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The Quality of Blood is not Affected by Drone Transport: An Evidential Study of the Unmanned Aerial Vehicle Conveyance of Transfusion Material in Japan

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Abstract: Unmanned aerial vehicles (UAVs), or drones, are used in Rwanda for transfusion transport, but they have not yet been used in Japan. This technology holds promise for transporting medical supplies during disasters or to remote places where the terrain makes it difficult to travel by land. One of the difficulties in using UAVs is the temperature-control requirements for red blood cell (RBC) solutions, i.e., 2 °C to 6 °C according to Japanese regulations. This study aimed to describe the effectiveness of UAV-based transport of RBC solution. For testing, we gradually increased the UAV travel distance, monitored the temperature of the RBC solution, and conducted laboratory tests to check the integrity of the blood sample. Lactate dehydrogenase (LD) was used as a hemolytic index to indicate the effect of the UAV flight on the blood samples. The UAV was able to exceed 7 km of travel distance despite the relatively heavy load needed for the RBC solution storage. The LD level was not significantly different between the flight and non-flight (control) samples. However, we were not able to completely maintain a temperature of 2 °C to 6 °C; nonetheless, the deviation was within the safe range.

Keywords: drone; unmanned aerial vehicle; transfusion; temperature; blood transportation; refrigerator; ATR

1. Introduction

The use of unmanned aerial vehicles (UAVs), or drones, for transporting medical supplies (vaccinations, blood, and other medical supplies) has been reported [1–3]. The UAV transport with a fixed-wing aircraft in Rwanda may be the first case of its use for blood transfusion, and the technology may be used in Canada soon [4]. However, to the best of our knowledge, no study has reported on the quality of blood for transfusion after flight.

The Japan Blood Donation Foundation (DBDF) conducts the conveyance of blood for transfusions in Tokyo at the request of medical institutions associated with the Japanese Red Cross (JRC) Society. Outside Tokyo, the conveyance is conducted by the JRC itself. Currently, the transportation of blood is mostly done by ground vehicles.

However, delivery to islands without land transportation is difficult, and during a disaster, there is an increased risk of unfavorable circumstances (e.g., delivery across terrain where bridges have collapsed or across rivers which have overflowed). Shipment of blood, which takes 25 hours or more for the Ogasawara Islands, was done in active transport refrigerators (ATRs) [5]. The ATR is a convenient blood transport system, but it is associated with certain risks, especially during marine transportation, due to turbulence during storms or seasonal variations. In addition, a study reported that the 2018 heavy snowfall in the Hokuriku area, Japan, resulted in delayed conveyance of blood samples because of the late removal of snow, despite the short distance for delivery [6], and after the Great East Japan Earthquake, the delivery of drugs was difficult because of ground blockades [7].

For UAV transport of transfusion materials, quality and safety are the most important factors in developing optimal flight protocols. In addition to maintaining the optimal temperature for the blood, a long-distance flight is required. Therefore, this study aimed to establish a basic UAV protocol by evaluating the integrity of transported blood for transfusion and the conditions of the conveyance container.

2. Materials and Methods

The present study design involved 7 UAV flight trials and 5 series of blood tests. To evaluate the effect of the flight on the RBC solution, we compared blood biochemical test results based on the presence or absence of flight. In addition, biochemical tests were done before the flight, after the flight, and again after filtration, since filtration was done before a transfusion (Table 1).

Table 1. Schedule of laboratory testing from the day of blood donation.

Trial No.	Before the Flight (days)	Unmanned Aerial Vehicle Flight [a] (days)	After Flight (Days)
1		Simulated blood	
2	11	14	15
3		Simulated blood	
4	10	12	13
5	12	13	15
6	11	13	15
7	11	13	15

[a] In trials 1 and 3, simulated blood was transported, and there were no data recorded.

In this study, we used an M1000 quadcopter (Mazex Co. Ltd., Osaka, Japan) with load capabilities of up to 24.9 kg on takeoff and a maximum speed of 58 km/h. For blood transport, an ATR 705 (FUJIFILM Toyama Chemical Co. Ltd., Tokyo, Japan) was used because it can be maintained at an optimal range for red blood cell (RBC) solutions (2 °C to 6 °C). The refrigerator itself weighs 7 kg. The transfusion supply bag was a DBDF ordinary bag for the transport of RBC solution. It weighed 2.8 kg and measured 340 mm × 270 mm × 300 mm. The cooler-box (Campers Collection, Yamazen, Corp., Tokyo, Japan) held blood packs during the UAV flight. This was a simple cooler-box for storage, with a volume of 8 L, measured 304 mm × 230 mm × 222 mm, and weighed 970 g. Another cooler was used as an outdoor refrigerator during the study (CLBOX30L, Thanko Co. Ltd, Tokyo, Japan). Blood packs were used for testing blood (KBP-66DC, Kawasumi Co. Ltd., Oita, Japan) and were wrapped in water absorption sheets to prevent the spilling of blood in case of leakage (Koyo Co. Ltd, Kanagawa, Japan). An electronic watch logger recorded the temperature each minute (KT-255U, Fujita Electric

Works, Ltd, Kanagawa, Japan), and a solid coolant that changed to a liquid state at approximately 4 °C was used to control the temperature of the blood packs (Cold-packs Type 3, JSP Corp., Tokyo, Japan) [8].

We divided the donated RBC solution (280 mL; 2 units) supplied by the JRC into packs. During transport, the blood packs were wrapped in a water absorption sheet to prevent blood from spilling in case of a tear to the bag, and they were placed in the ATR for UAV or car conveyance to the trial place. The container was moved to the ATR, to the DBDF bag, and then to the cooler. In addition, we used 2 packs of blood (2 units) for the second and fourth trials and further divided them into 2 packs each. Other trials used one blood pack. A pair of cold-packs was frozen at −15 °C; at 3 hours before the flight, the temperature was set to −5 °C. The resulting temperature inside the cooler was approximately 0 °C. The estimated surface temperature was 5 °C (data not shown).

The blood packs were placed in the container, with cold-packs sandwiched between the top and bottom (except when in the ATR). During flight trials, the ATR flew by the hanging method at first, but it was then fixed inside the drone with a net (Table 2).

Table 2. Study design.

Trial	Date 2019	Place of Flight	Blood Supplier	Containers for Blood Packs and Carrying Methods	
				Description of Flight Set-Up	Control (No Flight)
1	June 17	Higashi-Osaka	Simulated blood	2 packs in ATR/ ATR was hung	2 packs in ATR
2	June 25	Fukushima, RTF	JRC	2 packs in ATR/ ATR was hung	2 packs in ATR
3	July 6	Tomi	Simulated blood	2 packs in ATR/ ATR was hung	2 packs in ATR
4	July 20	Tomi	JRC	2 packs in transfusion bag/ transfusion bag was hung	2 packs in ATR
5	August 11	SFC	JRC	1 pack in a cooler-box/ cooler-box attached	1 pack in ATR
6	August 17	Tomi	JRC	1 pack in a cooler-box/ cooler-box attached	1 pack in ATR
7	September 1	SFC	JRC	1 pack in a cooler-box/ cooler-box attached	1 pack in ATR

Abbreviations: ATR, active transport refrigerator; JRC, Japan Red Cross; Higashi-Osaka(550km from Tokyo); RTF, robot test field (280 km); SFC, Shonan Fujisawa Campus (70 km); Tomi (180 km).

The refrigerator hung by a rope, and the rope could be easily released. The altitude was only 5 m, which is not very high if the refrigerator falls accidentally. At the Fukushima robot field, only our researchers were present.

The UAV flights were conducted 7 times. To estimate the maximum flight time, the travel distance was increased for each trial. The flight was confined to battery capacity. A record of the weather conditions at the time of the flight and the basic flight data were recorded.

At the flight point, blood packs were transported by car to Tokyo where the blood tests were performed to compare the change in the lactate dehydrogenase (LD) level. For biochemical testing, we collected the blood from each blood pack and measured levels of sodium (Na), potassium (K), RBCs, blood glucose, aspartate aminotransferase (AST), alanine aminotransferase (ALT), and LD.

Samples from packs of blood for transfusion were centrifuged at 3500 rpm for 10 min. The sera were transported to BML Inc., Tokyo, Japan. They were measured before the flights, after the flights, and after filtering by BML. BML measured LD by the ultraviolet method.

To compare biochemical results, the LD ratio was used to measure the rate of change in the LD level after filtration and the LD level before the experiment. The LD ratio utilized the LD level of the control group from the LD level after filtration and divided it by the LD level of the control before filtration. The ratio indicated the rate of blood destruction (hemolysis). Finally, we compared the differences in the ratios between the flight and non-flight (control) samples.

All statistical calculations were performed using JMP version 9.0 software (SAS Institute Inc., Cary, NC, USA). Data are expressed as mean ± standard deviation. The level of significance was 5%.

3. Results

3.1. UAV Flight

Table 3 shows the characteristics of the UAV flight. The flight was carried out at a low-lying plateau at the base of a mountain. The outside temperature in every trial exceeded 28 °C. The temperature on the surface of the cooler-box placed under direct under sunlight at Shonan Fujisawa Campus, Keio University in Kanagawa prefecture, exceeded 40 °C. The temperature of the non-flight blood samples ranged from (2.0 °C to 6.0 °C). With UAV trials 1 through 6, temperatures inside the storage container ranged from 4.7 °C to 9.8 °C during flights. By trial 7, the surface temperature of the blood pack was 4.4 °C. The flight was set on autopilot at a speed of 25 km/h. The distance in the first trials were approximately 300 m, obtained from the records of the UAV, but the trials were repeated until the travel distance exceeded 6700 m, and the flight took 35 minutes 52 seconds.

Table 3. Characteristics of unmanned aerial vehicle flight trials.

Trial	Outdoor Conditions				Flight Data [a]				
	Elevation (m)	Weather	Maximum Temperature (°C)	Local Pressure (hPa)	Maximum Temperature (°C) [b]	Maximum Speed (km/hour)	Scheduled Freight height (m)	Distance (m)	Time (min.sec)
1	1	Cloudy	28.5	No record	5.7	No record	5	300	5.23
2	5	Sunny	32.5	No record	5.0	12.7	5	600	4.0
3	1,060	Cloudy	29.0	No record	4.7	14.8	10	900	7.2
4	1,060	Cloudy	29.0	No record	No record	15.9	10	3000	14.19
5	35	Sunny	41.8	No record	9.8	16.1	10	3200	18.49
6	1,060	Sunny	34.8	894	9.3	22.5	10	3500	21.45
7	35	Sunny	30.5	1,013	4.4	25	10	6700	35.52

Note: [a] Automated flight except trial 1 (manual control); [b] Trials 1 to 6 temperatures were measured in the spaces in the containers and that of trial 7 was measured on the surface of a blood pack using a watch logger.

3.2. Biochemical Tests

The LD level of post-filtered RBC solutions after UAV flight did not increase compared with control (Table 4). Differences between flight and non-flight levels of Na, K, RBC, AST, ALT, and glucose were not obtained (data not shown).

Table 4. Effect of unmanned aerial vehicle transport on the levels of lactate dehydrogenase in blood.

Trial	Sample no.	Before the Trial LD (U/L)		After the Flight LD (U/L)		Post-Filtration				
						LD (U/L) [a]		LD Ratio [b]		
		Control	Flight	Control	Flight	Control	Flight	Control	Flight	p-Value *
1		No data (simulated blood)								
2	# 1	50.3±6.0	57.0±2.0	77.5±14.6	99.5±10.4	96.8±9.8	91.3±4.5	0.935±0.04	0.602±0.01	0.037
	# 2	85.8±5.1	72.5±0.6	109.0±6.1	122.5±8.1	126.3±4.0	127.8±8.5	0.472±0.00	0.762±0.01	0.010
3		No data (simulated blood)								
4	# 3	57.0±0.8	63.5±5.4	73.3±1.3	87.8±2.5	97.5±4.6	93.3±2.2	0.711±0.01	0.469±0.00	0.006
	# 4	51.8±4.8	54.3±1.7	64.3±3.4	77.5±6.6	87.5±7.0	86.3±10.0	0.691±0.00	0.590±0.00	0.37
5	# 5	59.0±1.6	62.5±6.7	71.0±4.8	75.5±3.1	87.5±2.4	92.3±6.1	0.483±0.00	0.476±0.01	0.9
6	# 6	69.5±17.3	61.5±4.4	121.8±3.2	111.5±3.0	155±10.0	139.8±4.3	1.23±0.00	1.27±0.00	0.18
7	# 7	114.8±4.6	103.3±1.5	157.8±2.2	151.5±4.5	236.3±6.1	217.8±5.0	1.06±0.00	1.11±0.00	0.21

Note: [a] LD level (U/L) is a hemolysis indicator. U: unit; [b] LD ratio = (LD level post filtration—LD level before trial)/LD before trial; * Student's t-test P-value of LD ratio: comparison between flight and control group samples.

The LD levels, which we measured as indicators of blood deterioration, rose during trial 2 for both flight and non-flight samples 1 and 2. At the fourth trial, we hung a transfusion conveyance bag with samples 3 and 4. The LD ratio of sample 3 transported by UAV was significantly lower than that of the control sample. No significant difference in the LD ratio of sample 4 was detected. For trials 5 to 7, the blood for samples 5 to 7 was collected from blood packs in the cooling box, which was attached to the UAV. The results from these trials show no differences in LD ratios between flight and non-flight samples (Table 2).

4. Discussion

In Japan, the required temperature during storage and transportation of RBC products is 2 °C to 6 °C. In this study, we investigated the feasibility of UAV transportation of RBC to develop a safe and effective protocol. The results showed small differences in post-filtration values of LD after UAV flights up to 7 km compared to non-flight samples, which were acceptable for transfusion.

Results of previous studies differ in terms of the optimal storage conditions for blood intended for transfusion. For example, Pick et al. report that blood can be left at a room temperature for 30 min [9], while Naito reported that it could remain at room temperature for more than 30 min [10]. In the present study, we worked with a blood sample left at room temperature for 30 min to test the recommendation and a sample that was kept at 2 °C to 6 °C for transfusion. We concluded that small variations in temperature for short periods may be acceptable.

We measured humidity and acceleration, but vibration was not measured in some trials. As all transfusion products were placed in plastic bags, humidity did not affect the data. In summer, the humidity in Japan is over 90%. In some trials, we checked the acceleration using an acceleration meter, but we did not find large accelerations, showing less than 2 g.

Recently, a UAV that transported a patient's blood sample fell down. Transporting patient's sample is more dangerous than transporting blood for transfusion. Transfusion blood should be free of virus infection. In addition, packs of blood for transfusion are heavy and need to be cared for.

At the beginning of the present study, we thought that we could evaluate any deterioration of the blood by comparing the LD levels of flight and non-flight samples. We hypothesized that the LD data were sensitive to damage during transport, and the diagnostics are inexpensive and easy to perform. In addition, LD levels were used as hemolysis indexes when drawing blood [11]. The measurements were performed before the flights, after the flights, and after the blood passed through a transfusion filter which removes fibrin and other components not necessary for transfusions. We checked laboratory data for any influence from the flight. Free hemoglobin is also evaluated as a hemolytic index, but we could not evaluate these results.

The UAV conveyance of transfusion material has been discussed in various medical and technology settings, but studies are limited by using data from only one flight [2]. In addition, data regarding the evaluation of blood samples, blood glucose, and change in K level suggests that these may be affected by a long-distance flights [12]. In the end, the question surrounding the hemolysis of transfusion material is the key information needed for successful transportation.

Some studies report that the temperature of transfusion materials transported long distances by multicoptor can be controlled appropriately. In the present study, we report that the UAV can carry a pack of blood for transfusion over 6 km. Of course, fixed-wing aircrafts can safely transport packs of blood, but the risks of UAV transport are concerning. It is hard to accept the risk of material being lost on the ground from UAV transport. However, we did not evaluate these risks and thus suggested them for additional study.

During a disaster, it is crucial to transport blood for transfusion safely and efficiently. As previously described, in the Hokuriku area, which is located North–West of Tokyo, heavy snow rendered ground transportation useless until the snow was removed. The Northern area of Japan is also susceptible. There are many cliffs with small-sized and medium-sized rivers where the terrain is difficult to cross.

There have been instances where bridges have been swept away after a typhoon. Even if emergency services can get to these spots, they may not have a steady supply of blood to treat casualties.

Therefore, the conveyance of transfusion materials using UAV is a good option to explore as a first-response policy during disasters. Once their use becomes more common in these situations, we think that medical supply transport by UAV will rapidly advance in Japan and make a positive impact on the healthcare system.

Finally, our discussion concerns five conditions regarding transportation, such as medicines by Hii et al. [13]. These are actually indexes when we conduct medicine transportation. However, the present conditions of the transfusion are special in medical supplies, which is central in this article. These are living cells. It is important whether the red blood cells in particular hemolyze or not. We cannot use much hemolytic blood.

At present, we are concerned with whether the transportation of red blood cells is feasible or not. If transportation is feasible, we will increase the haul distance and confirm the quality of blood products. However, at this time, our method is not in a stage of practical use. We mention other conditions as follows:

1. Flight ability of the device: In our trial, we used M1000, which is totally different from MAVIC used by Hii et al. MAVIC does not accept DJI, where it should be attached to a payload. It can only carry a camera. The maximal takeoff weight of M1000 is 32 kg, and the maximal payload is 32 kg. In our experiment, the total load weight was approximately 2.5 kg. The total body weight of M1000 was 18.9 kg plus batteries. In a different experiment, with a payload of 22 kg, a flight of 10 km leaves approximately 40% of battery life after the flight.
2. The focus of Hii et al. was drug quality, but blood transfusion products contain living cells; thus, the durability test according to Hii et al. is impossible. The principle of transfusion is to store transfusion products at 2–4 °C during the test, with a difference of only 30 min. Originally, our experiment was to remove platelets and leukocytes from blood and retain the red blood cells. However, there is major difference in the red blood cell count; hence, it cannot be used for transfusion. Therefore, we planned to determine the cut-off rate of hemolysis appropriate for blood products for transfusion.
3. In our trial, we examined the quality of blood, as described in #1. The blood environment is temperature controlled.
4. This aspect is indicated for future investigation.
5. No individual was injured in our use of the UAV. Confirming the safety requires further investigation. In addition, blood packs were wrapped; thus, if the UAV crashed, blood contamination would be avoided. Furthermore, we are planning to investigate the transportation of blood worldwide using drones. We will ensure that a general person is not injured.

5. Conclusions

Safe and effective transportation of blood transfusion materials by UAV is a close reality in Japan. Our UAV will fly out of our trial fields, where there are no special legal restrictions. In Japan, there are many legal restrictions that prevent illegal and dangerous flights. However, in the future, we plan to transport blood products for transfusion by UAV to an island in which blood delivery by other modes of transportation is not possible. At present, blood transportation by drones is difficult. Thus, blood is still transported by ships We are going to raise the blood shipment required in consideration of the security measures until acquiring sufficient evidence.

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