The Effects of Drone Transportation on Blood Component quality:

A prospective randomised controlled laboratory study

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MW, JB, JM, KO, KT, BP contributed to the study design, data management, statistical analysis and writing of the manuscript. CL and HJ provided the logistics necessary for drone travel. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

Competing Interests Declaration

Mixed competing interests: All authors have completed the ICMJE uniform disclosure form at http://www.icmje.org/disclosure-of-interest/ and declare: JM has provided consultancy for Apian Ltd; CL and HJ are medical directors of Apian Ltd. Neither CL nor HJ were involved in the

processing or analysis of the data. There were no other relationships or activities that may have influenced the submitted work.

Transparency statement

The lead author (the manuscript's guarantor) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as originally planned have been explained.

Public and patient involvement

Local airspace stakeholders were consulted regarding the use of a Temporary Danger Area (TDA) for drone flight in Northumbria prior to authorisation by the Civil Aviation Authority.

The deployment of drones in the transporting blood components was presented and discussed at the North East & Yorkshire Regional Transfusion Committee 2024.

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Abstract

Background: The use of Uncrewed Aerial Vehicles (known as drones) has increased over the last decade. However, their application in healthcare has not been fully examined. Previous regulations prevented drone flight beyond the visual line of sight.

Methods: This prospective randomised controlled laboratory study aimed to determine whether the *in vitro* quality of packed red blood cells is maintained when transported by drone, beyond visual line of sight. Ten identical pairs of packed red blood cell units were randomly allocated to transport by drone or by ground vehicle (1:1 with allocation concealment). Paired units of red blood cells were transported 68 km between two hospitals in Northumbria, UK. Markers of blood component quality, were compared, at 8, 14, 28 and 35 days following blood unit manufacture.

Findings: There was no statistical difference in percentage of haemolysis, concentration of potassium, total haemoglobin, glucose and lactate, haematocrit and mean cell volume was detected at any time point between 8 – 35 days post unit manufacture. The surface temperature of the packed red blood cell units did not deviate outside the recommended 2-10°C for transportation, regardless of the allocated transportation group. Temperature and journey time were comparable to ground transport.

Interpretation: This demonstrates the feasibility and safety of flying blood cell components by drone between active hospital sites in the UK, beyond the visual line of sight. There were no significant differences in packed red cell quality between units transported by drone compared to ground transport, up to the unit expiry date.

Introduction

Blood components are perishable, resulting in a fine balance between maintaining sufficient stock and minimising expiry losses[1]. Hospitals need to have sufficient blood stock to meet specific blood-type requirements; each patient must be matched for blood group (ABO), Rh factor D (RhD) and over 300 minor blood group antigens. A diverse donor pool is needed to match increasingly diverse recipient phenotypes [2]. There is also increasing use of massive transfusion protocols in trauma and obstetrics settings within the National Health Service (NHS), which puts strains on the supply of O RhD negative packed red blood cells, and AB plasma. As there is a wide range of different blood components (packed red cells, fresh frozen plasma, platelets and more), with dozens of component lines and highly variable supply chains, blood inventory management is complex and challenging.

NHS Blood and Transplant (NHSBT) are responsible for the supply of blood in England and Northern Ireland, with equivalent services in Scotland and Wales. Inventory management systems endeavour to trace blood supplies and reduce wastage. In the United Kingdom (UK), there are significant logistical challenges in the provision of blood components across the network of hospitals, and this relies heavily on accurate and rapid relay of information back to blood services.

One of the greatest challenges is the ability to rapidly react to changes in blood stock at, or between, hospitals. Forecasting of demand allows for seasonal variation to be taken into account, and is typically based on historical patterns of use. However, a sudden increase in demand results in an unexpected shortfall in supply. Responding to these events effectively is limited by the reactive speed of blood transport.

Current health systems depend primarily on ground transport – often in the form of cars, vans and motorcycles – to deliver blood components. Outside of healthcare, the use of Uncrewed Aerial Vehicles (UAVs) – also known as drones – has increased over the last decade, particularly in the delivery of military, humanitarian and commercial supplies.

Within healthcare, drones have been used in the delivery of medical devices, medicines, vaccines and organs for transplantation. Thirteen studies to-date have investigated the use of drones in the delivery of blood components (reviewed by Lammers et al [3]), however none of these studies have investigated deployment between active NHS hospital sites or undertaken *beyond visual line of sight* (BVLOS) flights within the UK.

Transporting blood components by drone may improve delivery speed, cost and supply chain resilience relative to ground vehicles, as well providing environmental benefits. However, exposure to abnormal temperatures and vibrations during flight may alter the viability of blood components [4]. For example, haemolysis of red blood cells increases the concentration of potassium within the unit of blood, predisposing patients to hyperkalaemia and transfusion-associated hyperkalemic cardiac arrest (TAHCA).

The aim of this study was to determine whether the *in vitro* quality of packed red blood cells is maintained when transported between hospitals by drone, compared to ground vehicles.

Method

Study design

This study was a prospective randomised controlled laboratory investigation conducted between April and May 2023. Ten identical pairs of packed red blood cell units were randomly allocated either to transport by drone or by ground vehicle (1:1 with allocation concealment) and stored at Northumbria Specialist Emergency Care Hospital (NSECH). Each paired unit of blood was driven to Wansbeck Hospital. From Wansbeck Hospital, units were either flown or driven to Alnwick Infirmary, and back to Wansbeck Hospital. Units were finally driven back to NSECH for storage (Figure 1). These healthcare facilities are part of the Northumbria Health NHS Foundation Trust. The 68 km flight path was not a straight line due to aviation and regulatory considerations; instead it travelled out to the coastline, along the coastline over the sea, and back in-land to each landing site for each 34 km leg. The ground vehicle path was chosen by an independent medical courier currently in use by Northumbria Healthcare NHS Foundation Trust; an estimated 74.6km journey along the A1 road.

Blood components

Two non-clinical-use packed red blood cells were supplied, pooled, mixed and split into two identical units by NHSBT. This process was repeated 10 times to produce 10 identical pairs of red blood cell units (20 units in total). Non-clinical-use red cell concentrates are used by NHSBT for research purposes as they are surplus to clinical requirements. These units are donated from appropriately-consented donors and are compliant with statutory and regulatory obligations including the Human Tissue Act (2004) and UK Blood Transfusion Code of Practice. Units utilised in this study were manufactured to the same standard as clinical red blood cells. After production and delivery, packed red blood cells were stored at 2-6°C at NSECH. There were no differences in the methods of storage and transport between control and test blood units outside of the study interventional period.

Drones

The drone used during this trial was a vertical take-off and landing (VTOL) UAV; Kookaburra (Swoop Aero) operated by Skyports. For further details regarding the drone specifications, see Supplementary Table 1. The flight corridor was approved by the UK Civil Aviation Authority.

Within the drone, two blood packs were placed into UN3373-compliant insulated cold storage (custom-made, Versapak Ltd, UK) with active cooling 2-8 ℃ phase-change material (PCM, Eutecma GmbH) according to Versapak packing instructions. This ensured that the blood remained at this temperature in line with the Joint UK Blood Transfusion Services (UKBTS) Professional Advisory Committee guidelines [5].

Data collection

Blood quality

Following drone or ground transport, each unit of blood was analysed to determine haemolysis, supernatant potassium, pH at 4 degrees centigrade, haemoglobin, haematocrit, mean cell volume, sodium, glucose, lactate concentrations, and lipaemic/icteric/haemolysis (LIH) index, at 8, 14, 28 and 35 days following blood unit manufacture. This was performed by laboratories at NSECH and NHSBT in Cambridge. For further information regarding the laboratory tests, see supplementary table 2

Temperature

Temperature was recorded by three digital thermometers that were calibrated to ISO17025 standards by a UKAS accredited organisation (Libero GL, ELPRO UK ltd.) every 5 minutes. The

temperature inside the transport box was measured as a surrogate for surface temperature of the blood packs, as well as the temperature external to the transport box, but within the drone's cargo hold.

Vibration

Vibration data were recorded using triaxial MEMS data logging accelerometers (AX6, Axivity Ltd) positioned centrally within the drone's cargo hold. Sensors were configured to sample at a rate of 1.6 kHz with a range of ±16 g. Vibration data were not recorded for journeys undertaken by ground transport, and a direct comparison between the two transport modes was not an objective in this study.

Weather

Weather data were obtained from the UK Meteorological Office and the European Centre for Medium-Range Weather Forecasts (ECMWF), including air temperature, humidity, air pressure and wind speed and direction. Weather data are shown in Supplementary data Table 3; In brief the mean temperature was 14 (range 9-18) degrees Celsius.

Randomisation

Each blood unit pair was randomly assigned a transport method (1:1 ratio, air to ground), using a random number generator in order to avoid bias. Blinding was lifted after analysis. Travel times were recorded using a detailed log of departure and arrival times for each vehicle (air and ground).

Statistical analysis

All data were tested for normality using the Shapiro-Wilk test. Haematology and biochemistry variables were compared between each paired unit, at each time interval. Two-tailed p values were

generated using the Wilcoxon signed rank test for paired data. Continuous parametric data, such as travel times, were examined using paired Student T test. There was no missing data, and all units of blood were analysed at each time point (8, 14, 28 and 35 days post manufacture). Data were analysed using Matplotlib 3.8 for Python 3.12 (Python Software Foundation), IBM SPSS Statistics version 25 (IBM, Armonk, NY, USA) and Prism version 8.3.0 (GraphPad, Boston, Massachusetts, USA).

Results

Maintenance of cold chain

During the study period, surface temperature of the packed red blood cell units did not deviate outside the recommended UKBTS range for transportation (2-10°C) regardless of the allocated transportation group (Figure 2, Table 1)

Table 1 – Summary data of internal bag temperature and external temperature by drone transport and ground vehicle transport across all journeys.

	Drone Transport	Ground Vehicle Transport
Internal Bag Temperature	7.30 ± 1.29 C (3.3 - 10.0 C)	6.10 ± 1.27 C (3.6 - 9.2 C)
External Temperature	10.55 ± 2.06 C (5.4 - 16.3 C)	8.35C ± 2.05 C (5.1 - 13.2 C)

Data expressed as mean ± standard deviation (minimum - maximum)

Measures of in vitro blood quality

There was no crossing over of the interventional groups. When comparing each pair of red cell units undergoing either drone or ground transport, no difference in percentage of haemolysis, concentration of potassium, total haemoglobin, glucose and lactate, haematocrit and mean cell volume was detected at any time point between 8 – 35 days post unit manufacture ($p > 0.05$ throughout, Figure 3). A statistical difference in sodium concentration was detected between the groups at day 28 only ($p = 0.02$). However, all unit component concentrations, including sodium, measured were within the range of NHSBT reference data for standard red cells. There was no difference in qualitative LIH measures between individual paired blood units between drone and ground travel, at days 8, 14, 28 and 35 post unit manufacture (Supplementary Table 4.

Travel time

Blood travelling by drone completed its journey in an average duration of 61 minutes (standard deviation 8 minutes, n=5), in contrast to blood travelling by road, which took 68 minutes (standard deviation 6 minutes, n=5). This did not reach statistical difference (p=0.20).

Vibration

Vibration data were obtained from all drone flights (n=5). The average overall resultant vibration level for all 5 flights was 0.32*g*, where *g* is the acceleration due to gravity (9.81 ms^{-2}). This is comparable to vibration levels expected in road transportation [6].

Discussion

This prospective randomised laboratory study indicated that there were no significant differences in packed red cell quality between units transported by drone compared to ground transport. The study considered the effect of unit longevity, testing the blood up to and including the expiry date in the UK. Travel by drone did not impair the quality or longevity of the packed red blood cells, including haemolysis, potassium release and glucose consumption/lactate production, suggesting that it is a safe alternative to ground transport.

The in vitro quality of blood in both transport groups is likely the result of comparable temperature and vibration conditions. Cold chain was maintained throughout, and the overall vibration level in this study was similar between drone and existing ground vehicle vibration data. Travel time may be improved with drone delivery, compared to ground transport. Although this did not reach statistical significance within this study, a reduced travel time of 6 minutes may be *clinically* significant, when considering the delivery of potentially life-saving treatment. Optimised flight paths, allowing straight line travel, may further hasten drone travel times.

In the US, drone transport of blood components was demonstrated by Amukele and colleagues, in which packed red blood cells were flown for 22 minutes within the pilots' visual line of sight [7]. The results corroborate our findings in that there was no difference in markers of haemolysis compared to ground travel. Flying blood components beyond the visual line of sight, between existing NHS hospital sites, demonstrates that this form of transport is logistically feasible in real-world settings.

We acknowledge the limitations of this study. The use of drones in this study was performed in a rural, north-eastern coastal area during British summer, and is not representative of UK geography or climate as a whole. Indeed, there are likely to be varying differences in weather, ground traffic and other environmental factors that may have altered the results if deployed elsewhere or at another time. Densely-populated cities in particular are likely to benefit more

significantly from the speed of UAV transport as there are greater levels of road congestion. The vibration and temperature profiles of other UAV-transportation setups must also be considered as a variable.

This study did not utilise blood for clinical use, and therefore there was no recipient of the blood transfusion following travel. Although there are numerous documented transfusions of blood components into recipients following drone delivery, there have been no published studies assessing their effect on physiology post-transfusion [3]. Drones have been investigated in the setting of organ transplantation into human recipients, including kidney [8,9] and lung transplantation [10], in which overcoming the logistics of ground transport in congested urban areas was quoted to be a significant benefit.

This study did not investigate the relative economic benefit of drones versus ground transport. If performed, an economic analysis would have to consider two main models of use. In the UK, blood establishments (BE) can be licensed to collect, process and distribute blood components for the purpose of transfusion. BE's distribute blood components to hospital blood banks (HBB). HBBs are licensed to perform compatibility testing and to store these products, ready for patient administration in hospital facilities. Drones may aid in distributing blood components from BE to HBB, as well as between individual HBBs. An economic analysis is necessary to determine whether the implementation of drone technology is economically viable in the distribution of blood components, in both BE-HBB and HBB-HBB settings. Another setting may also be in pre-hospital care, in which blood components are delivered to the site of a major incident [11, 12] . However, this is yet to be explored in the UK as the lack of a predetermined flight corridor presents logistical and regulatory challenges. Ochieng et al carried out a simulated economic analysis of the costs and cost-effectiveness of drones versus ground transport in west Africa for the transportation of laboratory samples in both urgent and non-urgent settings [13]. Across greater distances, drones demonstrated increased cost-effectiveness. However, there was no overall cost

benefit of drones in their simulations. In contrast, Zailani et al demonstrated a cost benefit of delivering blood components by drone compared to ground transport in Malaysia [14]. Nonetheless, the UK's logistics and geography need to be taken into account when considering the economic case for drones for this particular use-case. An economic analysis of this kind should also consider the effect of blood wastage, particularly of urgent O Rh negative blood stock, as this may be a key benefit of a rapid response to shortages within the network of HBB and BEs. There have not been any studies considering the relative benefit of drones in relation to carbon emissions and the environmental impact. This should also be considered in future studies.

Conclusion

This is the first published study investigating the feasibility and safety of flying blood cell components by drone between active hospital sites in the UK, and is the first study to conduct BVLOS flights carrying medical supplies in the UK. Results indicated that transport of packed red cells by drone did not influence their viability or longevity. Drone transport was logistically feasible between two hospitals, and safely maintained the cold chain. This may be applied to other blood products, or with other time- and temperature-dependent medical products.

Research in Context
Evidence before this study Drone are being deployed in various industries, and have been used to transport blood and organs in the US and abroad. To-date, there have not been any studies investigating their use *beyond visual line of sight* (BVLOS) within the UK. The effect of drone travel on red blood cell quality has not been examined in the UK
Added value of this study This study demonstrates that it is feasible and safe to fly packed red blood cells by drone, with comparable degrees of haemolysis between drone and ground vehicle, up to 35 days after component manufacture
Implications of all available evidence Drone transport of temperature and time-dependent may become autonomous and have a lesser impact on the environment

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Figure 1: Blood unit surface temperature between each paired unit travelling by drone and ground transport. All data fell within the UKBTS range for transportation (2-10°C). Data presented as median, quartiles, and minimum/maximum figures.

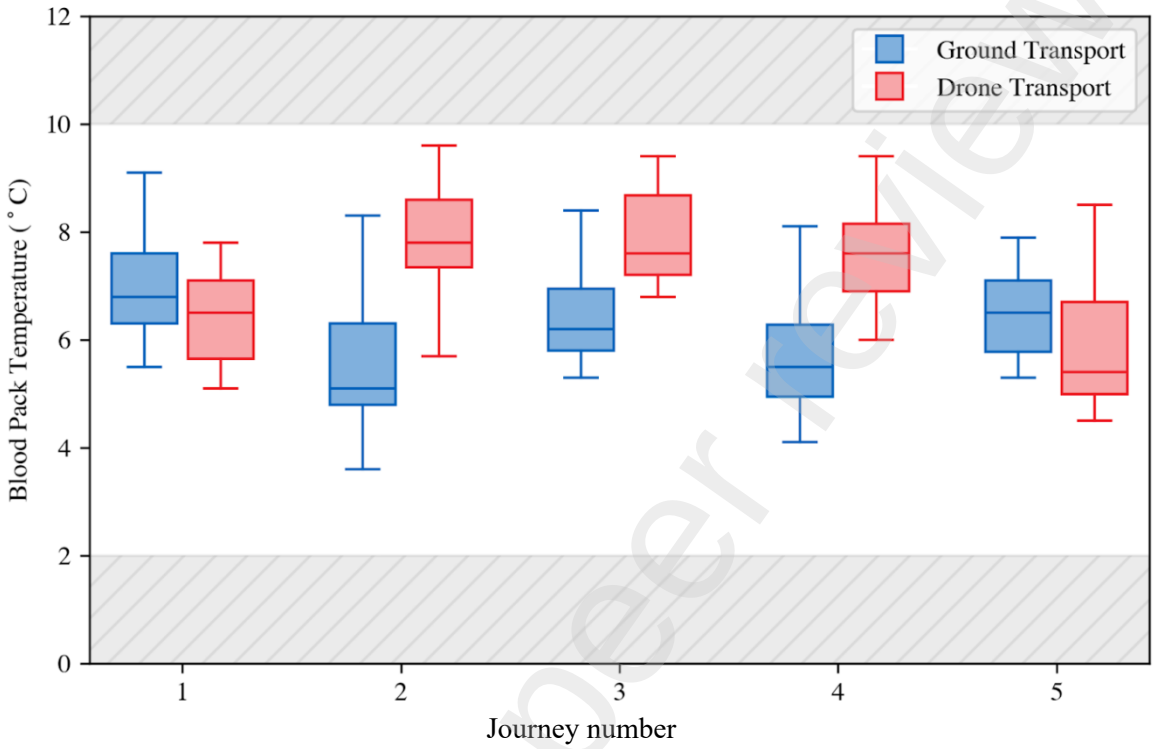
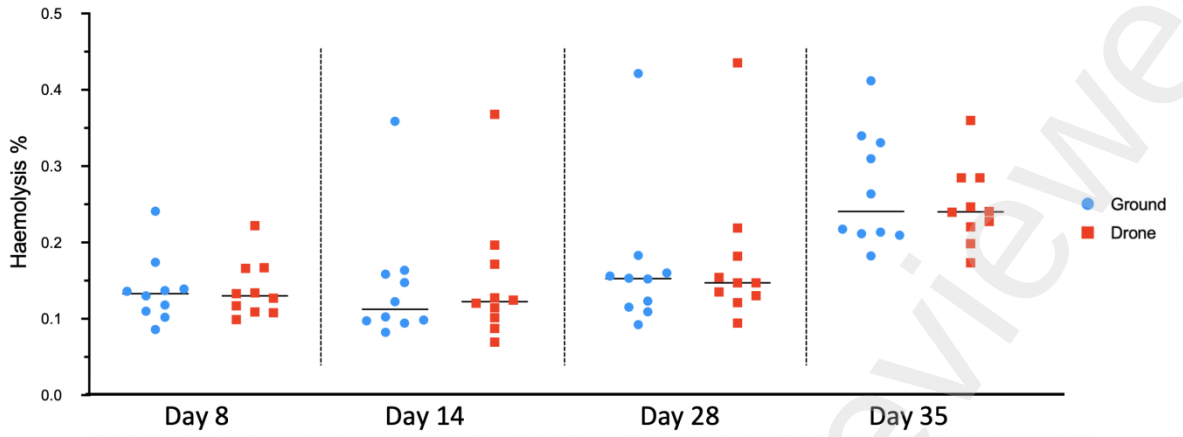


Figure 2: Differences in blood markers between paired units travelling by drone and by ground, at days 8, 14, 28 and 35 after unit manufacture for (A) Haemolysis (B) Potassium (C) Sodium (D) Haematocrit (E) Mean cell volume (F) Lactate (G) Glucose (H) pH at 4 degrees Celsius

A



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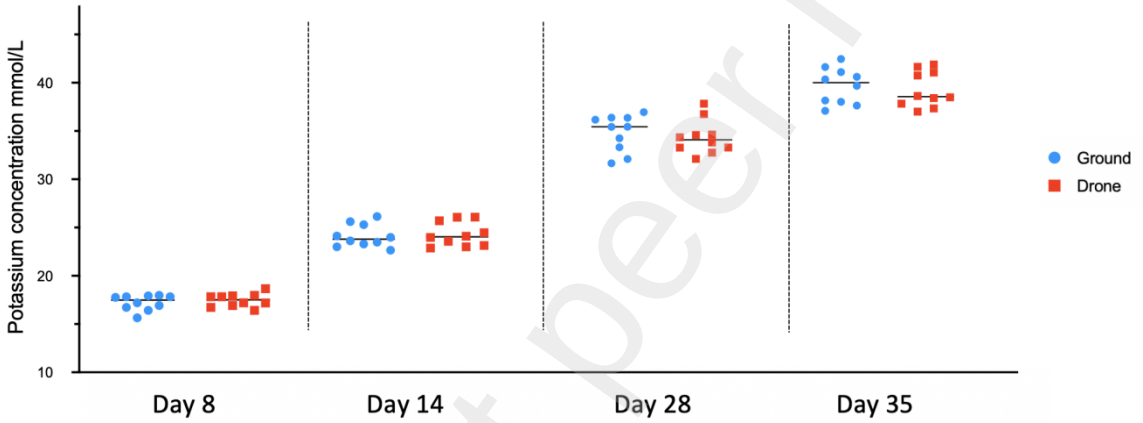

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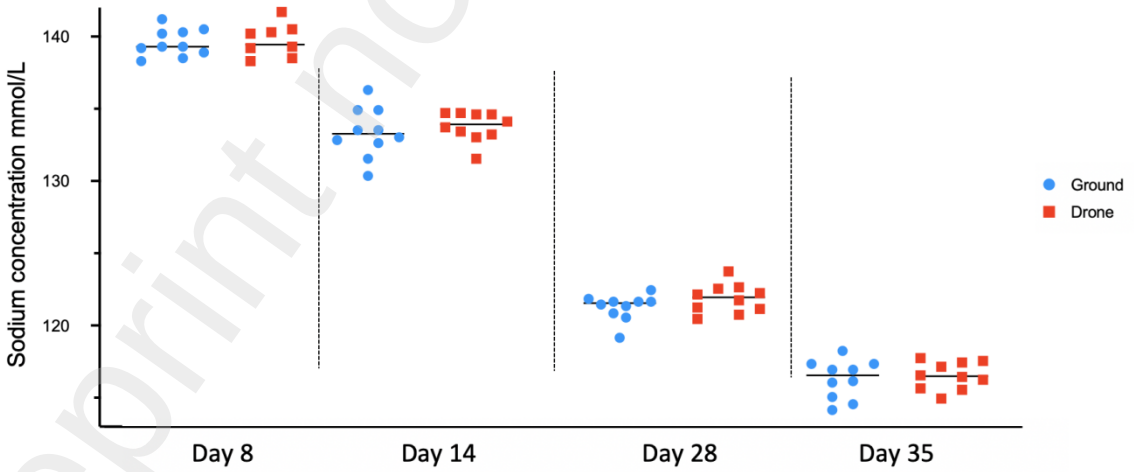

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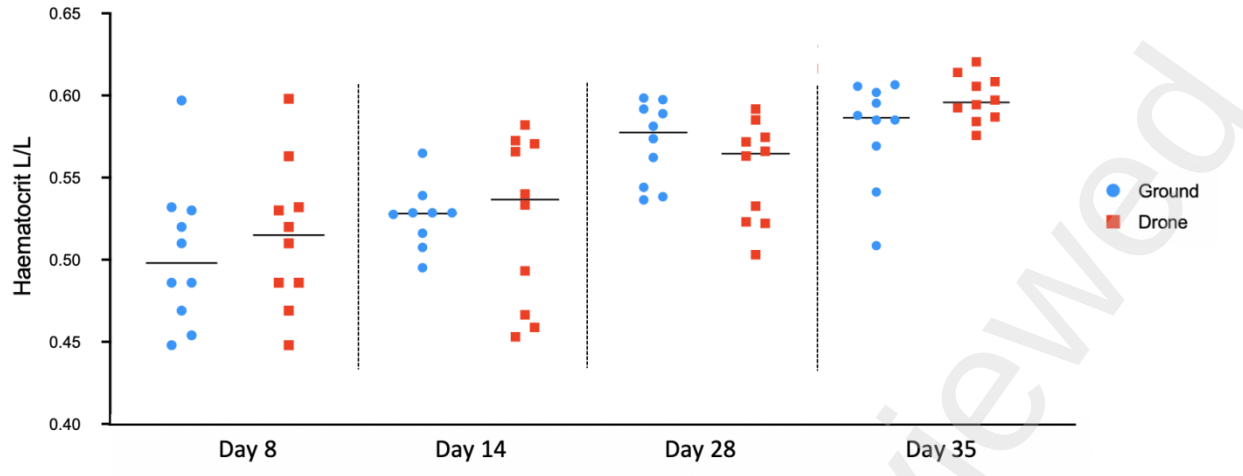

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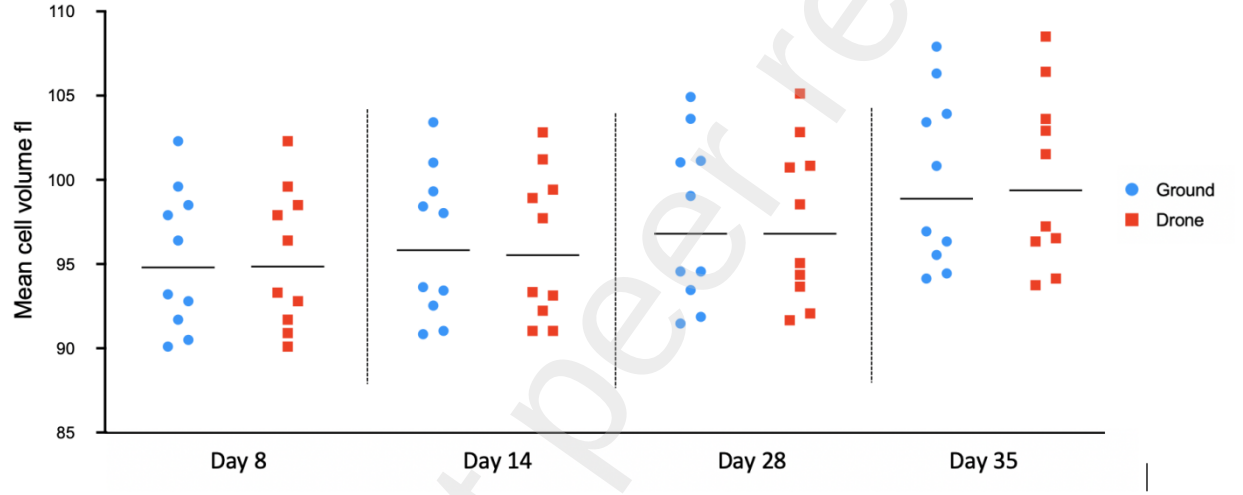

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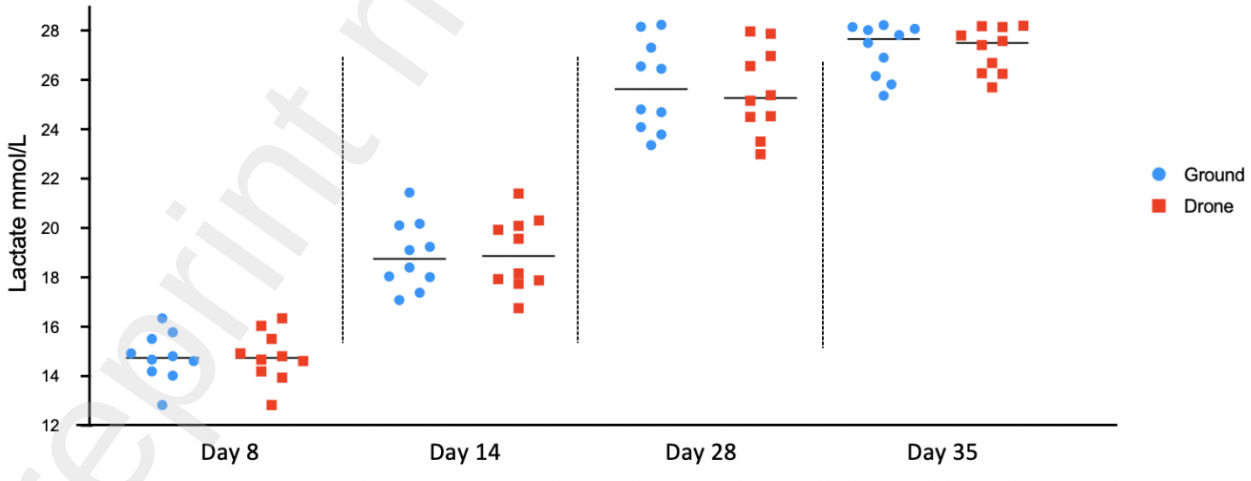

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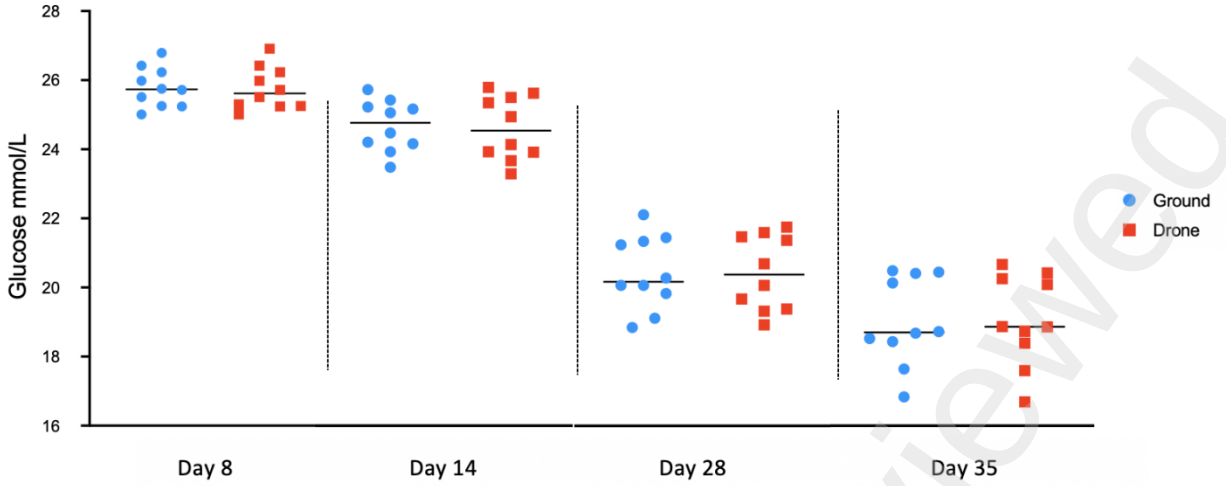

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