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Drone-based medical delivery in the extreme conditions of Himalayan region: a feasibility study

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ABSTRACT

Introduction Unmanned aerial vehicles, or drones, have emerged as versatile tools across various sectors, including defence, agriculture, surveillance, mining, infrastructure, emergency response, transportation, geospatial mapping and notably medical supply delivery to challenging terrains. This study aims to investigate the feasibility of using drones for delivering essential medical supplies in Keylong, Himachal Pradesh, situated amidst the Middle Himalayan Range, where heavy snowfall during peak winter restricts access to remote regions, posing logistical hurdles for healthcare provision.

Methods This cross-sectional used a mixed-method approach alongside assessing the drone-based medical delivery. Insights from healthcare workers were documented on sociodemographic characteristics, local healthcare facilities and challenges encountered during drone operations.

Results A total of 15 sorties were conducted, efficiently transporting 1000 units of medicines and 20 clinical samples. Throughout the drone operation, various technological and health-related challenges were encountered due to the high altitude and the cold weather conditions. Additionally, it has been observed that drones could play a pivotal role in supplementing traditional medical supplies. Particularly, the transportation of the medical supplies in emergency situations and delivery of diagnostic samples from peripheral villages.

Conclusion The study observed that drones present a viable solution for enhancing healthcare accessibility in hard-to-reach regions, particularly for expeditiously delivering diagnostic samples and essential medications during emergencies. The findings underscore the potential of drones to complement existing healthcare systems, providing an efficient means to address logistical challenges in remote areas.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ At Keylong, located at an altitude of >10 000 ft, the delivery of the medical supplies is impacted by winter road blockage and heavy snowfall. The population in the study area is sparsely distributed which further impacts the healthcare delivery in the region.

WHAT THIS STUDY ADDS

⇒ This is one of the initial studies conducted at high altitude and sub-zero temperature to see the feasibility of drones-based delivery, their utility and perception of healthcare workers (HCWs).
⇒ This study tries to identify the operational challenges and opportunities in drone-based deliveries at high altitude. The key findings are as follows:
⇒ The drone-based delivery can be more useful in picking up the clinical sample from peripheral healthcare delivery centre, also largely cut down the transportation time.
⇒ The lithium polymer batteries are a better alternative for drone operations at high altitudes.
⇒ At high altitude preheating, insulating and slow charging the batteries increases endurance.
⇒ Deliveries by drones need basic training of HCWs.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study identifies that drones can be useful in delivering diagnostic samples, emergency and peripheral medical supplies in tough terrains. The drone-based delivery might complement the conventional method of medical supplies. Incorporation of need-based deliveries of medicines and sample transportation may strengthen the healthcare delivery at the difficult terrains.

INTRODUCTION

In recent years, the utilisation of unmanned aerial vehicles (UAVs), commonly known as drones, has significantly expanded, leveraging technological advancements to navigate challenging terrains and complement existing conventional logistics systems. These drones have found diverse applications in surveillance, defence, agriculture, mining, infrastructure, emergency response, transportation, geospatial mapping and humanitarian aid delivery.[1–5] Notably, drones are being increasingly adapted for the transportation of medical samples and supplies globally.[6 7] Their role in delivering crucial medical resources such as vaccines, medications, blood and diagnostic kits has become pivotal, aiding in strengthening national healthcare systems and bridging the gap between hospitals and laboratories, especially benefiting remote communities by improving outcomes and reducing waiting times.[8 9]

Many countries have conducted studies on the use of drones as logistical support tools for delivering medical supplies. For instance, Ghana initiated one of the world's largest vaccine drone delivery programmes in 2019, facilitating the distribution of routine and emergency vaccines as well as healthcare products.[10] Similarly, in Vanuatu, a Pacific Island nation, the Ministry of Health, in collaboration with UNICEF, conducted drone trials aimed at delivering vaccines to the islands. The successful first phase trials involved accurately landing payloads within 2 m of the target after a 50 km flight over multiple islands and waypoints.[11] Additionally, various American and European countries have reported the efficacy of drones in delivering medicines.[12]

In India, the Indian Council of Medical Research (ICMR) conducted a pioneering feasibility study that effectively deployed drones to deliver medical supplies to remote and challenging terrains.[13] Despite significant infrastructural advancements in the country, delivering medical supplies to hard-to-reach locations in emergency situations remains an enduring challenge.[14] One such region, Keylong located in Lahaul and Spiti District, bordering Tibet, features a unique geography characterised by high altitude (~10 000 ft), harsh weather conditions and widely dispersed settlements within a small population. Although the district has witnessed substantial improvements in infrastructure such as roads, electrical supply and internet connectivity, several challenges persist, including the poor infrastructure development, intermittent internet access and limited healthcare services. Winter exacerbates these issues, isolating the valley from the outside world for up to 6 months annually due to heavy snowfall and the closure of the Rohtang Pass, situated at an elevation of ~13 000 ft above mean sea level (ASL). This study was undertaken to assess the feasibility of drone-based delivery of medical supplies to the challenging terrain of Keylong, Himachal Pradesh. It aims to uncover the obstacles and constraints faced by healthcare providers in ensuring adequate medical supplies and assesses the potential of drones as a logistical support solution in the region. The research also delves into the technical challenges associated with establishing connections between various healthcare delivery centres using drone-based medical supply systems, particularly considering the operationalisation of drones in delivering medical supplies amidst high altitudes and harsh cold weather conditions.

METHODOLOGY

Study setting

Keylong was identified as the site for conducting a feasibility study of drone operations due to its extreme climatic conditions, including high altitude and cold weather. Keylong is a town and the administrative centre of the Lahaul and Spiti district in the Indian state of Himachal Pradesh, India. Located at an elevation of 3080 m (10 100 feet) ASL, the temperature varies from −30°C to 25°C throughout the year. Lahaul and Spiti district, with a total population of about 32 000, predominantly comprises tribal communities which contribute to 81% of the total population of this district. This district is the third least populated district in India, with a population density of ~2 inhabitants per square km.[15] The region faces distinct isolation during winters due to heavy snowfall and a considerable drop in temperature, further exacerbating the challenges faced by its inhabitants. In Keylong, a total of 10 healthcare delivery centres are operational, encompassing 26 health subcentres in Lahaul, 8 primary healthcare centres (PHCs), 1 community health centre (CHC) and a regional hospital.[16]

In the context of India's healthcare system, subcentres (SCs) serve as the first point of contact for healthcare, offering basic health services through trained paramedical staff. The next level of care is provided by PHCs, which are staffed by a medical officer and paramedical personnel, offering outpatient services, along with basic preventive and curative care. Further up the system, CHCs are larger facilities with medical specialists and function as referral units for PHCs. At the highest level are district hospitals (DHs), which offer comprehensive services, including emergency care, surgeries, obstetric services and specialist consultations. Many DHs are designated as First Referral Units, providing 24/7 services.

Study design

This cross-sectional study used a mixed-method approach including qualitative and quantitative approaches for the data collection. To enhance the reporting of the study's findings, we followed the Strengthening the Reporting of Observational Studies in Epidemiology guidelines (online supplemental appendix 1). The in-depth interviews (IDIs) were conducted to find out the perspective of the healthcare providers in the region on utility of the drones in delivering healthcare facilities. Apart from this, the operation challenges and feasibility of drones at high altitudes were recorded. The recruitment involved purposive sampling, for improving the precision, comprehensiveness and credibility of reporting methods and results of the present study, we adopted the consolidated criteria for reporting qualitative research (COREQ) checklist (online supplemental appendix 2).

Study participants

The study was led by the ICMR Headquarters, Delhi with the help of ICMR-Keylong station attached to the ICMR-Regional Medical Research Centre (RMRC) in Gorakhpur, chief medical officer and the district administration (district commissioner, police department).

IDIs were conducted on 18 individuals including 8 implementation partners from the ICMR and 3 drone pilots. Apart from that, the key service providers—chief medical officer, two staff nurses, two medical officers, one forest officer and a police officer (SHO)—were also interviewed using open-ended questions (online supplemental appendix 3). All the participants provided their consent for the participation in the study and no one dropped out from the study.

Data collection and measures

Qualitative data collection

The study employed IDIs as the primary method of data collection. All interviews were conducted on-site using a face-to-face approach, with the research team members present at the interview location. The in-person setting facilitated rapport-building and enhanced the depth and richness of the data collected. Interviews took place in private, quiet locations to ensure the comfort and confidentiality of participants, minimising potential distractions. Two moderators, R1 and R2, guided the discussion. Both moderators introduced themselves to the participants by sharing their credentials and positions within the study. R1 (first author; public health expert and sientist) managed and led the entire process. Meanwhile, R2 and R3 (first author, research scientist) focused on collecting participants' thoughts and insights. The moderators brought a wealth of expertise in facilitating discussions to gather qualitative data. Only the moderators and the participants were present during the discussions, ensuring a focused and uninterrupted exchange of information. They explained the study's purpose, their voluntary participation and their right to withdraw at any time. Written informed consent was obtained to uphold ethical standards and respect participants' autonomy, The interview responses were audio recorded and noted, in some cases, participants declined audio recording, so field notes were taken to record their responses. Each interview lasted approximately 25–40 min and was completed in the expected time duration and there was no requirement for the repetition of the interview.

As the study was conducted with limited number of participants at remote location, two type of biases including selection and language bias were identified. Selection bias occurred because participants were included only from the sites where drone operations were conducted. To minimise this bias, we used purposive sampling from the selected participants to ensure the sample accurately represented the broader population we aimed to describe. While few study participants were not able to communicate in fluent language as they speak the regional language. To overcome this issue, one local implementation team member native to the area was present throughout the discussion with the healthcare worker (HCWs).

Quantitative data collection

For quantitative data collection, various variables including climatic and drone-related parameters such as propeller speed, battery endurance, payload capacity, distance covered, time taken, temperature were recorded. The specifics of these recorded parameters are detailed in table 1. Information regarding the participants' age and gender was collected during the interview, along with data on drone operation-related variables.

Data analysis

For the qualitative analysis, thematic analysis was conducted manually. This process involved carefully reviewing the data and identifying key themes and patterns, which were then coded and organised to provide a structured interpretation of the qualitative observations. Similarly, for the quantitative analysis, a statistical method was used to calculate descriptive statistics such as percentages. Additionally, we created diagrams and charts to visually represent the data, making it easier to interpret and compare the quantitative findings.

Preparatory phase for the drone operation

A thorough consultation meeting was convened with all stakeholders, including the implementation team and local administration such as the police department and health department. The purpose of this meeting was to discuss the project's objectives, scope and coordinate drone operations at designated study sites. To choose these sites, we visited health centres to assess their suitability for the project. Additionally, HCWs were trained in drone usage for medical purposes.

Drone procurement and specifications

An expression of interest outlining the required specifications for drone services was issued to identify a suitable commercial UAV. Following a competitive bidding process, TSAW drones emerged as the selected operator for this study. The drone selected to operate in this study

Table 1 Various parameters recorded in drone sortie

SN	Parameter	Details recorded	Platform/forms
1	Medicine supplies	Medications type and numbers, diagnostic samples number	Checklist, paper/computer based
2	Climatic condition	Temperature, wind speed, snowfall, sunlight	Indian meteorological website
3	Drone technical parameters	Battery endurance, propeller speed, payload weight, drone speed and altitude achieved	Digitally (Mission Planner, Drone company-developed app)
4	Distance covered	Aerial and terrestrial route	In house developed Mission planner
5	Sociodemographic conditions	Interview and discussion	Questionnaire based

was a hybrid-fixed wing vertical take-off and landing (VTOL) drone that falls within a small category as per drone rule India.[17] The drone's body was made from Styrofoam, and weighing ~7 kg without payload, it offered a maximum payload capacity of 1 kg. The drone provided a cruising speed of 21 m/s. Its design prioritised convenience, featuring tool-less quick disassembly for effortless maintenance and rapid deployment. For tracking the path of the drone, the ground control system was established at the Keylong DH. The drone pilot used indigenously developed software for flight control.

Coordination with local administration

The study site was located within the green zone, as classified by the Government of India's drone regulations in 2021.[17] Consequently, no additional approval was required for drone operation in this zone, and the local administration bodies were informed about the study. The drone's route and operational plan were shared in advance. The drones were authorised to operate up to an altitude of 400 feet Above Ground Level in Beyond the Visual Line of Sight conditions

RESULTS

Characteristics of the participants

The participants of this study were grouped largely on the basis of their role in this study. Consequently, two groups were made with one group having the implementation members from ICMR and the drone pilots. The other group was made up of local HCWs and the administrative personnel. The data were collected during the drone operation between the month of October and November 2023. The interview was conducted to collect data from 16 participants. Out of all the participants, 81% were male and 19% were female, ranging in age from 25 to 55 years.

Drone-based delivery to the health centres

Dry run from the DH to SC

The operational capabilities of the drone were assessed through the trial run from the Keylong Command Centre to the Kachrang SC, covering a distance of 4 km. The drone reached its destination within 5 min, which typically takes 20–30 min through terrestrial routes. The data gathered from this mission, which included detailed assessments of the battery endurance and other pertinent metrics, to prepare for its subsequent operational deployment were analysed (figure 1).

DH to PHC and return sortie

The first mission undertaken at the behest of a medical officer from Tholang PHC, involved the transportation of a payload weighing ~500 g, containing essential medicines, from the Keylong Regional Hospital (Command Centre) to Tholang PHC (table 2). The terrestrial distance between these locations spans approximately 18 km, typically requiring 45–60 min for travel during the summer. However, in peak winter, the travel time extends up to 2 hours. Remarkably, the UAV reduced the delivery time to 9–10 min, covering a total aerial distance of

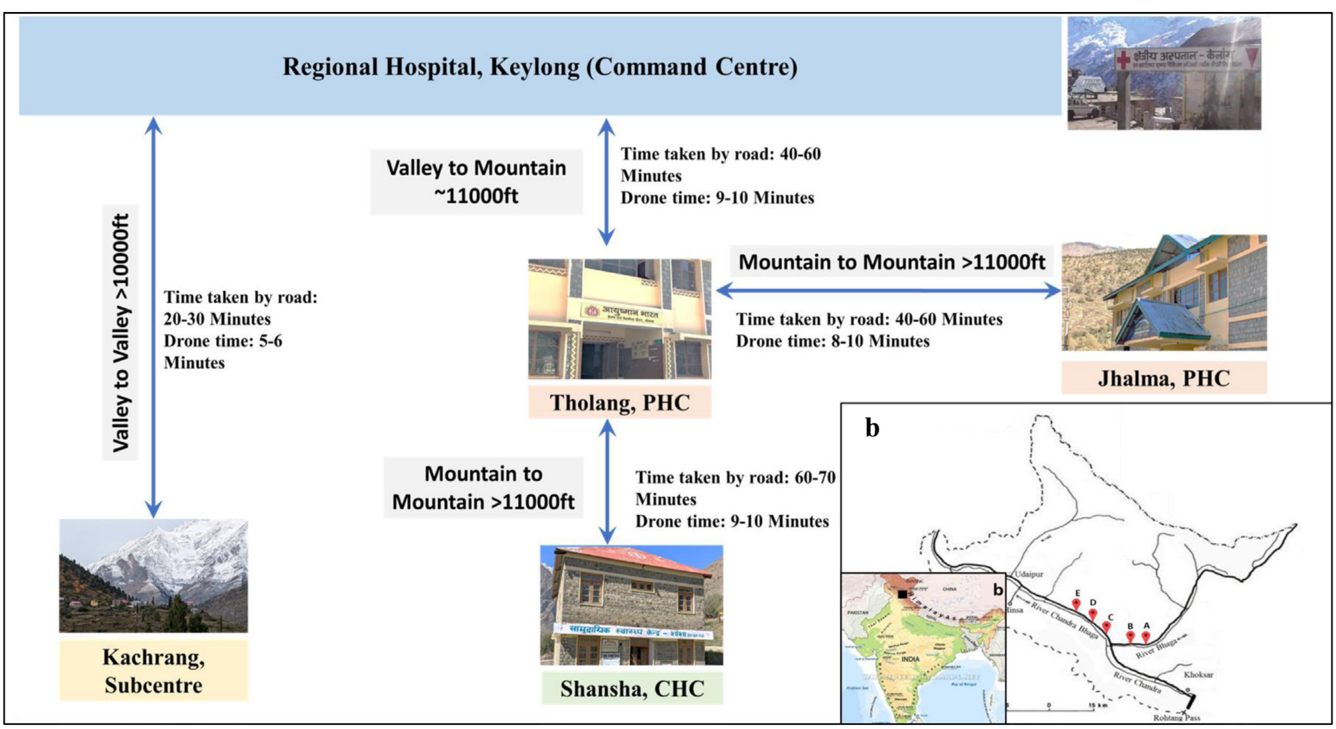

Figure 1 Different geographical landscapes connected in the drone operation (b) Terrain of Keylong, the locations shown in red tags are health centres connected during the operation to deliver medical items, A. Kachrang Subcentre, B. Keylong Regional Hospital, C, Tholang PHC, D. Shansha CHC, E Jhalma PHC and Image in satellite showing the location of Keylong on geographical map of India. PHC, primary healthcare centre.

Table 2 Healthcare centres connected, time taken to deliver medical supply using drone, terrestrial route and medicines delivered through drone

Route/road distance (km)	Time taken through terrestrial route (mins)/ payload weight (g)	Time taken by drone (mins)	Peak altitude attained by drone/ temperature	Medical supply delivered (units)	Return sorties
Keylong Regional Hospital to Tholang PHC/18 km	40–60 (~500 g)	9	11 000 ft/–10°C	► Amoxicillin 160 ► Antihistamine 80 ► IFA 60 ► Betadine (100 mL) 1 ► Cough syrup 1	► Diagnostic reports ► 8 sputum samples for TB diagnosis ► 12 blood samples for CBC.
Shansha CHC to Tholang PHC/10 km	40–60/ ~180 g)	8	11 000 ft/–5°C	► IFA 120 ► Antihistamine 160 ► Amoxicillin 160	► Diagnostic reports
Tholang PHC to Jhalma PHC/16 km	50–70/ ~200 g)	9	10 000 ft/–6°C	► IFA 120 ► Antihistamine 160	► Diagnostic reports
Keylong Regional Hospital Kachrang Subcentre/5 km	20–30	5	10 000 ft/–8°C	Dry run	Dry run

IFA, iron-folic acid; PHC, primary healthcare centre; TB, tuberculosis.

18 km. The drone operated at an altitude of ~11 000 feet and enduring temperatures as low as −10°C, the drone efficiently completed the return flight, successfully transporting clinical samples (sputum and blood) back to the Regional Hospital for testing (table 2).

CHC to PHC and PHC to PHC

In the subsequent missions, drones were used to transport >500 units of medicines from Shansha CHC to Tholang PHC and >280 units from Tholang PHC to Jhalma PHC (figure 1). In summer, the conventional travel times from Shansha CHC to Tholang PHC take 45–60 min, while from Tholang PHC to Jhalma PHC spans 60–70 min. However, leveraging drone-based delivery reduced the travel duration, accomplishing the task in 8–10 min at both locations (depicted in table 2). In winter, the snowfall and road blockage further extend the travel time.

The drone service partner was hired on a contractual basis, with the operating expense (OpEx) of each drone sortie ranging US$1.5 to 1.8/km (140–150 INR/km). In comparison, the cost of conventional transportation for the same route varies depending on the vehicle type, ranging from US$0.6 to US$1.2/km (50–100 INR/km) if a vehicle is hired or using public transport. Although the primary objective of the study is clear, cost-effectiveness depends on various factors, including manpower costs, OpEx, resource utilisation, time and speed of delivery.

Challenges during drone operationalisation

The operationalisation of the drone encountered several challenges, the observations were based on the perspective of the implementation team that consist of the experts and drone pilots (figure 2).

Technological challenges in drone operation

The harsh climatic conditions including high altitudes along with low temperatures and high wind speeds showed adverse impact on drone operations, there were several issues reported by the drone team which are as follows:

Selection of propellers

During drone operations, the study team faced high wind speeds at elevated altitudes, leading to multiple aborted missions. To address this, the team optimised propeller selection for stability, particularly in winds exceeding 25 m/s. Systematic testing two propeller sets tailored for high-altitude, low-temperature conditions led to the replacement of the initial 15-inch high pitch PVC propeller with an 18-inch propeller at 4600 rpm. This provided better lift and stability but increased battery consumption. Despite these challenges, the 18-inch high pitch propeller demonstrated superior performance and was chosen for the final flight trial, effectively addressing the challenging conditions.

> On the first day we used PVC propellers (15inch PVC, 3600 rpm), and the drone was not able to stabilize due to the low temperature, high wind, and low air density problems, so we used carbon fiber propellers at higher rotation (18-inch-High pitch, 4600 rpm) (Drone-pilot 2).

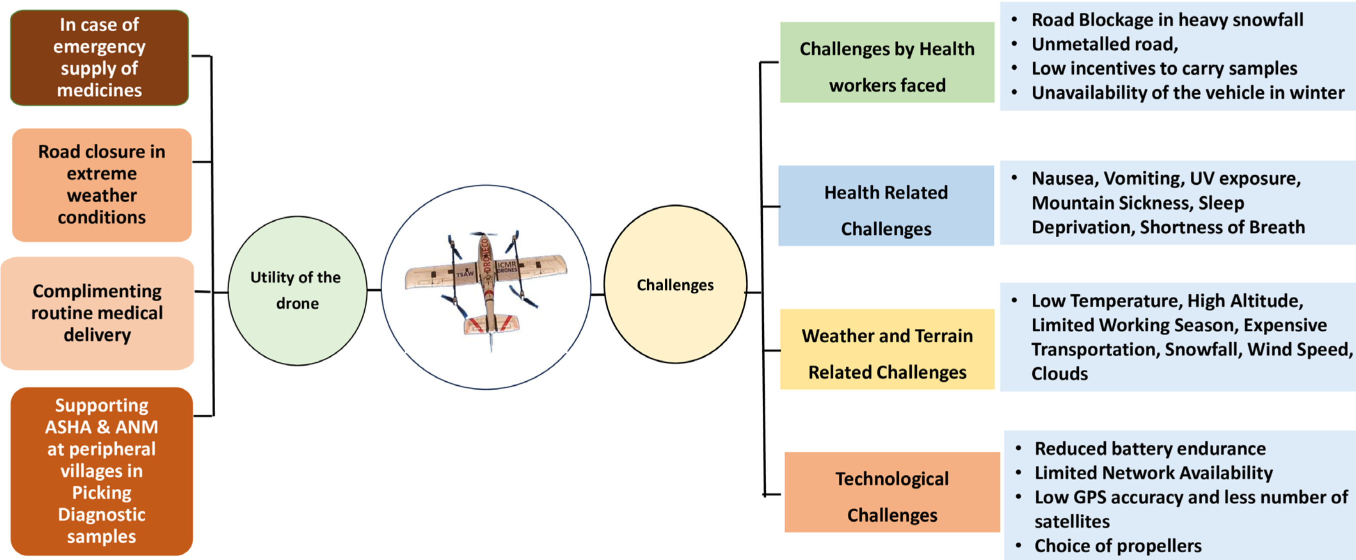

Figure 2 Challenges related to the drone operation at high altitude and various use case scenario identified for drone-based delivery at high altitude. ASHA, Accredited Social Health Activist; GPS, Global Positioning System.

Selection of battery

During the optimisation phase, initial attempts with Li-ion batteries fell short in providing the necessary endurance for drone operations in challenging weather conditions also the discharge rate was limited and ranged between 2 and 4C. As an alternative, 22 000 mAh lithium polymer (LiPo) batteries were used. However, the extremely cold weather conditions resulted in limited utilisation of only 2000mAh, that is, ~10% of the total battery capacity. At this capacity, the batteries only provided a cruise time of 6 min and a VTOL time of 7 min.

To enhance flight time preheating, insulating and slow charging the batteries before operation was done. This step resulted in an improved flight time of 14–18 min, enabling the batteries to consume up to 4000 mAh, ~20% of the total capacity. The drone pilot explained the effect of cold weather conditions on the endurance of the batteries.

> ………… Lithium Ion had very low discharge rate (2C to 5C) as compared to Lithium Polymer (8C to 10C) which has a higher discharge rate (At high altitude). Therefore, lithium polymer batteries were used at the site (Drone-Pilot 1).

Network connectivity

The drone sorties used two types of connectivity, one was the cellular network (terrestrial) provided by network providers and the Global Positioning System (GPS) network (satellite). The cellular connectivity, facilitated by only two telecom operators, exhibited better performance in hilly areas but struggled in valleys. However, for precision and accuracy, the drone relied on GPS connectivity. The drone's flight control involved two methods manual remote control, which was controlled by the drone pilot, and autopilot functionality that necessitated Keyhole Markup Language (KML) files. These KML files furnished essential data to the drone, encompassing geographical annotation and visualisation within both two-dimensional maps and three-dimensional Earth browsers. The drone pilot explained:

> Most of the drone flight was tracked. But the major difference between the plains and the high-altitude area was that in the plains the connectivity was better at ground level and poor when the flight was raised to higher altitude, but in hilly regions, the connectivity was poor at valley (not city area) and better at high altitude. (Drone Pilot-1)

The satellite availability ranged from 10 to 14, which resulted in low GPS accuracy due to high horizontal dilution of precision. In normal settings, the satellite availability is 14, which ensures better accuracy for the drone.

Calibration of the drones

The drone calibration was challenging at the location; high altitude, electromagnetic effects and the presence of metal structures at the site caused significant disturbances. The drone flight relied heavily on the compass sensor, which helped the drone fly and keep it stable in the air by itself.

> The problems occurred in the compass calibration in drones because, as per flight experience compass is given direction (North, West, South, and East) that was usually disturbed might be due to the mountains and metals availability at high altitude. (Drone Pilot-1).

Health-related challenges of the implementation team

Amidst the hard-to-work terrains of Keylong and its nearby areas, the study team encountered significant health hurdles primarily attributed to the high altitudes and chilling weather. Notably, prevalent symptoms such as shortness of breath and ultraviolet (UV) exposure persisted throughout our operations. Out of nine drone team members, all experienced shortness of breath (9/9, 100%) even after walking for short distances (online supplemental figure 1). Similarly, all the team members reported sunburns (9/9, 100%), while one member reported eye irritation due to long exposure to direct sunlight. The sleep disturbance was also reported (6/9, 67%), which is characterised by increased awakenings at night during sleep, frequent brief arousals, nocturnal hypoxaemia and periodic breathing. Two team members (2/9, 22%) even reported high altitude sickness and showed symptoms like palpitations, vomiting and nausea. The food-related challenges in the area also escalate the health issues as the supply chain is not well developed due to which the food items availability is limited and the fresh food items are to be imported from outside the district.

Perspective of the HCWs on the utility of the drones

Facilities and the current scenario at the health centres

Tholang PHC is located at ~10 000 ft ASL, PHC covers a population of 1661 individuals. The patient load in Tholang PHC is nominal with most of the patients visiting OPD suffering from chronic diseases including hypertension and diabetes, the population in the area is highly dependent on red meat, and they also consume alcohol, especially in the winter. In a conversation at another CHC, the medical officer explained

> The Community Health Center (CHC) serves a population of 1500 individuals; although the number of tuberculosis (TB) cases is relatively low, but considering the health centre's coverage of the total population, the incidence rate becomes significant (CHC-MO2, Shansha).

Apart from the infectious diseases, snakebite and dog bite cases are few but not rare, the patients visit the PHC, and the health centres are equipped with a stock of antidotes (ASV) and rabies vaccine. The HCWs further explained that they have sufficient stock of medicines even during winter season, a staff nurse (PHC-N1, Jhalma) from Jhalma PHC said:

> We usually have a stock of medicines for 6 months, and all the medicines and injectables are available in the pharmacy. We replenish the stock in the summer season, stock maintenance is not an issue here……………Although snakebite cases are rare but if we get patients of snakebite, the antidote is available in the PHC. (PHC-N1, Jhalma)

Challenges in providing healthcare facilities

The HCWs in the Keylong face several logistical challenges owing to the geography of the region (figure 2). During the field visit, it was noted through the discussion with the health workers that the accessibility to the remote locations is a challenge due to unmetalled roads to the peripheral villages, the harsh winter seasons and high altitude add more obstacles to medical delivery.

In the discussion with the nursing staff from Jhalma PHC, she explained that the nearby villages of Jhalma PHC are connected to the health centre through the kutcha (unmetalled) road, but due to the poor conditions of the road the health workers need to walk for 2–3 hours during the peak winter season, and the Valley is snow covered: she further explained that due to the winter season there is low frequency of the vehicles and sometimes insufficient incentives for transporting of the samples:

> …. We have to walk for like 2-3 hrs on snow-covered roads to the nearby villages as the vehicles are not able to reach the location …………………Asha workers have to travel on incentive, that is not sufficient sometimes due to road blockage and infrequent vehicles (Public Convenience) in winter season (PHC, N1, Jhalma).

A senior government official from Keylong further highlighted the poor infrastructural development at the peripheral villages which causes healthcare delivery challenges during peak winter season. Similarly, the medical officer from Tholang PHC further explained the accessibility issues in the region.

> …. if there is snowfall the rods get closed although the concerned department is active in functioning the main road. The villages are distant and PHCs are not accessible because of high altitude and other factors predominantly present in the area (DFO, Keylong).
>
> Lahaul and Spiti is very far from the rest of the state and it also experiences very harsh winter and during winter time it experiences snowfall. Road connectivity has improved since the functioning of Atal Tunnel, but in winters due to very heavy snowfall the peripheral road connectivity is cut off (PHC-MO1, Tholang)

Logistical support from the drone

While discussing the utility of the drones in delivering medical supplies, the nurse from Jhalma PHC explained the prevalence of tuberculosis (TB) infection in Keylong, she further explains that the drones can be used for the transportation of the diagnostic samples from the peripheral villages.

> It will be easy for us to collect the samples from the villages which are at the periphery as TB infection is prevalent and for collecting and transporting even a single sample (PHC, N1, Jhalma).

The utility of drones in delivering medicine supplies was further discussed and the medical officer in charge of Keylong Regional Hospital highlighted the geographical challenges of the region. He also added that the drones can be used for the delivery of the essential medicines.

> …… as it is a very tough region to reach out and most of the villages are very far from the regional center. The drone will help in delivering essential medicines and delivery to the patient's village or nearby PHC, it will be of great help. (CMO, Keylong).

The medical centres usually have all the basic medicines, but due to road closures in winter or any emergency the supply of the other medicines in need can be delivered by drone. Further one government official highlighted the use of drone in delivering medicines and samples.

> The drone can help us in delivering emergency medicine which is not on the list of essential medicine supplied by the government. (PHC, MO-1, Tholang)

> ……….if drones can transport medicine as well as get samples from PHC and villages it will be a great help for this area. (DFO, Keylong)

Concerns about safety, privacy and security

The study site is located nearby to the border area and has many military, police and defence establishments. However, due to the location of the site, the administrative bodies were intimated before the drone operation and amid certain security concerns such as aerial photography or videography of these establishments, persisted. To overcome these issues, two steps were taken into consideration. The drone route was selected in such a way that it did not fly over any military or defence establishment and the camera was not installed over the drone. The station in charge of Keylong police station advocated the need for coordination between the health department and the police department for such drone operations.

> …………there must be coordination between the health department and the police so we have all the information of the program. (SHO, Keylong)

DISCUSSION

In the present study, the feasibility of the transportation of the medical supplies to the peripheral healthcare centres in Keylong, and the challenges in drone operations related to the high altitudes, low temperatures, high wind speeds and the absence of adequate infrastructure were observed. Previously, various studies have shown the utility of the drones in delivering the medical supplies[9 12 18] Earlier research conducted by Aggarwal *et al* identified several technological and weather-related challenges that exacerbate flight operations.[13]

In the drone operations, the study team employed a Styrofoam-bodied hybrid fixed-wing VTOL drone, which conferred several advantages over alternative drones. Its lightweight design made it easy to transport, and it provided enhanced manoeuvrability crucial for navigating valleys at high altitudes. Earlier research by Paredes *et al* highlighted the advantages of fixed-wing drones in high-altitude environments.[19] Although due to its lighter weight, it was not able to lift heavy payloads.

Factors such as wind turbulence and low air pressure also contribute to decreased drone endurance, resulting in shorter flights these findings align closely with observations made in the present study. The selection of propellers significantly influences the vertical lifting capacity of drones. In the current study, carbon fibre propellers were employed, a choice consistent with prior research. These propellers offer distinct advantages over other available options like PVC and wooden propellers due to their lighter weight and lower inertia. These qualities result in reduced vibrations, and quicker and more controlled motor speed adjustments, ultimately enhancing the stability of drones.[20] To overcome these challenges, prerequisite optimisation of both batteries and propellers is essential before drone deployment, considering the potential adverse effects of weather conditions.[21]

Several studies have highlighted the preference for LiPo batteries over Li-ion batteries due to the adverse effects of high altitude on Li-ion battery performance, notably affected by lower temperatures. Furthermore, Li-ion batteries demonstrate reduced cooling capacity in such conditions.[22] LiPo batteries offer extended flying time due to their lighter weight and higher energy density compared with Li-ion batteries,[23] However, regardless of battery type, optimising their capacity utilisation poses a significant challenge in high-altitude and cold weather scenarios. Paredes *et al*, in their study, concluded that energy demands escalate at higher altitudes, consequently diminishing flight duration.[19] Insulation, slow charging and preheating are certain strategies used to optimise batteries, slow charging plays a crucial role as it promotes a more stable temperature environment within the battery during the charging process.[24] This gradual charging method enables the battery cells to warm up gradually, effectively mitigating the negative impact of low temperatures. Consequently, this approach aids in preserving the battery's charge capacity and reduces the risk of voltage sag during operation.

Additionally, network availability in high-altitude regions poses a significant hurdle. Drones rely on terrestrial wireless networks (cellular) or satellite communication to establish connections with ground terminals, in this study, both network types were used for communication. The limitation of terrestrial networks lies in their coverage, especially in remote and high-altitude areas. Moreover, in unforeseen disasters, ground infrastructure may suffer damage, causing disruptions or complete failure in terrestrial network functionalities. In such circumstances, satellite communication networks emerge as crucial alternatives, offering extensive coverage in difficult-to-access remote areas.[25–27] Similar observations were noted during the operations in Keylong, where terrestrial network connectivity proved inadequate along the route from the valley to the mountains. However, the drone's flight path was continuously tracked, and the operation was completed. Interestingly, contrary to prior understanding, network connectivity at relatively higher altitudes was comparatively better, attributed to the installation of towers on hilltops. Conversely, disruptions were observed as the drone flew at lower altitudes through valleys.

Operating at high altitudes presents challenges beyond technological aspects, as various studies have highlighted health issues associated with high-altitude environments.[28 29] The body's response to high altitude conditions varies significantly among individuals and encompasses

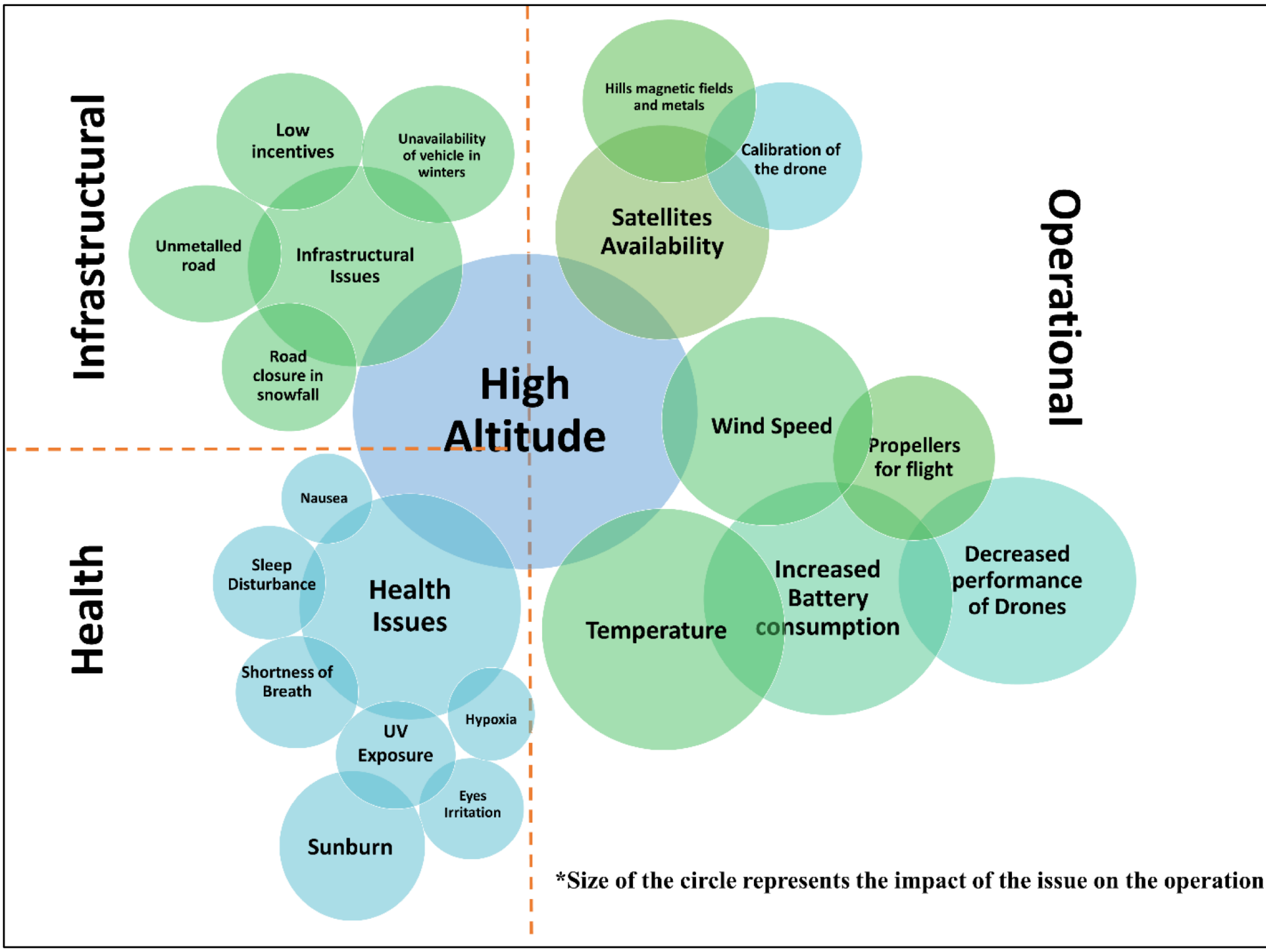

Figure 3 Challenges faced during the operationalisation of drone-based deliveries of medical supplies. UV, ultraviolet.

a spectrum of health issues known as high-altitude sickness. This condition arises due to sudden exposure to reduced oxygen levels.[30] High-altitude sickness encompasses three categories: acute mountain sickness entails mild symptoms such as headaches, nausea, dizziness, sleep disturbances and shortness of breath. High Altitude Pulmonary Oedema involves the accumulation of fluids in the lungs, which can become life-threatening. The most severe form may result in life-threatening condition such as High-Altitude Cerebral Oedema.[31] During the drone operations, the study team encountered various symptoms, including nausea, vomiting, shortness of breath, palpitations, sleep disturbances, eye irritation and sunburn (figure 3). To mitigate these health-related challenges at high altitudes, published literature recommends proper acclimatisation through gradual ascent, adequate hydration and a balanced diet.[32] In this study, a few members of the team undertook an acclimatisation process in Kullu, Himachal Pradesh, situated at an altitude of 4200 ft, before commencing operations at higher altitudes.

Similar to our findings, study conducted by Mishra *et al* reported the prevalence of various acute and chronic health issues, including respiratory infections, enteric fever, typhoid and TB, among the population residing in the high altitude such as Lahaul and Spiti.[33 34] Particularly during the winter season at high altitudes, heavy snowfall and low temperatures pose considerable challenges to healthcare operations, potentially disrupting medical services. This study involved HCWs sharing insights into the challenges they faced during the peak winter season at high altitudes.

It was observed that most of the healthcare centres maintained adequate stocks of essential medicines, certain critical supplies such as the rabies vaccine, antidotes for snake bites, etc. However, few other life-saving drugs were not constantly available to healthcare centres, in these situations, drones might be a viable solution for the prompt delivery of these emergency supplies in need. Globally, various studies have highlighted the efficacy of drones in transporting medical resources to inaccessible terrains during emergencies.[6 10 13 35] In Rwanda, Ackerman *et al* used drones to transport blood bags efficiently from blood banks to neighbouring healthcare centres. Similar studies have demonstrated significant reductions in delivery times for essential medical products, such as blood and its products.[36] Notably, in a study conducted in North East India during the COVID-19 pandemic, vaccines were successfully transported to diverse geographical landscapes encompassing islands, hills and foothills.[13]

Moreover, this study observed that apart from medicine delivery, drones can be effectively used in transporting diagnostic samples from remote villages that is difficult to access through conventional routes. During winter season, when heavy snowfall blocks roads, HCWs endure arduous 2–3 hours journeys on foot to gather diagnostic samples and distribute vital medicines to the peripheral villages. Discussions with HCWs highlighted that during winter seasons transportation costs of samples increase due to road blockage, unavailability of vehicle and public transport. Although, HCWs get incentive for sample collection and transportation of clinical sample of suspected case of few diseases like TB but incentive is not sufficient to cover commuting costs. Contrary to initial assumptions, HCWs expressed that drone-based delivery of emergency supplies and clinical sample pickups would be more valuable than routine medicine supplies. The observations demonstrate the efficacy of drones in medical supply delivery, while drones may not entirely replace conventional delivery methods, they serve as invaluable complements to medical logistics, especially in challenging terrains.

This study encountered several limitations. First, the research was conducted in October, just before the onset of heavy snowfall at the study site. Consequently, the study was unable to determine the impact of extreme cold weather (below −10°C) and heavy snowfall on drone operations, which is a crucial factor affecting aerial operations in such environment. The future exploratory studies under these environmental conditions would be helpful to understand these challenges and identify potential strategies for medical transport.

Additionally, the study's scope was constrained by a limited number of sorties predominantly along a single route. Expanding the number of sorties across diverse routes could have provided a more comprehensive understanding of operational challenges and opportunities at high altitudes, thereby enhancing our preparedness for similar endeavours in the future. Furthermore, it is important to note that the payload capacity notably decreased to approximately ~500 g due to heightened battery consumption at low temperatures, potentially impacting the drone's operational efficiency under such conditions.

CONCLUSION

In conclusion, this study outlines the feasibility and challenges of employing drones for medical supply delivery in high-altitude, low-temperature regions. The successful completion of drone sorties in delivering medical essentials to remote healthcare centres in the Lahaul and Spiti districts, despite encountering numerous challenges, demonstrates the potential of drones to complement healthcare logistics. However, the study highlighted critical obstacles such as decreased battery endurance in low temperatures, wind-related operational difficulties and communication disruptions due to varying terrains. Efforts to optimise battery performance through preheating and propeller selection underscored the importance of tailored solutions for extreme environmental conditions. Connectivity challenges between cellular and GPS networks showcased the significance of precision-based GPS control for drone navigation in challenging terrains. Despite these challenges, the study provides valuable insights into the successful use of drones for medical supply delivery, emphasising the need for further research and technological advancements to address operational limitations in harsh weather the findings contribute to the growing body of knowledge in leveraging drone technology for enhancing healthcare logistics, particularly in remote, inaccessible areas affected by severe weather.

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Contributors SA put forth the research ideas and conceptualised the research proposal. SA, RK and KN wrote the study implementation plan. SA, KN, VS, TM and AKP implemented the study on the ground. MM and RK guided the implementation of the study. VS combed the literature review and drafted the article based on the experiences of the whole field team. The initial draft was reviewed by SA, TM, and AKP. The critical revision of the full text was done by SA and MM, the final editing was done by VS. SA, KN and VS and contributed equally to this paper. All authors contributed to the article and approved the submitted version. SA is the guarantor of the overall content of this paper.

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REFERENCES

1 Larsen GD, Johnston DW. Growth and opportunities for drone surveillance in pinniped research. *Mamm Rev* 2024;54:1–12.
2 Shah SA, Lakho GM, Keerio HA, *et al*. Application of Drone Surveillance for Advance Agriculture Monitoring by Android Application Using Convolution Neural Network. *Agron* 2023;13:1764.
3 Kreps S, Lushenko P. Drones in modern war: evolutionary, revolutionary, or both? *Def & Sec Anal* 2023;39:271–4.
4 Minh DT, Dung NB. Applications of UAVs in mine industry: A scoping review. *J Sustainable Min* 2023;22:128–45.
5 Zhang JZ, Srivastava PR, Eachempati P. Evaluating the effectiveness of drones in emergency situations: a hybrid multi-criteria approach. *IMDS* 2023;123:302–23.
6 Eichleay M, Evens E, Stankevitz K, *et al*. Using the Unmanned Aerial Vehicle Delivery Decision Tool to Consider Transporting Medical Supplies via Drone. *Glob Health Sci Pract* 2019;7:500–6.
7 Haidari LA, Brown ST, Ferguson M, *et al*. The economic and operational value of using drones to transport vaccines. *Vaccine (Auckl)* 2016;34:4062–7.
8 Homier V, Brouard D, Nolan M, *et al*. Drone versus ground delivery of simulated blood products to an urban trauma center: The Montreal Medi-Drone pilot study. *J Trauma Acute Care Surg* 2021;90:515–21.
9 Flemons K, Baylis B, Khan AZ, *et al*. The use of drones for the delivery of diagnostic test kits and medical supplies to remote First Nations communities during Covid-19. *Am J Infect Control* 2022;50:849–56.
10 Ghana launches the world's largest vaccine drone delivery network. Available: https://www.gavi.org/news/media-room/ghana-launches-worlds-largest-vaccine-drone-delivery-network [Accessed 05 Jun 2024].
11 UNICEF Office of Innovation. Vanuatu: revolutionary technology for vaccine delivery. n.d. Available: https://www.unicef.org/innovation/drones/technology-for-vaccine-delivery-vanuatu
12 Konert A, Smereka J, Szarpak L. The Use of Drones in Emergency Medicine: Practical and Legal Aspects. *Emerg Med Int* 2019;2019:3589792.
13 Aggarwal S, Gupta P, Mahajan N, *et al*. Implementation of drone based delivery of medical supplies in North-East India: experiences, challenges and adopted strategies. *Front Public Health* 2023;11:1128886.
14 Sharma DC. India still struggles with rural doctor shortages. *Lancet* 2015;386:2381–2.
15 District census handbook. 2011. Available: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiUkZre6cOGAxVYrlYBHd4OPOwQFnoECBgQAQ&url=https%3A%2F%2Fcensusindia.gov.in%2Fnada%2Findex.php%2Fcatalog%2F1091%2Fdownload%2F3378%2FDH_2011_3302_PART_B_DCHB_CHENNAI.pdf&usg=AOvVaw1LXp4eS3_B5gsBtC0YoDyL&opi=89978449 [Accessed 05 Jun 2024].
16 Health set up | District Lahaul and Spiti, Government of Himachal Pradesh | India. n.d. Available: https://hplahaulspiti.nic.in/health-set-up/
17 The drone rules. 2021. Available: https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/jan/doc202212810701.pdf
18 Quintanilla García I, Vera Vélez N, Alcaraz Martínez P, *et al*. A Quickly Deployed and UAS-Based Logistics Network for Delivery of Critical Medical Goods during Healthcare System Stress Periods: A Real Use Case in Valencia (Spain). *Dr* 2021;5:13.
19 Paredes JA, Saito C, Abarca M, *et al*. Study of effects of high-altitude environments on multicopter and fixed-wing uavs' energy consumption and flight time. 2017 13th IEEE Conference on Automation Science and Engineering (CASE 2017); Xi'an, 2017:1645–50.
20 Misra A, Jayachandran S, Kenche S, *et al*. A Review on Vertical Take-Off and Landing (VTOL) Tilt-Rotor and Tilt Wing Unmanned Aerial Vehicles (UAVs). *J Eng (Stevenage)* 2022;2022:1–27.
21 Duffy JP, Cunliffe AM, DeBell L, *et al*. Location, location, location: considerations when using lightweight drones in challenging environments. *Remote Sens Ecol Conserv* 2018;4:7–19.
22 Oyama N, Hatozaki O. Lithium polymer battery with high energy density. *Macromol Symp* 2000;156:171–8.
23 Mehendale N. Investigating the Battery Life Issues in Unmanned Aerial Vehicles: An Analysis of Challenges and Proposed Solutions. *SSRN Journal* 2023;1–10.
24 Shahjalal M, Shams T, Tasnim MN, *et al*. A Critical Review on Charging Technologies of Electric Vehicles. *Energ* 2022;15:8239.
25 Ding J, Mei H, I C-L, *et al*. Frontier Progress of Unmanned Aerial Vehicles Optical Wireless Technologies. *Sensors (Basel)* 2020;20:5476.
26 Zhao Z, Zhang Z, Tan J, *et al*. 200 Gb/s FSO WDM Communication System Empowered by Multiwavelength Directly Modulated TOSA for 5G Wireless Networks. *IEEE Photonics J* 2018;10:1–8.
27 Huang X, Zhang JA, Liu RP, *et al*. Airplane-Aided Integrated Networking for 6G Wireless: Will It Work? *IEEE Veh Technol Mag* 2019;14:84–91.
28 Taylor AT. High-altitude illnesses: physiology, risk factors, prevention, and treatment. *Rambam Maimonides Med J* 2011;2:e0022.
29 High elevation travel & altitude illness | CDC yellow book 2024. 2024. Available: https://wwwnc.cdc.gov/travel/yellowbook/2024/environmental-hazards-risks/high-elevation-travel-and-altitude-illness
30 Luks AM, Hackett PH. Medical Conditions and High-Altitude Travel. *N Engl J Med* 2022;386:364–73.
31 Bhutia M, Goyal K, Rai A, *et al*. High altitude cerebral edema with a fatal outcome within 24 h of its onset: Shall acclimatization be made compulsory? *Saudi J Anaesth* 2013;7:488–9.
32 Viscor G, Corominas J, Carceller A. Nutrition and Hydration for High-Altitude Alpinism: A Narrative Review. *Int J Environ Res Public Health* 2023;20:3186.
33 Mallet RT, Burtscher J, Richalet JP, *et al*. Impact of High Altitude on Cardiovascular Health: Current Perspectives. *Vasc Health Risk Manag* 2021;17:317–35.
34 Mishra T, Goswami S, Deval H, *et al*. Recent public health concerns of the high-altitude tribal population of Lahaul and Spiti, Himachal Pradesh. *J Family Med Prim Care* 2023;12:660–5.
35 Hii MSY, Courtney P, Royall PG. An Evaluation of the Delivery of Medicines Using Drones. *Dr* 2019;3:52.
36 Ackerman E, Koziol M. The blood is here: Zipline's medical delivery drones are changing the game in Rwanda. *IEEE Spectr* 2019;56:24–31.