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Mechanisms of red blood cell transfusion-related immunomodulation

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Abstract

Red blood cell (RBC) transfusion is common in critically ill, postsurgical, and posttrauma patients in whom both systemic inflammation and immune suppression are associated with adverse outcomes. RBC products contain a multitude of immunomodulatory mediators that interact with and alter immune cell function. These interactions can lead to both proinflammatory and immunosuppressive effects. Defining clinical outcomes related to immunomodulatory effects of RBCs in transfused patients remains a challenge, likely due to complex interactions between individual blood product characteristics and patient-specific risk factors. Unpacking these complexities requires an in-depth understanding of the mechanisms of immunomodulatory effects of RBC products. In this review, we outline and classify potential mediators of RBC transfusion-related immunomodulation and provide suggestions for future research directions.

In the United States, 11 to 16 million red blood cell (RBC) units were administered annually during the past decade, equating to a RBC transfusion every 2 seconds.^{1–5} RBC transfusion is particularly commonplace in emergency departments, intensive care units, and operating suites, with 37% to 60% of intensive care unit patients receiving a transfusion during hospitalization.^{6–12} Nonetheless, RBC transfusion may have deleterious immunologic

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CONFLICT OF INTEREST

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effects, particularly for critically ill patients.^{13,14} Mounting evidence from predominantly observational studies demonstrate independent associations between RBC transfusion, dysregulated immunity, and increased mortality and morbidity, mechanisms of which are only partly understood.^{15–26} The following review will summarize current literature on mechanisms of RBC transfusion-related immunomodulation (TRIM), classify potential mediators, and propose a research agenda to fill critical knowledge.

RBC TRIM

Beginning in 1973, Opelz and colleagues²⁷ provided initial evidence for RBC TRIM with the observation that the survival rate of transplanted kidneys was significantly higher in cadaveric renal transplant patients who received RBC transfusion.¹³ These findings strongly suggested immunosuppressive effects of nonleukoreduced allogeneic RBC transfusion. More recent findings suggest both proinflammatory and immunosuppressive effects of RBC product exposure, including prestorage leukoreduced blood products. Clinically, RBC transfusion is associated with new or worsening organ dysfunction, the development of nosocomial infection, and cancer recurrence, suggesting dysregulated recipient immune responses.^{13,14,21,28–32} The extent to which RBC transfusion directly contributes to immuno-logic dysregulation in transfused patients remains unclear, although a wealth of preclinical evidence demonstrates that RBC products can directly modulate immune cell function. In a variety of preclinical models, RBC product exposure results in inflammatory effects including white blood cell (WBC) priming, enhanced neutrophil chemo-taxis, monocyte/macrophage activation, and inflammatory cytokine release.^{13,17,21,31,33–35} Immunosuppressive effects include impaired natural killer (NK) cell function, alterations in T lymphocyte ratios, defective antigen presentation, suppression of lymphocyte proliferation, and decreased macrophage phagocytic function.^{14,36–40} While evidence supporting both proinflammatory and immunosuppressive effects of RBC transfusion may seem contradictory, given the complex nature of transfused blood products and the multitude of potentially immunomodulatory mediators contained therein, mixed effects are not surprising. Indeed, mixed immunomodulatory potential of RBC transfusion may be particularly relevant for critically ill patients in whom both excess inflammation and immune suppression are significantly associated with adverse outcomes.¹⁴ Overall, defining the sum total immunomodulatory effects of particular RBC products in individual patients remains challenging. Future research to determine the effects of individual blood products on individual patients and to mitigate potential risks depends on understanding mechanisms of RBC TRIM.

While mechanisms for RBC TRIM are not yet fully characterized, many potential mediators have been identified. These include WBC-derived mediators, component hemolytic contents (heme, iron release), platelet (PLT)-derived factors, and extracellular vesicles (EVs; Fig. 1).

PROPOSED MECHANISMS

WBCs and WBC-derived mediators

The observation that prestorage leukoreduction may mitigate TRIM suggests that either intact WBCs and/or soluble WBC-derived mediators play a role in its development.^{41–44}

Leukoreduction removes most residual WBCs from stored blood components and appears to improve clinical outcomes. Randomized trials in surgical patients receiving leukoreduced versus nonleukoreduced RBCs, autologous versus allogeneic RBC transfusions, or restrictive versus liberal RBC transfusion thresholds demonstrate that in each case, subjects in the leukoreduced, autologous, or restricted transfusion arms developed fewer nosocomial infections.^{15,45–47} Likewise, meta-analyses demonstrate that leukoreduction, autologous RBC transfusions (which prevent exposure to allogeneic WBCs), and restrictive transfusion thresholds (which decrease exposure to residual allogeneic WBCs) are each associated with decreased risk of postoperative infection.^{15,45,47} RBC unit leukoreduction may also attenuate the systemic inflammatory response after cardiac surgery, with a dose-dependent increase in survival when leukoreduced RBCs are utilized.⁴⁸ Finally, animal models demonstrate that leukoreduction may reduce transfusion-associated cancer metastasis and T-cell apoptosis.^{29,49} Taken together, these data suggest that residual WBCs or WBC-derived mediators in RBC products may be harmful via immunomodulatory mechanisms. Although in the United States, 75% to 80% of RBC units transfused are leukoreduced before storage to mitigate these risks, it is worth noting that a substantial number of residual WBCs (approx. 5000 to approx. 5×10^6 WBCs/unit) remain despite current leukoreduction technologies.^{50–52}

Residual WBCs—Antigen-presenting cells (APCs; i.e., monocytes and dendritic cells) carry major histocompatibility complex (MHC) II molecules (i.e., HLA-DR) on their cell surfaces. MHC II molecules function to present processed antigens and activate lymphocytes. After transfusion, interactions between donor MHC II molecules on residual WBCs and recipient lymphocytes may result in either alloimmunization or immune suppression.^{53–56} Features such as the degree of HLA compatibility, the functionality of donor APCs, and the inflammatory state of the recipient likely determine whether residual allogeneic WBCs induce immune tolerance or alloimmunization.²¹ In the case of immune suppression, residual allogeneic APCs, which engage recipient T cells without necessary secondary or costimulatory signals, would be expected to produce antigen-specific T-cell anergy.²¹ The resulting immune tolerance is a proposed mechanism for allogeneic RBC transfusion-related adaptive immune cell (T-cell) suppression.²¹ T-cell immune tolerance may also be responsible for development of microchimerism in allogeneic blood transfusion recipients, whereby donor WBCs fail to elicit an immune response and become “accepted” by the recipient.⁵⁷ Microchimerism may be common in trauma patients and may persist for up to 2 years after transfusion.^{57,58} Moreover, immune tolerance and associated microchimerism may explain the observed shift to immunosuppressive T_H2 responses after blood transfusion.^{38,59–62} However, clear demonstration of direct causal links between HLA molecules on residual allogeneic APCs and posttransfusion immune suppression is currently lacking.

In addition to residual functional allogeneic WBCs, it is possible that apoptotic WBCs in RBC products may also induce immune suppression.⁶³ During collection and storage, WBCs undergo apoptosis.⁶⁴ One of the early steps in apoptosis involves exposure of phosphatidylserine on the outer leaflet of the cell membrane. Interaction between immune cells and phosphatidylserine has been shown to induce immunosuppressive signals,

including release of anti-inflammatory cytokines interleukin (IL)-10 and transforming growth factor (TGF)- β , inhibition of proinflammatory cytokine release, inhibition of APC activation, and predominance of immunosuppressive regulatory T cells.^{63,65} The degree to which apoptotic residual WBCs in RBC units contribute to recipient immune suppression in the clinical setting remains unknown. However, it is worth noting that similar responses may also be seen in response to phosphatidylserine-containing membrane fragments or microparticles.

Soluble WBC-derived mediators—Removal of supernatant from stored RBC units by washing reduces the inflammatory response in pediatric cardiac surgery patients and preclinical studies suggest that RBC-induced immunomodulation can be recapitulated using RBC unit supernatants.^{24,25,66,67} Thus, it seems likely that soluble mediators also play a role in TRIM pathogenesis.

There are multiple soluble WBC-derived factors, including cytokines, WBC degranulation products, soluble FAS-L, and soluble HLA molecules, which directly inhibit the immune response.^{68,69} Of these, sFAS-L and the anti-inflammatory cytokine TGF- β have the strongest evidence suggesting that they may promote TRIM, particularly in nonleukoreduced blood products.^{36,68} In vitro studies indicate that sFAS-L and TGF- β found in blood components may directly induce innate immune cell apoptosis, impair neutrophil chemotaxis, and decrease NK cell activity.^{36,69,70} Immunosuppressive effects may not be limited to these, as TGF- β is a known anti-inflammatory cytokine with broad immunosuppressive effects.

In addition to anti-inflammatory cytokines, proinflammatory cytokines may also accumulate in blood products during storage.^{71–74} However, in some reports prestorage leukoreduction appears to substantially decrease the accumulation of proinflammatory cytokines in RBC products such that levels are undetectable.^{72,74} When cytokines are detected, it is unclear whether their concentrations are high enough to strongly influence recipient immune function.^{73,74} In addition to cytokines, WBC degranulation products such as histamine and eosinophil cationic protein have been detected in RBC components.⁷⁵ Each of these mediators has immunomodulatory potential. For example, histamine has been shown to inhibit neutrophil chemotaxis and decrease T-cell proliferation, while eosinophilic cationic protein may also reduce T-cell proliferation.^{76,77}

While WBCs and WBC-derived soluble mediators appear to promote TRIM, such effects are likely reduced by prestorage leukoreduction. Because evidence for TRIM remains in the postleukoreduction era, it is likely that non-WBC-derived factors are also involved.¹⁴

RBC storage lesion and decompartmentalized RBC contents

Another potential mechanism for TRIM arises from the RBC itself. As RBC units age under refrigerated conditions, a well-described “storage lesion(s)” develops. The RBC storage lesions are characterized by altered RBC morphology, rheologic changes, metabolic derangements, changes in oxygen affinity, changes in osmotic regulation, and changes in the ability to vasoregulate.^{78–85} In addition, RBC hemolysis (both during storage and after transfusion) can lead to reduced pH, increased lactate and other metabolic wastes, and

release of microparticles as well as accumulation of cell-free hemoglobin (Hb), heme, and iron.^{26,78,86–90} Iron content can be in the form of transferrin-bound iron, non-transferrin-bound iron (NTBI), or labile plasma iron. Given the well-described bioactivities of these species, RBC hemolysis can disturb plasma redox balance and broadly disrupt normal signaling in coagulation, vascular, and immune systems.^{4,22,23,78,86,91,92}

In normal physiology, plasma haptoglobin sequesters cell-free Hb, forming a complex for removal by macrophages via CD163.^{18,22,23,93} However, in critical illness, even moderate intravascular hemolysis may overwhelm plasma-binding capacity resulting in unbound extracellular Hb. When extracellular Hb is unbound, it becomes oxidized to methemoglobin, releasing free heme. Free heme can then undergo the Fenton reaction to cause further release of iron.^{67,93–97} Accumulation of uncomplexed heme and iron in plasma is associated with significant tissue damage, presumably by iron-catalyzed generation of reactive oxygen species, promotion of other radical chains, increases in WBC activation and migration, up regulation of adhesion molecules, and subsequent deleterious effects to tissue barriers and to immunity.^{22,93,98–104} In murine models, transfusion of long-stored RBCs led to increased iron in the form of NTBI and augmented circulating proinflammatory cytokine release.^{22,23,105,106} However, in human healthy volunteers, while transfusion with older versus fresher RBCs significantly increased circulating NTBI levels, a proinflammatory cytokine response was not observed.^{91,105,107} The lack of observed inflammatory response in the human studies may relate to differences between mice and humans or relative transfusion dose, or the inflammatory response to RBC transfusion may not be apparent in healthy subjects (without underlying inflammation). That said, in a study of 33 premature neonates, while levels of NTBI were increased after transfusion, NTBI levels were not associated with increases in plasma inflammatory cytokines.¹⁰⁸ These data suggest that proinflammatory effects of NTBI may be minimal.

Red blood cell transfusion may also burden the mononuclear phagocyte system, delivering large amounts of Hb and RBC contents to monocytes and macrophages.⁹³ Phagocytosis of RBCs by macrophages (i.e., extravascular hemolysis) increases macrophage intracellular heme and iron to a degree that can trigger inflammation- some activation and proinflammatory cytokine release via NLRP3 and NF- κ B signaling; this process is further exacerbated by generation of iron-related reactive oxygen species.⁹³ Conversely, macrophage exposure to high concentrations of heme may also bias macrophage phenotype from the activated/ inflammatory (M1) phenotype toward an immunosuppressive (M2) profile via up regulation of heme oxygenase 1 and release of the anti-inflammatory cytokine IL-10.¹⁰⁹ Similarly, macrophage iron loading may promote immune suppression by inhibiting interferon (IFN)- γ -mediated secretion of proinflammatory cytokines, reducing expression of MHC II and impairing nitric oxide synthesis. Cumulatively, these effects compromise phagocytic and microbicidal macrophage activity.¹¹⁰ Iron overload may also further promote immune suppression by impairing proliferation and activation of T, B, and NK cells.¹¹¹ Additionally, independent of direct effects on immune cells, uncomplexed heme and iron may directly promote bacterial growth.^{78,93,105}

Finally, an additional compound of interest is ubiquitin, an intracellular regulatory protein present in a variety of cell types. RBCs carry large amounts of ubiquitin relative to other cell

types, and extracellular ubiquitin has been found to accumulate in RBC unit supernatants during storage.¹¹² Extracellular ubiquitin has varied effects on immune cell function, including blunting lipopolysaccharide (LPS)-induced tumor necrosis factor- α production while augmenting LPS-induced IL-8 production.^{112–114} Additionally, extracellular ubiquitin found in RBC units may skew helper T-cell function toward an immunosuppressive Th2 phenotype, as evidenced by increased IL-4 production and decreased IFN- γ production by LPS-stimulated PBMCs exposed to 35-day-old stored RBC supernatant or ubiquitin.^{112,114} The mix of proinflammatory and immunosuppressive effects of extracellular ubiquitin mirrors immunomodulatory effects observed in response to RBC supernatants in vitro and may explain mixed responses reported in vivo.

In summary, soluble mediators resulting from RBC aging and breakdown are varied, and individual mediators likely have pleiotropic effects on recipient immune response. Although animal studies show worsened survival and increased inflammation from transfusion with longer stored RBCs, these findings have not been demonstrated in recently published human randomized controlled trials.^{4,16,78,87,115} This may be because animal studies can carefully delineate “fresh versus old” RBC cutoffs (i.e., >21 days) which has proven difficult in human randomized controlled trials, where a mean duration of RBC storage in the United States of 17.9 days results in comparisons between “fresh” versus “middle-age.”^{87,116} Additionally, storage duration effects may be more robust if transfusion occurs in the setting of more significant baseline inflammation, although to date this question has not been adequately evaluated. The relative impact of inflammatory and immunosuppressive effects of RBC-derived mediators for individual patients, particularly in the setting of baseline inflammation or immune suppression, remains largely unknown. It is likely that a complex interplay between decompartmentalized RBC contents and underlying host immune response contributes to patient-specific immune modulation, a topic of active ongoing research.

Residual PLTs and PLT-derived factors

While less is known about PLT-derived factors as TRIM mediators, emerging data strongly suggest that PLTs and PLT-derived factors have important immunomodulatory potential.^{117–119} For instance, PLT-derived microparticles are capable of inducing both immune cell suppression and activation.^{120,121} PLTs themselves may play important roles in modulating immune cell response in both health and disease, suggesting that residual PLTs found in RBC products likely contribute to immunomodulation. Nonleukoreduced RBC units have been shown to accumulate PLT-WBC aggregates over time, which correlate with immune cell apoptosis and monocyte tissue factor expression.¹²² These changes are expected to be immunomodulatory; however, effects of PLT-WBC aggregates on recipient immune cells were not evaluated. Likewise, the immunomodulatory potential of residual PLTs within leukoreduced RBC products is unknown.

Bioactive lipids and EVs

Bioactive lipids—Bioactive lipids with proinflammatory and procoagulant activity accumulate during storage in RBC units and may contribute to inflammatory complications of RBC transfusion, including transfusion-related acute lung injury (TRALI).^{83,123}

Accumulation of some bioactive lipids, such as lysophosphatidylcholines, appears to be reduced by leukoreduction.¹²⁴ However, a variety of polyunsaturated fatty acids, including arachidonic acid, linoleic acid, docosahexaenoic acid, and their metabolites, accumulate in RBC units despite leukoreduction.^{123,125} Arachidonic acid and its oxidized metabolites, when isolated from older stored RBC supernatants, are capable of priming neutrophils in vitro. Further, infusion of these bioactive lipids in rats that are primed by LPS induces acute lung injury—providing evidence that bioactive lipids may provide the second-hit in the two-hit model of non-antibody-mediated TRALI.^{125,126} Observational studies demonstrating the presence of lipids with neutrophil priming activity in the plasma of TRALI patients provide additional supportive evidence of the link between bioactive lipids and non-antibody-mediated TRALI.¹²⁷ The extent to which bioactive lipids may contribute to systemic inflammation or modulation of immune function outside of TRALI remains unclear and is a topic deserving of further study.

EVs

EV count and profile in blood products.: The term “extracellular vesicle” broadly encompasses larger micro-vesicles (200–1200 nm), exosomes (30–150 nm), and apoptotic bodies (50–500 nm).^{128–130} For more than a decade, it has been appreciated that plasma from healthy subjects contains EVs, including exosomes, derived from WBCs, PLTs, RBCs, and endothelial cells.^{131–133}

EV counts in RBC products increase with storage duration.^{86,134} Storage-related morphologic changes to RBCs are accompanied by shedding and release of RBC-derived EVs, while residual PLTs and WBCs contribute to PLT-derived and WBC-derived EVs.^{135–138} Tracking EV cell of origin reveals that RBC-derived EVs increase continuously during storage, while PLT-derived EV counts peak at 3 to 4 weeks of storage.^{86,139} EV release and accumulation are significantly influenced by component manufacture processes and storage conditions such that individual products may have very different EV profiles despite similar storage duration.^{140,141}

In vitro evidence for EV TRIM effects.: Although once considered debris without bioactivity and discounted as artifact, EVs are increasingly recognized as playing a central role in the body’s complex network of intercellular signaling, both in normal physiology and in disease.¹⁴² EVs derived from stored PLTs bind to and activate neutrophils in vitro and have anti-inflammatory or proinflammatory effects on monocytes and macrophages.^{135,143,144} Neutrophil- and RBC-derived EVs are also capable of suppressing inflammatory responses.^{130,145} Similar to the variability in effects of EVs from various cell types, EVs isolated from plasma have dual proinflammatory and immunosuppressive effects.^{139,146} The proposed mechanism of action of blood-derived EVs varies, with immunosuppressive effects potentially mediated by FasL expression by EVs and inflammatory effects resulting from direct activation of monocytes and other APCs after EV uptake by these cells.^{139,146}

In vivo evidence for EV TRIM effects.: Given the incomplete understanding of how EVs from different cells of origin might act, it is not surprising that in vivo evidence of an EV-based role in TRIM is scant. The circulating half-life of EVs appears to be fairly short, less

than 15 to 20 minutes in a rat model.⁸⁶ However, the biologic activity of EVs is likely related to EV uptake by target cells rather than plasma concentration. For example, injected EVs are rapidly and widely distributed to the spleen, liver, kidneys, and lungs in mice.¹⁴⁷ Donor dendritic cell–derived EV uptake by dendritic cells in a recipient mouse can activate responding T cells in an antigen-specific manner.¹⁴⁸ This property has been exploited by several groups as a potential vaccine delivery approach.^{149–151} Additionally, adoptive transfer of CD154 (CD40L)-expressing PLT-derived EVs is sufficient to stimulate immunoglobulin G production and germinal center formation in mice after adenovirus vaccination, indicating that exogenous EVs can modulate a nascent immune response.¹⁵² The significance of the immunomodulatory effects of EVs found in blood products transfusion recipients remains an open question and an area of active research. Better understanding EV interaction with the human immune system would allow manipulation of this pathway, both in the context of TRIM and in the context of immune perturbation seen in many hospitalized patients.

FUTURE DIRECTIONS

Ample evidence exists that RBC products are capable of interacting with and modulating immune cell function through a variety of mechanisms and mediators; however, conclusive clinical evidence of TRIM effects in transfused patients remains elusive. Given recent clinical studies that fail to demonstrate benefit to fresh RBC transfusion compared to longer stored products, one might conclude that RBC TRIM does not exist in the era of prestorage leukoreduced blood products or that RBC storage duration does not contribute to TRIM mechanisms.^{87,115,153,154} However, emerging evidence suggests that the concentrations of potentially immunomodulatory mediators vary not only with storage duration, but also with donor characteristics, manufacturer, storage solution, and other processing factors.^{88,155–158} We are only beginning to understand the complex interplay between storage duration, processing methods, RBC unit contents, and subsequent potential TRIM effects. Similarly, a patient's underlying state of inflammation and/or immune suppression at the time of transfusion likely influences the immunologic response to transfusion. Critically ill patients, in particular, exhibit both exaggerated systemic inflammation and immune suppression that fluctuate over time.^{159–164} In this context, one would expect that immunologic effects of RBC trans-fusion might vary widely based on the underlying state of the recipient's immunologic response. However, most studies to date have failed to sufficiently characterize or account for individual differences in pretransfusion immune function. Additionally, patients who are trans-fused with RBCs often also receive other blood products, which may have different or additive TRIM effects.^{14,165} Overall, much work remains to understand interactions between individual blood product characteristics and patient-specific risk factors with respect to clinical consequences of TRIM.

Defining immunomodulatory mediators found within blood products, and understanding how these mediators may modulate recipient immunity, is essential to identify potential TRIM effects at the bedside. A bench-to-bedside approach must carefully attempt to define these mediators in context of host immune function. Next, guided by an enhanced understanding of TRIM biology, observational studies will be necessary to determine patient-specific risk factors for specific TRIM effects and related clinical consequences.

Moreover, delineation of the effects of RBC donor, product processing, and storage conditions upon accumulation of immunomodulatory mediators can then inform future prospective and interventional trials aimed at defining and ameliorating TRIM effects for those patients most at risk.

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ABBREVIATIONS:

APC(s)	antigen-presenting cell(s)
EV(s)	extracellular vesicle(s)
LPS	lipopolysaccharide
NTBI	non–transferrin-bound iron
TRIM	transfusion-related immunomodulation

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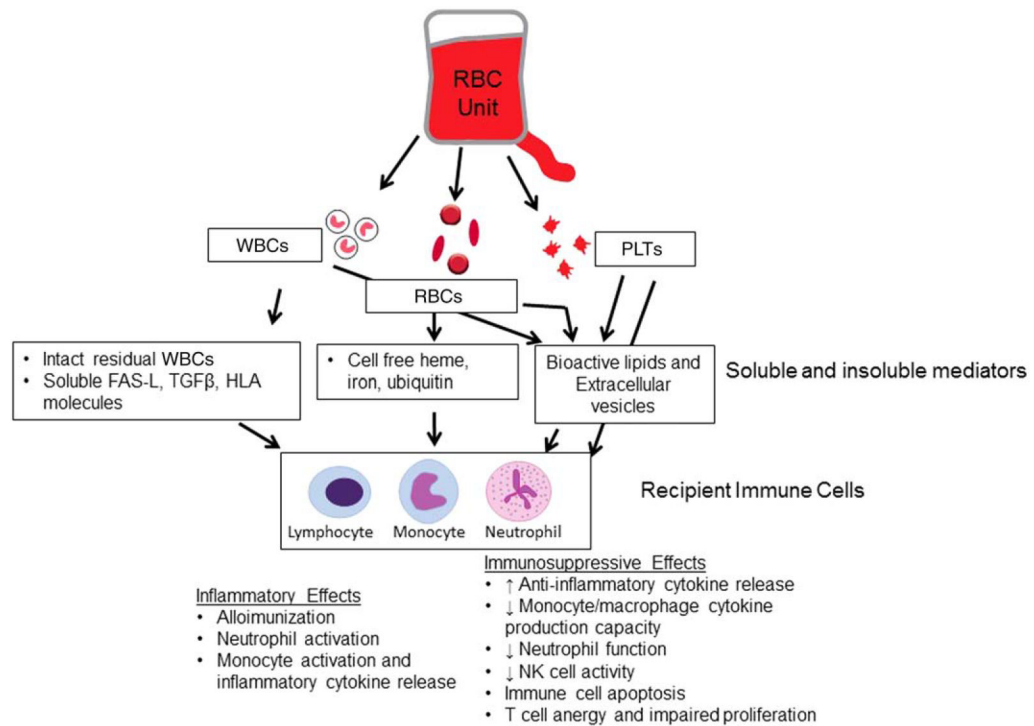
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**Fig. 1.**

Proposed mechanisms of RBC TRIM. RBC units contain multiple immunomodulatory mediators, including WBC-derived, RBC-derived, PLT-derived, and lipid and microvesicle-derived factors. Effects of these mediators on immune cell function vary and include both inflammatory and immunosuppressive changes. As such, the sum total immunomodulatory effects of RBC transfusion on recipient immune function will likely vary based on individual unit and recipient characteristics