drones

MDPI

Article

Preanalytic Integrity of Blood Samples in Uncrewed Aerial Vehicle (UAV) Medical Transport: A Comparative Study

Noel Stierlin [1,2,*], Fabian Loertscher [2], Harald Renz [3], Lorenz Risch [1,2,4] and Martin Risch [1,2,*]

[1] Faculty of Medical Sciences, Private University of the Principality of Liechtenstein, 9495 Triesen, Liechtenstein; lorenz.risch@risch.ch
[2] Labormedizinisches Zentrum Dr. Risch, 9470 Buchs, Switzerland; fabian.loertscher@risch.ch
[3] Institute of Laboratory Medicine and Pathobiochemistry, Molecular Diagnostics, University Hospital Giessen and Marburg, Philipps University Marburg, Baldingerstraße, 35043 Frankfurt, Germany; renzh@med.uni-marburg.de
[4] Centre of Laboratory Medicine, University Institute of Clinical Chemistry, University of Bern, 3010 Bern, Switzerland
* Correspondence: noel.stierlin@risch.ch (N.S.); martin.risch@risch.ch (M.R.)

Abstract: The integration of unmanned aerial vehicles or uncrewed aerial vehicles (UAVs)—commonly known as drones—into medical logistics offers transformative potential for the transportation of sensitive medical materials, such as blood samples. Traditional car transportation is often hindered by traffic delays, road conditions, and geographic barriers, which can compromise timely delivery. This study provides a comprehensive analysis comparing high-speed drone transportation with traditional car transportation. Blood samples, including EDTA whole blood, serum, lithium-heparin plasma, and citrate plasma tubes, were transported via both methods across temperatures ranging from 4 to 20 degrees Celsius. The integrity of the samples was assessed using a wide array of analytes and statistical analyses, including Passing–Bablok regression and Bland–Altman plots. The results demonstrated that drone transportation maintains blood sample integrity comparable to traditional car transportation. For serum samples, the correlation coefficients (r) ranged from 0.830 to 1.000, and the slopes varied from 0.913 to 1.111, with minor discrepancies in five analytes (total bilirubin, calcium, ferritin, potassium, and sodium). Similar patterns were observed for EDTA, lithium-heparin, and citrate samples, indicating no significant differences between transportation methods. Conclusions: These findings highlight the potential of drones to enhance the efficiency and reliability of medical sample transport, particularly in scenarios requiring rapid and reliable delivery. Drones could significantly improve logistical operations in healthcare by overcoming traditional transportation challenges.

Keywords: unmanned aerial vehicles; uncrewed aerial vehicles; medical logistics; blood sample transportation; drone technology; sample integrity; comparative analysis; rapid delivery

check for updates

Citation: Stierlin, N.; Loertscher, F.; Renz, H.; Risch, L.; Risch, M. Preanalytic Integrity of Blood Samples in Uncrewed Aerial Vehicle (UAV) Medical Transport: A Comparative Study. *Drones* **2024**, *8*, 517. https://doi.org/10.3390/drones8090517

Academic Editor: Diego González-Aguilera

Received: 16 August 2024
Revised: 20 September 2024
Accepted: 21 September 2024
Published: 23 September 2024

1. Introduction

Uncrewed aerial vehicles (UAVs), or drones, have emerged as a groundbreaking technology with significant potential to revolutionize various sectors, including healthcare [1–6]. The ability of drones to navigate challenging terrains, avoid traffic congestion, and provide rapid delivery makes them an attractive option for transporting critical medical materials such as blood samples [7,8]. Traditional car transportation, while effective, is often hindered by traffic delays, road conditions, and geographic barriers, which can compromise the timely delivery of medical samples [9]. However, drone transportation can sometimes be more expensive compared to car transportation, especially if established car or van routes, such as postal services or milk delivery rounds, are available for transporting the samples [6,10–12].

Currently, drones are already being utilized to transport critical medical materials such as blood samples, vaccines, and medications in remote and underserved regions [13].

For instance, in Rwanda and Ghana, drones operated by companies like Zipline have been successfully delivering blood products and essential medical supplies to rural healthcare facilities, significantly reducing delivery times and overcoming logistical challenges posed by difficult terrains and poor infrastructure [14,15]. These applications underscore the versatility and efficiency of drones in enhancing healthcare delivery, particularly in areas where traditional transportation methods are hindered by geographical and infrastructural barriers. This study aims to further explore the ecological impact and efficiency of drones compared to traditional transportation methods in the context of medical sample transportation in Central Europe.

The importance of maintaining sample integrity during transport cannot be overstated, as delays and environmental conditions can significantly impact the accuracy of diagnostic tests [16–18]. This study aims to bridge the knowledge gap by systematically examining the impact of high-speed drone transportation compared to traditional car transportation on the analytical results of different analytes. By subjecting various blood materials and analytes to both transportation modalities under diverse weather conditions, this study seeks to elucidate the differential effects on sample integrity and analytical outcomes.

2. Materials and Methods

This chapter outlines the study design, starting with the collection of various blood samples—EDTA whole blood, serum, lithium-heparin plasma, and citrate plasma tubes—using standard venipuncture techniques. It then describes the two transportation methods compared: drone and traditional car, each performed under varying environmental conditions. Finally, the section details the analytical methods, including Passing–Bablok regression and Bland–Altman analysis, used to evaluate the integrity of the samples transported by both modalities.

2.1. Sample Collection and Preparation

Blood samples, including those in EDTA, serum, lithium-heparin plasma, and citrate plasma tubes (BD Vacutainer™), were collected using standard venipuncture techniques by trained healthcare professionals. Immediately after collection, the samples were aliquoted into appropriate containers to minimize preanalytical variability and maintain the integrity of the samples.

2.2. Transportation Modalities

Blood samples were transported using two distinct modalities: high-speed drone transportation and traditional car transportation. For drone transportation, a custom-built UAV equipped with secure sample containers (Vacuette®) was utilized (Jedsy Drone Company, Sankt Gallen, Switzerland). The BD Vacutainer™ Tubes containing the blood samples were transported inside the Vacuette® container (Figure 1c,d). The drone's maximum speed exceeded 100 km/h, enabling rapid transit between designated pickup and delivery points. Car transportation involves the use of standard medical transport vehicles operated by trained personnel following established protocols. The duration of the samples transported by drone was 32 min. The duration of transportation by car was 32 min.

2.3. Dangerous Goods

The authorized container used for transporting the blood samples with the drone was the VACUETTE® Transport Box (VTB), manufactured by Greiner Bio-One GmbH (Frickenhausen, Germany). This container is certified to safely transport UN3373 Biological Substance Category B, ensuring that the blood samples were securely handled during transit.

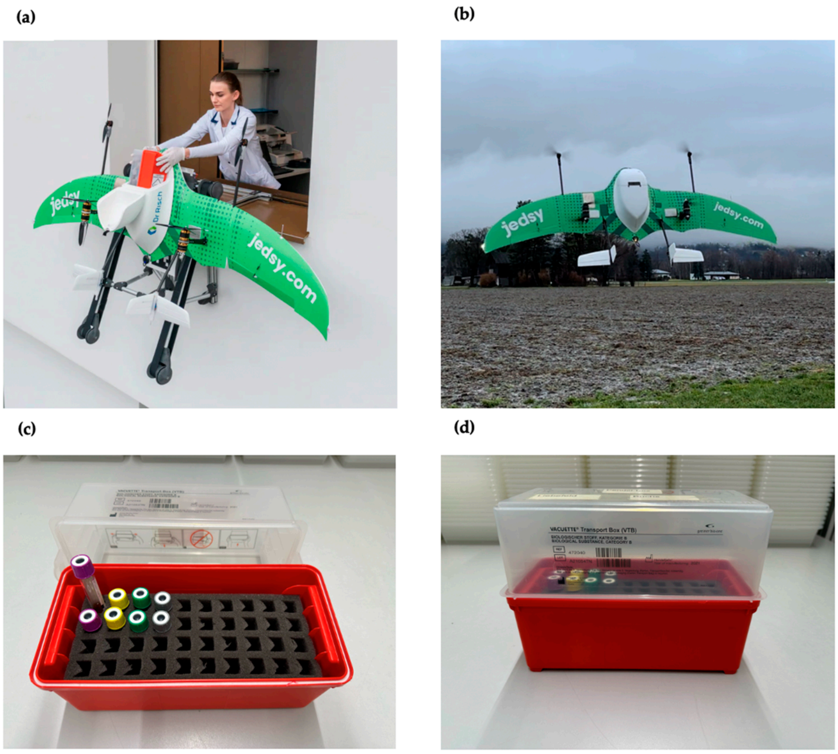

Figure 1. Images of the Uncrewed Aerial Vehicle (UAV) used for medical transport and the blood sample containers employed in the study. (**a**) Drone used for the tests. (**b**) Drone in hoovering mode. (**c**) open savety box. (**d**) savety box to transport the blood samples.

2.4. Experimental Design

Transportation experiments were conducted under diverse weather conditions, ranging from 0 to 20 degrees Celsius, in realistic scenarios to assess the resilience of each transportation modality. These experiments aimed to encompass a spectrum of environmental factors likely to influence sample integrity during transit. Throughout the transportation process, temperature (using Libero CL V9.14, Elpro, Büx, Switzerland) and vibration (using TDK InvenSense, InvenSense, 1745 Technology Dr., San Jose, CA, USA) data were continuously monitored with data loggers and accelerometers.

2.5. Vibration Metrics

TDK InvenSense accelerometers were used to measure the vibration levels experienced during transportation. These high-precision sensors were placed inside the sample containers (Vacuette®) and embedded in the foam in which the sample tubes are held to capture real-time vibration data throughout the journey. The accelerometers measured tri-axial vibrations (x, y, and z axes) and recorded data at a high frequency of four times per second to ensure an accurate representation of the transportation conditions. The vibration data were then analyzed to determine the impact of transportation-induced mechanical agitation on blood sample integrity.

2.6. Analytical Assays

A comprehensive panel of analytes covering clinical chemistry, hematology, and coagulation parameters was selected for analysis to assess the impact of transportation modalities on sample integrity and analytical outcomes. This included testing 27 analytes on serum samples, 20 on EDTA whole blood, 26 on lithium-heparin plasma, and 5 on citrate plasma, ensuring a broad spectrum of clinically relevant markers was evaluated.

2.7. Statistical Analysis

Statistical analyses were conducted using established methodologies, such as Passing–Bablok regression and Bland–Altman analysis, to evaluate the agreement between transported samples and reference controls. Correlation coefficients (r) and slopes were calculated to quantify the degree of concordance between transportation modalities. Additionally, mean percentage differences were assessed to identify analytes showing significant deviations from the negative control and to determine the clinical relevance of these discrepancies. These analyses were performed using MedCalc Statistical Software version 22.030 (MedCalc Software, Ostend, Belgium; https://www.medcalc.org; 2020: accessed on 28 June 2024).

2.8. Quality Control Measures

Stringent quality control measures were implemented throughout the transportation and analytical processes to ensure the reliability and validity of the results. Regular calibration checks, instrument maintenance, and proficiency testing were conducted to maintain analytical accuracy and precision. Additionally, temperature monitoring using Libero CL V9.14 and data logging mechanisms were employed to continuously monitor sample conditions during transportation, safeguarding against potential deviations (Table 1). The table summarizes the flight planning and execution details, including the software used, flight paths, average altitude (100 m), number of flights (12), flight duration (30 min each), and weather conditions like light rain, winds up to 40 km/h, and sunshine.

Table 1. Summary of flight planning and execution details.

Flight Planning	Details
Software Used	Pix4D and PX4 Autopilot
Flight Paths	Detailed paths planned to cover the entire study area, ensuring comprehensive coverage and data overlap
Altitude	Average altitude of 100 m (see Tables 1 and 2 for specifics)
Flight Execution	**Details**
Number of Flights	12 flights conducted over the study period
Duration	Each flight lasted approximately 30 min
Weather Conditions	Various conditions, including light rain, winds (up to 40 km/h), and sunshine

Table 2. Flight geography.

cruising	Horizontally	35 m on each side of the Flight Path. This accounts for the inaccuracy of navigation due to GPS imprecision or meteorological conditions and allows the aircraft to safely maneuver within the margins of error.
cruising	Vertically	20 m above the Flight Path -> 120 m AGL.
hovering	Horizontally	10 m on each side of the flight path. This accounts for the low speed of the aircraft.
hovering	Vertically	10 m above the Flight Path -> 40 m AGL. This accounts for the low speed of the aircraft.

2.9. Aircraft

Operations were conducted using the Jedsy Glider. The aircraft configuration includes an ADS-B IN transceiver, FLARM, and Remote ID broadcast capabilities. Each aircraft is equipped with a serial number compliant with ANSI/CTA-2063-A-2019, which governs Small Unmanned Aerial Systems Serial Numbers, in accordance with Article 40 (4) of Regulation (EU) 2019/945.

The manufacturer code for Jedsy, assigned by the International Civil Aviation Organization, is 1883. Flight planning tools and flight geography are listed in Tables 2 and 3, respectively. Table 4 presents the technical data of the hybrid drone used in this study. The drone, equipped with glider technology for improved efficiency, can transition into hover mode for precise landings. This table outlines key specifications such as flight duration, average altitude, and weather conditions under which the drone was tested. These technical details are essential for understanding the operational efficiency of the drone in medical sample transportation.

Table 3. Contingency Volume.

cruising	Horizontally	35 m on each side of the Flight Geography. This conservatively allows the aircraft to automatically initiate the Flight Geography contingency procedure to stop and hover from a cruise speed of 30 m/s (approx. 26 m), considering a positioning inaccuracy of 4m and an extra margin of 5 m.
cruising	Vertically	20 m above the Flight Geography -> 150m AGL assuming 1s of reaction time at 45 deg pitch up at 20 m/s + 4m of GPS error
hovering	Horizontally	10m on each side of the Flight Geography. This accounts for the low speed of the aircraft.
hovering	Vertically	10 m above the Flight Geography -> 50 m AGL This accounts for the low speed of the aircraft and the flight mode.

2.10. Routes

The drone's route was between Vaduz, Liechtenstein (47.134787, 9.513150) and Buchs SG, Switzerland (47.166668, 9.466664). The average flight altitude was 540 m above mean sea level, with an average height of 100 m above the ground.

2.11. Functionality of the Flight Termination System (FTS)

The Flight Termination System (FTS) is a critical safety feature designed to ensure the controlled stabilization and landing of a drone in the event of an emergency. The following table outlines the step-by-step process involved in the activation and operation of the FTS, from the initial command by the Remote Pilot in Command (RPIC) to the safe landing of the aircraft. This system is activated through a mobile app separate from the Ground Control Station (GCS), ensuring that the FTS operates independently of the primary control link (Table 4).

Table 4. Functionality of the Flight Termination System (FTS).

Step	Action
1	The RPIC activates the FTS using a mobile phone app, which is segregated from the Ground Control Station (GCS).
2	The app sends the activation command through the mobile network to the FTS comms module installed on the aircraft using a different network provider from the C2 link.
3	The FTS comms module activates the FTS device.
4	The FTS reroutes the motor and servo inputs to be controlled by the auxiliary Flight Controller, which is pre-programmed to stabilize and stop the aircraft in Hovering mode as quickly as possible (approx. 4G deceleration).
5	The aircraft navigates to the horizontal GPS location where the FTS was triggered, remaining in Hovering mode at a slow speed of 5 m/s.
6	The aircraft turns into the wind using the weathervane function to allow the Cruising motor to counter the wind more efficiently.

Table 4. *Cont.*

Step	Action
7	The aircraft slowly descends at 3 m/s or less until touchdown.
8	The aircraft is disarmed upon touchdown.
9	The RPIC can disable the FTS at any time using the same segregated trigger, regaining full control of the aircraft (only in case of inadvertent activation).

2.12. Comparative Analysis of Drone and Automobile Transportation Environments

A comparative analysis of their respective transportation environments was conducted to evaluate the suitability of drones and automobiles for medical sample transportation. This analysis focused on key factors, including temperature control, vibration exposure, and speed, which are critical for maintaining the integrity of medical cargo during transit.

Drones, while offering faster delivery speeds, face challenges such as limited temperature control and higher vibration levels due to aerial movement, particularly during takeoff and landing. These factors make drones more susceptible to environmental conditions, potentially impacting sensitive medical materials. In contrast, automobiles typically provide a more stable environment with better insulation and climate control, reducing the risk of temperature fluctuations and vibration exposure. However, the speed of automobiles is more variable, depending on traffic and road conditions, and generally lower than that of drones (Table 5).

Table 5. Comparative Analysis of Drone and Automobile Transportation Environments.

Factor	Drone Transportation Environment	Automobile Transportation Environment
Temperature Control	Limited control; highly dependent on external weather conditions.	Typically more stable with better insulation and climate control.
Vibration Exposure	High due to aerial movement, especially during takeoff, landing, and flight.	Moderate to low; roads provide a relatively stable platform, though road quality can cause variations.
Speed	Variable; average cruising speed around 30 m/s (59 KIAS).	Variable; average speed ranges from 13 m/s (47 km/h) in urban areas to 27 m/s (100 km/h) on highways.
Altitude	Operates at varying altitudes (e.g., 100 m above ground).	Operates at ground level; altitude variation is negligible.
Environmental Exposure	Direct exposure to weather conditions (wind, rain, temperature).	Typically shielded from direct weather impacts due to the vehicle’s structure.
Impact of Weather	Significant; wind, rain, and temperature directly affect flight stability.	Minimal; vehicles are designed to operate in various weather conditions, though extreme conditions may affect safety.
Reliability of Transportation	Potentially affected by weather, requiring contingency planning.	Generally more reliable, with less susceptibility to environmental conditions.
Energy Efficiency	Dependent on altitude, payload, and wind conditions; can vary significantly.	Generally more consistent; efficiency depends on driving conditions and vehicle type.
Infrastructure Dependency	Requires minimal infrastructure (e.g., clear airspace, GPS).	Requires extensive road infrastructure and is subject to traffic conditions.

2.13. UAV and Blood Sample Container Design for Secure Medical Transport

In this study, a custom-built Uncrewed Aerial Vehicle (UAV) was utilized for medical transport, specifically designed for the secure delivery of blood samples (Table 6). The UAV, shown in Figure 1, was attached to its landing rig on the window of the laboratory where the samples were analyzed (Figure 1a). During transport, the UAV operated in hovering mode to ensure stable flight conditions (Figure 1b). Blood samples were placed inside Vacuette® containers (Figure 1c), which were designed with foam inlays to mitigate vibrations and impacts. These containers also provided temperature insulation to protect the integrity of the samples. A closed-lid Vacuette® container is also depicted (Figure 1d), highlighting the secure method used for sample transport during the drone flights.

Table 6. Technical data of the drone used.

Aircraft type	Unmanned electric aircraft capable of vertical takeoff and landing (eVTOL) and fixed-wing flight. x
Dimensions	35 × 290 × 240 cm [H × W × L]
Weight	18 Kg empty incl. batteries
	21 Kg max. gross takeoff weight (MGTOW)
Propulsion	Hovering motors: 8× 150Kv motors with 22inch propellers (IP 45 rating)
	Cruising motors: 2× 360Kv motors with 12inch propellers
Avionics	1× 64 Bit ARM 6 Cores, 6 MB L2 + 4 MB L3, 8 GB RAM, 128-Bit-LPDDR4x 59.7 GB/s
	1× 32 Bit ARM, 480MHz, 2MB memory, 512KB RAM
	1× 32 Bit ARM, 24MHz, 8KB SRAM (3× Accelerometers/Gyros, 2× Barometers, 2× airspeed sensors, 1× GPS Module)
	1× 32 Bit ARM, 480MHz, 2MB memory, 512KB RAM
	1× 32 Bit ARM, 72MHz, 64KB SRAM (2× Accelerometers/Gyros, 2× Barometers, 1× GPS Module)
Awareness systems	1× downward-facing awareness systems
	2× forward-facing awareness systems
	1× LiDAR ground altimeter: downward facing for long range
Awareness radios	1× ADS-B In
	1× FLARM in and out
	1× remote ID, compliant with FAR Part 89
Connectivity (CON2)	3× LTE SIM card slots for three different providers
Flight modes	Multicopter mode and Fixed-wing mode
Cruise Speed	59 KIAS (30 m/s)
Stall Speed (MGTOW) in Fixed-wing mode	33 KIAS (17 m/s)
Max Density Altitude	2438 m
Max Endurance	118 min
Max Wind	29 KTS (15 m/s)
Max Precipitation	Light to moderate
Operating time	Day, Night (under dev)
Operating temperature	−20° to 50 °C
Range	max 120 km, 2 min hovering, 3 kg payload, 5 m/s of headwind, ideal cruising speed, 200 m AMSL, no altitude changes or curves, 10% reserve
Weather limitations	suitable for operation in coastal and offshore climate
	no operation during heavy rain, icing conditions, hail, and thunderstorms
Noise Emissions	While cruising at 60m above ground level: 58 dB
Delivery methods	Mailbox docking on balcony or window (under development)
	Ground landing
Customer Privacy	The video transmitted to the pilot for landing is blurred at the source
	The recorded flight data are deleted and overwritten after every flight

2.14. System Architecture

This diagram provides an overview of the Flight Termination System (FTS) architecture (Figure 2) and its integration with the main and auxiliary flight controllers (FCs) on an unmanned aerial vehicle (UAV). The illustration details the communication flow between the Ground Control Station, the mobile app, and the FTS device, highlighting the segregation of control between the main FC and the auxiliary FC. The diagram also shows how motor telemetry is relayed back to the main FC and displayed on the Ground Control Station, allowing the Remote Pilot in Command (RPIC) to monitor system performance and verify FTS functionality during pre-flight checks.

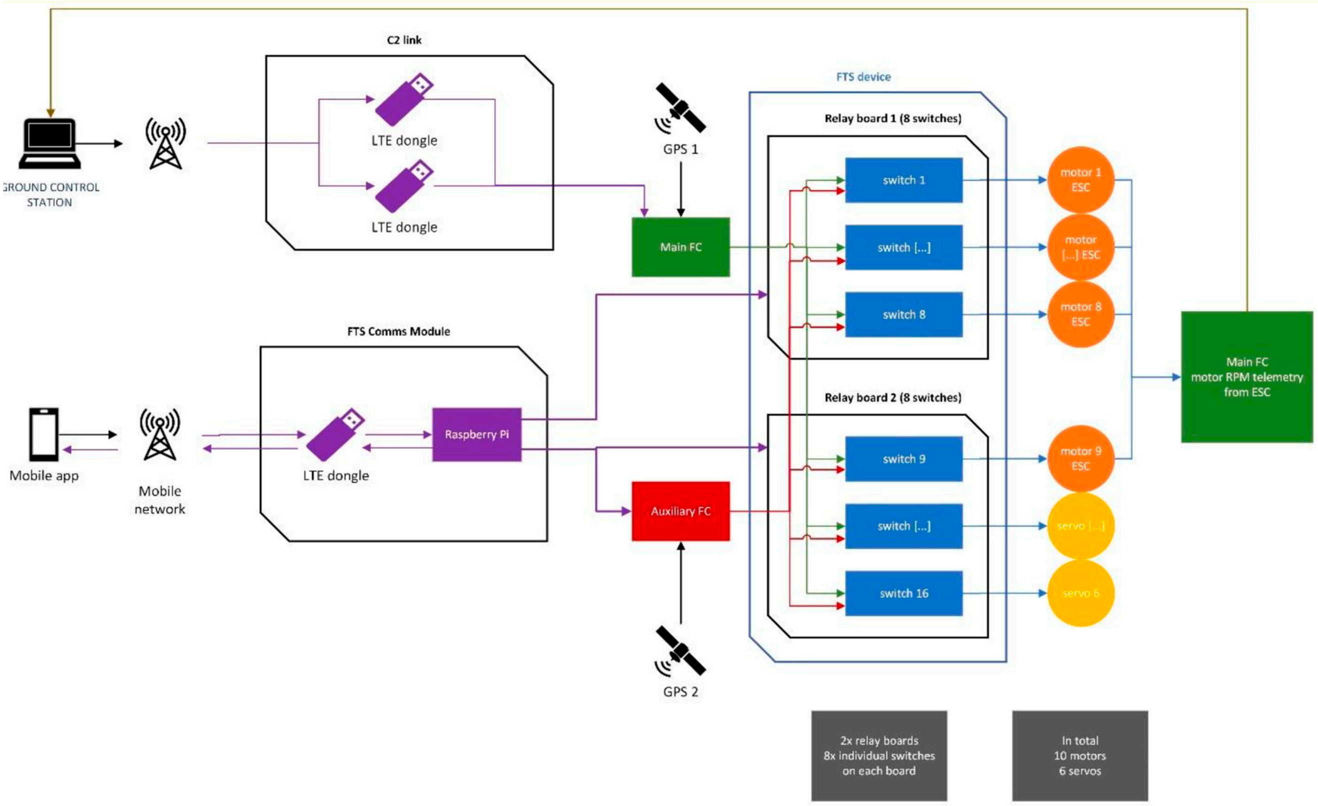

Figure 2. Functional diagram.

The Flight Termination System (FTS) is designed to ensure safe and controlled operation in the event of an emergency or system failure. The functionality is divided into three key sections.

(1) FTS Communication Module

This module includes an LTE dongle for mobile network connectivity and a Raspberry Pi, which manages the connection between the mobile app trigger and the FTS device. The Raspberry Pi sends the activation command to the FTS device and the auxiliary flight controller (FC) while also transmitting its status back to the mobile app. This setup allows for constant monitoring of the FTS connection during operations.

(2) Flight Controllers and Sensors

The main flight controller (FC) is responsible for normal operations and has access to all the aircraft's sensors except for GPS module 2. In contrast, the auxiliary FC, which is used when the FTS is engaged, only has access to GPS module 2 and its own built-in sensors (IMUs and barometer). These sensors are completely segregated from those used by the main FC, ensuring independent operation during FTS engagement.

(3) FTS Device and Control Switching

The FTS device consists of 16 switches distributed across two relay boards, each controlling a motor or servo command line. These switches determine which flight controller (main or auxiliary) has control over the motors and servos. During normal operations, the main FC controls these components. However, when the FTS is activated, control is transferred to the auxiliary FC. The motors' electronic speed controllers (ESC) output their telemetry data, including RPM values, to the main FC, which are displayed on the Remote Pilot in Command (RPIC) interface at the Ground Control Station. This telemetry data are crucial for verifying the functionality of the FTS during pre-flight checks.

2.15. Overview of Hardware Components for Flight Termination System (FTS)

A range of specialized hardware components were utilized to ensure the reliable operation of the Flight Termination System (FTS). These components include relay modules, communication modules, an auxiliary flight controller, and a high-performance computing platform. The following table provides a detailed overview of each component, including specifications and key attributes, to offer a clear understanding of the hardware setup used to support the FTS functionality (Table 7).

Table 7. Overview of Hardware Components for Flight Termination System (FTS).

Component	Details
FTS Device	Relay Modules (2×)
Specifications	- Relay switching current: approx. 8 × 60 mA - Operating voltage: 3.3 V to 5 V - 8× relay (DC: max. 30 V/10 A, AC: max. 250 V/10 A) - Relay with three contacts (change switch) - Direct control via microcontroller digital output - Header pin for control RM 2.54 mm - 8× three-screw terminals each for load connection - 8× status LED for relay status - 4× mounting holes 3 mm - Size: 138 × 50 × 19 mm - Weight: 105 g
FTS Comms Module	LTE Dongle
Features	- Provides LTE connectivity for communication - Compact and easy to integrate with the FTS system
Key Attributes	- BCM 2835 SOC @ 1GHz - 512MB RAM - On-board wireless LAN (2.4 GHz 802.11 b/g/n) - On-board Bluetooth 4.1 + HS Low-energy (BLE) - micro SD slot - mini HDMI type C connection - 1× micro-B USB for data - 1× micro-B USB for power supply - CSI Camera Connector - Equipped 40-pin GPIO connector - Compatible with pHAT/HAT boards - Dimensions: 65 × 30 × 5 mm
Auxiliary FC	Holybro Pixhawk 6C
Core Components	Processors and Sensors: - FMU Processor: STM32H743 (32 Bit Arm® Cortex®-M7, 480 MHz, 2 MB memory, 1MB SRAM) - IO Processor: STM32F103 (32 Bit Arm® Cortex®-M3, 72 MHz, 64 KB SRAM) - Accel/Gyro: ICM-42688-P, BMI055 - Mag: IST8310 - Barometer: MS5611 Physical Dimensions: - Dimensions: 84.8 × 44 × 12.4 mm - Weight (Plastic Case): 34.6g - Operating temperature: −40 to 85 °C

Table 7. *Cont.*

Component	Details
Platform	NVIDIA Jetson Xavier NX KI System-on-Modul
System Details	- High-performance AI computing module - Supports a wide range of AI workloads - Compatible with Jetson Xavier NX/Nano/TX2 NX

3. Results

The comparative analysis of high-speed drone transportation versus traditional car transportation revealed nuanced differences in the integrity and preanalytical parameters of blood samples across diverse weather conditions. A total of 27 analytes were assessed in serum samples, 20 in EDTA whole blood, 26 in lithium-heparin plasma, and 5 in citrate plasma, encompassing a comprehensive spectrum of clinical markers.

Serum samples (Table 8): for serum samples transported via both drone and car, correlation coefficients (r) ranged from 0.830 to 0.998, indicating strong to perfect agreement between transportation methods. Slopes varied from 0.947 to 1.023, demonstrating minimal deviations from unity. Notably, five analytes (total bilirubin, calcium, ferritin, kalium, and sodium) exhibited discrepancies between transported samples and negative controls, characterized by correlation coefficients lower than 0.800 and mean percentage differences outside the range of ±10%. However, no significant differences were observed between drone and car transportation modalities.

Table 8. Passing–Bablock and Bland–Altman analyses comparing the different transportation methods: drone flight compared with car transportation of serum (combustion car).

							Bland–Altman
Analyte	**Unit**	**n**	**Mean**	**Slope**	**r**	**Intercept**	**Arithmetic Mean %**
Alk. Phos.	U/L	20	77.85	1.000	0.984	0.000	−0.10
Billirubin total	umol/L	20	3.53	1.000	0.867	0.800	−5.79
Calcium	mmol/L	20	2.41	1.000	0.934	0.000	−0.05
Cholesterol	mmol/L	20	5.06	1.000	0.991	0.000	−0.20
Creatine kinase	U/L	20	92.30	1.009	0.997	−0.595	−0.50
CRP	mg/L	20	4.04	1.010	0.997	−0.413	−0.40
Protein total	g/L	20	68.50	1.000	0.845	0.000	−0.20
Ferritin	ng/mL	20	188.46	1.023	0.998	−2.668	−0.40
Folate	nmol/L	20	20.19	0.974	0.978	0.231	0.90
ɣGT	U/L	20	29.70	1.000	0.995	0.000	−0.80
Glucose	mmol/L	20	5.71	1.000	0.989	0.000	0.20
AST	U/L	20	24.40	1.000	0.961	0.000	−0.90
ALT	U/L	20	23.65	1.000	0.975	0.000	−0.30
HDL	mmol/L	20	1.52	1.000	0.991	−0.005	0.40
Uric acid	umol/L	20	290.40	1.018	0.994	−5.041	0.20
Potassium	mmol/L	20	4.65	1.000	0.993	0.000	0.30
Creatinine	umol/L	20	80.65	0.947	0.908	4.289	−1.10
LDH	U/L	20	148.85	1.000	0.997	−0.500	0.00
LDL Cholesterol	mmol/L	20	2.93	0.988	0.995	0.025	0.20

Table 8. *Cont.*

							Bland–Altman
Analyte	**Unit**	**n**	**Mean**	**Slope**	**r**	**Intercept**	**Arithmetic Mean %**
Lipase	U/L	20	41.20	1.000	0.997	−0.500	0.80
Sodium	mmol/l	20	138.80	1.000	0.830	0.000	0.22
HDL Cholest.	mmol/l	20	1.52	1.000	0.991	−0.005	0.40
Non-HDL Chol	mmol/l	20	3.54	0.989	0.989	0.050	−0.50
Phosphate	mmol/l	20	1.12	1.000	0.970	−0.010	0.60
Triglyceride	mmol/l	20	1.51	1.000	0.994	0.000	0.30
Vitamine B12	pmol/L	20	366.84	1.005	0.965	−10.332	1.50
TSH	mU/L	20	2.04	1.000	0.998	0.010	−0.70

Similar patterns were observed in EDTA whole blood (Table 9), citrate plasma samples (Table 10), and lithium-heparin plasma (Table 11). For EDTA whole blood, the slopes ranged from 0.960 to 1.158, and the correlation coefficients (r) ranged from 0.860 to 0.999. For citrate plasma samples, the slopes ranged from 0.944 to 1.000, and the correlation coefficient (r) from 0.926 to 0.981. Lithium-heparin plasma samples had slopes ranging from 0.938 to 1.077 and correlation coefficients (r) from 0.806 to 0.997.

Table 9. Passing–Bablock and Bland–Altman analysis comparing the different transportation methods: drone flight compared with car transportation of EDTA plasma (combustion car).

							Bland–Altman
Analyte	**Unit**	**n**	**Mean**	**Slope**	**r**	**Intercept**	**Arithmetic Mean %**
Hemoglobin	g/L	20	139.35	1.000	0.994	1.000	−0.70
Hematocrit	%	20	39.80	1.000	0.992	0.000	−0.80
Erythrocytes	$\times 10^6$/uL	20	4.48	1.000	0.999	0.100	−1.10
RDW-CV	%	20	13.15	1.000	0.987	0.000	−0.07
MCV	fl	20	88.85	1.000	0.988	0.000	−0.16
MCH	pg	20	31.30	1.000	0.860	0.000	0.50
MCHC	g/L	20	351.55	1.075	0.888	−28.842	0.60
PDW	fl	20	12.39	1.158	0.899	−2.092	0.10
MPV	fl	20	10.50	1.125	0.951	−1.356	0.30
Leukocytes	$\times 10^3$/uL	20	6.80	1.014	0.983	−0.089	0.50
Eosinophils	%	20	3.00	1.000	0.953	−0.100	6.90
Eosinophils	$\times 10^3$/uL	20	0.19	1.000	0.977	0.000	0.00
Basophils	%	20	0.69	1.000	0.923	0.000	−5.30
Monocytes	%	20	9.01	1.072	0.928	−0.575	−2.00
Monocytes	$\times 10^3$/uL	20	0.69	1.000	0.959	0.000	0.90
Thrombocytes	$\times 10^3$/uL	20	227.05	1.071	0.954	−24.853	4.30
Lymphocytes	%	20	31.05	0.977	0.994	0.361	1.30
Lymphocytes	$\times 10^3$/uL	20	2.02	1.000	0.990	−0.050	2.30
Neutrophils	%	20	56.26	0.960	0.997	2.663	−1.10

Table 10. Passing–Bablock and Bland–Altman analysis comparing the different transportation methods: drone flight compared with car transportation of citrate plasma (combustion car).

							Bland–Altman
Analyte	**Unit**	**n**	**Mean**	**Slope**	**r**	**Intercept**	**Arithmetic Mean %**
Quick	%	20	111.20	1.000	0.926	−1.500	1.50
INR		20	0.96	1.000	0.926	0.010	0.70
aPTT	s	20	24.73	0.944	0.948	1.481	−1.40
Fibrinogen	g/L	20	2.72	1.000	0.981	−0.100	2.30
D-Dimer	ug/L	20	420.67	0.990	0.979	10.847	−2.70

Table 11. Passing–Bablock and Bland–Altman analysis comparing the different transportation methods: drone flight compared with car transportation of lithium-heparin plasma (combustion car).

							Bland–Altman
Analyte	**Unit**	**n**	**Mean**	**Slope**	**r**	**Intercept**	**Arithmetic Mean %**
Alk. Phos.	U/L	20	64.38	1.000	0.997	1.000	−0.50
Billirubin total	umol/L	20	8.32	1.000	0.974	−0.500	0.50
Calcium	mmol/L	20	2.41	1.067	0.945	−0.164	0.10
Cholesterol	mmol/L	20	5.01	1.000	0.995	0.000	−0.20
Creatine kinase	U/L	20	157.35	1.000	0.996	0.000	−0.50
CRP	mg/L	20	1.84	1.005	0.980	0.003	−2.40
Protein total	g/L	20	74.47	1.000	0.984	0.000	−0.10
Ferritin	ng/mL	20	134.61	1.008	0.991	0.538	−1.60
Folate	nmol/L	20	20.23	1.077	0.964	−1.346	−0.80
ɣGT	U/L	20	23.23	1.000	0.993	0.000	1.00
Glucose	mmol/L	20	4.45	1.000	0.986	0.000	0.60
AST	U/L	20	24.81	1.000	0.958	1.000	−2.40
ALT	U/L	20	26.77	1.000	0.993	0.000	−0.50
HDL	mmol/L	20	1.68	1.000	0.997	0.000	−0.20
Uric acid	umol/L	20	281.69	0.988	0.994	3.593	0.10
Potassium	mmol/L	20	3.87	1.000	0.964	0.000	−0.40
Creatinine	umol/L	20	77.15	0.938	0.972	4.120	0.80
LDH	U/L	20	180.00	1.062	0.932	−3.962	−5.70
LDL Cholesterol	mmol/L	20	3.05	1.000	0.988	0.000	0.30
Lipase	U/L	20	38.26	1.000	0.993	0.000	0.20
Sodium	mmol/L	20	139.19	1.000	0.806	0.000	0.22
Non—HDL Chol	mmol/L	20	3.33	1.000	0.990	0.000	−0.10
Phosphate	mmol/L	20	0.94	1.000	0.970	0.000	−0.40
Triglyceride	mmol/L	20	1.07	1.000	0.996	0.000	0.30
TSH	mU/L	20	1.56	1.003	0.995	−0.003	0.00
Vitamine B12	pmol/L	20	358.23	1.026	0.985	−12.053	0.70

Analyzing specific analytes within each sample type revealed a few discrepancies between transported samples (natrium, potassium) and reference controls, characterized by deviations in correlation coefficients and mean percentage differences. However, these discrepancies did not exhibit a consistent pattern across transportation modalities, with no significant differences observed between drone and car transportation methods.

Accelerometer measurements showed higher vibrations with the drone but without a noticeable impact on sample integrity (Figure 3).

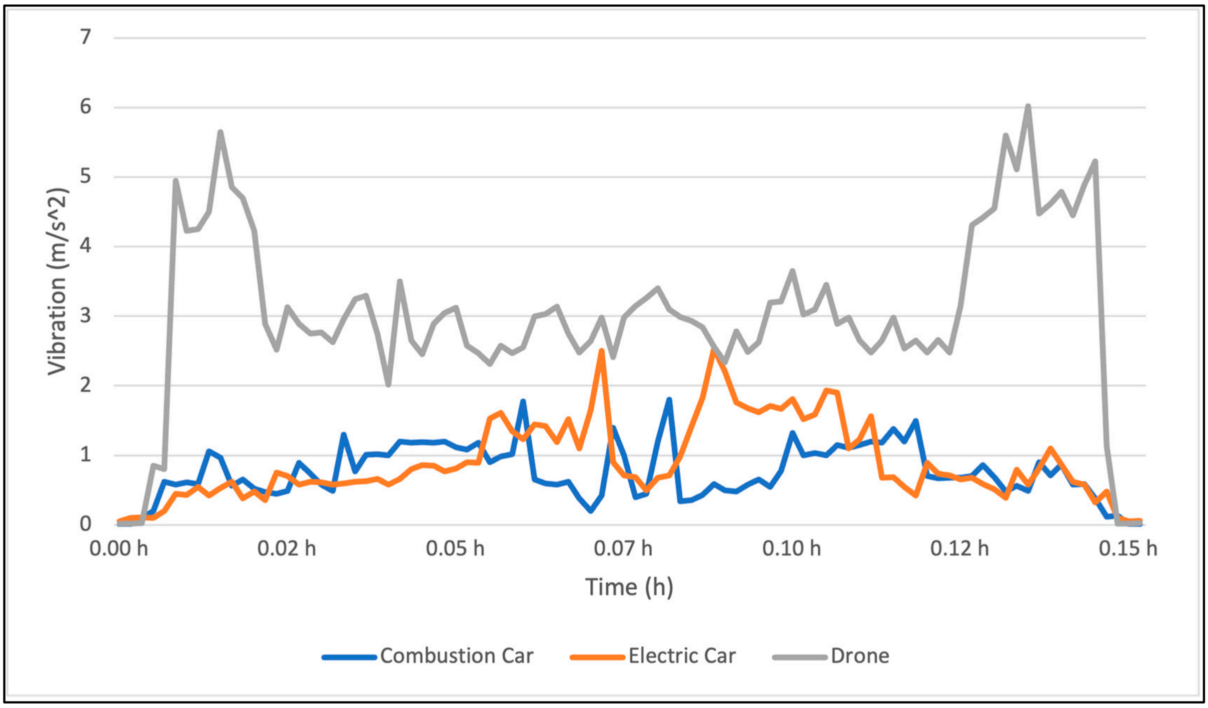

Figure 3. Vibration metrics: comparing the vibrations experienced by the blood sample during drone flight and transportation by electric and combustion car.

Furthermore, sample temperature decreased by 4.3 °C (from 20.0 to 15.7 °C) at 0 °C outside temperature at an altitude of 1800 m above sea level (AMSL) and a flown distance of 31.8 km over 30 min of flight. At other altitudes and higher outside temperatures, the decrease in sample temperature was even less pronounced.

4. Discussion

The findings of this study provide valuable insights into the feasibility and efficacy of high-speed drone transportation in the context of medical logistics, particularly concerning the transportation of sensitive blood samples. The results indicate that high-speed drone transportation maintains the integrity of blood samples as effectively as traditional car transportation, which has significant implications for the future of medical logistics.

The use of drones for transporting medical samples presents numerous advantages, especially in terms of speed and accessibility. Drones can bypass many of the logistical challenges faced by ground vehicles, such as traffic congestion, road conditions, and geographic barriers. This capability is particularly advantageous in remote or underserved areas where access to timely medical transportation is limited. The results of our study underscore that drones, despite the higher vibrations measured during transport, do not negatively impact the integrity of blood samples. Specifically, for serum samples, the correlation coefficient (r) ranged from 0.830 to 1.000, and the slopes varied from 0.913 to 1.111. Five analytes, including total bilirubin, calcium, ferritin, kalium, and sodium, showed discrepancies with correlation coefficients lower than 0.800, slopes not between 0.8 and 1.2, and mean percentage differences outside the range of ±10%. However, no significant differences were observed between drone and car transportation. This finding aligns with previous research that highlights the robustness of blood samples to vibrations experienced during transportation [19].

Traditional car transportation has long been the standard for transporting medical samples, but it is not without its drawbacks. Factors such as traffic delays and route inefficiencies can compromise the timeliness of sample delivery. Our study shows that drones offer a comparable, if not superior, alternative to cars, particularly in urban areas with significant traffic congestion or rural areas with difficult terrain. Similar patterns emerged in EDTA whole blood, lithium-heparin plasma, and citrate plasma samples. The correlation coefficients (r), when comparing drone versus car transportation, ranged from 0.829 to 0.997 for EDTA, 0.939 to 0.998 for lithium-heparin, and 0.830 to 1.000 for citrate samples. The slopes ranged from 0.956 to 1.051 for EDTA, 0.938 to 1.085 for lithium-heparin, and 0.913 to 1.111 for citrate samples. Analyzing specific analytes, a few discrepancies were identified, but no significant differences were observed between the transportation methods. This is supported by research from Rosser et al. (2018) [20], who demonstrated the potential for drones to reduce delivery times significantly in healthcare logistics.

One of the critical aspects of blood sample transportation is maintaining a stable temperature to preserve sample integrity. Our study found that although the temperature of samples decreased during drone flights, the decrease was within acceptable limits. Specifically, sample temperature decreased by 4.3 °C (from 20.0 to 15.7 °C) at 0 °C outside temperature at an altitude of 1800 m above sea level and a flown distance of 31.8 km over 30 min of flight. This finding is consistent with the work of Sharma et al. (2019) [21], who found that temperature fluctuations during drone transport did not adversely affect the quality of medical samples. Future drone designs could incorporate more advanced temperature control mechanisms to further ensure sample stability, even in extreme weather conditions.

The higher vibrations recorded during drone transportation did not result in significant discrepancies in analyte concentrations. This suggests that the design of drone transport containers can mitigate the effects of mechanical agitation or that the vibrations themselves are still too weak to influence the samples. Previous studies have also shown that while drones may experience higher levels of vibration compared to ground transportation, the impact on sample integrity is negligible when appropriate measures are taken [17]. Accelerometer measurements showed higher vibrations with the drone but without a noticeable impact on sample integrity.

The integration of drones into medical logistics has broader implications for healthcare delivery. By reducing transportation times and ensuring the rapid delivery of critical medical materials, drones can enhance the overall efficiency of healthcare systems. This is particularly important in emergency situations where time is of the essence [8,9,22,23]. The ability to quickly deliver blood samples for diagnostic testing can expedite treatment decisions and improve patient outcomes. Additionally, drones can play a crucial role in disaster response scenarios where traditional transportation infrastructure may be compromised [24,25].

While the potential benefits of drone transportation are clear, several regulatory and practical considerations must be addressed to facilitate widespread adoption. Regulatory frameworks need to be developed to ensure the safe and ethical use of drones in medical logistics. Issues such as airspace management, privacy concerns, and public acceptance must be carefully navigated. Collaborative efforts among policymakers, regulatory agencies, healthcare providers, and technology developers will be essential to establish clear guidelines and standards for drone operations in healthcare settings.

5. Conclusions

The findings of this study demonstrate that high-speed drone transportation of blood samples does not significantly alter analyte concentrations when compared to traditional car transportation. Any observed discrepancies between transported samples and reference controls were attributed to the transportation process itself rather than the mode of transportation. This underscores the potential of drone technology to enhance the efficiency and reliability of medical sample transport, particularly in scenarios requiring rapid and reliable delivery for timely diagnosis and treatment. Moving forward, continued research, innovation, and collaboration will be essential to harness the full transformative potential of drones in healthcare delivery and logistics.

While this study provides valuable insights, several limitations must be considered. The study was conducted under specific environmental conditions, with a particular focus on temperature and vibration during drone transport. However, the conditions for car transportation were not controlled or documented with the same rigor, potentially introducing biases when comparing the two modalities. Additionally, the study focused on a selected panel of analytes, which may not fully represent the broad spectrum of tests performed in clinical settings. The impact of drone transport on other, perhaps more sensitive, analytes remains unexplored.

Furthermore, the sample size was relatively small, and the study was conducted in a specific geographic region, which may limit the generalizability of the findings to other regions or scenarios, particularly those with different environmental conditions or healthcare infrastructure. The study also did not address the cost-effectiveness or scalability of drone transportation compared to traditional methods, which are critical factors for assessing the practicality of widespread implementation in healthcare logistics.

Future research should aim to address the limitations identified in this study and explore additional areas to further validate and expand upon the findings. Conducting studies across diverse geographic regions and under varying environmental conditions will provide a more comprehensive understanding of the impact of different transportation modalities on sample integrity. Including a wider range of analytes, especially those that are more sensitive to environmental changes, would help to determine the full scope of drone transportation's impact on blood samples.

Moreover, investigating the long-term viability of samples transported via drones, including their stability over extended periods and under different storage conditions post-transport, would be valuable. A detailed cost-benefit analysis is also necessary to assess the economic viability of drone transportation in comparison to traditional methods, taking into account factors such as operational costs, maintenance, and scalability. As drone technology continues to develop, research should also focus on addressing regulatory and ethical challenges, particularly in relation to privacy, airspace management, and public acceptance. By addressing these areas, future research can build on the findings of this study, contributing to the development of robust and scalable drone-based solutions for medical logistics.

Author Contributions: Conceptualization, N.S., L.R., H.R. and M.R.; methodology, N.S and L.R.; formal analysis, N.S.; resources, L.R. and M.R.; data curation, N.S. and F.L.; writing—original draft preparation, N.S.; writing—review and editing, N.S., L.R., F.L. and M.R.; visualization, N.S.; supervision, L.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We extend our heartfelt gratitude to all those who contributed to this research. Special thanks to the laboratory personnel and transportation providers in Liechtenstein and Switzerland for their invaluable support during data collection. We are particularly grateful to Loren Risch and Martin Risch for their guidance and expertise. Our thanks also go to the environmental experts and stakeholders who participated in our workshops and whose insights helped shape the study. Finally, we thank our families and friends for their constant encouragement and understanding, without which this work would not have been possible.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sigari, C.; Biberthaler, P. Medical drones: Disruptive technology makes the future happen. *Der Unfallchirurg* **2021**, *124*, 974–976. [PubMed]
2. Zailani, M.A.H.; Sabudin, R.Z.A.R.; Rahman, R.A.; Saiboon, I.M.; Ismail, A.; Mahdy, Z.A. Drone for medical products transportation in maternal healthcare: A systematic review and framework for future research. *Medicine* **2020**, *99*, e21967. [PubMed]
3. Ananya Elizabeth George. Employment of drones in medical, emergency and relief settings. *Int. J. Res. Humanit. Arts Sci.* **2017**, *5*, 21–27.
4. Sharon, W.; Rivas, H.; Matabuena, P. Drones in healthcare. In *Digital Health: Scaling Healthcare to the World*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 159–168.
5. Oigbochie, A.E.; Odigie, E.B.; Adejumo, B.I.G. Importance of drones in healthcare delivery amid a pandemic: Current and generation next application. *Open J. Med. Res.* **2021**, *2*, 1–13.
6. Yakushiji, K.; Fujita, H.; Murata, M.; Hiroi, N.; Hamabe, Y.; Yakushiji, F. Short-range transportation using unmanned aerial vehicles (UAVs) during disasters in Japan. *Drones* **2020**, *4*, 68. [CrossRef]
7. Konert, A.; Smereka, J.; Szarpak, L. The use of drones in emergency medicine: Practical and legal aspects. *Emerg. Med. Int.* **2019**, *2019*, 3589792.
8. Johnson, A.M.; Cunningham, C.J.; Arnold, E.; Rosamond, W.D.; Zègre-Hemsey, J.K. Impact of using drones in emergency medicine: What does the future hold? *Open Access Emerg. Med.* **2021**, *13*, 487–498. [CrossRef]
9. Stierlin, N.R.; Loertscher, F.; Risch, M.; Risch, L. A Green Laboratory Approach to Medical Sample Transportation: Assessing the Carbon Dioxide (CO_2) Footprint of Medical Sample Transportation by Drone, Combustion Car, and Electric Car. *Drones* **2024**, *8*, 489. [CrossRef]
10. Wolfe, M.K.; McDonald, N.C.; Holmes, G.M. Transportation barriers to health care in the United States: Findings from the national health interview survey, 1997–2017. *Am. J. Public Health* **2020**, *110*, 815–822.
11. Weiss, D.J.; Nelson, A.; Vargas-Ruiz, C.A.; Gligorić, K.; Bavadekar, S.; Gabrilovich, E.; Bertozzi-Villa, A.; Rozier, J.; Gibson, H.S.; Shekel, T.; et al. Global maps of travel time to healthcare facilities. *Nat. Med.* **2020**, *26*, 1835–1838.
12. Oakey, A.; Grote, M.; Smith, A.; Cherrett, T.; Pilko, A.; Dickinson, J.; AitBihiOuali, L. Integrating drones into NHS patient diagnostic logistics systems: Flight or fantasy? *PLoS ONE* **2022**, *17*, e0264669.
13. Poljak, M.; Šterbenc, A. Use of drones in clinical microbiology and infectious diseases: Current status, challenges and barriers. *Clin. Microbiol. Infect.* **2020**, *26*, 425–430.
14. Demuyakor, J. Ghana go digital Agenda: The impact of zipline drone technology on digital emergency health delivery in Ghana. *Humanities* **2020**, *8*, 242–253. [CrossRef]
15. Tarr, A.A.; Perera, A.G.; Chahl, J.; Chell, C.; Ogunwam, T.; Paynter, K. *Drones—Healthcare, Humanitarian Efforts and Recreational Use*; Drone Law and Policy; Routledge: London, UK, 2021; pp. 35–54.
16. González-Domínguez, R.; González-Domínguez, Á.; Sayago, A.; Fernández-Recamales, Á. Recommendations and best practices for standardizing the pre-analytical processing of blood and urine samples in metabolomics. *Metabolites* **2020**, *10*, 229. [CrossRef]
17. Gerber, T.; Taschner-Mandl, S.; Saloberger-Sindhöringer, L.; Popitsch, N.; Heitzer, E.; Witt, V.; Geyeregger, R.; Hutter, C.; Schwentner, R.; Ambros, I.M.; et al. Assessment of pre-analytical sample handling conditions for comprehensive liquid biopsy analysis. *J. Mol. Diagn.* **2020**, *22*, 1070–1086. [PubMed]
18. Thuile, K.; Giacomuzzi, K.; Jani, E.; Marschang, P.; Mueller, T. Evaluation of the in vitro stability of direct oral anticoagulants in blood samples under different storage conditions. *Scand. J. Clin. Lab. Investig.* **2021**, *81*, 461–468.
19. Amukele, T.K.; Sokoll, L.J.; Pepper, D.; Howard, D.P.; Street, J. Can unmanned aerial systems (drones) be used for the routine transport of chemistry, hematology, and coagulation laboratory specimens? *PLoS ONE* **2017**, *12*, e0180183.
20. Rosser, J.C.; Vignesh, V.; Terwilliger, B.A.; Parker, B.C. Surgical and medical applications of drones: A comprehensive review. *JSLS J. Soc. Laparosc. Robot. Surg.* **2018**, *22*, e2018.00018.
21. Sharma, A.; Kwon, J.; Ravichandran, N.; Park, S. Evaluation of blood sample transportation using small drones. *Clin. Chem. Lab. Med. CCLM* **2019**, *57*, 1778–1785.
22. Roberts, N.B.; Ager, E.; Leith, T.; Lott, I.; Mason-Maready, M.; Nix, T.; Gottula, A.; Hunt, N.; Brent, C. Current summary of the evidence in drone-based emergency medical services care. *Resusc. Plus* **2023**, *13*, 100347.
23. Zailani, M.A.; Azma, R.Z.; Aniza, I.; Rahana, A.R.; Ismail, M.S.; Shahnaz, I.S.; Chan, K.S.; Jamaludin, M.; Mahdy, Z.A. Drone versus ambulance for blood products transportation: An economic evaluation study. *BMC Health Serv. Res.* **2021**, *21*, 1308. [CrossRef] [PubMed]
24. Anand, R.; Muneshwar, M.M.S.; Tuppada, S.; Swetha, M.S.; Anil, G.N. Emergency Medical Services Using Drone Operations in Natural Disaster and Pandemics. In *Inventive Communication and Computational Technologies, Proceedings of ICICCT 2021, New Delhi, India, 25–26 June 2021*; Springer: Singapore, 2022.
25. Sivasuriyan, V. Drone usage and disaster management. *Bodhi Int. J. Res. Humanit. Arts Sci.* **2021**, *5*, 93–97.