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Prehospital Blood Management in Trauma Patients: Current Status, Challenges, and Future Perspective

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Abstract

Trauma-induced hemorrhage is one of the primary causes of preventable mortality globally, accounting for a substantial proportion of prehospital deaths and underscoring the critical demand for prompt and effective blood management strategies during prehospital transport. This narrative review aims to synthesize the current state, key challenges, and future perspectives of prehospital blood management for trauma patients. This review evaluates established trauma assessment tools (e.g., Shock Index, ABC score), the global implementation of prehospital blood product transfusion—including low-titer group O whole blood, packed red blood cells, and plasma—by emergency medical services in the United States, Europe, and Australia, as well as non-transfusion interventions such as early tranexamic acid administration, crystalloid/colloid resuscitation, and physical hemostatic interventions.

Recent advances, including lyophilized plasma, point-of-care viscoelastic monitoring, telemedicine platforms, artificial intelligence–driven decision support systems, real-time blood-loss monitoring technologies, and automated transfusion devices, are reviewed for their potential to optimize trauma care delivery. Major challenges identified include resource constraints in remote or austere environments, marked heterogeneity in transfusion protocols and triggering criteria, suboptimal assessment and monitoring capabilities, and deficiencies in prehospital provider training and continuing education.

Optimization strategies encompass standardized operating procedures, strengthened interdisciplinary collaboration, enhanced public and professional trauma education initiatives, and structured competency-based training frameworks. By clarifying these key elements and outlining priority research directions—including personalized transfusion protocols and integration of large-scale data analytics—this review serves as a fundamental reference for the development of evidence-based clinical guidelines and consensus statements. Ultimately, this review seeks to advance protocol standardization and improve survival outcomes for patients with life-threatening traumatic hemorrhage.

Keywords

Prehospital Blood Management, Trauma Patients, Blood Products, Blood Transfusion, Tranexamic Acid

Introduction

Trauma represents a major global public health challenge, contributing to an estimated 4.9 million deaths each year, which accounts for roughly 8% of all-cause mortality worldwide [1]. In China, trauma accounts for an estimated 700,000 deaths each year, representing the leading cause of mortality among individuals under 45 years and contributing to a substantial disease burden [2]. Trauma-induced hemorrhage is a critical determinant of patient prognosis and survival, posing a significant public health challenge. Prehospital bleeding profoundly influences clinical outcomes. Therefore, early detection and control of hemorrhage are essential to improve survival rates. The primary objective of prehospital blood management is to deliver optimal care during patient transport, particularly for patients with life-threatening hemorrhage. Timely blood transfusion and effective hemostatic interventions can substantially reduce trauma-related mortality.

In recent years, improved understanding of the pathophysiological mechanisms underlying traumatic hemorrhage has driven the evolution of prehospital blood management strategies. Interventions such as early coagulation support, prehospital administration of tranexamic acid [3], and point-of-care coagulation monitoring have demonstrated efficacy in reducing blood product utilization in emergency settings and improving in-hospital outcomes for trauma patients [4]. Currently, prehospital blood management extends beyond the administration of blood products to emphasize the early detection and mitigation of hemorrhage-related complications, including coagulopathy and acidosis. This paradigm shift has highlighted the urgent need for evidence-based protocols to identify high-risk bleeding patients in the prehospital setting, which has emerged as a central focus of contemporary emergency medicine research.

Despite the growing body of evidence supporting the use of prehospital blood management strategies for traumatic hemorrhage, their real-world implementation continues to encounter substantial challenges. These include limited resource availability, inadequate training of healthcare personnel, equipment constraints in out-of-hospital settings, and risks associated with the decentralized administration of blood products [5]. Existing practices are hindered by the absence of standardized protocols, marked by substantial variability across studies and a paucity of validated guidelines. This review systematically summarizes the current status and challenges of prehospital blood management in trauma patients. By providing in-depth insights and reflections on future directions, it offers novel perspectives and practical strategies for standardizing and optimizing prehospital blood management protocols. Furthermore, the review aims to serve as a foundational reference for developing evidence-based guidelines and consensus statements in this critical clinical field.

Current Status of Prehospital Blood Management in Trauma Patients

Assessment of Prehospital Blood Management Needs in Trauma Patients:

Trauma patients often present with various bleeding patterns, making rapid and accurate assessment of their blood management needs critically important. Common scoring systems used to evaluate the severity of traumatic hemorrhage include the Shock Index (SI), Assessment of Blood Consumption (ABC) score, Trauma Associated Severe Hemorrhage (TASH) score, and Battlefield Acute Traumatic Hemorrhage (BATT) score [6]. These tools enable clinicians to estimate bleeding severity and determine the necessity of interventions such as blood transfusion. The SI reflects the patient's shock status via the ratio of heart rate to systolic blood pressure, thereby providing an indirect indication of hemorrhage. By contrast, the ABC score integrates multiple clinical parameters to assess the risk of massive transfusion requirements. Accurate assessment of transfusion needs establishes a foundation for the rational implementation of subsequent blood management strategies, enables prompt and appropriate intervention, and ultimately improves patient prognosis (**Table-1**).

Prehospital Blood Product Use in Trauma Patients:

In the international setting, prehospital blood transfusion (PHBT) has been implemented in numerous countries. Since 2009, the United States has pioneered plasma transfusion during helicopter emergency medical services (HEMS) for patients with severe

trauma. As of October 2023, 121 emergency medical service agencies across 24 states have successfully adopted PHBT, with particularly high implementation rates in Texas, North Carolina, and Virginia [5].

In several U.S. regions, low-titer group O whole blood (LTOWB) is approved as a standard product for trauma resuscitation and is routinely stocked on ambulances. Similarly, countries including the United Kingdom, France, and Australia have introduced PHBT programs, supplying packed red blood cells (pRBCs), lyophilized plasma, and, in some cases, LTOWB.

A survey of 378 advanced life support ambulance units in France found that 82% had performed prehospital blood transfusions [7]. Among the products used, pRBCs accounted for 100% (95% of which were group O RhD-negative RBCs), fresh frozen plasma for 27%, lyophilized plasma for 7%, and platelets for 1%.

In China, routine and timely blood transfusion during prehospital emergency care for patients with severe trauma remains limited. Only isolated case reports and emergency drills have described prehospital applications. The Chinese Expert Consensus on Blood Support Models and Transfusion Strategies for Emergency Treatment of Patients with Severe Trauma (2024) recommends that, for prehospital patients with life-threatening non-compressible massive hemorrhage or grade IV hemorrhagic shock, universal donor products such as LTOWB, group O suspended red blood cells, or thawed group AB or group A fresh frozen plasma may be transfused [8] **(Table-2)**.

Non-Transfusion Strategies in Prehospital Management of Trauma Patients:

Non-transfusion strategies also play a vital role in prehospital trauma management. Crystalloid and colloid solutions are commonly employed as blood substitutes to restore intravascular volume and maintain hemodynamic stability. However, careful attention must be given to dosage and timing to prevent adverse effects associated with overhydration [9].

Table-1: Comparison of Common Scoring Systems for Prehospital Assessment of Traumatic Hemorrhage

Scoring System	Key Components	Threshold for Intervention	Advantages	Limitations	Primary Clinical Use
Shock Index (SI)	Heart rate / systolic blood pressure	SI > 0.9–1.0	Simple, requires only vital signs, rapid	Does not account for mechanism or other factors	Initial screening for shock and occult hemorrhage
Assessment of Blood Consumption (ABC) Score	Penetrating mechanism, SBP ≤90 mmHg, HR ≥120 bpm, positive FAST	Score ≥2 predicts massive transfusion need	Quick, based on easily obtainable prehospital data	Limited sensitivity in some populations	Prediction of massive transfusion requirement
Trauma Associated Severe Hemorrhage (TASH) Score	Complex (includes Hb, base excess, gender, etc.)	Score ≥16–18	Higher accuracy for massive transfusion prediction	Requires laboratory values (less feasible prehospital)	In-hospital or advanced prehospital settings
Battlefield Acute Traumatic Hemorrhage (BATT) Score	Adapted for military; includes vital signs and injury patterns	Varies by protocol	Designed for austere environments	Primarily validated in military settings	Combat or resource-limited trauma

Table-2: International Comparison of Prehospital Blood Product Transfusion Practices

Country/Region	Implementation Level	Common Blood Products Used	Key Features/Notes
United States	High (121 EMS agencies in 24 states as of Oct 2023)	LTOWB, pRBCs, plasma (liquid or lyophilized)	Pioneered plasma in HEMS; LTOWB routinely stocked on ambulances in several regions
United Kingdom	Moderate to high	pRBCs, lyophilized plasma, LTOWB in some services	Established prehospital transfusion programs
France	High	pRBCs (95% group O RhD-negative), FFP (27%), lyophilized plasma (7%), platelets (1%)	82% of advanced life support units have performed prehospital transfusions
Australia	Moderate	pRBCs, lyophilized plasma, LTOWB in select services	Growing adoption in retrieval medicine
China	Limited	LTOWB, group O suspended RBCs, or thawed group AB/A FFP (recommended in specific cases)	Routine use remains limited; only isolated case reports and emergency drills

Among pharmacological interventions, tranexamic acid has gained prominence as an antifibrinolytic agent that inhibits the fibrinolytic system, thereby exerting hemostatic effects. Early administration of tranexamic acid in patients with traumatic hemorrhage has been shown to reduce the risk of bleeding progression and mortality [10].

Supplementation with coagulation factors is likewise utilized in select cases, particularly when patients exhibit clear deficiencies or severe consumption due to massive blood loss; such replacement therapy helps restore coagulation function and control ongoing hemorrhage. Additionally, physical hemostatic measures - including pressure dressings and judicious use of tourniquets—enable rapid control of external bleeding in the prehospital setting, thereby providing critical time for definitive treatment [11].

Novel Blood Products and Transfusion Advances in Prehospital Trauma Care:

The development and clinical application of novel blood products represent a major research focus in prehospital trauma care. These specially processed or modified products are designed to prolong shelf life while improving safety and efficacy [12]. Certain next-generation red blood cell products maintain oxygen-carrying capacity while potentially reducing the risk of immune-mediated reactions.

Rapid transfusion technologies continue to advance, with more efficient devices now capable of delivering large volumes of blood products in minimal time to meet the demands of trauma resuscitation. Furthermore, data-driven clinical decision support systems are increasingly integrated into prehospital blood management. By combining patient injury data, vital signs, and laboratory results through big data analytics and artificial intelligence algorithms, these systems generate precise recommendations on transfusion timing, blood product selection, and dosing, thereby enhancing both the efficiency and quality of emergency care [13].

Emerging Blood Technologies in Prehospital Trauma Care:

Recent innovations in blood product formulation and delivery systems are poised to overcome longstanding logistical barriers in prehospital environments. Lyophilized (freeze-dried) plasma remains a cornerstone advance, offering room-temperature stability for up to 2–3 years and rapid reconstitution with sterile water at the point of care. Unlike fresh frozen plasma, it requires no cold-chain infrastructure, making it ideal for remote, rural, or mass-casualty settings. Clinical trials have confirmed its safety and feasibility; however, its potential mortality benefits in patients with isolated traumatic brain injury or hemorrhagic shock remain under investigation in ongoing studies [14].

Table-3: Emerging Blood Technologies for Prehospital Trauma Management

Technology	Description & Mechanism	Prehospital Advantages	Current Evidence (2025–2026)	Limitations / Development Stage
Lyophilized / Freeze-Dried Plasma (FDP)	Spray- or freeze-dried plasma; reconstitutes in minutes	Room-temp storage (2–3 years); no cold chain	Safe & feasible; mixed mortality benefit in RCTs; valuable in austere settings	Not yet FDA-approved for routine US use; ongoing trials
Biosynthetic Oxygen Carriers (e.g., ErythroMer HBOC)	Encapsulated hemoglobin nanoparticles	Universal compatibility; no typing/cross-matching	Promising in trauma models; reduces immune reactions	Phase 2–3 trials; long-term safety data pending
Synthetic Platelets (e.g., SynthoPlate)	Biomimetic nanoparticles mimicking platelet function	Shelf-stable; no donor dependency	Preclinical & early clinical data in hemorrhage models	Limited human prehospital data
Pathogen-Reduced LTOWB & Cold-Stored Platelets	Treated whole blood or platelets	Extended shelf life; reduced infection risk	Expanding US EMS adoption; SWiFT trial ongoing	Logistical training required
AI-Driven Transfusion Prediction	ML models using prehospital vitals/injury data	AUC ~0.87; earlier identification of high-risk patients	Validated in multinational registries; superior to SI/ABC	Requires prospective implementation studies
Advanced POC Diagnostics	Microfluidic/electrochemical sensors for Hb/coagulation	Real-time assessment in ambulance	Emerging for rapid transfusion-need forecasting	Device miniaturization and EMS integration ongoing

Complementing these are next-generation red blood cell substitutes and biosynthetic oxygen carriers, including hemoglobin-based oxygen carriers (HBOCs) such as ErythroMer and synthetic platelet mimics (e.g., SynthoPlate). These products maintain oxygen-carrying capacity while minimizing immune-mediated reactions and eliminating the need for blood typing. Pathogen-reduced low-titer group O whole blood (LTOWB) and cold-stored platelets further expand the prehospital armamentarium by extending shelf life and reducing transfusion-related complications [15-17].

Rapid transfusion technologies have also evolved, with automated infusion devices now capable of delivering high-volume boluses in under 2 minutes via barcode-guided, error-minimizing systems. Integration of point-of-care microfluidics, electrochemical sensors, and fluorescent microscopy enables real-time hemoglobin, coagulation, and transfusion-need assessment directly in ambulances [12].

Artificial intelligence (AI)–driven predictive models represent a transformative leap. Using only prehospital data (vital signs, injury patterns, and medication history), machine-learning algorithms achieve high predictive accuracy (AUC ≈ 0.87) for identifying patients requiring massive transfusion—outperforming traditional scores such as Shock Index or ABC. These tools facilitate earlier resource mobilization and personalized resuscitation protocols [13].

Collectively, these technologies shift prehospital blood management from reactive component therapy toward proactive, individualized, and logistically resilient care, particularly in austere or prolonged-transport scenarios [12] **(Table-3)**.

Challenges in Prehospital Blood Management for Trauma Patients

Prehospital Blood Management in Resource-Limited Settings:

Prehospital blood management for trauma patients faces substantial challenges stemming from limited resources and inconsistent access to blood products. In resource-constrained environments, particularly rural or remote areas, medical facilities frequently experience chronic shortages of blood supplies, which severely compromise their ability to meet urgent transfusion needs [5].

This shortfall creates a critical gap in care, as trauma patients are often deprived of timely life-saving transfusions during the critical "golden hour" of resuscitation, markedly increasing mortality risk. For example, in areas impacted by natural disasters or prolonged conflicts, disrupted supply chains and inadequate cold-chain infrastructure further aggravate blood product scarcity, resulting in preventable deaths from hemorrhagic shock. Enhancing the availability of blood products, especially in high-demand trauma scenarios, is therefore essential for improving the effectiveness of prehospital blood management. Transport and storage conditions for blood products also exert significant effects on their quality and usability [5].

Non-Standardized and Heterogeneous Prehospital Blood Transfusion Strategies:

The absence of standardized prehospital blood transfusion strategies represents a major challenge, resulting in inconsistent practices and suboptimal outcomes in trauma care. Current protocols exhibit considerable global variation in transfusion triggers (e.g., hemoglobin thresholds), blood product ratios (e.g., 1:1:1 RBC:plasma:platelets versus crystalloid-dominant resuscitation), and eligibility criteria [4].

This fragmentation is particularly pronounced in resource-limited settings, where only 40% of blood donations meet international safety standards and approximately 30% of transfusions are deemed inappropriate owing to protocol ambiguity. Recent studies underscore the clinical consequences of such variability. For instance, a 2022 Finnish study conducted in ground-based emergency medical services demonstrated that prehospital transfusions initiated within 54 minutes of injury raised systolic blood pressure by 40 mmHg (from 76.5 to 116.6 mmHg) without severe adverse events [18].

In contrast, a 2017 meta-analysis revealed divergent mortality outcomes: civilian studies showed no survival benefit, whereas military data indicated a 15% reduction in mortality among severely injured patients.

These inconsistencies highlight the pressing need for unified, evidence-based guidelines [4].

Prehospital settings - ranging from ambulances to disaster zones - display wide variation in transfusion protocols. Different emergency medical services (EMS) systems often follow divergent or even absent guidelines. Consequently, patients sustaining similar traumatic injuries may receive markedly different blood transfusion treatments. Some systems prioritize early administration of packed red blood cells, while others defer transfusion until hospital arrival; certain teams employ whole blood, whereas others rely exclusively on component therapy.

This heterogeneity frequently leads to suboptimal outcomes, as delayed or inappropriate transfusions can worsen hypovolemic shock, thereby elevating the risk of organ failure and death. Moreover, the lack of standardization impedes rigorous comparative research and the development of evidence-based best practices. Establishing unified, evidence-based prehospital blood transfusion guidelines across EMS systems is therefore urgently required to ensure consistent, high-quality care for trauma patients irrespective of location or treating team [4] **(Table-4)**.

Suboptimal Prehospital Assessment and Monitoring Technologies:

In prehospital trauma management, the limited availability of advanced assessment and monitoring technologies constitutes a significant challenge. Traditional coagulation assays are often time-consuming and lack the precision required to rapidly evaluate a patient's coagulation status. Routine laboratory tests frequently fail to accurately predict bleeding risk or assess coagulation capacity in trauma patients, thereby hindering timely clinical decision-making. Although thrombelastography (TEG) and rotational thromboelastometry (ROTEM) have emerged in recent years, their adoption remains limited, especially in resource-constrained environments [19]. Consequently, the development and broader implementation of rapid, accurate point-of-care monitoring technologies are essential to improve the quality of prehospital trauma care [20].

Complexity of Prehospital Blood Management During Transfer and High Personnel Requirements:

The prehospital blood management process for trauma patients during transfer involves multiple sequential phases, including clinical assessment, real-time transfusion decision-making, and blood product administration. Critically, the proficiency of prehospital providers in identifying sources of hemorrhage and prioritizing transfusion urgency profoundly affects resuscitation outcomes.

Table-4: Variation in Prehospital Blood Transfusion Protocols and Strategies

Aspect	Common Variations Observed	Clinical Consequences of Heterogeneity	Example Evidence Cited in Manuscript
Transfusion triggers	emoglobin thresholds; vital-sign based (e.g., hypotension, tachycardia)	Delayed or inappropriate transfusion; increased organ failure risk	Global variation noted
Blood product ratios	1:1:1 RBC:plasma:platelets vs. crystalloid-dominant resuscitation	Suboptimal outcomes in civilian vs. military settings	2017 meta-analysis (civilian: no benefit; military: 15% mortality reduction)
Eligibility criteria	Life-threatening non-compressible hemorrhage; grade IV shock; ABC/TASH score thresholds	Inconsistent care across EMS systems	Finnish study (BP increase within 54 min) vs. divergent mortality data
Product selection	Whole blood vs. component therapy; universal donor vs. type-specific	Resource wastage and variable efficacy	US (LTOWB standard); France (pRBCs dominant)
Setting-specific protocols	Ambulances vs. disaster zones; ground vs. air medical services	Fragmented research and best-practice development	EMS systems follow divergent or absent guidelines

Inadequate training programs and delayed knowledge updating among medical personnel are key contributors to suboptimal prehospital blood management. Deficiencies in early hemorrhage recognition and adherence to evidence-based transfusion protocols frequently cause delays in hemorrhage control, thereby compromising the critical "golden hour" for effective resuscitation. Furthermore, the lack of structured continuing medical education programs limits providers' capacity to incorporate the latest clinical guidelines and technological advances. Therefore, the implementation of systematic, competency-based training frameworks with regular updates is vital to strengthen provider expertise and enhance time-sensitive decision-making in prehospital trauma care [21].

Application of Emerging Technologies in Prehospital Blood Management for Trauma Patients

Application of Novel Blood Products:

In prehospital trauma care, emerging technologies—particularly novel blood products—are transforming blood management strategies. These innovations show strong potential to substantially improve patient outcomes. A prominent example is lyophilized plasma. Unlike traditional fresh frozen plasma, which requires stringent cold-chain storage and is thus impractical in prehospital settings, lyophilized plasma can be stored at room temperature for prolonged periods. This facilitates rapid deployment in emergencies. It can be swiftly reconstituted with sterile water at the point of care, promptly supplying clotting factors and other essential components to manage trauma-induced hemorrhage [14].

For instance, in remote areas or mass-casualty incidents where access to fully equipped blood banks is limited, lyophilized plasma is readily transportable in ambulances or first-aid kits, enabling immediate plasma support for bleeding patients.

Techniques for Real-Time Blood Loss Monitoring:

Real-time blood loss monitoring is essential in prehospital trauma management. Traditional approaches, which primarily depend on clinical symptoms and vital sign changes, often fail to detect hemorrhage at an early stage. In recent years, novel technologies such as pulse arrival time (PAT) and whole-body bioimpedance have demonstrated the ability to identify bleeding earlier and deliver real-time feedback, potentially enhancing management efficiency and patient safety [22].

Telemedicine and Data-Driven Decision Support Systems:

The rapid advancement of telemedicine has introduced innovative strategies for prehospital trauma management. Through telemedicine platforms, clinicians can access real-time patient data remotely and communicate instantaneously with hospital-based specialists. This approach not only expedites emergency response but also enhances clinical decision-making.

Studies have shown that remote monitoring systems are particularly valuable for managing high-risk trauma and hemorrhage patients by facilitating early intervention and coordinated, evidence-based care. Additionally, mobile devices and applications facilitate efficient data collection and sharing, strengthening patient-provider interactions, supporting self-management, and promoting health education. These elements collectively contribute to improved outcomes across the trauma care continuum [13].

Automated Transfusion Systems and Rapid Transfusion Technologies:

Automated blood transfusion systems hold considerable promise for improving the safety and efficiency of transfusions in prehospital settings. Conventional manual transfusion processes are susceptible to human error and delays. In contrast, automated systems leverage barcode scanning and real-time monitoring to enhance accuracy and timeliness.

Research demonstrates that their implementation significantly improves documentation compliance and reduces transfusion-related errors. Furthermore, data-driven optimization minimizes resource wastage, simultaneously protecting patient safety and improving the efficient use of medical resources. As technology advances, automated transfusion systems are anticipated to see broader adoption, ultimately elevating the standard of prehospital trauma care [23].

Optimization Strategies for Prehospital Blood Management in Trauma

Development of Standardized Operating Procedures:

Formulating standardized operating procedures is essential for improving treatment efficiency and reducing medical errors in prehospital blood management for trauma patients. These protocols ensure that all healthcare providers implement consistent interventions, thereby enhancing the overall effectiveness of blood management.

For example, such procedures should include rapid bleeding assessment, timely transfusion decision-making, and early recognition and management of trauma-induced coagulopathy (TIC). Clear protocols enable prompt responses in emergencies, minimizing delays arising from information gaps or procedural inconsistencies. Moreover, standardized procedures should address blood product selection, pre-transfusion preparation, and post-transfusion monitoring to ensure patient safety and therapeutic efficacy [24].

Strengthening Interdisciplinary Collaboration and Communication:

Multidisciplinary collaboration is critical in prehospital blood management, given that trauma care spans multiple specialties, including surgery, emergency medicine, anesthesiology, and hematology. Effective communication channels enable professionals to share real-time updates on patient status and treatment plans, facilitating more informed and coordinated strategies.

For example, prehospital responders can rapidly evaluate vital signs at the scene and maintain continuous communication with the receiving hospital team, ensuring seamless implementation of blood transfusion and other interventions prior to arrival. Furthermore, regular multidisciplinary training and simulation exercises foster team cohesion and enhance collaborative efficiency, ultimately improving patient outcomes [4].

Enhancing Trauma Awareness Among the Public and Medical Staff:

Strengthening trauma awareness among both the general public and healthcare professionals represents a key strategy for optimizing prehospital blood management. Greater public awareness promotes trauma prevention and encourages prompt seeking of medical care, thereby reducing trauma incidence. Similarly, heightened awareness among medical personnel directly improves their ability to perform rapid assessment and management of trauma patients.

Targeted public education campaigns that disseminate first-aid knowledge, combined with continuous professional development for clinicians, have proven effective in raising awareness. Enhanced understanding equips medical staff to better recognize and address patient needs, enabling more effective prehospital interventions [25].

Enhancement of Continuing Medical Education and Training:

Continuing medical education and training play a vital role in improving trauma management, particularly in the prehospital setting. Trauma awareness forms a foundational element of this process. For the public, sustained health education campaigns - such as community workshops and online programs - can reduce trauma incidence by promoting prevention measures and safe practices.

Post-education assessments, including surveys and quizzes, allow evaluation of knowledge gains. For healthcare professionals, ongoing training is indispensable to ensure familiarity with the latest rapid assessment techniques and early identification of trauma-induced coagulopathy (TIC). Simulation-based scenarios enable skill practice, with pre- and post-training performance comparisons providing objective measures of effectiveness. Ultimately, continuous education fosters more proactive attitudes toward trauma care, encouraging prompt help-seeking by the public and greater confidence and efficiency among prehospital providers [26].

Future Research Directions in Prehospital Blood Management for Trauma Patients

Application of Big Data and Artificial Intelligence in Blood Management:

The integration of big data and artificial intelligence (AI) in prehospital blood management for trauma patients is emerging as a prominent research focus. By processing large volumes of clinical data, AI can support real-time assessment of bleeding risk and predict patient responses to various blood products. Machine learning algorithms analyze physiological parameters, laboratory results, and historical medical records to generate personalized transfusion recommendations.

Such optimization minimizes unnecessary transfusions and associated complications. Furthermore, continuous AI-driven monitoring of vital signs enables prompt detection of hemorrhage, facilitates early intervention, and ultimately lowers trauma-related mortality. Future studies should prioritize the seamless integration of AI into existing clinical decision support systems to enhance the efficiency and precision of prehospital blood management [13].

Exploration of Individualized Prehospital Blood Management Strategies:

Individualized blood management strategies are gaining increasing importance in prehospital trauma care. Conventional "one-size-fits-all" transfusion protocols, as highlighted in multiple studies, frequently fail to address the specific physiological needs of individual patients.

For example, patient age markedly influences responses to trauma and blood loss; older individuals often present with comorbidities such as cardiovascular disease, which complicate transfusion decision-making. Researchers are actively developing personalized transfusion protocols that incorporate comprehensive patient-specific factors, including age, sex, comorbidities, and trauma type (e.g., abdominal versus pelvic trauma).

Optimal strategies differ substantially across trauma subtypes - for instance, non-operative management may suffice in select abdominal injuries, whereas pelvic trauma often demands immediate surgical intervention. Future investigations should refine individualized approaches by integrating biomarker and genomic data. A recent study on trauma-associated deep vein thrombosis identified specific biomarkers predictive of blood-related complications, offering potential for more targeted blood management. Incorporating such data will enable tailored interventions and improved clinical outcomes for trauma patients [27].

Establishment of Monitoring and Evaluation Mechanisms:

Robust monitoring and evaluation frameworks are essential for effective prehospital blood management in trauma care. Continuous real-time surveillance of vital signs - including heart rate, blood pressure, and oxygen saturation - provides immediate insights into bleeding status during prehospital resuscitation. For instance, acute hypotension may signal substantial hemorrhage.

Additional key metrics include time from injury to transfusion initiation and transfusion rates. Evaluation should be multifaceted, encompassing validation of AI-based bleeding risk predictions through comparison of forecasted versus observed hemorrhage severity. Similarly, the clinical impact of individualized strategies can be assessed via patient-centered outcomes such as survival rates and complication incidence.

Regular performance audits in simulated trauma scenarios further identify training gaps among prehospital providers. Collectively, these mechanisms are critical for continuously improving the quality and safety of prehospital trauma blood management [4].

International Collaboration and Experience Sharing:

International collaboration is vital for advancing both research and clinical practice in prehospital blood management for trauma patients. Experiences and lessons learned from diverse countries and regions offer important insights for global health initiatives.

For example, nations that have successfully deployed large-scale prehospital transfusion protocols can disseminate best practices through international conferences and joint projects. Multinational studies also facilitate identification of population-specific responses to blood products, supporting global standardization of evidence-based guidelines. Future efforts should focus on strengthening international

networks to promote knowledge exchange and resource integration, ultimately improving trauma care outcomes worldwide [24].

Conclusion

Prehospital blood management constitutes a cornerstone of trauma care and directly determines the survival and prognosis of patients with life-threatening hemorrhage. In recent years, the widespread application of low-titer group O whole blood, lyophilized plasma, and point-of-care coagulation monitoring has continuously optimized prehospital transfusion practice, while non-transfusion strategies, including tranexamic acid and physical hemostatic measures, serve as indispensable complementary interventions.

Nevertheless, clinical implementation still faces prominent challenges, such as resource constraints in austere environments, heterogeneous transfusion protocols, insufficient assessment and monitoring capabilities, and inadequate training of prehospital providers.

To address these obstacles, standardized operating procedures, strengthened interdisciplinary collaboration, enhanced public and professional education, and structured competency-based training are urgently needed to promote consistent and high-quality care. Meanwhile, emerging technologies - including novel blood products, real-time blood loss monitoring, automated transfusion systems, telemedicine platforms, and AI-driven decision support systems - provide new tools to refine transfusion timing, product selection, and personalized dosing.

Future research should prioritize the integration of big data and artificial intelligence, development of individualized transfusion strategies, establishment of robust monitoring and evaluation mechanisms, and international experience sharing. By promoting protocol standardization, technological innovation, and systematic capacity building, prehospital blood management can be further optimized to effectively reduce trauma-related mortality and improve long-term outcomes for patients with traumatic hemorrhage. This review synthesizes the current status, challenges, and future directions in this field, providing a fundamental reference for formulating evidence-based guidelines and advancing clinical practice.

Conflict of Interest

The authors have read and approved the final version of the manuscript. The authors have no conflicts of interest to declare.

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