Original article

Delivery time and wastage of red blood cell units in a Swiss transfusion network: a 5-year retrospective study

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Background - Efficient distribution of red blood cell concentrates (RCCs) is essential for maintaining product quality and minimizing wastage. This study examined RCC distribution across three Swiss cantons and temporal patterns across the COVID-19 period.

Materials and methods - A retrospective analysis of Interregional Blood Transfusion SRC (Swiss Red Cross) data was conducted on RCCs distributed to hospitals in Vaud, Valais and Bern between 2019 and 2023. Delivery time was defined as the time between donation and the recorded delivery event at a clinical or laboratory recipient, and wastage as recorded discard-coded records. Analyses examined delivery time by destination region, recipient hospital type, ABO/Rh blood group, collection kits, product type and COVID-19 period.

Results - A total of 312,340 records were included, comprising 295,544 clinical/laboratory deliveries and 10,364 recorded discards (3.3%). Mean delivery time was 15.4 days (median 15 days) and ranged from 13.3 to 17.3 days across canton and institution groups. Among standard products, the longer-shelf-life collection system had a longer mean delivery time (20.8 *vs* 14.7 days, p<0.001) and more deliveries after 35 days (3.3% *vs* 1.0%). Delivery after 35 days occurred in 12.5% of AB+ and 5.6% of AB– deliveries, compared with 0.5%-1.3% for A and O groups. Irradiated and washed RCCs had recorded discard proportions of 0.3% and 0%, respectively, whereas paediatric splits had a recorded discard proportion of 36.6%. Mean delivery times were 15.3, 14.5 and 16.0 days across the three predefined calendar COVID-19 periods; recorded discard proportions were 3.8%, 3.4% and 3.0%, respectively.

Discussion - RCC delivery times remained within licensed storage limits, but disparities persisted across regions, recipient types and blood groups. Calendar-period differences did not establish a causal effect of the pandemic. These findings highlight opportunities to optimize inventory management and reduce wastage, particularly for least common blood groups.

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INTRODUCTION

Efficient distribution of red blood cell (RBC) units from blood centers to hospitals is fundamental to transfusion service quality. Delivery time, the interval between donation

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and delivery to the recipient institution, represents a critical operational metric, as prolonged storage may affect RBC quality. During storage, RBCs undergo progressive biochemical and biomechanical changes collectively termed as storage lesions, including depletion of 2,3-diphosphoglycerate and adenosine triphosphate, metabolome and proteome modifications, increased membrane fragility, morphology changes, hemolysis and microparticle accumulation[1-7]. Understanding factors that influence distribution patterns is therefore essential for optimizing blood inventory management and minimizing product wastage.

Blood product wastage remains a significant concern for transfusion services worldwide, representing both economic burden and loss of valuable donor contributions. Wastage incurs direct costs related to collection, processing and storage, whilst raising ethical concerns regarding appropriate utilization of a limited volunteer-donated resource. Wastage can also reduce the reserve available during sudden increases in blood demand and may result from quality or handling failures, including mishandling. Previous studies have identified factors associated with increased wastage, including inventory management practices, hospital characteristics, blood group distribution and collection system variations[8,9]. However, comprehensive analyses of RBC concentrate (RCC) distribution patterns across diverse geographical and institutional settings remain limited in the European context.

The Swiss transfusion system provides a unique model for studying distribution efficiency due to its decentralized organization. Coordinated nationally by Swiss Transfusion SRC (Swiss Red Cross) which sets uniform standards for donor eligibility, product specifications and hemovigilance, and implemented by regional blood transfusion services that collect, manufacture and distribute components, the system adapts to diverse geographical terrains from urban centers to Alpine valleys. The Interregional Blood Transfusion SRC Ltd (TIR) serves three distinct cantons (Vaud, Valais and Bern), each with varying hospital types, geographical characteristics and patient populations. Regional blood services can exchange components directly, with national coordination particularly during crises and searches for rare products. Together, deliveries to institutions in Vaud, Valais and Bern accounted for 30.3% of the reported national RCC volume during 2019-2023. This diversity offers an opportunity to examine how regional and institutional factors influence RCC distribution efficiency whilst controlling for national quality standards.

The COVID-19 pandemic introduced unprecedented challenges to blood supply chains globally, disrupting donor attendance, altering hospital transfusion practices and creating logistical constraints[10,11]. Early in the pandemic, many countries reported reduced blood donations coupled with decreased transfusion demand due to postponement of elective surgeries. Switzerland maintained stable blood donation volumes during 2020-2022; however, the extent to which regional distribution patterns and wastage were affected has not been systematically evaluated.

This study describes, in function of donors' characteristics and product types, RCC delivery times and product wastage across three Swiss cantons with distinct geographical and organizational characteristics, identifies factors associated with prolonged storage and increased wastage, and compares distribution patterns across prespecified calendar periods spanning the COVID-19 pandemic from 2019 to 2023. The primary question was how donation-to-delivery time and recorded discard proportions varied by recipient setting, blood group, collection system, product type and calendar period.

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MATERIALS AND METHODS

Study design and setting

This retrospective analysis used anonymized operational data from TIR, which provides blood products to hospitals in the cantons of Vaud, Valais and Bern, Switzerland. The study period encompassed January 2019 through December 2023, enabling comparison of pre-COVID, during-COVID and post-COVID periods.

Data source and study population

Data were extracted from the operational databases of TIR. They included: donation date, ABO and Rhesus D blood groups, donor age and sex, type of blood collection kit, delivery and institution date. Only records from donors who had provided research consent were included (No.=312,340). Final dispositions were 295,544 clinical/laboratory deliveries, 10,364 recorded discards, 6,143 blood-service transfers,

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287 internal/research/quality-control records and two unclassified destinations. Clinical-delivery analyses used the 295,544 clinical/laboratory records; clinical deliveries ranged from 1 to 49 days. Missing ABO/Rh information represented 634 records (0.2%) and was excluded only from blood-group-specific analyses.

Variables and definitions

Blood products

Whole blood donations were collected in either Top-Top or Top-Bottom kit. Whole blood (450±50 mL) was collected into 63 mL citrate-phosphate-dextrose; Top-Bottom units were prepared using CQ32250 sets (Fresenius Kabi, Bad Homburg, Germany) and Top-Top units using FQE 6241LU sets (now known as FQE 641U, MacoPharma, Mouvaux, France). The Top-Top kit includes whole-blood filtration and storage of RCCs in phosphate-adenine-glucose-guanosine-saline-mannitol (PAGGSM) additive solution, with a nominal shelf life of 49 days, whereas the Top-Bottom kit uses component filtration and saline-adenine-glucose-mannitol (SAGM), with a nominal shelf life of 42 days. Blood was centrifuged (hard-spin, according to standard operating procedures; Roto Silenta 630 RS, Hettich AG, Bäch, Switzerland) and expressed on a CompoMat G5 (Fresenius Kabi). Irradiated RCCs (25-50 Gy) are irradiated no later than day 14 after donation and must be transfused within 14 days of irradiation or 28 days of donation, whichever occurs first (rule in effect during the studied period). Washed RCCs are less than 14-day old before processing, resuspending in SAGM and stored for 7 days post-washing. Irradiated and washed RCCs are less than 5-day old before processing, with a maximum of 7 days post-treatment in pediatrics. Finally, pediatric splits are 72 mL units ± 12 mL with a storage of 10 days post-donation.

Delivery time

Delivery time was defined as calendar days between donation date and the recorded delivery event at a clinical or laboratory recipient. No separate release timestamp or transfusion date was available. Maximum licensed storage duration for RCCs in Switzerland is 42-49 days depending on the additive solution.

Ordering and delivery

Hospitals order online, or by telephone for urgent requests, and TIR issues units on demand rather than as a standing allocation, first-in-first-out, with a target of at least two weeks of remaining shelf life at issue; special products and fresh O RhD-negative units for maternity services are the exceptions. Regional blood transfusion services exchange units directly when stock is short or in excess. Delivery routes differ between cantons (**Figure 1**) and regional organizations in Switzerland: in Vaud the university hospital is supplied through a transfusion medicine unit operated by TIR, in Bern the university hospital operates its own transfusion medicine unit, and in Valais units pass through a TIR distribution service located within the canton, so the recorded delivery event corresponds to a different point in the chain in each canton.

Wastage

Wastage was operationalized as recorded discard-coded records divided by all included records within each subgroup. Recorded discards comprised 7,183 production rejections, 539 distribution-site rejections, 2,589 expiry-labelled records and 53 CHUV damaged products. Blood collection failures were not recorded here. Release status and originating hospital were not available for all discard records.

Variables examined as predictors included: canton (Vaud, Valais, Bern); hospital type (university hospital, peripheral hospital, other specialized centers); ABO/Rh blood group; collection system; donor age and sex; and COVID-19 period [pre-COVID: January 2019-February 2020; during COVID: March 2020-June 2021 (including the two Swiss lockdowns); post-COVID: July 2021-December 2023].

Statistical analysis

Analyses were performed using R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria). Continuous variables were summarized using mean, median, standard deviation, 95% confidence intervals and interquartile range. Categorical variables were expressed as frequencies and percentages.

Comparisons between groups used non-parametric tests: Kruskal-Wallis test for multiple-group comparisons with Dunn's *post-hoc* test and Bonferroni adjustment; Wilcoxon rank-sum test for two-group comparisons. Proportions were compared using chi-square tests. Statistical significance was set at $p<0.05$. Additional analyses examined the proportion of units delivered more than 35 days after donation.

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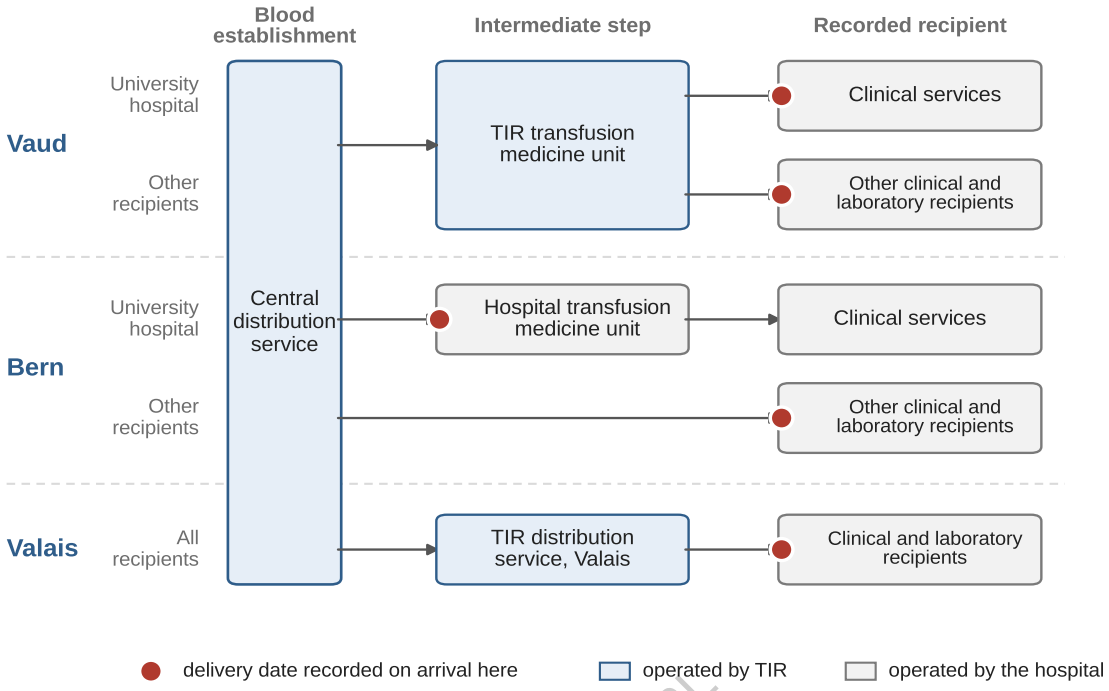


Figure 1 - Schematic of hospital distribution pathways in the three TIR networks
Blue boxes denote TIR-operated services, grey boxes hospital-operated services, and red dots the recorded recipient endpoints. Recorded endpoints differ between regional pathways, as described in the Methods. Exceptions may exist.

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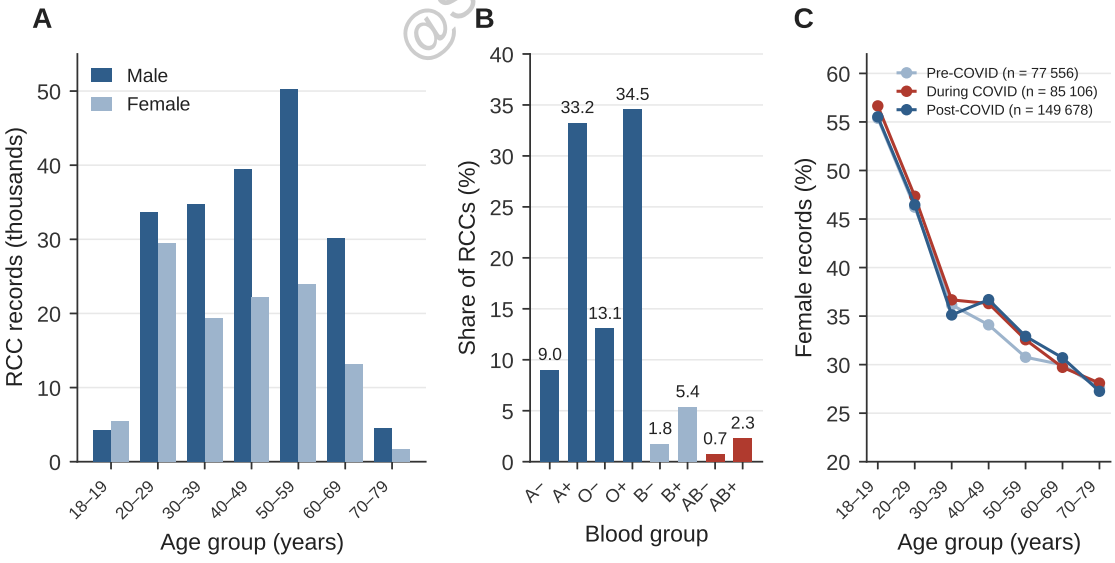


Figure 2 - Record-weighted donor characteristics and ABO/RhD distribution, 2019-2023
(**A**) RCC records by donor age group and sex. (**B**) ABO/RhD distribution among records with known blood group. Percentages are based on records rather than unique donors. (**C**) Proportion of female records by age group in each calendar period, with the number of records per period. In (**B**), colours reflect blood-group rarity: common groups (A and O) are shown in dark blue, B groups in light blue and AB groups in red; the same colour code is used in **Figure 3**.

Ethical considerations

This study used anonymized operational data from routine blood transfusion service activities. Data were anonymized prior to analysis in accordance with Swiss data protection regulations; only donations from donors who provided research consent were included.

RESULTS

Overview of RCC distribution and donor characteristics

The cohort comprised 312,340 records: 295,544 clinical/laboratory deliveries, 10,364 recorded discards, 6,143 blood-service transfers, 287 internal/research/quality-control records and two unclassified destinations. Annual-included records decreased from 66,637 in 2019 to 57,957 in 2023. Donor characteristics are shown in **Figure 2**. Donors were predominantly male (63.1%), with a mean donor age of 43.5 years (median 45 years, range 18-75 years). The most represented age group was 50-59 years in male and 20-29 in female donors (**Figure 2A**). Among donations with known blood group, the most frequent groups were O+ (34.5%), A+ (33.2%), O− (13.1%) and A− (9.0%) (**Figure 2B**). Groups AB− (0.7%) and B− (1.8%) were infrequent. ABO/RhD was unavailable in 634 records (0.2%).

Delivery time by destination region and recipient type

Overall mean delivery time was 15.4 days (median 15 days, standard deviation 7.8 days). Delivery after 35 days occurred in 3,777/295,544 clinical/laboratory deliveries (1.3%).

Mean delivery times were 14.1 days in Bern (No.=158,818), 17.0 in Vaud (No.=92,280) and 16.9 in Valais (No.=35,957), as shown in **Table I**. A further 8,463 deliveries (2.9%) could not be assigned to a region and 26 went to institutions outside the three cantons. The three-canton comparison was significant (Kruskal-Wallis H=10,761.5, df=2, p<0.001), with all Dunn-Bonferroni pairwise comparisons p<0.001.

Recipient type also differed in delivery time (Kruskal-Wallis H=2,333.9, df=1, p<0.001). University recipients accounted for 135,539 clinical deliveries (mean 14.8 days) and other clinical/laboratory recipients for 160,005 (mean 15.9 days). In Vaud, university and other recipients averaged 17.3 and 16.7 days; in Bern, 13.3 and 14.9 days.

Delivery time by collection system

Delivery times differed significantly according to collection system. Among standard products, Top-Top units had longer mean delivery times than Top-Bottom units (20.8 *vs* 14.7 days, respectively, Wilcoxon rank-sum test p<0.001), a 6.1-day difference.

Delivery after 35 days occurred in 1,382/41,453 Top-Top deliveries (3.3%) and 2,395/247,126 Top-Bottom deliveries (1.0%). Recorded discard proportions were 1,881/44,202 (4.3%) and 8,015/260,649 (3.1%), respectively. Date-derived donor age was lower for Top-Top than Top-Bottom records (40.6 *vs* 44.0 years); male proportions were similar (63.0% *vs* 63.1%). Detailed comparison is provided in **Table II**.

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Table I - *Clinical/laboratory delivery time by destination region and recipient type, 2019-2023*

Destination region / recipient	Delivery No.	Mean (SD), days	Median [IQR], days	>35 days, No. (%)
Bern, all	158,818	14.1 (8.2)	13 [8-20]	1,770 (1.1%)
Bern: other clinical/laboratory	75,421	14.9 (6.9)	14 [9-20]	287 (0.4%)
Bern: university hospital	83,397	13.3 (9.1)	12 [6-20]	1,483 (1.8%)
Vaud, all	92,280	17.0 (7.3)	16 [12-21]	1,750 (1.9%)
Vaud: other clinical/laboratory	40,140	16.7 (6.1)	16 [13-21]	142 (0.4%)
Vaud: university hospital	52,140	17.3 (8.1)	16 [12-22]	1,608 (3.1%)
Valais, all	35,957	16.9 (6.5)	16 [13-21]	207 (0.6%)
Other, all	26	9.5 (7.3)	8 [3.25-15]	0 (0.0%)
Unknown/Unresolved, all	8,463	16.8 (6.2)	16 [13-21]	50 (0.6%)
All regions: other recipients	160,005	15.9 (6.6)	15 [11-21]	686 (0.4%)
All regions: university	135,539	14.8 (9.0)	14 [8-21]	3,091 (2.3%)
Overall	295,544	15.4 (7.8)	15 [10-21]	3,777 (1.3%)

Clinical/laboratory delivery records. SD: standard deviation; IQR: interquartile range. Regional comparison restricted to Bern, Vaud and Valais (No.=287,055): Kruskal-Wallis H=10,761.5, df=2, p<0.001; all Dunn-Bonferroni pairwise comparisons p<0.001. Recipient-type comparison: H=2,333.9, df=1, p<0.001. No. hospital-specific discard rate was estimated.

Annual volume of Top-Top units showed considerable variation (12,635 units in 2019 to 4,845 units in 2020). The quarantine fresh frozen plasma initially collected from the Top-Top kit was progressively replaced in 2019 by pathogen inactivated fresh frozen plasma from the Top-Bottom kit. This latter remained more stable, ranging from 47,181 to 57,520 units annually.

Delivery time and recorded discards by blood group

Delivery-time distributions differed markedly across ABO/Rh groups (**Figure 3A**). Common groups in the population (O+, A+), as well O– and A–, displayed narrow distributions with peaks around 10-20 days, and distributions that tend to 0 beyond 35 days after donation. As for least common groups (AB+ and AB–), broader densities were observed with right-shifted distributions extending toward the upper range. B– and B+ groups exhibited intermediate profiles. The proportion of units delivered after more than 35 days was low for common groups (0.5% for A+ and 0.9% for O+) but increased sharply for least common groups, reaching 5.6% for AB– and 12.5% for AB+ (**Figure 3B**), alongside their higher recorded discard proportions. Recorded discard proportions varied considerably by blood group (**Figure 3C**). Common blood groups (A and O) demonstrated consistently low recorded discard proportions of 2.0-2.6%, including low proportions of expired RCCs. In contrast, least common blood groups showed substantially higher recorded discard proportions: AB+ 17.7% and AB– 13.5%, representing a 5-7 fold increase in recorded discards compared with common groups (chi-square p<0.001). B+ and B– groups showed intermediate wastage rates of 6.9% and 4.9%, respectively.

Table II - *Standard-product collection systems, 2019-2023*

Characteristic	Top-Bottom	Top-Top
Donations, No.	260,649	44,202
Clinical deliveries, No.	247,126	41,453
Delivery time, mean (SD), days	14.7 (7.4)	20.8 (8.3)
Delivery time, median [IQR], days	14 [9-20]	21 [16-26]
Delivery >35 days, No. (%)	2,395 (1.0%)	1,382 (3.3%)
Recorded discards, No. (%)	8,015 (3.1%)	1,881 (4.3%)
Donor age, mean, years	44.0	40.6
Donations from male donors, No. (%)	164,497 (63.1%)	27,865 (63.0%)
Donations by donor age, No. (%)		
<20 years	6,947 (2.7%)	2,571 (5.8%)
20-29 years	50,359 (19.3%)	11,170 (25.3%)
30-39 years	45,373 (17.4%)	7,538 (17.1%)
40-49 years	51,929 (19.9%)	8,261 (18.7%)
50-59 years	63,096 (24.2%)	9,349 (21.2%)
60-69 years	37,456 (14.4%)	4,821 (10.9%)
70-79 years	5,489 (2.1%)	492 (1.1%)
Annual donations, No./Clinical deliveries, No./Mean, days		
2019	52,570 / 49,758 / 14.7	12,635 / 11,663 / 19.4
2020	57,520 / 54,458 / 14.8	4,845 / 4,472 / 20.5
2021	54,298 / 51,734 / 13.7	8,013 / 7,643 / 19.5
2022	49,080 / 46,521 / 14.3	9,076 / 8,538 / 20.6
2023	47,181 / 44,655 / 16.4	9,633 / 9,137 / 24.0

Standard products only. Delivery >35 days uses clinical deliveries as denominator; recorded discards, donor sex and age groups use all corresponding records. Delivery-time comparison: Wilcoxon rank-sum p<0.001; recorded-discard comparison: Pearson χ^2=167.7, df=1, p<0.001. Age was calculated from birth and collection dates.

Product type

Pediatric splits represented a special category with particularly high wastage: 448/1,224 recorded discards (36.6%) compared with 9,897/304,852 (3.2%) for standard products. It reflects inherent challenges of managing small-volume products with limited shelf life after processing and the precise matching required with pediatric recipients. Non-pediatric irradiated and washed RCCs showed minimal recorded discards: 19/6,238 (0.3%) and 0/16 (0%), respectively (**Figure 3D**), likely reflecting rapid utilization for specific clinical indications. Mean delivery times were 15.6 days for standard products, 6.4 for pediatric splits, 7.7 for non-pediatric irradiated products and 9.4 for washed products.

Impact of COVID-19 pandemic on distribution and wastage

Mean delivery times in the pre-COVID, during-COVID and post-COVID periods were 15.3, 14.5 and 16.0 days, based on 72,885, 80,993 and 141,666 clinical/laboratory deliveries, respectively (**Figure 4**).

All pairwise comparisons between COVID-19 periods remained highly significant after Bonferroni adjustment (all p<0.001). Delivery-time distributions by period are illustrated in **Figure 4**, showing not only shifts in median values but also changes in distribution shape, with the

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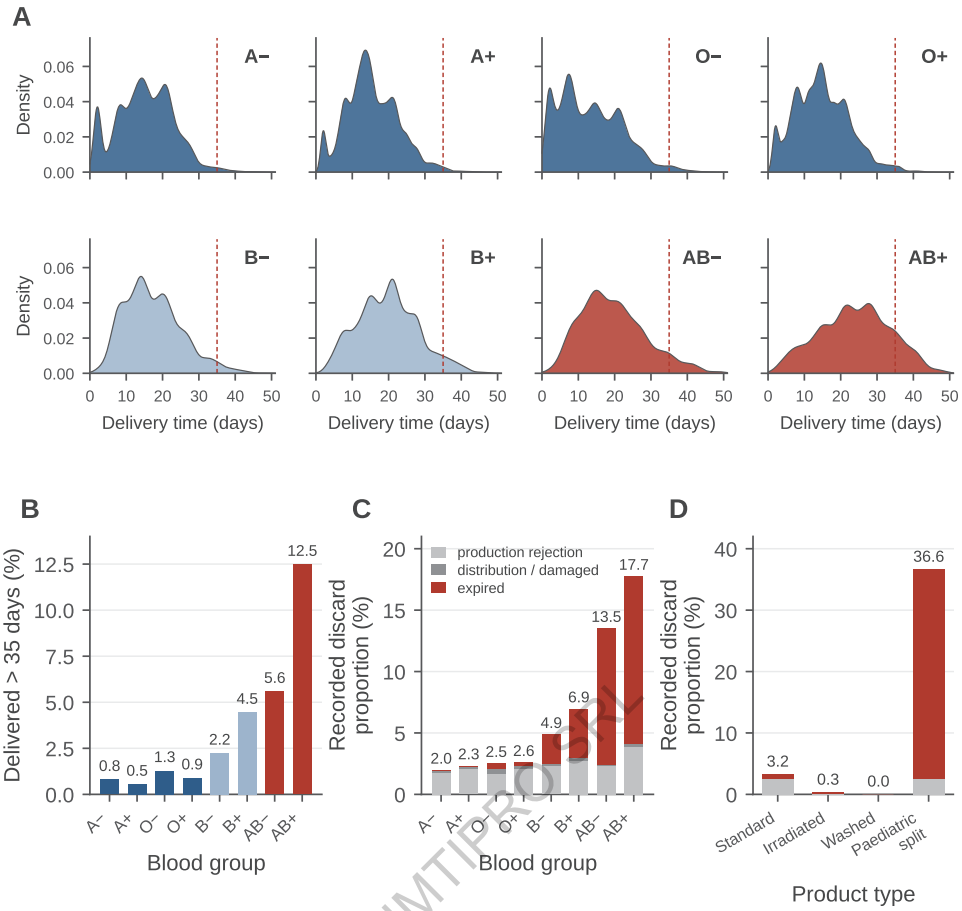


Figure 3 - Donation-to-recorded-recipient intervals and recorded discards by blood group and product type
(**A**) Delivery-time distributions by ABO/RhD group; the dashed line indicates 35 days. (**B**) Percentage of clinical/laboratory deliveries occurring after 35 days within each blood group. (**C**) Recorded discard proportion within each blood group, stratified by discard category (production rejection, distribution-site rejection or damaged product, expiry). Blood groups are shown in the order A−, A+, O−, O+, B−, B+, AB−, AB+. (**D**) Recorded discard proportion within each product type, using the corresponding product-specific denominator.

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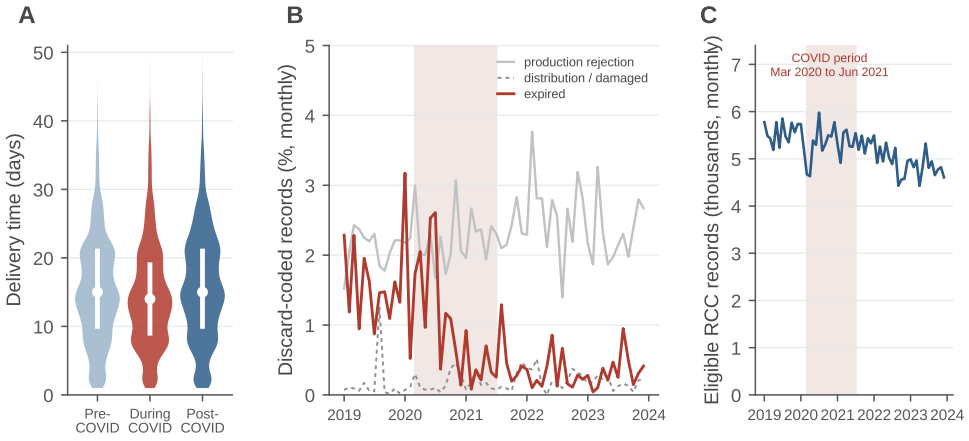


Figure 4 - Donation-to-recorded-recipient intervals and monthly recorded-discard patterns across the pre-COVID, during-COVID and post-COVID periods
(**A**) Delivery-time distributions by period (No.=72,885, 80,993 and 141,666 clinical/laboratory deliveries, respectively). (**B**) Monthly proportions of discard-coded records by category (production rejection; distribution-site rejection or damaged product; expiry). (**C**) Monthly number of eligible RCC records. The shaded area indicates the during-COVID period.

during-COVID period showing a slightly narrower distribution.

Recorded discard proportions were 2,977/77,556 (3.8%) in the pre-COVID period, 2,897/85,106 (3.4%) during COVID and 4,490/149,678 (3.0%) in the post-COVID period. Expiry-labelled records accounted for 1.6%, 1.0% and 0.4%, respectively. March 2020 had 235/4,670 discard-coded records (5.0%).

DISCUSSION

This analysis of 312,340 records from the regional network found a mean clinical delivery time (and not a transfusion time) of 15.4 days, remaining well below licensed storage limits. However, significant disparities exist across cantons, hospital types, blood groups and collection systems. These findings highlight specific areas where targeted interventions could improve efficiency and reduce wastage. The higher proportion of O– donations in the cohort compared with the O– blood group frequency in the Swiss general population (13.1% *vs* approximately 6%) is consistent with targeted recruitment strategies aimed at maintaining adequate stocks of O– units for emergency transfusion support[12].

Moreover, our results resonate with observations from Germany and Canada. In a large German cohort[13], the majority of donors were male (around 70%) and older than 40, which is broadly similar to our 63% male proportion and mean age around 44 years. Likewise, Charbonneau *et al.*[14] found in Quebec (Canada) that whole blood donors tend to be older and more stable repeat donors compared to apheresis donors, who are often younger and more motivated by altruistic factors. European donor demographics also vary across countries and over time, as well frequencies of permitted donations, so sex distributions observed in a single network should not be assumed to be universal[15]. Although our study focuses exclusively on whole blood-derived RCCs, the age distribution confirms a predominance of middle-aged donors sustaining the blood supply.

Regional determinants and operational factors

Mean delivery times differed across cantons, ranging from 14.1 days in Bern to 17.0 days in Vaud, with 16.9 days in Valais. Two structural factors account for much of this variation, and neither is geographical. First, the recorded endpoint differs between cantons (**Figure 1**): one step before the clinical service in Bern, at the service itself in Vaud, and after an internal TIR transfer in Valais. Second, inventory turnover differs: RCC use per 1,000 inhabitants (average 2019-2023) is 32.4 in Bern, 29.0 in Vaud and 22.2 in Valais, against a national average of 24.8 (in 2025: 28.5, 26.3, 17.8, and 22.2, respectively; data from the Federal Statistical Office and TIR), and higher turnover lowers the age of units at delivery.

Vaud and Valais showed longer mean delivery times than Bern, and transport distance is not required to account for this ranking. The Vaud university hospital showed slightly longer mean delivery times than other Vaud clinical/laboratory recipients, suggesting that institutional classification alone is insufficient to predict demand complexity. University hospitals may manage more complex case-mixes requiring specialized blood products, different ordering patterns or larger safety stocks due to their role as referral centers. This aligns with previous studies demonstrating that geographical and institutional factors significantly influence blood distribution efficiency[16,17].

Collection system and inventory management

Here, in routine practice, Top-Top kits are often used for new donors or when production of buffy-coat-derived platelet concentrates is not required; Top-Bottom kits are more often used for established donors. Under first-in-first-out issuing, a 49-day unit collected on the same day as a 42-day unit is issued after it, and the two-week remaining-shelf-life target allows Top-Top units to be delivered up to day 35, against day 28 for Top-Bottom-derived units. Top-Top units had longer delivery times than Top-Bottom units (20.8 *vs* 14.7 days) and a higher proportion delivered after 35 days (3.3% *vs* 1.0%). RCCs stemming from the Top-Top kit are stored in PAGGSM with a nominal shelf life of up to 49 days, compared with 42 days for Top-Bottom units. PAGGSM provides improved preservation during storage, although storage lesions still progressively develop over time. The longer delivery times observed for Top-Top units should therefore be interpreted in the context of product age at delivery rather than as evidence of poorer product quality[1,18].

Least common blood groups and special products

The markedly elevated recorded discard proportions for least common blood groups (AB+: 17.7%, AB–: 13.5%) compared to common groups (2.3-2.6%) represent a

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significant challenge and highlight a classic inventory paradox in blood banking. AB recipients can receive non-AB RBC units, but AB RCCs can be issued only to AB recipients, making AB units vulnerable to expiry when local demand is low. This inherent mismatch between supply (based on donor population frequencies) and demand (constrained by compatibility rules) creates unavoidable tension in inventory management.

Similar challenges have been documented in other blood transfusion systems, particularly in low-volume hospitals where emergency readiness competes with limited turnover[16,17]. The high wastage rates likely reflect difficulty matching these units with appropriate recipients, leading to prolonged inventory holding and eventual expiry. Consistent with this, AB discards were predominantly expiry-coded (**Figure 3C)**. The broader delivery-time distributions for AB+ and AB– units, with substantial proportions exceeding 35 days, confirm this pattern.

Blood centers should consider inventory strategies for short-dated and low-turnover blood groups, including closer monitoring or automated alerts and, where validated, redistribution to centers with greater turnover. Near-expiry redistribution has been implemented elsewhere: Denesiuk *et al.* reported 106 RCCs transferred from remote hospitals and subsequently transfused at a higher-use center in Alberta (Canada), using a validated transport system[19].

The extremely high wastage rate for pediatric splits (36.6%) underscores unique challenges of managing small-volume products. Once processed, these specialized products (1/4 of the initial RCCs) have limited shelf life to 10 days post-donation. Moreover, the 4th product could be too small because of the target of 72 mL and hence discarded, and the remaining splits might be reserved for the patient to favor unique donor transfusion. Strategies to reduce pediatric split wastage might include improved demand forecasting, just-in-time splitting or better coordination between neonatal and pediatric units. Nevertheless, the concentration of wastage in these specific categories is due to the personalized-medicine approach with blood products prepared on-demand. The margins to reduce waste are therefore low. Similarly, Kanbur *et al.* reported inefficient pedipack use and short expiry of irradiated pedipacks, although their study did not provide a directly comparable aliquot-specific wastage rate[20].

COVID-19 impact and blood supply chain resilience

Mean delivery time was lower during COVID (14.5 days) than pre-COVID (15.3 days) and higher post-COVID (16.0 days). Recorded discard proportions were 3.8%, 3.4% and 3.0%, respectively, although March 2020 showed a transient peak of 5.0%. These differences occurred alongside major changes in hospital activity and blood supply, but the dataset cannot isolate the effect of the pandemic from concurrent changes in demand, collection, allocation or other operational factors. The absence of a sustained increase in delivery time or recorded discards during COVID is consistent with operational resilience of the regional blood supply network. These findings are consistent with international reports showing that blood services rapidly adapted collection and inventory practices during the COVID-19 pandemic[10,11,21].

Clinical implications

Whilst observed delivery times remain within licensed limits, variation in product age at delivery may have clinical implications warranting consideration. RBC storage is associated with progressive biochemical changes including depletion of key metabolites, morphological changes and increased hemolysis[1,4,22].

Large randomised trials such as INFORM showed no significant mortality difference between shorter-term (younger available, median of 13 days) and longer-term (standard-of-care, median of 24 days) stored RBCs[23,24], with similarly neutral results in ICU trials (ABLE, TRANSFUSE)[25,26] and cardiac surgery (RECESS)[27]. However, observational studies suggest that transfusion of units near the end of shelf life may be associated with worse outcomes in selected high-risk populations[28,29], as well as with a reduced hemoglobin increment at 24h and 48h post-transfusion in patients older than 70 years transfused with RCCs older than 35 days. In addition, the upcoming introduction of DEHP-free bags (aiming at removing DEHP components due to toxicity concerns) could be of concern since these new storage conditions are known to increase storage lesions[30,31].

In the present analysis, most units were delivered to hospital around two weeks after donation and only a minority exceeded 35 days, mainly in least common blood groups. Therefore, inter-cantonal differences reported here in donation-to-delivery time are unlikely to translate into clinically meaningful effects for most

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recipients. However, they remain relevant for inventory stewardship and for specific indications where very fresh RCCs are recommended, such as neonatal or intrauterine transfusions, exchange transfusions and certain patients with severe hemoglobinopathies[32]. The finding that 3.3% of Top-Top deliveries and 12.5% of AB+ deliveries, e.g., are delivered after 35 days warrants consideration in patient blood management programs, particularly for high-risk populations.

These findings suggest actionable opportunities for improving RBC distribution efficiency where operational strategies targeting the "high-risk" inventories are likely to yield the largest efficiency gains: (1) implementing targeted interventions and optimized delivery schedule for cantons with longer delivery times; (2) optimizing inventory management through enhanced monitoring and blood centers/hospitals coordination; (3) developing specialized strategies for least common blood group and pediatric split management (such as near-expiry redistribution across hospitals, dynamic stock thresholds, pediatric demand forecasting, and flexible planning between whole-blood and plasma donation according to inventory needs); and (4) incorporating pandemic preparedness into blood supply planning.

Limitations

This study has several limitations. Delivery data do not necessarily reflect actual transfusion practices, because final transfusion status and release timestamps were unavailable. The recorded delivery endpoint represents different logistical stages across regions, limiting direct regional comparisons. Hospital inventories, transfusion indications and complete return trajectories were unavailable, and discard records could not be linked reliably to originating hospitals; hospital-specific wastage therefore could not be estimated and would be added on the top of the presented data. Analyses were primarily descriptive and do not allow causal inference; calendar-period findings should not be interpreted as causal effects of COVID-19.

CONCLUSIONS

Recorded discards were concentrated in least common blood groups and pediatric products, while delivery-time patterns differed across destination regions and collection systems. These findings identify specific inventories for targeted management rather than suggesting that all deliveries require uniform acceleration. Calendar-period differences were observed across the COVID-19 era without establishing causality. Overall, the results support targeted inventory-management strategies and further linked analyses of hospital stocks, returns and transfusion use.

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Authors' contributions

DD contributed to data analysis, interpretation and manuscript drafting. FG contributed to data collection, analysis and critical revision. MP conceived the study, supervised all aspects and critically revised the manuscript. All Authors approved the final version for submission.

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