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REVIEW ARTICLE

WAR AND BLOOD TRANSFUSION CRISES: ADDRESSING BLOOD SHORTAGES, COLD-CHAIN DISRUPTIONS AND TRANSFUSION RISKS THROUGH CONFLICT-RESILIENT BLOOD SYSTEMS

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Abstract

Armed conflict results in a complicated situation for blood transfusion services by halting blood collection, decreasing donor availability, harming healthcare infrastructure, disrupting cold-chain processes, and raising the demand for vital transfusions. These problems affect trauma victims, women dealing with obstetric hemorrhage, children suffering from severe anemia, and those requiring ongoing transfusion support. This narrative review examines the impact of conflict on blood supply, the quality of components, transfusion safety, and continuous care. It analyzes shortages caused by conflicts, failures in refrigeration, delays in transportation, disruptions in compatibility testing, emergency blood transfusion releases, and lack of hemovigilance. Focus is on methods to improve resilience in blood services, including decentralized collection and distribution, strategic inventory management, solar-powered refrigeration, authorized alternative transport, digital traceability, and patient blood management. The evaluation also includes fair distribution, safeguarding the healthcare workforce, regulatory supervision, and humanitarian partnership. Advanced technologies like drones and renewable energy systems can enhance operational continuity but need validation, ongoing funding, and context-specific assessment. Future studies ought to evaluate cold-chain efficiency, compare logistics, enhance hemovigilance, and analyze cost-effectiveness and equitable access. Ultimately, successful blood transfusion services must integrate reliable infrastructure, trained personnel, evidence-based clinical protocols, structured supply networks, and continuous quality evaluation to reduce preventable transfusion-related harm and uphold life-saving assistance before, during, and after military conflicts.

Keywords: armed conflict, blood transfusion, blood shortages, cold-chain integrity, hemovigilance.

INTRODUCTION

Blood transfusion plays a vital role in modern medicine, assisting in the management of traumatic injuries, obstetric bleeding, severe anemia, significant surgeries, blood disorders, and life-threatening situations. The effectiveness of transfusion services depends on an interconnected series of steps, encompassing voluntary blood donation, donor assessment, laboratory testing, component processing, appropriate storage, transportation, compatibility evaluation, clinical delivery, and post-transfusion observation. Any disruption at any stage can threaten blood supply, the quality of products, and the safety of patients[1]. These weaknesses are particularly noticeable during armed conflicts, as healthcare systems are required to address swiftly increasing clinical demands while functioning amidst insecurity, compromised infrastructure, and scarce resources[2]. Armed conflict presents a dual challenge for blood transfusion services: it raises the need for blood components while decreasing the capacity to gather, process, store, and distribute them. Gunshot injuries, blast injuries, traumatic limb loss, crush injuries, and emergency surgical procedures can lead to substantial transfusion requirements in short periods. Simultaneously, attacks on healthcare infrastructures, displacement of populations, restricted movement, fuel shortages, and interruptions in electricity and communication can undermine usual blood-service operations[3].

Consequently, blood shortages during conflicts arise not just due to a lack of donations; they also indicate

interconnected failures in supply chain consistency, infrastructure reliability, lab capacity, and emergency management[4].

The effects reach further than just those harmed in warfare. Women experiencing postpartum hemorrhage, children with severe anemia, patients with sickle cell disease or thalassemia, and individuals undergoing treatment for blood cancers may encounter delayed or disrupted transfusion support. These impacts are particularly concerning in low- and middle-income countries, where blood services may already face challenges such as limited donor bases, insufficient laboratory resources, unreliable electricity, and inadequate transportation networks. Conflict can intensify these pre-existing weaknesses, increase inequalities in healthcare access, and raise the chances of preventable disease and mortality[5]. An essential but sometimes neglected element of the crisis is preserving the quality of blood components. Red blood cells, platelets, and plasma necessitate distinct storage and handling conditions, rendering them susceptible to several cold-chain disruptions. Power outages, faulty refrigeration, prolonged transport delays, and inadequate temperature control can threaten product integrity or cast doubts on its suitability for transfusion. In emergencies, the restricted availability of lab reagents and the urgency to quickly process blood can hinder donor screening, compatibility testing, documentation, and quality control[6]. Although emergency release procedures are essential in specific life-threatening situations, improper execution can increase the risk of identification errors, incompatible transfusions, and other preventable adverse events[7].

Conventional blood-service frameworks typically depend on centralized processing facilities, expected transport routes, stable electricity availability, and frequent donor participation. These assumptions could collapse in times of extended insecurity or humanitarian emergencies. Cultivating resilience involves transitioning from emergency purchases made in response to crises to a holistic strategy that predicts interruptions, preserves vital services, and facilitates rapid recovery. Potential methods include decentralized blood distribution, regional stock management, strategic emergency reserves, renewable energy cooling, confirmed alternative transportation, digital tracking, and improved hemovigilance[8]. Effective management of patient blood may also reduce the demand for unnecessary transfusions, provided that conservation strategies do not delay or replace clinically essential treatment[9]. However, technological progress alone cannot guarantee the safety or reliability of transfusions. Refrigeration powered by solar energy necessitates suitable design, upkeep, and temperature assessment, whereas delivery methods like drones demand an assessment of product quality, operational dependability, regulatory adherence, and cost-efficiency. Similarly, digital traceability must persist during connectivity interruptions and incorporate essential data security protocols. These measures must be evaluated according to essential outcomes, including blood supply, minimized product waste, timely access to transfusions, fair service delivery, and patient safety[10]. This narrative review examines how armed conflict affects blood supply, disrupts cold-chain maintenance, and threatens transfusion safety. It evaluates the clinical and operational consequences of these disruptions and examines practical strategies for developing conflict-resilient blood systems. It emphasizes cohesive preparedness, reliable infrastructure, suitable clinical protocols, workforce safety, fair distribution, and continuous hemovigilance. The fundamental concept is that strong conflict resilience depends not only on adequate blood supplies; it requires a structured method that protects component quality, ensures equitable access, and maintains safe transfusions throughout the conflict and the subsequent recovery phase.

METHODS

This narrative review compiled studies on the effects of armed conflict on blood supply, cold-chain maintenance, transfusion safety, and the ongoing delivery of healthcare services. We performed targeted searches in PubMed/MEDLINE and Scopus utilizing various combinations of keywords like armed conflict, blood transfusion, blood shortages, cold-chain disruption, transfusion safety, hemovigilance, and healthcare resilience amid conflict. Advice from the World Health Organization, the International Committee of the Red Cross, and recognized transfusion medicine bodies was also considered. The synthesis relied on research regarding emergency blood availability, storage and transportation of components, management of patient blood, alternative delivery mechanisms, and readiness in humanitarian healthcare. The evidence was comprehensively examined to identify critical system vulnerabilities, successful mitigation strategies, and areas of research focus. In line with the narrative review method, we did not implement a formal systematic review protocol, quantitative meta-analysis, or a study selection guided by PRISMA. The findings were integrated thematically to develop a unified framework for improving blood transfusion services during armed conflicts and humanitarian emergencies.

Review approach and scope

This article employs a narrative review to merge established transfusion medicine protocols, humanitarian healthcare considerations, and innovative approaches for maintaining blood services during armed conflict. It encompasses blood collection, donor safety, blood component processing, storage and transportation, compatibility testing, emergency transfusions, inventory management, hemovigilance, ethical allocation, and system recovery. The dialogue utilizes established concepts in transfusion medicine, patient blood management, emergency preparedness, humanitarian healthcare, and quality assurance. It also takes into account the potential implementation of renewable-energy cooling, digital inventory management, remote surveillance, and various transportation methods. These innovations are assessed in terms of practical feasibility and implementation needs instead of assumed clinical effectiveness. This is a narrative

synthesis instead of a systematic review or a meta-analysis. It is not claimed that all relevant publications have been completely found or that the proposed interventions have received a formal quantitative assessment. As a result, recommendations should be interpreted in relation to current national regulations, institutional policies, and pertinent international standards.

How armed conflict disrupts blood transfusion systems

Warfare causes sudden increases in blood necessity from penetrating injuries, blast trauma, vascular damage, burns, traumatic limb loss, and emergency surgical procedures. People facing severe bleeding might require rapid resuscitation with red blood cells, plasma, platelets, and additional haemostatic strategies depending on the clinical situation and current protocols. The concurrent influx of several victims can strain blood banks, which generally maintain supplies sufficient for regular hospital functions[11]. Doubt regarding the number, intensity, and geographic spread of casualties adds to the complexity of demand. A blood center could encounter an unexpected increase in requests for group O red blood cells while receiving fewer compatible units from local facilities. In the absence of synchronized information sharing and emergency stock redistribution, some hospitals may accumulate excess units while others face significant shortages[12]. The clinical consequences become particularly serious when blood is unavailable during the early management of haemorrhagic shock. Delays in controlling bleeding and inadequate resuscitation can result in tissue hypoperfusion, coagulopathy, organ dysfunction, and death[13]. However, the relationship between blood supply and outcomes is also affected by transport time, surgical skill, injury severity, and the overall quality of emergency care. Thus, trauma systems ought to integrate blood supply measures instead of viewing them as separate procurement initiatives[14] (Table 1).

Table 1: Disruption of blood transfusion systems.

Disruption	Principal mechanisms	Consequences
Increased transfusion demand	Mass casualties, traumatic injuries, emergency surgery	Rapid depletion of blood stocks
Reduced donor availability	Insecurity, displacement, restricted movement	Declining blood collection
Infrastructure damage	Destruction of blood centers, laboratories, and hospitals	Reduced processing and storage capacity
Supply-chain interruptions	Fuel shortages, road closures, disrupted reagent supplies	Delayed collection, testing, and distribution
Cold-chain failure	Power outages, refrigeration breakdown, inadequate temperature monitoring	Component deterioration and product wastage
Workforce shortages	Staff displacement, injury, fatigue, and insecurity	Reduced service capacity and increased errors
Laboratory disruption	Reagent shortages, equipment failure, interrupted testing	Delayed release and compromised safety assurance
Weak coordination	Communication failures and fragmented inventory management	Unequal distribution and preventable shortages

Declining donor availability and disrupted collection

Voluntary, unpaid blood donations are crucial for maintaining sustainable blood services. In times of conflict, fear, displacement, restricted movement, halted transportation, and the cessation of public services can lessen donor engagement. Routine collection sessions could be called off, and mobile teams might not be able to access communities impacted by insecurity[15]. Potential donors may encounter injuries, acute illnesses, malnutrition, or various other problems that could impact their eligibility, either for a short time or indefinitely. Healthcare providers and blood-service personnel may be relocated or encounter dangers themselves, reducing the number of staff available for donor engagement, blood gathering, testing, and processing[16]. Emergency appeals can attract considerable public attention, but a rise in donors doesn't always lead to a corresponding boost in available blood. Selection of donors, testing capabilities, availability of consumables, preparation of components, and appropriate storage continue to be significant constraints. Disorganized recruitment may result in temporary surpluses of certain blood types or components, leaving other requirements unmet[17]. A conflict-adapted donor strategy should encompass recruitment from various geographic areas, leverage reliable community networks for communication, permit adaptable collection schedules, and incorporate continuity plans for ongoing donors. The safety of donors and informed consent must continue to be a priority. Coercion, biased selection, and surpassing safe blood collection thresholds are unacceptable responses to shortages.

Infrastructure destruction and supply-chain failure

Blood services depend on reliable electricity, water, lab equipment, IT systems, safe facilities, and medical resources. Armed conflict can either directly damage these resources or impede them by creating fuel shortages, cyber incidents, telecommunications breakdowns, and interrupted supply chains[18]. Laboratory operations can be impacted by an absence of blood grouping reagents, antibody screening equipment, cross matching materials, blood bags, sterile collection instruments, and quality control resources. Even with blood donation, the absence of confirmed testing or processing ability might impede its secure distribution[19]. Centralized blood-processing

systems may be particularly vulnerable when a single facility provides services to multiple hospitals. Damage to that facility or the roads connecting it to recipient institutions might interrupt supply across an entire region. In contrast, poorly overseen decentralisation can replicate limited resources and weaken quality control[20]. Resilience requires a structured framework of adequately outfitted central facilities, strategically located collection or distribution points, and validated referral systems. When feasible, vary critical supplies, encompassing reserve stocks and different buying options. Infrastructure planning must prioritize the safety of staff and patients: blood services should not justify placing employees in dangerous positions or establishing collection sites without adequate infection control, security, and clinical support[21].

Blood Shortages and Their Clinical Consequences

Unequal access to life-saving transfusion

Blood shortages during conflicts usually do not impact all patient groups uniformly. Patients with trauma may receive higher priority because their injuries are visible, while individuals requiring chronic transfusions deal with less obvious yet potentially serious complications. Obstetric emergencies, neonatal complications, severe anemia due to infectious diseases, and blood disorders may receive diminished attention when clinical teams face limited resources (Table 2)[22].

Table 2: Blood shortages and their clinical consequences.

Patient group	Principal transfusion need	Potential consequences of shortages
Trauma patients	Red cells and haemostatic components	Haemorrhagic shock, organ failure, death
Obstetric patients	Blood components for severe hemorrhage	Maternal morbidity and mortality
Children with severe anaemia	Red-cell transfusion when clinically indicated	Tissue hypoxia, cardiac complications, death
Patients with sickle cell disease	Indication-specific transfusion support	Stroke-related complications and interrupted disease management
Patients with thalassaemia	Regular red-cell transfusions	Worsening anaemia and treatment interruption
Patients with haematological malignancies	Red cells and platelets	Symptomatic anaemia, bleeding, treatment delays
Surgical patients	Perioperative blood components	Delayed procedures and complications from uncontrolled bleeding
Remote and displaced populations	Timely access to compatible blood	Delayed treatment and inequitable healthcare access

In settings with limited resources, shortages can be worsened by weak referral systems, limited transportation, inadequate laboratory facilities, and the financial difficulties encountered by displaced or marginalized populations. People living in rural areas may encounter serious drawbacks if blood supplies are concentrated in urban hospitals and transportation options are unreliable[23]. These inequalities highlight the necessity for clear clinical guidelines in emergency resource distribution instead of arbitrary choices or societal influence. Allocation policies should take into account urgency, expected advantages of transfusion, available treatment options, and the consequences of postponing care. They must also protect against discrimination based on nationality, ethnicity, status of displacement, disability, socioeconomic background, or perceived societal worth.

Chronic transfusion dependence and interrupted treatment

People with sickle cell disease, thalassemia, some bone marrow disorders, and particular cancers might require several transfusions. Disruptions may exacerbate anaemia, impede disease management, or elevate the likelihood of serious complications. Individuals with sickle cell disease may need transfusions for certain acute issues, like stroke and severe acute chest syndrome. Decisions must follow recognized clinical protocols and cannot be generalized to assert that every acute symptom requires a transfusion[24]. Regular transfusions also create specific safety standards. Patients may develop red cell alloantibodies, making it difficult to identify suitable blood units. Historical antibody records, improved antigen typing or genotyping when available and appropriate antigen-matched blood is particularly important for patients needing regular transfusions. Disparate records among facilities can increase the chances of delayed compatibility assessments or avoidable transfusion problems during conflict-driven displacements[25]. Continuity plans should recognize patients at elevated risk from treatment disruptions, maintain easily accessible transfusion records, and guarantee collaboration in care between hospitals and blood banks. When resources are insufficient for all planned transfusions, prioritization should be determined by clinical urgency and established disease-specific protocols.

Obstetric and paediatric emergencies

Postpartum hemorrhage remains an important cause for acquiring appropriate blood products. During conflicts, delays in referrals, interruptions in antenatal care, limited surgical resources, and shortages of uterotonics or other supplies for hemorrhage management can worsen the impact of inadequate blood supply. Transfusion preparedness should be incorporated into emergency obstetric referral frameworks and supported by protocols for recognizing, managing bleeding, and rapid escalation[26]. Children with severe anaemia might require urgent transfusion, depending on their haemoglobin levels, symptoms, pre-existing health conditions, and overall clinical condition. In regions where malaria is prevalent, conflicts can obstruct the

prevention, diagnosis, and treatment of the disease, as well as restrict access to safe blood supplies. In children, transfusion necessitates accurate, weight-adjusted dosing, suitable component selection, and vigilance for complications related to the procedure[27]. A solid system must therefore guarantee access to blood for both unpredicted mass-casualty situations and regular emergencies. Concentrating exclusively on combat trauma might ignore individuals whose health deteriorates fatally due to interrupted standard medical care.

Cold-chain disruptions and blood-component integrity

Blood components have unique storage requirements that should not be considered the same. Red blood cells are typically stored at 2–6°C, following appropriate guidelines, while platelets are generally held at 20–24°C with gentle, continuous agitation. Frozen plasma needs to be maintained under specific frozen conditions, with varying requirements depending on the product and applicable regulations. The shelf life depends on the component, method of processing, blend of additives, and jurisdiction[28]. These conditions preserve product characteristics within acceptable limits. Variations in temperature, mishandling, freezing of chilled red blood cells, or unverified transport conditions can compromise component quality. Importantly, visual inspection by itself cannot always evaluate the impacts of an outing. A unit that appears normal may have experienced a temperature history that contradicts its designated storage conditions[29]. Blood centers must employ calibrated temperature-monitoring devices, record alarm responses, utilize validated transport containers, and maintain written procedures for handling deviations. In case of a breach, the affected units must be identified; isolated if needed, and assessed by competent quality personnel in accordance with applicable regulations and verified stability data. Employees should not independently prolong shelf life or distribute compromised items solely due to restricted availability.

Power failures can disable blood-bank fridges, platelet incubators, plasma coolers, alarm systems, and laboratory devices. Fuel shortages may obstruct backup generators, and compromised electrical systems can postpone repair efforts. These risks hold significant importance in facilities that rely on a single refrigeration system or lack continuous temperature monitoring[30]. Refrigeration powered by solar energy, supported by suitably sized batteries and validated temperature control systems, provides a practical option for locations with unreliable grid power. However, solar installation by itself does not guarantee blood safety. System design must take into account local solar conditions, storage options, temperature stability, and battery degradation, and maintenance, availability of spare parts, equipment notifications, and contingency strategies for prolonged periods of reduced output[31]. Facilities need to establish a cold-chain continuity plan that details critical equipment, alternative power sources, secure transfer procedures, assigned staff, and additional storage locations. Contingency drills should evaluate the capacity to identify temperature changes, uphold records, transfer components safely, and assess the condition of impacted units.

Road obstructions, damaged bridges, security checkpoints, night time limitations, fuel shortages, and safety hazards can extend the duration required to deliver blood from collection sites to hospitals. Delays may heighten exposure to severe temperatures, vibrations, physical impacts, and handling mistakes. These risks are influenced by the component, packaging, transportation equipment, duration of travel, and environmental factors[32]. Confirmed insulated transport containers and specific component temperature monitoring can lessen uncertainty. Each shipment needs to have traceable records of dispatch and receipt, identification of responsible personnel, and a documented process for managing transport discrepancies. When suitable, receiving staff must verify packaging condition, shipping identification, temperature records, and compliance with local acceptance criteria before incorporating items into the usable inventory[33]. Drones and other alternative transport technologies can assist in regions where roads are inaccessible or travel durations are excessively lengthy. However, the appropriate method varies based on the particular product and route. Validation is essential for the stability of the payload, temperature control, vibration levels, acceleration, and integrity of packaging, safety during flight, compliance with regulations, prevailing weather, and handover procedures. Faster delivery alone does not ensure improved patient outcomes or cost-efficiency[34].

Red blood cells, platelets, and plasma necessitate unique cold-chain procedures due to their varying storage requirements and clinical functions. Platelets are especially vulnerable to disturbances during storage and transport at room temperature, while plasma relies on adequate frozen storage and confirmed thawing techniques. Red blood cells may be negatively impacted by excessive heat, cold, or improper storage conditions[35]. Implementing one emergency logistics protocol uniformly across all elements may inadvertently lead to avoidable risk. Conflict-resilient systems must maintain particular standards for packaging, monitoring, handling, and releasing each component. These controls need to be incorporated into standard operating procedures and highlighted through practical staff training.

Transfusion safety risks during armed conflict

In situations of severe bleeding, healthcare professionals may need to initiate transfusions before completing comprehensive compatibility testing. Emergency-release protocols are vital in appropriately selected scenarios, but they require clear authorization, reliable patient identification, documented clinical justification, and timely execution of compatibility evaluations whenever feasible[36]. Uncontrolled emergency releases can increase the chances of ABO-incompatible transfusions, particularly when identification systems malfunction or many patients are treated simultaneously. Restricted availability of previous antibody records could further complicate the selection of compatible red-cell units[37]. Services

resilient to conflict must implement predefined emergency-release protocols that specify criteria for ungrouped blood, the choice of emergency red blood cell types, the shift to specific group components, and clear communication between clinical teams and transfusion laboratories. Group O red blood cells can be vital during emergencies, yet their availability is limited. Policies should emphasize maintaining inventory, understanding local patient demographics, considering RhD factors, and transitioning to type-specific blood according to clinical urgency and established standards[38]. The emergency protocol must not be confused with regular transfusion practices. Once the immediate danger has been addressed, it is crucial to conduct accurate blood typing, antibody testing, cross matching, and maintain thorough records.

The safety of blood relies on selecting donors, testing for pertinent infections that can be transmitted through transfusions, validated laboratory procedures, and effective quality control measures. Conflicts may hinder screening services due to shortages of reagents, equipment failures, decreased workforce, and the urgency to expedite product releases. Such interruptions pose a risk of introducing inadequately tested blood into the transfusion procedure. However, conflict by itself does not demonstrate that rates of transfusion-transmitted infections have increased; the risk relies on the efficiency of local blood screening methods and the type of disruption present[39]. Essential safeguards include maintaining established screening procedures, managing reagent stocks, keeping quality-control records, and preventing the unauthorized sharing of untested substances. If capacity testing is temporarily lowered, officials must activate existing contingency plans, provide access to other accredited laboratories, and maintain clear communication with healthcare institutions. Dependence on unverified blood should not turn into a standard substitute for regular testing. Emergency procedures must operate in alignment with applicable national regulations and established standards for addressing clinical risks[40].

Transfusion reactions may still happen even if blood has been correctly collected, tested, and stored. Major complications include acute hemolytic reactions, febrile non-hemolytic reactions, allergic reactions, transfusion-associated circulatory overload, transfusion -related acute lung injury, and delayed hemolytic reactions. Risks differ depending on the patient, component, reason for the transfusion, and clinical status. Workload from conflict, staff burnout, diminished monitoring ability, and inadequate records can impede prompt recognition or handling of these problems. In emergency rooms, simultaneous resuscitation tasks can hinder the detection of a transfusion reaction's onset unless monitoring responsibilities are explicitly assigned[41]. Minimum precautions involve confirming patient identity at the bedside, performing necessary patient evaluations, documenting component and administration times, supervising according to clinical guidelines, and quickly probing any suspected reactions. Facilities need to establish protocols to stop transfusions when required, assess the patient, notify the transfusion lab, and protect the impacted unit and associated samples for examination.

Substantial blood loss requires coordinated management of hemorrhage, coagulation problems, hypothermia, and metabolic imbalances. Inappropriate selection of components or hold-ups in laboratory assessment can result in insufficient haemostatic resuscitation. Conversely, unnecessary blood transfusions may expose patients to avoidable complications and exhaust scarce resources[42]. Massive transfusion protocols should be customized to local resources while adhering to evidence-based clinical standards. Detail the activation criteria, availability of components, communication protocols, evaluations in the lab or point-of-care when feasible, and plans for reassessment as clinical circumstances evolve. Emergency readiness should include training in controlling hemorrhaging, precise fluid delivery, warming patients, and quickly identifying active bleeding. Transfusion reaches optimal effectiveness when paired with conclusive hemorrhage control and appropriate surgical or obstetric interventions[43].

Hemovigilance and digital traceability

Hemovigilance involves the systematic tracking of adverse events and reactions associated with blood donation and transfusion, including their investigation, evaluation, and avoidance. During armed conflicts, hemovigilance is particularly crucial as crises can obscure ongoing problems in collection, storage, transportation, compatibility testing, and clinical administration. However, inadequate reporting systems, lack of personnel, lost records, and poor laboratory follow-up frequently undermine monitoring. Negative occurrences might be inadequately reported, and inconsistent denominators make it difficult to compare transfusion outcomes between different facilities or time frames[44].

A minimum conflict-adapted hemovigilance framework should capture:

- Component identification, collection or processing details, and traceability.
- Storage and transport temperature deviations.
- Emergency-release transfusions and completion of subsequent testing.
- Suspected transfusion reactions, investigations, and clinical outcomes.
- Product wastage, expiry, recalls, and inventory shortages.
- Delayed or cancelled transfusions and their documented clinical consequences.

Digital systems can improve traceability by employing electronic records for inventory, barcode identification, temperature tracking, and communications between blood centers and hospitals. Nonetheless, advanced platforms might not be suitable in situations where electricity, network availability, cyber security, or technical assistance is unreliable. A system that breaks down in a communication failure may be less efficient than a simple platform with established offline functions and reliable synchronization. As a result, physical contingency documentation should stay available, along with procedures to balance them after

digital services are reinstated. System design should incorporate patient privacy, role-specific access, data security, and backup strategies[45]. Hemovigilance should focus on fostering learning instead of merely counting adverse incidents. Regular review meetings can reveal ongoing issues, implement corrective actions, and evaluate whether interventions reduce avoidable waste or problems related to transfusions. Consolidated, appropriately anonymized data can inform regional planning and humanitarian initiatives while protecting patients and personnel from avoidable risks[46].

Conflict-resilient blood systems: Practical solutions

1. Decentralised services and regional coordination

Decentralisation can minimize dependence on a vulnerable blood center by designating particular collection, storage, and distribution responsibilities to strategically positioned facilities. However, decentre-lisation should not imply that every facility independently conducts all laboratory and processing activities (Table 3). This approach might be risky or financially impractical in situations where there is a lack of skilled staff, and quality control capabilities.

Table 3: Conflict-resilient blood systems: Practical solutions.

Challenge	Recommended intervention	Expected benefit
Blood shortages	Diversified donor recruitment and strategic reserves	Improved blood availability
Unequal distribution	Decentralised storage and regional stock coordination	Equitable access and reduced delays
Power interruptions	Solar-powered refrigeration and backup energy	Improved cold-chain continuity
Transport disruptions	Validated alternative routes and delivery systems	More reliable component delivery
Laboratory supply shortages	Emergency reagent reserves and alternative validated laboratories	Continuity of testing and compatibility assessment
Transfusion errors	Standardized emergency-release protocols and staff training	Improved transfusion safety
Poor traceability	Digital inventory systems with offline backup	Better tracking and accountability
Adverse transfusion events	Strengthened hemovigilance and incident reporting	Earlier detection and prevention of harm
Excessive blood demand	Patient blood management and rational transfusion	Reduced avoidable blood utilisation
Workforce disruption	Cross-training, staff protection, and contingency staffing	Sustained service delivery

A practical framework combines centralized expertise with locally distributed adaptability. Regional centers are capable of performing tasks that require advanced laboratory infrastructure, whereas properly sanctioned peripheral facilities maintain designated emergency reserves and participate in actions supported by their accredited competencies. Coordinated transportation, shared emergency supplies, standardized part identification, and developed redistribution strategies can help reduce regional inequalities. These setups require explicit governance, including responsibility for stock ownership, shipping costs, quality assurance, emergency approvals, and replacement of moved components[47].

2. Strategic stock management and demand forecasting

Inventory management needs to weigh the danger of running out of stock against the threat of spoilage and waste. This becomes especially difficult during conflicts, as demand can change rapidly and usual consumption trends might not correspond to urgent requirements. Blood services should leverage existing information on previous usage, current hospital activities, anticipated casualty patterns, component shelf life, donor availability, and transportation constraints to inform inventory decisions. Predictions need to be updated as circumstances change instead of being seen as unchangeable forecasts. A tiered inventory system can distinguish among standard operational inventories, emergency reserves, and regionally allocated contingency supplies. Rotation protocols should highlight the proper utilization of parts before expiration while ensuring sufficient capacity for critical demands. Reserve levels must correspond to local epidemiology, service capacity, and the feasibility of replenishment; a uniform numerical target is probably not suitable for every conflict situation. Better demand forecasting can arise from improved communication between emergency departments, maternity services, surgical units, hematology departments, and blood centers. In cases where digital tools are unavailable, standardized telephone or radio reporting combined with routine stock reconciliation can act as an effective alternative.

3. Renewable energy and resilient infrastructure

Refrigeration powered by solar energy, energy-efficient appliances, battery storage systems, and properly maintained backup generators can enhance the reliability of blood storage in regions with unstable electrical grids. These actions are particularly relevant for establishments that experience regular disruptions or are situated far from major supply centers. Execution must begin with an assessment of refrigeration requirements, environmental factors, equipment appropriateness, energy production capa-bility, battery longevity, maintenance strategies, and accessibility of spare parts. Temperature stability must be verified under real operating conditions, including periods of reduced solar energy production. Investment in infrastructure should also address laboratory ventilation requirements, water supply, secure storage solutions, communication networks, and the protection of vital equipment. Redundancy is essential: various power supplies, alternative storage sites, and defined transfer methods can lessen dependence on one system. Sustainability encompasses more than simply obtaining equipment. Workers need training in routine checks, alarm responses, maintenance procedures, and documentation. Funding must include replacement batteries, maintenance, consumables, and equipment upgrades during the operational life of the system[50].

4. Alternative transportation and logistics

Transportation systems that can withstand conflict should operate multiple viable routes and methods instead of depending solely on a single road corridor. Choices consist of safe land transport, regional distribution, authorized humanitarian logistics systems, and, if necessary, drones. Drones can assist in reaching distant areas or solving unique transport issues, but their function must be guided by established operational needs. Prior to deployment, blood services need to verify payload capacity, packaging integrity, temperature control, vibration exposure, route reliability, handover procedures, and adherence to aviation and health regulations. The evaluation should extend past the speed of delivery. Important metrics encompass product quality, efficiency of delivery rates, cost per effective unit dispatched, performance under severe weather conditions, access equity, environmental effects, and, when measurable, clinical results. Drone delivery should improve, rather than substitute, essential investment in blood centers, terrestrial logistics, and sustainable storage[51].

5. Patient blood management and appropriate utilization

Patient blood management (PBM) is a cooperative approach designed to improve patient outcomes through the management of anemia, reduction of blood loss, and support of the body's ability to tolerate anemia, while using transfusions thoughtfully. It can lessen excessive reliance on limited blood supplies, but it cannot substitute for transfusion when medically required. Conflict-adapted PBM should focus on quickly identifying and addressing treatable anaemia whenever feasible, preventing and managing bleeding, appropriate laboratory tests, effective surgical techniques, and evidence-based transfusion thresholds. Restrictive transfusion strategies need to take into account the patient's health, current bleeding, cardiac status, and particular clinical indications. Clearly established clinical protocols can reduce unnecessary transfusions and improve consistency in resource-constrained environments. However, blood preservation should not justify withholding essential treatment. Emergency allocation and PBM should operate together: the goal is to ensure that each available unit is used appropriately, rather than to limit transfusions without considering clinical need[52].

6. Workforce protection and competency-based training

The consistent operation of blood services depends on proficient laboratory scientists, transfusion experts, nurses, healthcare professionals, drivers, maintenance personnel, and quality control officers. Employee turnover, fatigue, injuries, and psychological strain can impair productivity despite equipment being functional. Readiness strategies should identify essential roles, train personnel for crucial responsibilities, establish secure staffing frameworks, and define explicit escalation paths. Training based on competencies should encompass emergency compatibility procedures, management of components, cold-chain monitoring, and identification at the bedside, handling of adverse reactions, documentation, and reporting of incidents. The safety of staff is an essential operational necessity, rather than an optional extra. Facilities need to evaluate security risks, implement efficient communication procedures, and refrain from placing staff in positions that expose them to undue danger. Psychological assistance, adequate rest, and fair working conditions can aid in sustaining performance during prolonged crises[53].

7. Humanitarian coordination and recovery planning

Blood systems frequently become part of larger humanitarian health programs. Cooperation between health ministries, national blood services, hospitals, humanitarian organizations, professional associations, and global partners can enhance awareness of shortages and lessen duplicate efforts. Standardized reporting templates and established referral guidelines can assist in regional redistribution and urgent purchasing. External assistance should bolster current national systems when feasible, instead of generating parallel supply chains that become unviable once humanitarian financing ceases. Recovery planning should begin during the ongoing emergency. Essential duties involve fixing impaired infrastructure, replenishing inventory, reconstructing transfusion documentation, evaluating staff competencies, probing significant events, and regaining donor confidence. Post-conflict recovery offers an opportunity to address persistent challenges in laboratory capacity, quality assurance, and equitable access[54].

Ethical, Regulatory, and Governance Considerations

1. Ethical allocation of scarce blood

Distributing blood in warfare presents challenging ethical issues as the need for transfusions can surpass the available supply. Allocation policies should prioritize clinical urgency, the chance of substantial benefit, and the effects of delaying treatment, employing transparent, uniformly applied criteria. Decisions should not be swayed by economic condition, political affiliations, ethnicity, citizenship, military position, or personal relationships. A multidisciplinary review can enhance consistency in difficult decisions when time permits. Policies should differentiate between allocating scarce resources and refusing treatment when a transfusion is medically required[55].

2. Protection of blood services and humanitarian access

Blood collection centers, laboratories, hospitals, and medical transport systems require protection in compliance with applicable international humanitarian law. Assaults on medical personnel and institutions, hindrance of humanitarian aid, and interruption of essential medical resources can jeopardize critical care. National agencies and humanitarian organizations need to ensure safe access to healthcare, safeguard medical personnel. Blood services personnel require customized security assessments and procedures for stopping or relocating operations when necessary[55].

3. Regulatory oversight and accountability

Crisis situations might necessitate temporary changes to current protocols, but these alterations must remain

accountable. National blood agencies must create acceptable emergency-release procedures, alternative laboratory setups, transportation specifications for components, and strategies for managing storage discrepancies. Independent quality monitoring, detailed incident analysis and transparent reporting are essential to prevent emergency exceptions from evolving into risky standard procedures[12].

CONCLUSIONS

Armed conflict interrupts blood transfusion services due to a range of interconnected problems impacting blood collection, donor accessibility, storage and transportation, laboratory testing, and post-transfusion monitoring. Such disruptions threaten the accessibility, quality, and safety of blood products, heightening the risk for trauma patients, women experiencing obstetric hemorrhages, children afflicted with severe anemia, and individuals requiring frequent transfusions. Tackling these challenges necessitates a cohesive approach that enhances the whole transfusion system, from sourcing donors and gathering blood to clinical application and monitoring patients. In the end, blood systems that are resilient to conflict must guarantee the continuous availability, integrity, safety, and equitable distribution of blood components before, during, and after armed conflict.

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AUTHOR'S CONTRIBUTIONS

Obeagu EI: formal analysis, conceptualisation, data organisation, writing original draft. **Chimwara O:** data analysis, manuscript writing, literature survey. **Nwankwo OB:** critical review, editing. Final manuscript was checked and approved by the both authors.

DATA AVAILABILITY

The related author can provide the empirical data supporting the study's conclusions upon request.

CONFLICT OF INTEREST

There are no conflicts of interest in regard to this project.

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