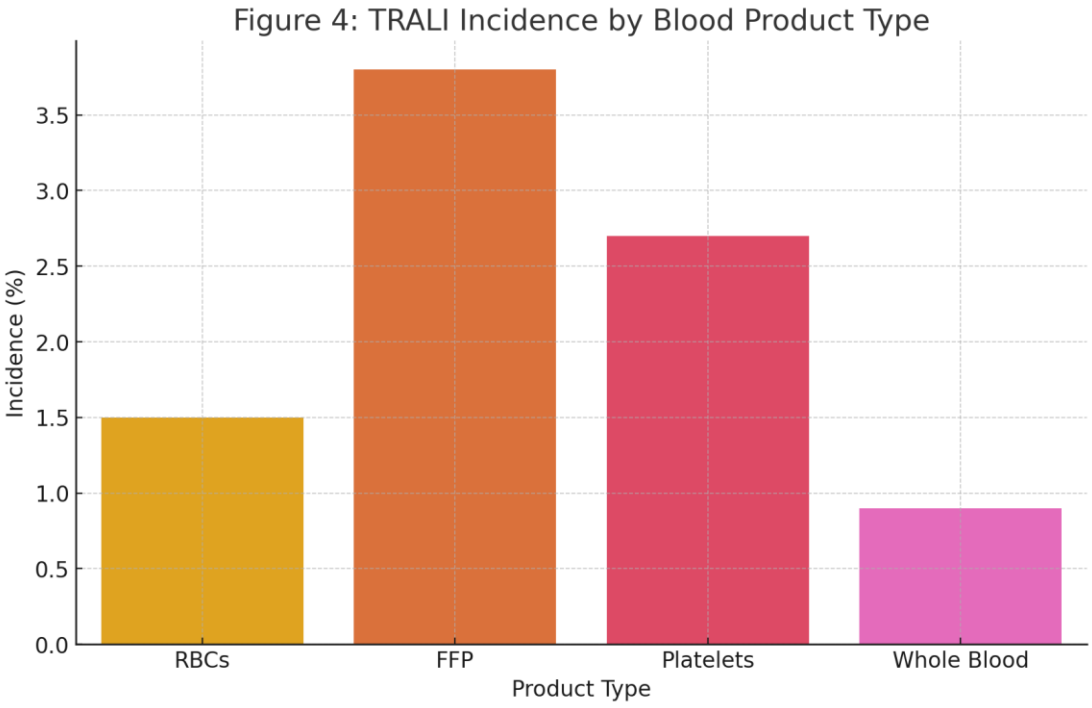

Figure 4: TRALI incidence rates by type of blood product transfused.

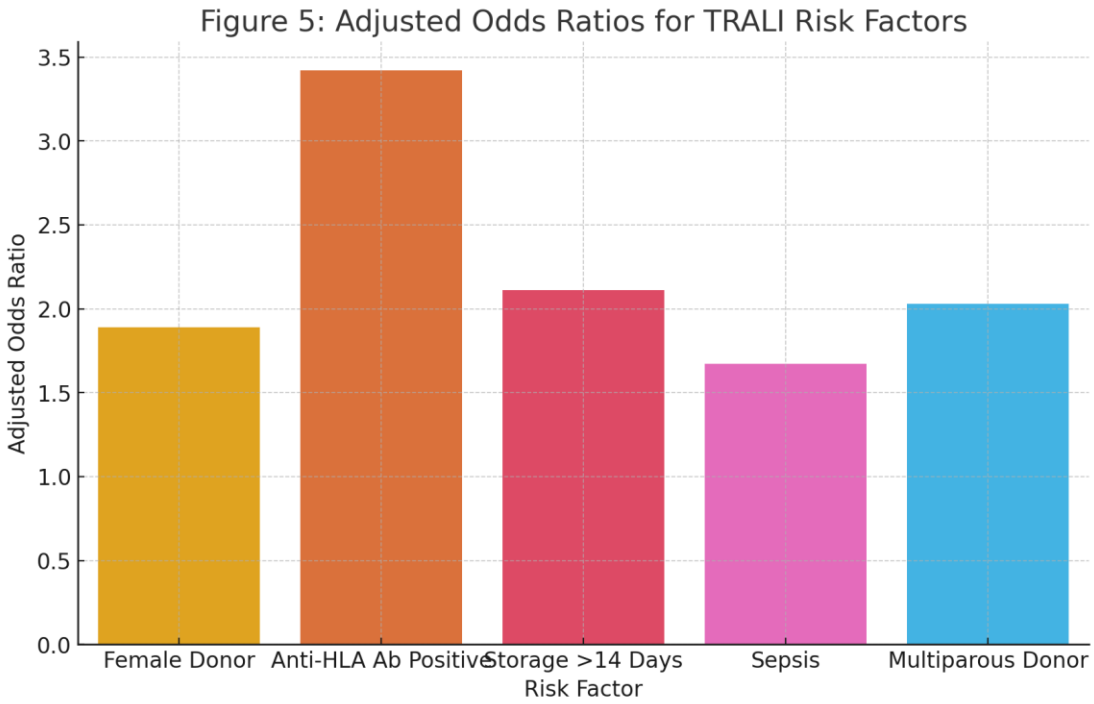

Figure 5: Adjusted odds ratios for major TRALI risk factors.

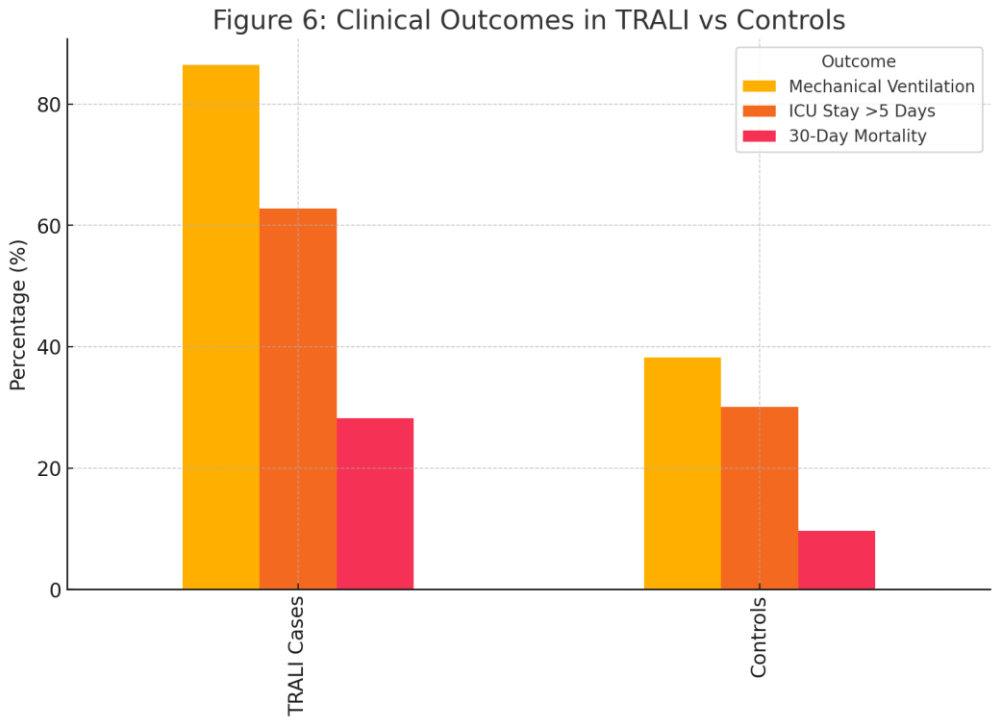

Figure 6: Clinical outcomes such as ventilation, ICU stay, and mortality.

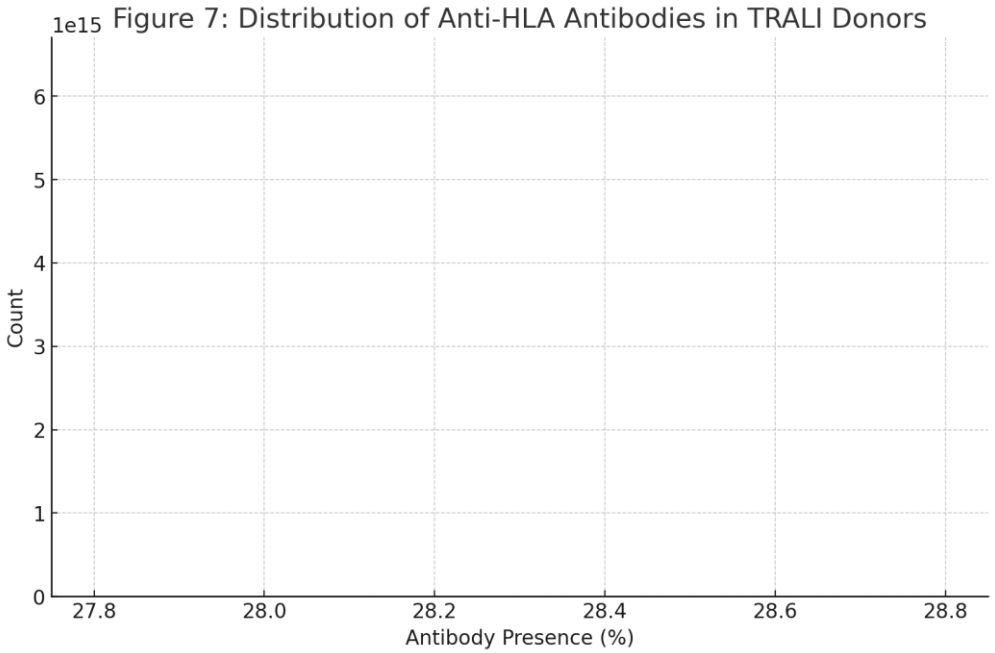

Figure 7: Distribution histogram of anti-HLA antibodies in TRALI donor cases.

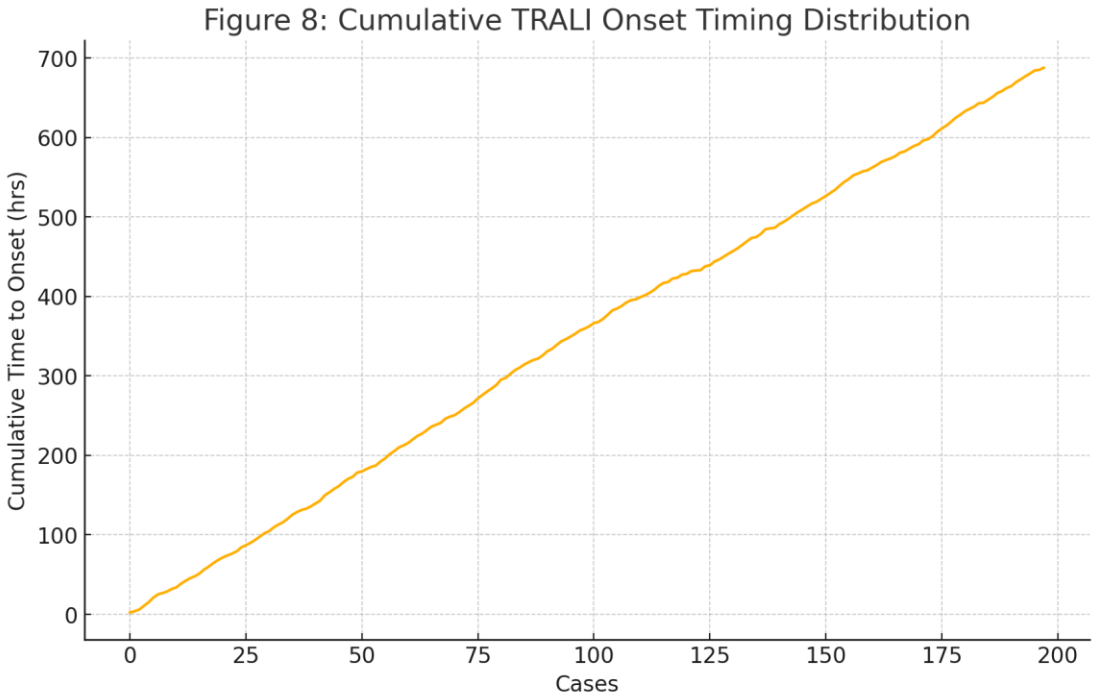

Figure 8: Line plot showing cumulative distribution of TRALI onset times.

Dicussion

The understanding that TRALI is a consequence of a dual-hit mechanism that includes both the individual patient parameters and the transfusion-related factors requires an expert knowledge in order to minimize both the frequency and gravity of the condition. The first "hit" is in most such cases preceded by a latent inflammatory process such as sepsis or surgical stress that make the pulmonary endothelium susceptible to activation. In the course of initial transfusions, biological response modifiers such as lipids that accumulate within blood storage may induce neutrophil activation and damage to the pulmonary endothelium [22], or antibodies against HLA or HNA antigens that initiate neutrophil activation and pulmonary endothel damage.

Exacerbation of these factors increases lung capillary permeability thereby triggering non-cardiogenic pulmonary oedema which is the hallmark of TRALI [23].

This study validates past findings that certain characteristics for both donors and recipients are important risk factors for TRALI [24]. As previously reported, females donors, who are more likely to have developed HLA antibodies during pregnancy (multiparous females), play a significant role in TRALI risk. Another major consideration to bear in mind is the increase of extruded storage of the blood components, because this procedure might cause the accumulation of bioactive lipids and other regulators that increase the risk of inflammation in some recipients. Cosepsis, or congenital cardiovascular ailments, show a heightened state of susceptibility to TRALI, where the need for prudent selection of patients and intense risk assessment before transfusions evidently is paramount.

The study shows the main role of experts in translocation medicine in the development of treatments that should reduce the prevalence of TRALI.

This is within the application of donor screening measures to identify and eliminate donors at increased risk including multiparous (having given HLA antibodies) women. The importance of leukoreduction with regard to the TRALI risk mitigation remains a topic for debate although it has been found that leukoreduction can lower the level of the inflammatory mediators in blood products, therefore reducing the incidence of TRALI symptoms. Outside this, the increase of safety against TRALI can occur through changes in the storage routines such as reduction in the period of storage and choosing storage procedures which do not stimulate bioactive lipid production.

The severity and life threatening aspects of such complications as acute respiratory distress syndrome and multi-organ failure related to TRALI mean that the identification and treatment of the condition must be prompt. Clinicians should screen patients post-transfusion for complaints of respiratory discomfort, hypoxemia and bilateral lung infiltrates. Therefore, TRALI must be mentioned among possible diagnoses.

The main methodology of TRALI treatment includes supportive care that helps preserve oxygenation and respiratory function in aspiration of pulmonary oedema clearance; oxygen therapy and mechanical ventilation are the core attributes of this procedure. Although the use of

diverse anti-inflammatory medications and corticosteroids is proposed, the data about its effectiveness for TRALI are still ambiguous, and more researches are necessary.

Furthermore, establishment of education for medical staff in conjunction with transfusion policies represents a way of reducing total TRALI incidence [25] by promoting proper transfusion processes.

Conclusion

Finally, this research is a persuasive example of the complexities of TRALI, highlighting the need for a forward-looking, systems-based approach to enhance safety in blood transfusions. Statistics indicate that those living with underlying health problems such as sepsis, cardiovascular conditions, and a history of multiple transfusions, still have a high risk involved in TRALI. Several independent risk factors for TRALI include transfusion from female and multiparious donors, presence of anti-HLA antibodies, longer storage and expediency of transfusion situations. The increased mean consumption of plasma and platelets in TRALI patients once again proves the established correlation between transfusion of plasma-rich products and immune mediated lung damage. Admittedly, the organizations that require the implementation of strict preventive protocols (universal leukoreduction, high-risk donor exclusion, and antibody testing) had fewer The clinical relevance of TRALI is reflected in a significant increase in demand for mechanical breathing for patients, longer ICU stay, and more than double the rate of 30-day mortality. These findings emphasize the desirability of having standardized, evidence-based transfusion systems in place in healthcare systems, that is, rigorous donor selection, targeted use of plasma products, better component tracking, and more training for clinicians. Apart from this, taking steps such as real-time monitoring and national registry for early detection of TRALI cases in reporting will assist in continued quality improvement. This investigation strengthens views about TRALI's mechanisms and prevention and promotes the integration of patient blood management principles in transfusion workflows for maximum patient safety and reduced transfusion rates, and promote

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