# Multi-Tier Temperature Control of Low-Titer O Whole Blood During the Swords of Iron War

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## Abstract

**Background:** Prehospital use of whole blood is constrained by strict temperature requirements. During the Swords of Iron War, low-titer group O whole blood (LTOWB) became the primary resuscitation product on Israel Defense Forces (IDF) evacuation platforms. This study quantified battlefield cold-chain failures.

**Methods:** This retrospective observational study examined cold-chain failures of LTOWB distributed to IDF ground combat medical teams between 27 October 2023 and 31 December 2025. Medical teams checked storage temperatures every 4 hours and reported any excursion through the medical chain of command; compromised units were classified as disposed, shelf-life-reduced, or unaltered. The primary outcome was the cooling-failure rate; the secondary outcome was reduced product usability. Data were analyzed descriptively.

**Results:** A total of 4,507 LTOWB units were distributed to approximately 50 battalion-level or higher medical teams. Of these, 507 cooling-failure events were documented (11.2%): 144 in 2023 (28.1%), 147 in 2024 (9.0%), and 216 in 2025 (9.2%). Excursions shortened the expiration date in 252 events (49.7%), required disposal in 211 (41.6%), and had no meaningful impact in 28 (5.5%); the outcome was not documented in 16 (3.1%). Disposal fell from 66.0% in 2023 to 36.1% in 2024 and 29.2% in 2025.

**Conclusions:** Maintaining LTOWB temperature control at the battalion level is operationally demanding but feasible. Multi-tiered control - field refrigerators, four-hourly checks and passive coolers as backup - was accompanied by a fall in the cooling-failure rate after the first year and a shift from disposal to shortened shelf-life.

**Keywords:** Blood tranfusion, Military medicine, Resuscitation, Israeli Defense Forces, Warfare.

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## Introduction

Hemorrhagic shock is the leading cause of preventable death on the battlefield [1]. To address this challenge, military trauma management prioritizes hemorrhage control, volume resuscitation, and rapid evacuation [2], a framework known as damage control resuscit ation [3,4]. Historically, volume resuscitation relied predominantly on crystalloid solutions; however, modern evidence emphasizes prioritizing blood components [5], such as packed red blood cells and freeze-dried plasma, or administering low-titer group O whole blood (LTOWB) [6].

Early administration of blood products is associated with improved survival and with mitigation of the lethal triad of coagulopathy, hypothermia, and acidosis in combat trauma patients [7]. Compared with component therapy or freeze-dried plasma, LTOWB has been associated with improved outcomes in civilian settings, while military evidence remains inconclusive [8]. Based on civilian data and operational reasoning, consensus guidance recommends that LTOWB be available in the military within 30 minutes of casualty wounding, on all medical evacuation platforms, and at all resuscitation and surgical team locations [9].

While clinically superior, LTOWB introduces substantial logistical burdens compared with freeze-dried plasma or crystalloid-based resuscitation [10], particularly because of the stringent cold-chain requirements needed to maintain product integrity across austere, high-temperature combat zones [11,12]. Despite increasing military adoption of LTOWB, data on large-scale battlefield cold-chain maintenance remain scarce. Deployment of LTOWB in this war has been described [13], but cold-chain failure rates at the battalion level have not.

The Israel Defense Forces Medical Corps (IDF-MC) first introduced LTOWB in 2018, initially limited to aerial medical evacuation teams [14]. In 2022, the IDF-MC expanded LTOWB use to include several ground intensive care unit ambulances [3]. During the Swords of Iron War, LTOWB was introduced across ground and aerial evacuation platforms and became the primary resuscitation product [13,15].

Multi-tiered control mechanisms and continuous operational learning were introduced to maintain LTOWB at frontline ground medical units from the battalion level upwards, under battlefield conditions.

This study aimed to quantify battlefield LTOWB cold-chain failures, evaluate their impact on product usability, and describe operational mitigation strategies implemented during prolonged combat operations.

## Methods

### Study design and setting

This retrospective observational study was conducted during the Swords of Iron War in Israel between 27 October 2023 and 31 December 2025. During this period, LTOWB was progressively introduced into frontline combat medical evacuation teams within the IDF-MC. Initially, LTOWB capability was limited to brigade-level medical teams at the start of the Swords of Iron ground maneuver because of logistical constraints and limited cold-chain capacity. Over time, additional combat units were equipped with dedicated coolers and field refrigerators, enabling broader LTOWB deployment and storage capability [13].

The IDF-MC institutional review board approved the study (approval number 1948-2018), with approval renewed annually.

### LTOWB Regulations

On 29 October 2023, the IDF-MC issued a formalized standard operating for blood product management. This protocol described the standardized methodologies for ordering, supplying, transporting, storing, and returning blood products. This operating procedure was mandated across all operational units maintaining LTOWB inventories. Medical teams were required to check blood storage temperatures every 4 hours, with a target range of 2-6 °C. Any abnormal temperature recording required the submission of a standardized report. This report included: the cause of the logistical or mechanical failure, the peak or trough abnormal temperature recorded, and the duration of temperature excursions. Based on these reports, the compromised LTOWB units were classified into three mutually exclusive categories: disposal, shortened shelf-life, or unaltered. Events with no documented outcome were classified as 'Unknown'. The criteria were as follows.

Generally, when a unit was exposed, we classified it according to the criteria below; excursions above 24 °C were referred to Israel's national blood bank for a case-by-case decision. Exposure to temperatures between 6 and 10 °C for less than 24 hours reduced the expiration date by one day. For exposures between 10 and 24 °C, the shelf life was reduced by one day for every two hours of cumulative exposure. For temperature excursions above 24 °C, the unit was referred to Israel's national blood bank. Finally, any thermal deviation below 1.2 °C resulted in disposal of the unit.

## LTOWB Storage and Cooling Systems

LTOWB units at the ground echelon (non-aerial teams) in the IDF were stored by two primary means: passive coolers and refrigerators. At the field echelon, they used reusable passive cooling containers designed to maintain storage temperatures across multiple use cycles. The three models in use during the study period were the ChillTech® 4L Reusable Insulated Shipper (Sonoco ThermoSafe, Arlington Heights, IL, USA), the Crēdo Cube™ Series 4 496 4L Reusable Shipper (Peli BioThermal, Maple Grove, MN, USA), and the Golden Hour™ Mobile Series 4 Reusable Container (Peli BioThermal, Maple Grove, MN, USA). The primary limitations of the passive cooling containers were their relatively short cooling duration (up to 72 hours under ideal conditions, substantially shortened by high ambient temperatures), fixed volume constraints, and the requirement to freeze their phase-change material panels for at least 24 hours before use. The refrigerators deployed on ground evacuation platforms were the Dometic CFF 12 Mobile Compressor Cooler (Dometic Group, Stockholm, Sweden) and the Autonomous Portable Refrigeration Unit (APRU-6L) (Delta Development Team, Tucson, AZ, USA). The primary advantage of the refrigerators was their ability to maintain stable temperatures and their compatibility with the 12 V power outlets available on evacuation platforms. However, the Dometic CFF 12 refrigerator requires a continuous power connection, so the evacuation vehicle must remain running at all times. In the event of a vehicle malfunction, no backup solution exists for maintaining blood unit storage. The APRU-6L refrigerator, by contrast, incorporates an integrated rechargeable battery that can sustain operation for up to 72 hours without an external power source, providing a reliable backup when power is unavailable. Two additional refrigerators maintained whole-blood inventory at larger IDF facilities; these were stationary, higher-capacity units: the Electrolux RCB42P Blood Bank Refrigerator (Electrolux, Stockholm, Sweden) and the AcuTemp® AX56L Mobile Temperature Management Unit (CSafe Global, Dayton, OH, USA). Internal temperatures across all cooling systems, except the APRU-6L, were verified using a ThermoWorks RT801 Digital Fridge/Freezer Alarm Thermometer (ThermoWorks, American Fork, UT, USA) to ensure strict adherence to required blood preservation temperatures.

## Data collection

We obtained data from two primary sources.

The IDF Trauma Registry (IDF-TR) is a prehospital trauma registry established in 1997 to document point-of-injury and en-route care of trauma patients treated by IDF-MC teams [16]. The registry data are based on casualty cards completed during treatment and additional data entered by advanced life support providers as part of the after-action report. A dedicated team quality-checks and maintains the data.

Logistical data regarding LTOWB distribution and cooling failures were obtained from records maintained by the Southern Command Medical Equipment Officer and the IDF Medical Equipment and Biomedical Engineering Branch. A designated field medic collected LTOWB temperature data under the oversight of the battalion medical officer, then reported to the brigade medical non-commissioned officer and forwarded to the divisional and command levels. These records included all LTOWB units distributed to ground medical teams operating within the Southern Command during the study period.

## Study variables and Outcomes

The primary outcome was the cooling-failure rate, defined as the number of reported temperature-excursion events divided by the number of LTOWB units distributed in the same period. The secondary outcome was reduced LTOWB usability, defined as either shortened product shelf-life or mandatory disposal.

Variables extracted from the IDF-TR included the quantities of LTOWB administered during the study period.

## Statistical Analysis

Descriptive statistics summarized LTOWB distribution, cooling-failure events, and effects on product usability. We performed statistical analyses using R statistical software, version 4.3.1. We did not perform a sample-size calculation; the study included every LTOWB unit distributed to eligible ground combat medical teams during the study period, as recorded in the Southern Command and IDF Medical Equipment and Biomedical Engineering Branch logistical records.

# Results

In total, 5,204 casualties were recorded in the IDF Trauma Registry during the study period, and 459 LTOWB units were administered.

Approximately 50 battalion-level or higher combat medical teams maintained LTOWB capability during the study period. A total of 4,507 LTOWB units were distributed to ground combat medical teams over the 26-month study period, corresponding to a mean monthly distribution of 173 LTOWB units. In 2023, 513 units were distributed over two months (27 October to 31 December 2023). In 2024, 1,640 units were distributed, and in 2025, 2,354 units were distributed.

A total of 507 cooling-failure events were documented during the study period, representing 11.2% of distributed LTOWB units. Annual cooling-failure events were 144 in 2023 (28.1% of distributed units), 147 in 2024 (9.0%), and 216 in 2025 (9.2%) (Figure 1).

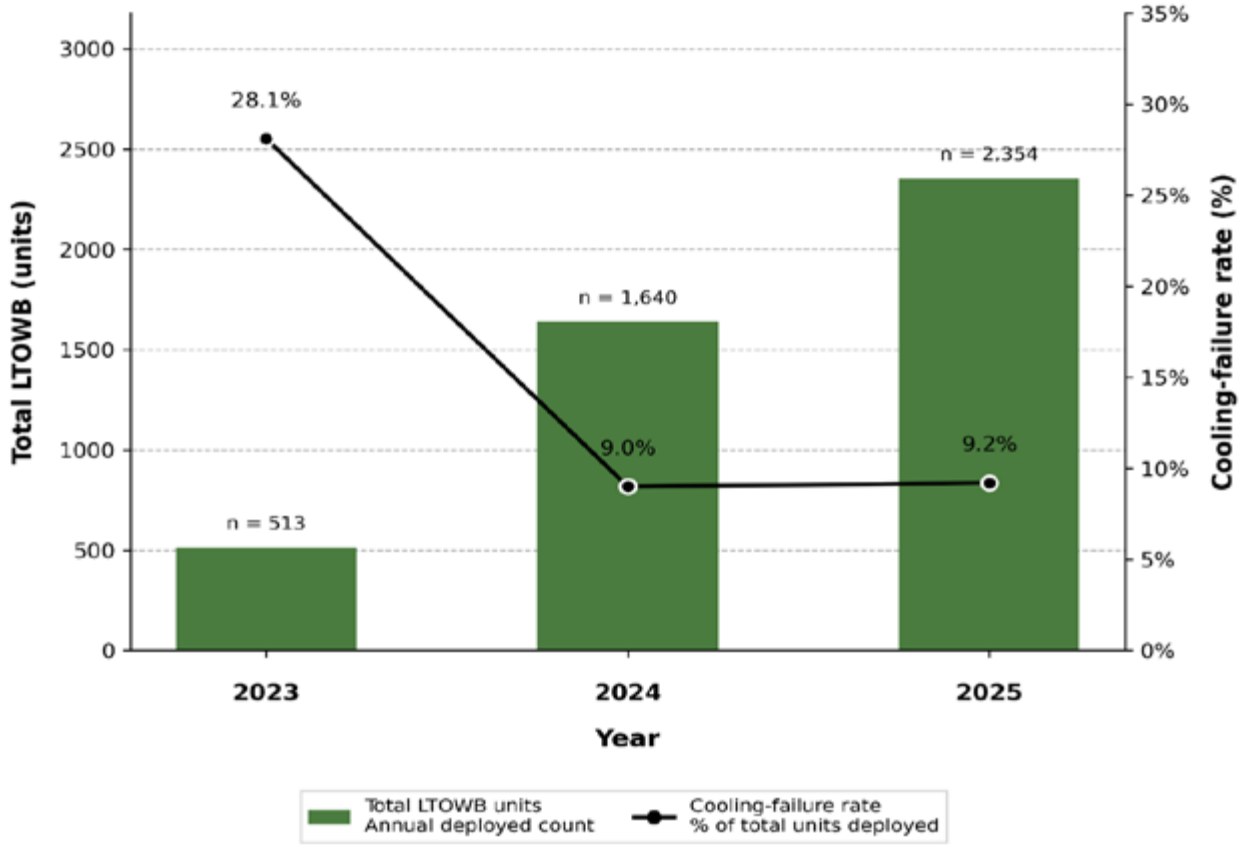



**Figure 1. Annual LTOWB distribution and cooling-failure rate, 2023–2025.**
Bars show units distributed each year; the line shows cooling-failure events as a percentage of units distributed that year.

The operational consequences of temperature excursions changed over the study period (Figure 2). In 2023, most events ended in mandatory disposal (66.0%), with shortened shelf-life in 16.0% and no meaningful impact in 11.1%. From 2024 onwards, shortened shelf-life replaced disposal as the predominant outcome (62.6% in 2024 and 63.4% in 2025), while the proportion of events ending in disposal fell to 36.1% and 29.2%, respectively; no unit remained fully usable in 2024, compared with 5.6% in 2025. The outcome was not documented for a small proportion of events in each year (Figure 2).

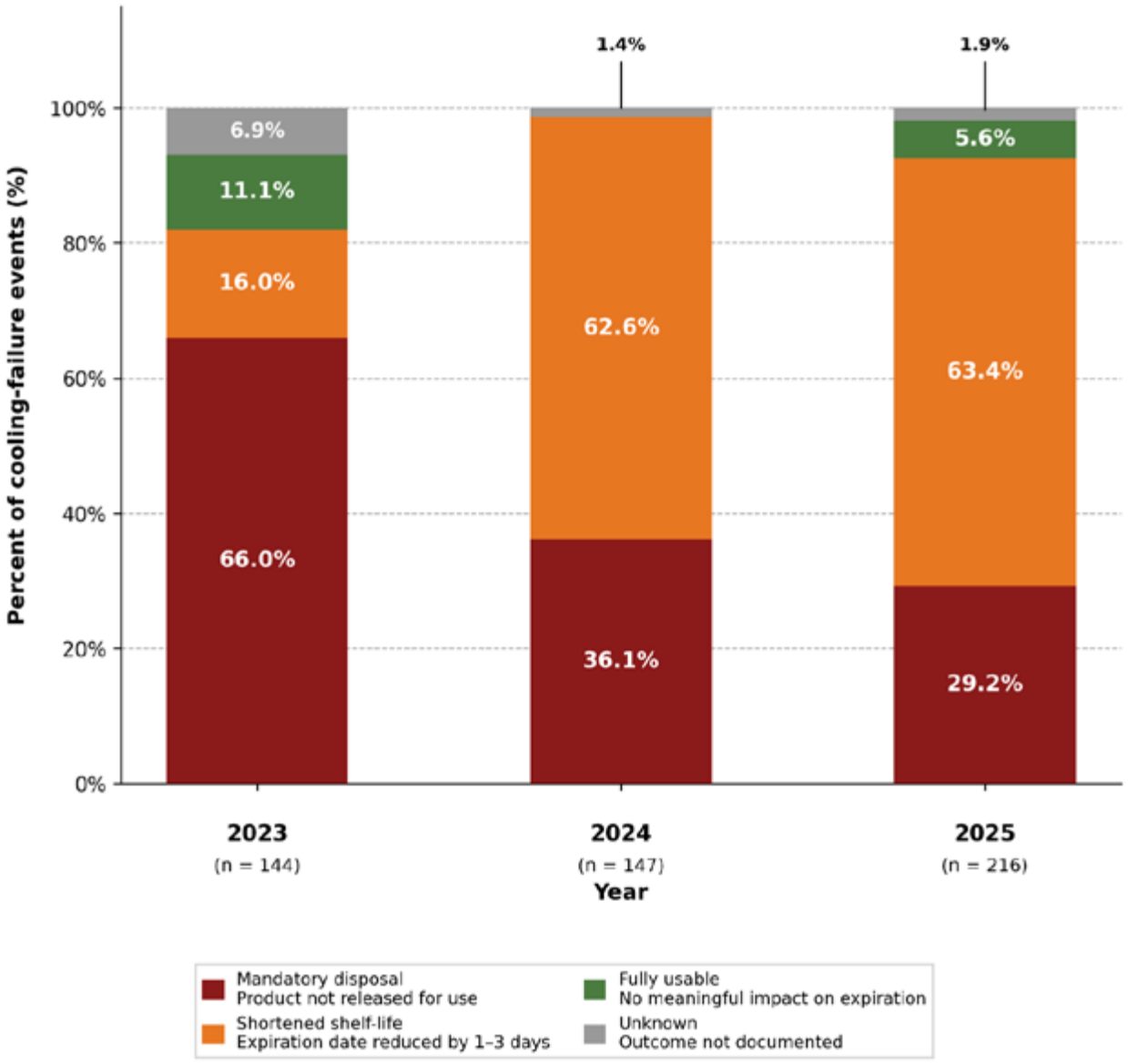



**Figure 2. Operational consequences of cooling-failure events by year.**
Stacked bars show the percentage of events ending in disposal, shortened shelf-life, no meaningful impact, or an undocumented outcome.

Analysis of cooling-failure events by quarter showed a non-uniform pattern throughout the study period (Figure 3). In Q4 2023, the initial quarter of the war, 144 cooling-failure events were recorded. During 2024, failure rates stabilized, ranging from 21 events in Q1 to a peak of 49 in Q3, followed by a decline to 32 events in Q4. In 2025, a marked rise occurred in Q2 and Q3, peaking at 92 events in Q3 2025 before declining sharply to 25 events in Q4 2025.

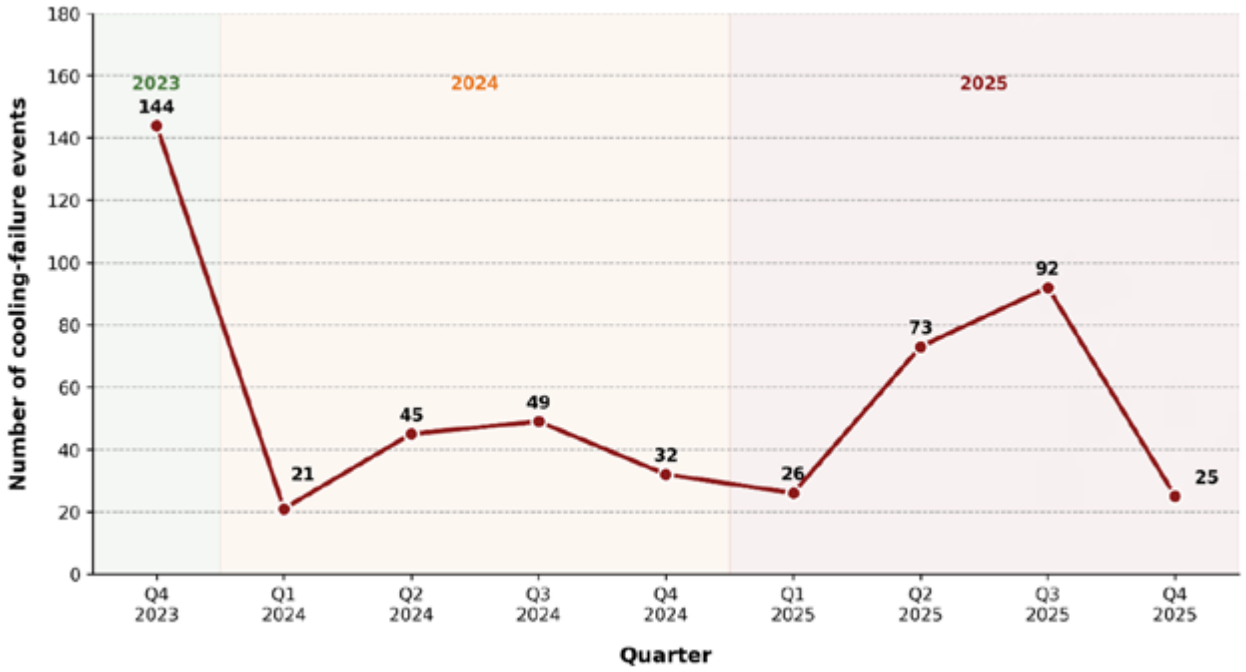



**Figure 3. Quarterly distribution of cooling-failure events, Q4 2023 to Q4 2025.**
Absolute event counts per quarter; quarterly denominators were unavailable, so rates are not shown. Q4 2023 covers 27 October to 31 December 2023.

## Discussion

Maintaining LTOWB capability at the battalion level during prolonged combat operations is operationally feasible but poses substantial logistical and cold-chain challenges. In this study, cooling failures occurred in 11.2% of distributed units, highlighting the inherent difficulty of preserving blood products under battlefield conditions characterized by extreme temperatures, prolonged deployment durations, and limited infrastructure. Despite these challenges, the overall cooling-failure rate fell from 28.1% in the first months of the war to approximately 9% in each of the following two years, and 41.6% of failures ended in disposal.

The Israeli experience during the Swords of Iron War is, by number of units distributed and by duration, among the larger reported operational deployments of LTOWB to Role 1 - the first echelon of medical care, at or near the point of injury - in a modern military setting [17]. During the study period, 4,507 LTOWB units were distributed, and 459 were administered. Sustaining this capability throughout an extended, high-intensity conflict required integrating transfusion logistics, medical command structures, and operational feedback mechanisms into a single blood-management program [15].

A notable distinction emerges when comparing these findings with the US military experience in whole-blood logistics. In the IDF, LTOWB is integrated at the Role 1 level, placing the cold-chain burden directly on ground medical teams operating with limited infrastructure and exposure to extreme temperatures. Prehospital whole blood use at the point of injury in the US military remains comparatively limited: a secondary analysis of

the Prehospital Trauma Registry found that only 28 of 1,357 patient encounters (2%) involved a prehospital blood product, with whole blood accounting for fewer than half of those administrations [17]. Storing blood products remains a challenge for medical personnel at the point of injury. Despite product availability for special operations forces, many conventional units still struggle to obtain blood products through their supply chain [17]. The logistical advantages of far-forward LTOWB - that is, LTOWB held at or near the point of injury - are also documented in the US experience. LTOWB simplifies resuscitation by eliminating the need for thawing or crossmatching, while also being space-efficient and reducing time to transfusion [18]. At the theater level - the whole operational area of a campaign - the US Central Command's transition to a whole-blood-dominant strategy has been reported to reduce overall blood product destruction and to simplify cold-chain storage compared with managing multiple components with differing handling and temperature requirements [12]. These findings reinforce the rationale underlying the IDF's adoption of LTOWB as the primary resuscitation product at the forward echelon, even as they highlight the logistical challenge of maintaining an uninterrupted cold chain at the most forward point of care.

A key finding of this study is the progressive reduction in the operational consequences of cooling failures over the course of the war. The reduction in severe cooling failures over time may reflect organizational learning and process refinement, along with the progressive introduction of more advanced cooling technologies. Over the course of the war, the cold chain evolved from predominantly passive cooling systems to active field refrigeration units. Unlike traditional insulated coolers, these systems provide continuous temperature regulation through external power sources. This effort was led by the IDF Medical Equipment and Biomedical Engineering Branch, which redesigned the refrigerators' connection interfaces, originally intended for standard civilian vehicles, to enable compatibility with armored military evacuation platforms. Another contributing factor was the introduction of field generators, which made it easier to connect refrigerators to a power source. These improvements were informed by feedback from field medical personnel, gathered through phone consultations and scheduled visits to forward units.

In addition, throughout the study period, frontline medical personnel became increasingly familiar with LTOWB storage requirements and temperature-monitoring procedures. Several medical non-commissioned officers also began transitioning to digital documentation of LTOWB unit temperatures, accompanied by tighter divisional- and brigade-level oversight. This growing operational experience may have enabled earlier identification of cold-chain deviations and more timely corrective actions, thereby reducing the likelihood that temperature excursions progressed to irreversible product loss.

A further observation was the consistently higher number of cooling-failure events in Q2 and Q3 - the summer months of April to September - in both 2024 and 2025. This seasonal pattern likely reflects the impact of ambient heat and the reduced capacity of passive coolers and refrigerators to maintain adequate temperatures under extreme environmental conditions, particularly within non-ventilated evacuation vehicles that heat rapidly during the summer months.

Structured monitoring processes and continuous operational feedback disseminated lessons learned across deployed units. Collectively, these technological, organizational, and educational adaptations likely contributed to the observed shift from failures resulting in product disposal toward events associated primarily with shortened shelf life or no meaningful impact on product availability. These findings are consistent with adaptive quality-improvement processes helping to maintain blood-product readiness during prolonged military operations.

## Future Directions for Cold-Chain Optimization

Some wastage is inherent to forward deployment, where the mandate for immediate life-saving capability requires a surplus that inevitably risks expiration [18]. Future efforts should focus on maximizing product availability while minimizing avoidable losses.

The observed reduction in the consequences of temperature excursions highlights opportunities to optimize forward blood-management systems. Priority

should be given to automated temperature-monitoring technologies that continuously record storage conditions and provide early warnings of impending cold-chain breaches. Such systems could improve assessment of excursion duration and severity, facilitate evidence-based decisions regarding product usability, reduce unnecessary wastage, and further strengthen the resilience of forward-deployed LTOWB programs.

## Limitations

This study has several limitations. First, its retrospective design limits the ability to fully characterize all factors contributing to cooling failures. Second, documentation of temperature excursions relied primarily on manual reporting by frontline medical personnel rather than continuous automated systems, introducing bias in ascertaining thermal deviations. This limitation is particularly relevant in high-intensity combat environments, where operational priorities may compromise routine monitoring and documentation practices [19,20]. These reports did not record the type of cooler, refrigerator, or platform involved; therefore, the specific causes of cooling-failure events could not be determined. The direction of any reporting error is uncertain: units have an incentive to report failures to obtain replacement stock, which may inflate counts, while manual four-hourly checks cannot detect a transient excursion that resolves between checks, which would deflate them.

Third, the study focused primarily on ground combat medical teams within the Southern Command and excluded aerial evacuation platforms from analyses of LTOWB distribution and cooling failures due to their fundamentally different storage infrastructure and operational workflows. Therefore, the findings may not be generalizable to all military evacuation and resuscitation platforms.

Another limitation is the lack of quarterly data on LTOWB unit distribution; only annual totals were available. This precluded calculating quarterly cooling-failure rates as a proportion of units distributed, limiting the quarterly trend analysis to absolute event counts rather than relative rates.

Finally, although a national protocol governed classification in this setting, no internationally standardized criteria exist for classifying blood units after temperature excursions - specifically for disposal, shelf-life reduction, or continued viability - which limits comparison with other military and civilian cold-chain programs.

## Conclusions

Maintaining LTOWB capability at the battalion level during prolonged combat operations is feasible but logistically demanding. As deployment expanded through the Swords of Iron War, the proportion of cooling failures ending in complete product loss fell, alongside continuous operational learning and multi-tiered temperature control. Over time, most temperature excursions shifted from disposal to reductions in product shelf-life, enabling sustained forward availability of whole blood on the battlefield.

These findings describe sustained LTOWB cold-chain maintenance at the battalion level during active warfare and may inform future military blood-sustainment strategies.

### Conflict of interest

The authors declare no conflicts of interest.

### Source of Support

None to declare.

### Disclaimer

The views expressed are the authors' own and not an official position of the institution, the funder, the IDF, or the IMA.

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