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The economic and operational value of using drones to transport vaccines

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ABSTRACT

Background: Immunization programs in low and middle income countries (LMICs) face numerous challenges in getting life-saving vaccines to the people who need them. As unmanned aerial vehicle (UAV) technology has progressed in recent years, potential use cases for UAVs have proliferated due to their ability to traverse difficult terrains, reduce labor, and replace fleets of vehicles that require costly maintenance.
Methods: Using a HERMES-generated simulation model, we performed sensitivity analyses to assess the impact of using an unmanned aerial system (UAS) for routine vaccine distribution under a range of circumstances reflecting variations in geography, population, road conditions, and vaccine schedules. We also identified the UAV payload and UAS costs necessary for a UAS to be favorable over a traditional multi-tiered land transport system (TMLTS).
Results: Implementing the UAS in the baseline scenario improved vaccine availability (96% versus 94%) and produced logistics cost savings of $0.08 per dose administered as compared to the TMLTS. The UAS maintained cost savings in all sensitivity analyses, ranging from $0.05 to $0.21 per dose administered. The minimum UAV payloads necessary to achieve cost savings over the TMLTS, for the various vaccine schedules and UAS costs and lifetimes tested, were substantially smaller (up to 0.40 L) than the currently assumed UAV payload of 1.5 L. Similarly, the maximum UAS costs that could achieve savings over the TMLTS were greater than the currently assumed costs under realistic flight conditions.
Conclusion: Implementing a UAS could increase vaccine availability and decrease costs in a wide range of settings and circumstances if the drones are used frequently enough to overcome the capital costs of installing and maintaining the system. Our computational model showed that major drivers of costs savings from using UAS are road speed of traditional land vehicles, the number of people needing to be vaccinated, and the distance that needs to be traveled.

1. Introduction

Immunization programs in low and middle income countries (LMICs) face numerous challenges in getting life-saving vaccines to the people who need them. After entering a country, vaccine vials typically travel by road through two to four storage locations before arriving at clinics where health workers administer doses to patients [1]. Non-vaccine costs of routine immunization systems are expected to rise by 80% between 2010 and 2020, with more than one-third of these costs attributable to supply chain logistics [2]. Supply chain bottlenecks and inefficiencies can cause vaccines to spoil and valuable resources to be wasted before vaccines reach the people who need them, suggesting a need for innovative and lower cost methods for distribution. As non-military unmanned aerial vehicle (UAV) technology has advanced in recent years, interest in potential humanitarian and development use cases for UAVs have proliferated due to their ability to traverse difficult terrains, reduce labor, and replace fleets of vehicles. UAVs have already been successfully deployed for surveillance and aid

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delivery in humanitarian sectors and commercial systems are currently being developed to transport medical samples and supplies, including vaccines [3–5].

Despite this growing interest, limited evidence is available regarding the impact of UAVs for routine delivery of medical supplies. As with any new technology, the costs of purchasing, maintaining, and operating UAVs and their supporting launch/recovery and maintenance infrastructure – collectively called an unmanned aerial system (UAS) – may be prohibitive. The limited carrying capacity and required flight conditions of UAVs may also pose significant obstacles. Determining whether a UAS would be beneficial to an immunization program is difficult without a model to forecast supply chain performance and costs. We used simulation modeling to assess the impact of using a UAS for vaccine distribution under a range of circumstances and to identify the necessary conditions for a UAS to be favorable over traditional land-based transport.

2. Methods

2.1. HERMES models of Gaza province, Mozambique vaccine supply chain

Our team used our HERMES (Highly Extensible Resource for Modeling Event-driven Supply Chains) software platform, described in previous publications [6,7], to develop a discrete-event simulation model of the World Health Organization (WHO) Expanded Program on Immunization (EPI) supply chain in Gaza, a province in southern Mozambique with a 2015 population of 1,416,810 [8]. This HERMES model includes virtual representations of each vaccine vial, facility, storage equipment, transport device, route, and personnel in the supply chain. Vaccines flow according to ordering and shipping policies in an attempt to meet the anticipated demand at each immunization location. The model includes characteristics of the vaccines in the 2015 EPI schedule, as well as new and upcoming vaccine introductions, summarized in Table 1.

The traditional multi-tiered land transport system (TMLTS) for distributing vaccines throughout Gaza consists of three tiers (Fig. 1A). One provincial store picks up vaccines from the national warehouse quarterly using a 4×4 truck (taking additional trips as needed, due to limited cold storage and transport capacity) and delivers monthly to 12 district stores. Districts distribute vaccines to 123 health centers each month using a combination of pick-up truck or motorbike deliveries and health workers traveling via public transit to pick up vaccines. Health workers administer vaccines to the population at each health center.

One commercial UAS currently under development for the distribution of medical samples and health products utilizes fixed-wing, battery powered vehicles and fixed hubs for vaccine storage and the launching, recovery, storage, and maintenance of UAVs. We modeled a potential implementation of this system in Gaza province (Fig. 1B) in which the provincial store delivers vaccines monthly to three UAS hubs supplying the 106 health centers in southern Gaza via UAV shipments on an as-needed basis to meet population demand. Modeling scenarios assumed that each UAV can carry 1.5 L of vaccines to a health center as far as 75 km from its hub, a range and payload well within currently available UAV specifications (for example, Wings for Aid offers a UAV that can carry up to 100 kg with a range of 500 km) [9,10]. Because northern Gaza has a much lower population density which would require a relatively large number of hubs to supply a small number of health centers, we included the TMLTS in the northern region where 3 district stores would supply 17 health centers.

The above systems provided a baseline comparison between the TMLTS and a realistic UAS implementation – alongside the TMLTS in the north – to serve the entire province of Gaza. To account for other possible current and future UAVs, sensitivity analyses varied baseline characteristics of the UAS as well as the environment, population, and vaccine schedule and aimed to identify necessary conditions for the UAS to be advantageous. For a direct comparison between the TMLTS and a supply chain using the UAS throughout, these experiments studied a subset of the locations in the Gaza vaccine supply chain which included only the provincial store and locations within its 75 km radius. For the TMLTS (Fig. 1C), the provincial store distributes vaccines to 7 district stores which supply 69 health centers. The UAS implementation (Fig. 1D) co-locates one hub with the provincial store to deliver vaccines to the 69 health centers via UAVs.

2.2. Experiments

To compare the UAS with the TMLTS in the baseline scenario and the $\leqslant$75 km subset, we calculated vaccine availability using the following formula:

$$\text{Vaccine availability} = \text{Number of people receiving vaccines} \div \text{Number of people arriving at health centers for immunization}$$

Another supply chain performance metric comparing the systems was the logistics cost per dose administered:

$$\text{Logistics cost per dose administered} = \text{Annual logistics costs} \div \text{Annual vaccine doses administered}$$

Logistics costs included storage (storage equipment maintenance, energy, and amortization), transport (driver per diems and vehicle maintenance, fuel/electricity, and amortization), buildings (infrastructure overhead and amortization at storage and

Table 1
Characteristics of EPI and introductory vaccines in Mozambique.

	Presentation	Doses per person	Doses per vial	Vaccine packed volume per dose (cm^3)	Diluent packed volume per dose (cm^3)
Current EPI vaccines					
Bacille Calmette-Guérin tuberculosis (BCG)	Lyophilized	1	20	1.2	0.7
Diphtheria-tetanus-pertussis-haemophilus influenza type B-hepatitis B (Pentavalent)	Liquid	3	10	2.6	n/a
Measles (M)	Lyophilized	1[a]	10	3.5	4.0
Oral polio (OPV)	Liquid	4	10	2.0	n/a
Pneumococcal conjugate (PCV)	Liquid	3	2	4.8	n/a
Tetanus toxoid (TT)	Liquid	2	10	3.0	n/a
Introductory vaccines					
Rotavirus (RV)	Liquid	2	1	17.1	n/a
Inactivated polio (IPV)	Liquid	1	10	4.8	n/a
Human papillomavirus (HPV)	Liquid	2	2	2.46	n/a

[a] A second dose of measles vaccine (MSD) is included as an introduction.