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Improving early infant diagnosis for HIV-exposed infants using unmanned aerial vehicles for blood sample transportation in Conakry, Guinea: a comparative cost-effectiveness analysis

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ABSTRACT

Background Early infant diagnosis (EID) for HIV-exposed infants is essential due to high mortality during the first months of their lives. In Conakry (Guinea), timely EID is difficult as traffic congestion prevents the rapid transport of blood samples to the central laboratory. We investigated the cost-effectiveness of transporting EID blood samples by unmanned aerial vehicles (UAV), also known as drones.

Methods and findings Using Monte Carlo simulations, we conducted a cost-effectiveness comparative analysis between EID blood samples transportation by on-demand UAV transportation versus the baseline scenario (ie, van with irregular collection schedules) and compared with a hypothetic on-demand motorcycle transportation system. Incremental cost-effectiveness ratio (ICER) per life-year gained was computed. Simulation models included parameters such as consultation timing (eg, time of arrival), motorcycle and UAV characteristics, weather and traffic conditions. Over the 5-year period programme, the UAV and motorcycle strategies were able to save a cumulative additional 834.8 life-years (585.1–1084.5) and 794.7 life-years (550.3–1039.0), respectively, compared with the baseline scenario. The ICER per life-year gained found were US$535 for the UAV strategy versus baseline scenario, US$504 for the motorcycle strategy versus baseline scenario and US$1137 per additional life-year gained for the UAV versus motorcycle strategy. Respectively, those ICERs represented 44.8%, 42.2% and 95.2% of the national gross domestic product (GDP) per capita in Guinea—that is, US$1194.

Conclusion Compared with the baseline strategy, both transportation of EID blood samples by UAVs or motorcycles had a cost per additional life-year gained below half of the national GDP per capita and could be seen as cost-effective in Conakry. A UAV strategy can save more lives than a motorcycle one although the cost needed per additional life-year gained might need to consider alongside budget impact and feasibility considerations.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The cost-effectiveness of unmanned aerial vehicles—UAV (drones) for transporting blood products remains limited in the Global South.

⇒ We aimed to investigate the cost-effectiveness of urgent blood sample transportation for early HIV infant diagnosis (EID) by on-demand UAV transportation versus the baseline scenario (ie, van with irregular collection schedules) and compared with a hypothetic on-demand motorcycle transportation system.

WHAT THIS STUDY ADDS

⇒ Over the 5-year programme period, the UAV and motorcycle strategies were able to save a cumulative additional 834.8 life-years (585.1–1084.5) and 794.7 life-years (550.3–1039.0), respectively, compared with the baseline scenario.

⇒ The incremental cost-effectiveness ratio per life-year gained was US$535 for the UAV strategy versus baseline scenario, US$504 for the motorcycle strategy versus baseline scenario and US$1137 per additional life-year gained for the UAV versus motorcycle strategy.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Compared with the baseline strategy, both transportation of EID blood samples by UAVs or motorcycles had a cost per additional life-year gained below half of the national gross domestic product per capita (ie, US$1194) and could be seen as a cost-effective strategy in Conakry.

⇒ The UAV strategy can save more lives than the motorcycle strategy, although the cost required per additional life-year gained might need to be considered alongside budget impact and feasibility considerations.

INTRODUCTION

Every year, more than 150 000 children are infected with HIV and one-third of these new infections occur in West and Central Africa.[1] In this region, 58% of pregnant women living with HIV are receiving antiretroviral therapy (ART) and the HIV mother-to-child transmission rate exceeds 20%.[1] Without ART initiation, newborn mortality is particularly high, especially in the second and third months of life and more than half die before their second birthday.[2] Early infant HIV-diagnosis (EID) from 6 weeks of age is recommended by the WHO in order to initiate ART before 8 weeks of age for those HIV infected and thus significantly improving their life expectancy.[3] However, only 27% HIV-exposed infants benefit from EID in West and Central Africa.[1]

Because maternal HIV antibodies persist in the blood of infants until the age of 12–18 months, PCR tests are required to provide a diagnosis. The recent development of point-of-care (POC) machines have considerably reduced PCR assay time processing and increased the number of HIV-exposed infants receiving their test result the same day as recommended by the WHO.[3–5] For example, an observational study of 1793 children in Malawi showed that sites equipped with POC reduced the time from sample to result from 56 days to 1 day, and allowed 91.1% of infected children to receive ARV treatment before 60 days, compared with 41.9% with the standard strategy where blood sample are referred to the central laboratory.[5] While the cost-effectiveness of POC implementation has been demonstrated in settings with a high volume of testing,[6 7] the significant operational costs associated with POC sites (eg, specific laboratory equipment and personnel) make them only marginally cost-effective in settings with low testing volumes, such as low HIV prevalence areas.[8] For example, in Guinea, the low prevalence of HIV (1.7%) and the decentralisation of the prevention of mother-to-child HIV-transmission programme to more than 300 health facilities across the country makes it difficult to justify the provision of POC equipment for HIV diagnostics in each site. In addition, while there is a gradual trend to repurpose PCR machines for multiplex assays (eg, tuberculosis, HIV, SARS-CoV-2) which will optimise operational cost of POC sites, the scale up of POC platform will require substantial investment and time.[9]

In most African countries with low HIV prevalence, blood samples are sent to central laboratories. Alongside delays due to bottlenecks at the central laboratories such as sample batching,[10] the long turnaround time needed for sample transportation and to dispatch the test results to the referring facility remains a major obstacle to timely EID.[11 12] In addition, once the results are available, it can take up to several months for caregivers to return for the results,[11 12] further delaying ART initiation among HIV-infected children and significantly increasing their risk of death. Lost to follow-up of HIV-tested children who did not receive their results is also particularly high in non POC contexts and up to half of them never come back for the results.[13]

To reduce the time taken to transport medical samples and supplies to inaccessible places, the use of unmanned aerial vehicles (UAV), also known as drones, has been explored in several studies in low-income countries.[14–19] For example, UAVs are supplying blood bags to 20 transfusion sites located in isolated rural areas in Rwanda.[19] While most studies show that UAV transportation is faster but more expensive than through road,[14 16 17 20] the cost-effectiveness of this strategy (ie, consideration of life-saving benefit) remains poorly documented in low-income countries.[21] In addition, UAV transportation focuses on rural environments,[14–18 21 22] while urban areas with severe traffic congestion and inadequate road networks could benefit from faster emergency delivery through UAV.[20 23]

The aim of this research was to assess the cost-effectiveness (ie, cost per life-year gained) of EID blood sample transportation by UAV in Conakry, the capital of Guinea, and its suburbs. We compare this strategy to the current transport system, a unique van with irregular collection schedules, and to a hypothetical on-demand motorcycle transport system. We conducted this study from the perspective of the healthcare system.

METHODS

Study context

Conakry is an equatorial urban city in West Africa with an estimated population of 2 million.[24] It is located on the Camayenne peninsula which stretches out over a 40 km long strip of land 0.2 and 6.5 km wide (figure 1). The economic activities and main governmental buildings are concentrated at the tip of the peninsula accessible by a single main road which creates bottlenecks at several points in the city.[25]

Currently, in the Conakry region, most blood samples collected at health centres for PCR HIV testing are transported by road to a private laboratory located within a kilometre from the Donka hospital. This private laboratory uses Abbott platforms, which require sufficient batching (eg, 40 or 80 samples) before running the tests. The current consideration is to redirect the EID blood samples to the central laboratory embedded in the Donka hospital because this laboratory benefits from GeneXpert technology for Point-of-Care (figure 1). GeneXpert technology enables the analysis of multiple samples with different starting times and provides individual results for each test in under 2 hours.

To date, the main obstacle to timely EID in Conakry is the transportation of blood samples. A single van is allocated to the collection of blood samples, but it has an irregular collection schedule (once or twice a month, or when enough blood samples are available for collection). This delays EID, especially in centres with low volumes of HIV-exposed children. This vehicle is also assigned to transport medical products to supply the sites and is often stuck in traffic jams and struggles to quickly access the various health centres.

The current plan to reduce these delays is to develop an on-demand emergency-type transport system that collects blood samples for EID as soon as they are available in

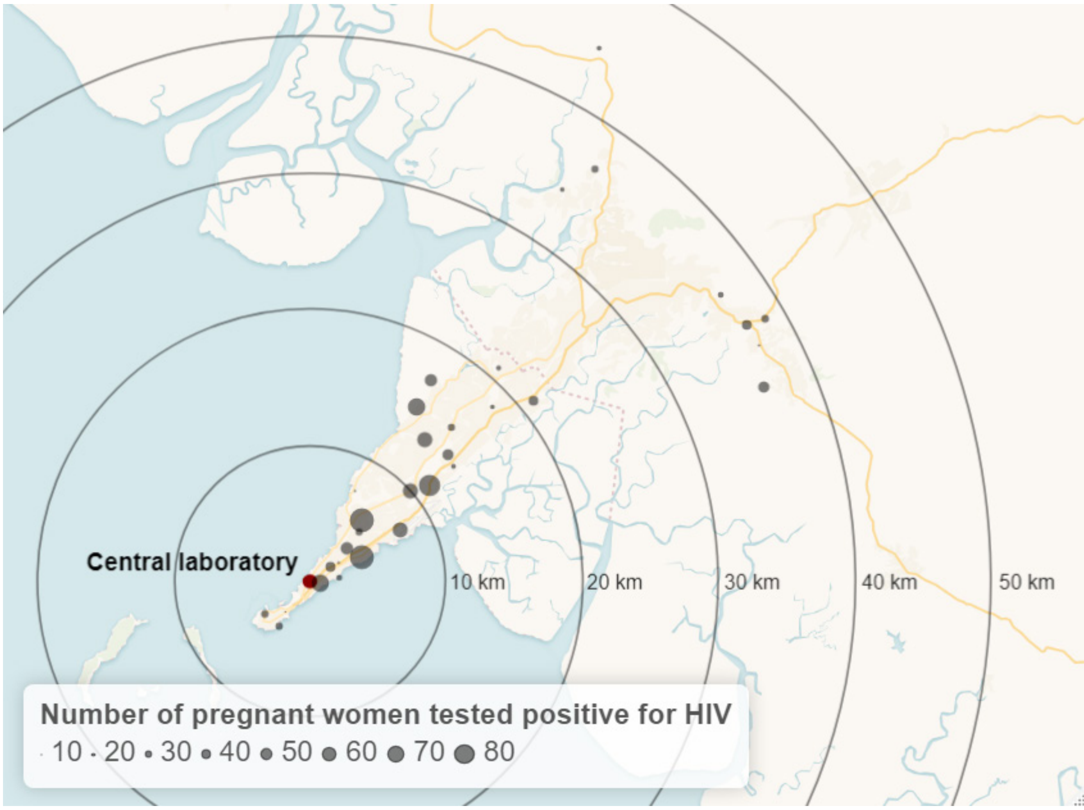

Figure 1 Map of public health centres and hospitals in Conakry and number of pregnant women testing positive for HIV in 2021, Guinea. Note 1: black dots indicate the health centres included in our analysis. Note 2: the map was generated using the Leaflet open library (https://leafletjs.com/) using OpenStreetMap (http://www.openstreetmap.org/) background.

health centres, sends them to the central laboratory for testing, and then returns the test results by telephone call to the health centres. The goal is to minimise the time of each step and thus increase the number of HIV-exposed infants receiving their results the same day and, if found to be HIV infected, initiating ART. In this study, we consider two types of vehicles that are adapted for the urgent transportation of blood samples: (1) one motorcycle, which is more flexible than a van in urban congested environments and (2) one UAV.

Study design

We conducted a cost-effectiveness analysis of UAVs versus motorcycles versus baseline scenario (ie, van) for transporting blood samples for EID in Conakry. The unit of cost-effectiveness was the differential cost per additional year of life gained between strategies. We considered a 5-year implementation period.

We included all 33 public health centres providing postnatal care in Conakry and its suburbs in our model. An average of 1208 pregnant women in these facilities tested positive for HIV in 2021 (extended data, online supplemental appendix 1). Considering the rate of HIV-exposed infants receiving a PCR test at 6 weeks,[26] our base case assumptions model assumed an annual average number of 778 (min–max: 574–981) HIV-exposed infants seen in consultation at 6 weeks.

For the UAV and motorcycle strategies, we considered the different steps such as arrival of mothers in postnatal services, waiting time before consultation, time to transport the blood sample to the central laboratory, timing for test result delivery to mothers, timing of ART initiation and child survival (online supplemental appendix 2). For the baseline scenario, because the current transport system for EID is not an on-demand type transportation with irregular collection schedule (once or twice a month or when a certain amount of samples are ready to be collected), we considered the overall collection-to-results turnaround time documented in the scientific literature—that is, turnaround time from blood collection at health facility to laboratory results returned to the mother. Based on collection-to-results turnaround times, we then estimated timing of ART initiation and child survival.

Parameters and assumptions

We defined our models' assumptions based on existing published literature, local surveys or observations and discussions with two UAV manufacturers (table 1).

Healthcare data

Healthcare data were collected through local surveys or observations, and published literature. The mother's arrival time at the health centre was collected using data on women's attendance at two health centres in Conakry (online supplemental appendix 3). Waiting times in the health centre before being seen in consultation were

Table 1 Main technical assumptions for the cost-effectiveness simulation model

Parameters	Value	(min–max)	Distribution	Sources
Healthcare				
Mother-to-child transmission rate at 6 weeks	7.7%		Point estimate	PNLSH*
HIV-exposed infant receiving PCR test at 6 weeks	64.4%	(47.5–81.2)	Random point estimate	26
Mothers' arrival time at the health centre	9:00 hours	(7:00–16:30 hours)	Beta PERT	Field survey (online supplemental appendix 3)
Waiting time before being seen in consultation (min)	133.8	SD: 66.7	Normal with truncation of negative values	Literature review (online supplemental appendix 4)
Time required to perform a PCR test at the central laboratory (min)	105	(90 –120)	Random point estimate	Field observations with GeneXpert
Work departure time of healthcare workers in postnatal services	16:30		Point estimate	Field observations
Mothers able to wait until healthcare workers leave	40.2%	(10.6–69.9)	Point estimate	Field survey (online supplemental appendix 5)
Maximum duration mothers can wait in the health centre (min)	160	(3 –570)	Beta PERT	Field survey (online supplemental appendix 5)
No of days needed to return for the test results if not collected the same day (median)	21	(0–365)	Cumulative gamma	Literature review (online supplemental appendix 6)
Median number of days for collection-to-results turnaround times (baseline scenario)	35	(0–365)	Cumulative gamma	Literature review (online supplemental appendix 7)
ART initiation acceptance rates	92.3%		Point estimate	4
Average age at ART initiation among children after 1 year	4.7	(1.0–21.7)	Exponential	IeDEA data (online supplemental appendix 8)
UAV				
UAV price	US$11 562		Point estimate	DeltaQuad
Operational horizontal speed (km/hour)	65		Point estimate	DeltaQuad
Operational vertical speed (km/hour)	4.32		Point estimate	DeltaQuad
Flight altitude required (metres)	80		Point estimate	Field observations
Autonomy (min)	110		Point estimate	DeltaQuad
Maximal flight distance (km)	100		Point estimate	DeltaQuad
Preparation times, for example, UAV deployment (min)	4		Point estimate	DeltaQuad and Field observations
Weather inoperability	2.7%		Point estimate	Meteoblue (online supplemental appendix 9)
UAV loss rates (per 100 000 flights)	2.5	(0.0–5.0)	Point estimate	Drone Volt, DeltaQuad, assumptions†
Motorcycle				
Motorcycle price	$3238		Point estimate	CFAO motors Guinea
Lifespan (en km)	55 000	(30 000–70 000)	Beta PERT	14
Breakdown rate (per 10 000 km)	0.6		Point estimate	14
Minor accident rate (per 100 000 km)	1.65		Point estimate	14
Major accident rate (per 100 000 km)	0.43		Point estimate	14
Weather inoperability	0.2%		Point estimate	Meteoblue (online supplemental appendix 9)

*Routine data collected in Conakry by the National Programme for HIV and hepatitis (Programme National de Lutte contre Le VIH/Sida et les Hepatites) in 2021 among 881 HIV-exposed children tested at 6 weeks in public health centres (68 positive results).
†We based our assumptions on publicly available data on the Alphabet's drone service (https://wing.com/) operating on-demand delivery in US, Finland and Australia. To date, 5 crashes have been reported (3 in Australia and 2 in Finland) for a total of 200 000 flights.
ART, antiretroviral therapy; CFAO, Corporation For Africa & Overseas; IeDEA, International epidemiology Databases to Evaluate AIDS; PERT, Program evaluation review technique; UAV, unmanned aerial vehicles.

obtained from five studies conducted in sub-Saharan Africa (online supplemental appendix 4).

Mothers were assumed to receive the results the same day if the lab test results were delivered both (1) before the average work departure time of healthcare workers in postnatal services and (2) before the maximum waiting time of the mothers. The maximum waiting time of mothers was obtained by conducting a local survey among 82 women (online supplemental appendix 5). When the test result was not received the same day, we created a probabilistic function to estimate the number of days before returning to get the results using data from five studies conducted in sub-Saharan Africa (online supplemental appendix 6). Because of the use of GeneXpert platform at the central laboratory, we assume that EID samples were processed immediately when they arrive at the laboratory.

For the baseline scenario, we created a probabilistic function to estimate the number of women receiving their results during the first year and the collection-to-results turnaround time, using data from eight studies conducted in sub-Saharan Africa (online supplemental appendix 6).

We assume that HIV-infected infants whose mothers do not receive the test results during the first year do not initiate ART elsewhere. For surviving infants who have not initiated ART after 1 year, we consider their probability of initiating ART at a later age by computing a probabilistic function (online supplemental appendix 7).

UAV and motorcycle parameters

We obtained data inputs from two qualified UAV manufacturers, DeltaQuad (badhoevedorp, North Holland, Netherlands) and Drone Volt (Villepinte, Seine-Saint-Denis, France), both having significant experiences of unmanned aircraft system implementation in sub-Saharan Africa. UAV flight demonstrations were carried out in Conakry during the study to collect UAV real-life data and identifying specific challenges. UAV data were based on the DeltaQuad Pro produced by DeltaQuad (https://www.deltaquad.com/vtol-drones/map/). The DeltaQuad Pro is a small UAV with rotor-wing that allows vertical take-off and landing in limited space which is well adapted for urban environments. Flight routes can be planned to allow fully autonomous flights which reduce the risk of mishaps induced by human errors.

Motorcycle related data were collected from local dealerships such as Corporation For Africa & Overseas motors (Conakry, Guinea) and local market observations. The motorcycle model chosen was the Suzuki TF125 for its robustness and its ability to ride on rough or unpaved road.

Travel time

As we assumed both the UAV and the motorcycle were stationed at the central laboratory, computed travel times are for a return journey. We assumed that a phone call would be made from the laboratory to the health centre to inform the clinic about the test result and save additional travel times for result delivery. For model simplicity and based on practical experience, we assumed that motorcycles and UAVs do not make multiple stops.

Travel times by motorcycles between the central laboratory and the health centres were estimated using Google Maps data (maps.google.co.uk). These estimations account for travel times variability depending on months, day, time slots and travel directions. After timing several travels by motorcycle between the central laboratory and the health centres, we found that the Google Maps 'optimistic' estimations were closest to real-life travel times (online supplemental appendix 8). In case of breakdown or accident, we assume blood samples delivered to the laboratory the same day but related results available the following day.

Travel times by UAV were estimated using vertical and horizontal speeds as well as preparation times. We consider the UAV cruise speed to allow best speed/autonomy ratio. Given the low weight of a blood sample and its associated container (less than 50 g), we considered its impact on the UAV speed negligible. All UAV assumptions were based on our discussion with DeltaQuad, Drone Volt and from field observations during a pilot study. We account for geofencing around the airport and adapt travel itineraries and related durations in situations where UAV flight path from the central laboratory to the health centre went over the international airport.

Weather conditions

Meteoblue website (www.meteoblue.com) was used to collect wind and rain data in Conakry to estimate the weather operativity for UAV and motorcycle transportation (online supplemental appendix 9). Meteoblue is a weather forecasting website created by the University of Basel in Switzerland which can provide up to 40 years of historical hourly weather data worldwide.

We considered light rain (<2.5 mm/hour) as the limit of use for the UAV and moderate rain (<7.6 mm/hour) for the motorcycle. The maximum airworthiness limit of the UAV was set at 33 km/hour as indicated in the UAV platform specifications. Since we have considered a return journey, we assume that the slowing down of the UAV in case of a headwind would be compensated during the return trajectory of the UAV.

Survival

Survival curves were computed according to the infant status: (1) HIV-exposed but uninfected infant, (2) HIV infected infant not initiating ART and (3) HIV infected infant initiating ART. Data from the International epidemiology Databases to Evaluate AIDS cohort of HIV-infected children in West Africa[27] and other existing literature were used to compute the different survival curves using double Weibull distributions (online supplemental appendix 10).

Costs

We devised cost functions to calculate costs from the perspective of the healthcare system (including all levels of government and donors) in 2021 US$. Euros and CFA francs costs identified have been converted to 2021 US$. All costs have been adjusted for inflation based on the year of data collection. The costs for both the UAV and motorcycle transportation strategies included purchase price, maintenance, insurance, fuel consumption, staff salaries and HIV-care related costs (for the full list, see online supplemental appendix 11). Training costs for the UAV pilot and healthcare staff were considered for UAV. We assumed that the salary for a UAV pilot in Conakry was more than double for a dispatch rider employed by international NGOs in Conakry.

For the baseline scenario, the van being also allocated to the transportation of other healthcare products, neither the UAV nor the motorcycle strategies would lead to the replacement of the van. Thus, we omit all costs associated with the van transportation.

We omitted the residual values of the motorcycle and the UAV after the 5-year programme. We assumed that the main UAV pilot will be trained at the UAV manufacturer site in the Netherlands, and that all additional pilots would be trained by the main pilot in addition to the online course provided by the manufacturer. This would minimise international travel costs. We assumed that health centre staff would be trained for half a day on loading and unloading the UAV as well as security procedures. We exclude import duty and licensing costs for UAV because Guinea, such as many African countries, waives licensing costs for equipment and vehicles used in public health programmes. Because of the latter, we assumed that air navigation fees would be waived.

ART cost was determined from the ART regimens prescribed and their annual cost. In Guinea, data from several paediatric HIV care specialists show that ART regimens prescribed among children are: (1) AZT+3TC+LPV/r (80%), ABC+3TC+LPV/r (10%) and AZT+3TC+EFV (10%) for children under 3 years of age and (2) ABC+3TC+EFV (100%) for those between 3 and 10 years of age. For patients over 10 years of age, ART regimens prescribed were determined using the 2016 report of the National HIV/AIDS Committee on the follow-up of patient living with HIV.[28] ART regimen costs were based on the price reference list published by the Clinton Health Access Initiative and other available materials.[29 30] Non-ART care-related costs (eg, tests, consultations, fixed costs) were estimated from another study conducted in the sub-Saharan context.[31]

Analyses

The cost-effectiveness analysis was conducted using Monte-Carlo simulations. In each simulation, each parameter was randomly drawn from its distribution (table 1).

The unit of cost-effectiveness was the incremental cost per year of life gained by the UAV strategy compared with the motorcycle strategy and the baseline scenario. For each of the 10 000 simulations run for the base case scenario, the total cost and the number of survival life-years obtained were computed. Then, the differential costs between each transportation strategy were divided by the survival life-year differential to obtain the incremental cost-effectiveness ratio (ICER). Because of the criticisms of the use of cost-effectiveness threshold as a decision rule,[32–34] we did not use a threshold to define whether an intervention would be cost-effective. However, as an indicative reference point, we compared the ICERs to the gross domestic product per capita in Guinea, that is, US$1194.[35] We applied a 3% discount to both the costs and life-years gained per year.[36]

Sensitivity analyses were performed to identify the parameters that had the greatest influence on the ICER.

Analyses were conducted using the R software V.4.2.2. (R Core Team. Vienna, Austria).

Patient and public involvement

Patients or the public were not involved in the design, recruitment, conduct or dissemination of this study. A reflexivity statement on equitable authorship in the publication of research from international partnerships is available (see online supplemental materials).

RESULTS

Travel times

The average round-trip time per day was 106 min (73–144) for the UAV and 213 min (142–293) for the motorcycle strategy—representing an average of 3 missions per day for each strategy. UAV transport saved an average of 35.8 min in travel time, and up to an average of 109.0 min for the most remote centres, over 50 km from the laboratory (online supplemental appendix 12). No time was gained by the UAV for the two centres located within 3 km range of the laboratory.

Health outcomes and survival

A higher proportion of test results were delivered to mothers the same day with the UAV strategy (47.4% (90% prediction interval: 26.3%–68.5) vs 42.4% (21.6%–63.1%) for the motorcycle strategy versus none for the baseline scenario). The proportion of mothers receiving the results within 30 days was 73.4% (63.5%–83.3%), 70.8% (61.0%–80.8%) and 28.5% (27.3%–29.7%) for the UAV, motorcycle and baseline strategies, respectively. These results correspond to a reduction of respectively 202.5 and 6.4 days for ART initiation with the UAV strategy compared to the baseline and motorcycle strategies. Over the 5-year period programme, the UAV and motorcycle strategies were able to save a cumulative additional 834.8 life-years (585.1–1084.5) and 794.7 life-years (550.3–1039.0), respectively, compared with the baseline scenario. The difference of life-years gained between UAV and motorcycle strategies was 40.1 (−4.3 to −84.6).

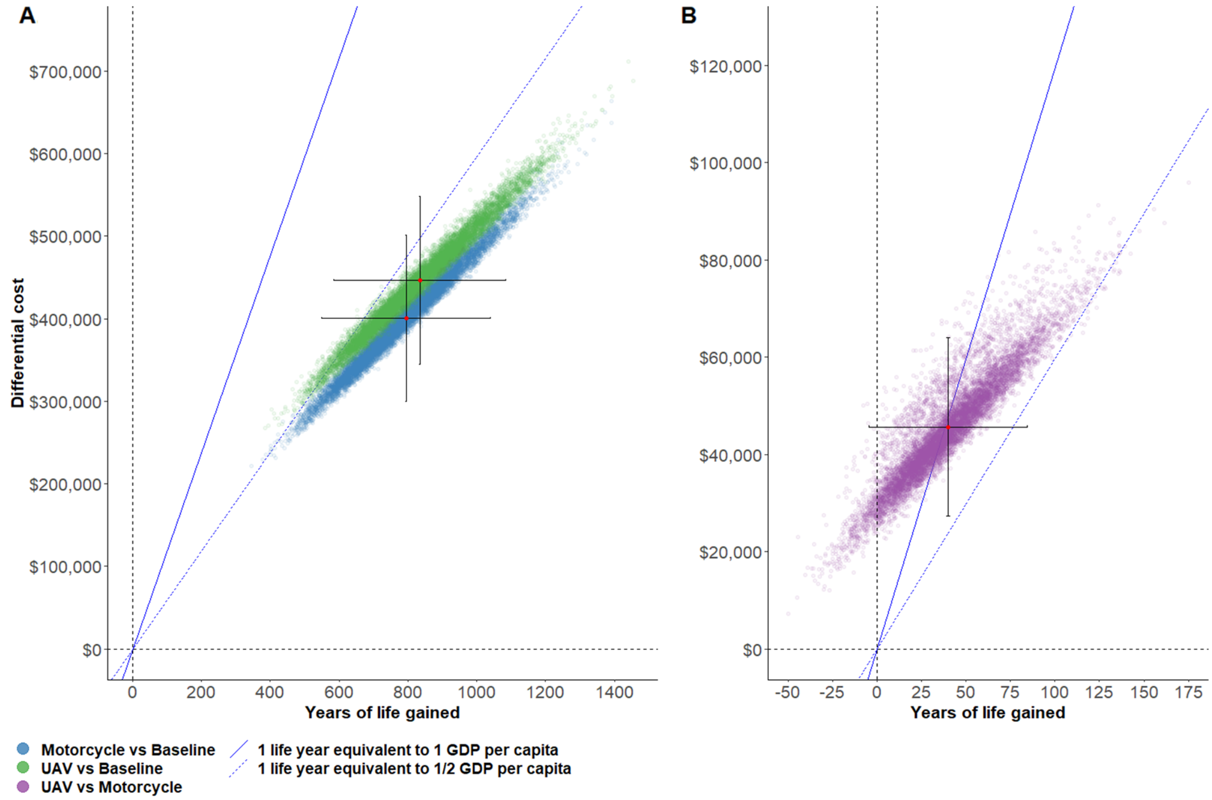

Figure 2 Cost-effectiveness plane of blood sample transportation by UAV or motorcycle versus the baseline scenario (A) and UAV versus motorcycle (B).Note: Each dot represents a simulation. Error bars show 90% prediction intervals. GDP, gross domestic product; UAV, unmanned aerial vehicle.

Cost

Excluding treatment and HIV care costs, the median investment costs were US\$95 670 (IQR: US\$95 608–US\$95 739) and US\$67 293 (US\$65 830–US\$68 727) for the UAV and motorcycle strategies, respectively. Compared with the baseline scenario, the additional transport costs per blood sample were US\$24.8 (US\$23.7–US\$26.1) by UAV and US\$17.3 (US\$16.9–US\$17.8) by motorcycle. When considering all costs (including ART and care costs), the UAV strategy costs an additional of US\$11.5 (US\$9.7–US\$13.7) per infant tested compared with the motorcycle strategy.

Cost-effectiveness analysis

The ICERs found were US\$535 per additional life-year gained for the UAV strategy versus the baseline scenario, US\$504 for the motorcycle strategy versus the baseline scenario and US\$1137 per additional life-year gained for the UAV versus the motorcycle strategy. These ICERs represented 44.8%, 42.2% and 95.2% of the national gross domestic product (GDP) per capita—that is, US\$1194 (figure 2). Both the UAV and motorcycle strategies were able to save more lives to the baseline scenario in all the 10 000 simulations performed. The maximum cost per life-year found was US\$763 for the UAV strategy and US\$686 for the motorcycle strategy (equivalent to 63.9% and 57.4% of the GDP per capita). Compared with the motorcycle strategy, the UAV transport strategy was able to save more life years in 95.3% of the 10 000 simulations performed. In 44.1% of simulations, cost per life-year was found below the GDP per capita the UAV transport strategy with 0.7% of simulations with a cost per life-year below half of the GDP per capita.

Sensitivity analyses

The cost-effectiveness of the UAV compared with the baseline scenario was dependent on the number of children infected (ie, mother-child transmission rate), ART costs, distance from central laboratory of the health centres included and discount rates (figure 3). The motorcycle strategy was mainly sensitive to the same parameters (online supplemental appendix 13). Whatever the scenario considered, none had an ICER exceeding US\$692 (58.0% of the national GDP per capita) for the UAV strategy and US\$664 (55.6% of the national GDP per capita) for the motorcycle strategy.

The cost-effectiveness of the UAV compared with the motorcycle strategy was highly dependent on five factors: (1) the capacity of the UAV to be faster than the motorcycle, (2) weather inoperability, (3) UAV loss risk, (4) number of children infected and (5) UAV purchase price (figure 3). The worst-case scenario had an ICER of US\$2528 (2.1 times the national GDP per capita) with a 10% UAV weather interoperability. The best scenario had an ICER of US\$782 (65.5% of the national GDP per capita) with a UAV purchase cost of US\$3469.

To allow generalisation of our results to other contexts, we ran a series of different scenarios that consider a similar

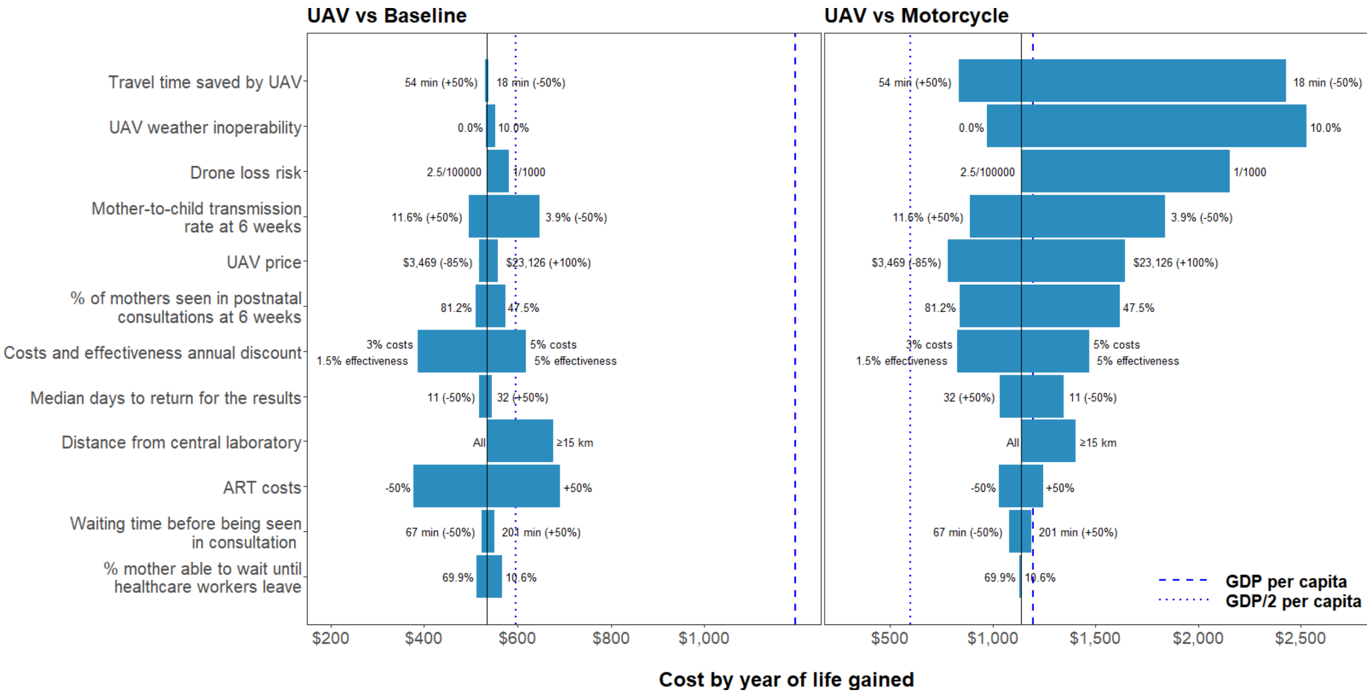

Figure 3 Sensitivity analysis of key parameters, UAV strategy versus the baseline scenario versus motorcycle strategy. Note: Including only centres at a certain distance mechanically reduces the number of children exposed to HIV as fewer centres are included. ART, antiretroviral therapy; UAV, unmanned aerial vehicle.

number of HIV-exposed infants seen every year in each health centre (figure 4). Higher weather inoperability can be balanced with higher time saved by UAV transportation if a minimum of HIV-infected infants benefit from the strategy. UAV price reduction or increase have less effect on the cost-effectiveness of the UAV strategy in the case of a high number of HIV-infected infants benefiting from the strategy.

DISCUSSION

Our results showed that transporting blood samples for EID by on-demand UAV or motorcycle transport in the Conakry region could be cost-effective strategies when compared with the usual transportation system. Both strategies had a cost per additional life-year gained below half of the national GDP per capita and could be seen as a cost-effective strategy even when taking account the ‘opportunity costs’—that is, health foregone because other interventions cannot be provided.[37] The use of UAVs has been found to save more lives than motorcycle transportation, although the additional cost per life-year saved was close to the national GDP. This cost would need to be considered alongside budget impact and feasibility considerations. The UAV transport strategy has the potential to be cost-effective in contexts where there is sufficient time saved in transportation, enough HIV-infected infants benefit from the UAV transportation, and weather conditions that do not result in too many downtimes.

This is one of the first studies to investigate the cost-effectiveness of UAV transportation in a Global South country and to demonstrate the possibility of UAV transport systems to save lives and to be potentially cost-effective in this specific context. Although our analysis focuses on the specific case of the Conakry region, evidence from our study suggests that UAV transportation of blood samples for EID is a strategy that could be implemented and be more cost-effective in other relatable contexts. First, our base case assumptions considered a mother-to-child transmission at 6 weeks of 7.7% where this rate is higher in many countries, in particular in the sub-Saharan region.[38 39] As the cost-effectiveness of the UAV strategy was particularly sensitive to the number of HIV-infected infants, this suggests that this strategy may be considered in similar Global South contexts with high rates of mother-to-child HIV transmission. Second, GDP per capita is particularly low in Guinea, as it is one of the world’s poorest countries, which suggests that the UAV strategy could be more cost-effective in a similar context in other low-income or middle-income countries. Third, the UAV in our analysis flew on average for 106 min per day due to the limited range of the UAV, but also to the localisation of the central laboratory, where the UAV was based, which does not take advantage of the full area the UAV operation radius can cover. A similar study in a setting with a more centralised laboratory or an inland rather than coastal location could increase the number of health centres reached by the UAV and thus increase the number of HIV-exposed infants benefiting from the intervention. Fourth, the UAV market and technology is not yet mature enough which entails quick evolutions in prices drop and UAV technology development which are likely to make the UAV more affordable and efficient.[40] Thus, it is expected that UAV will become

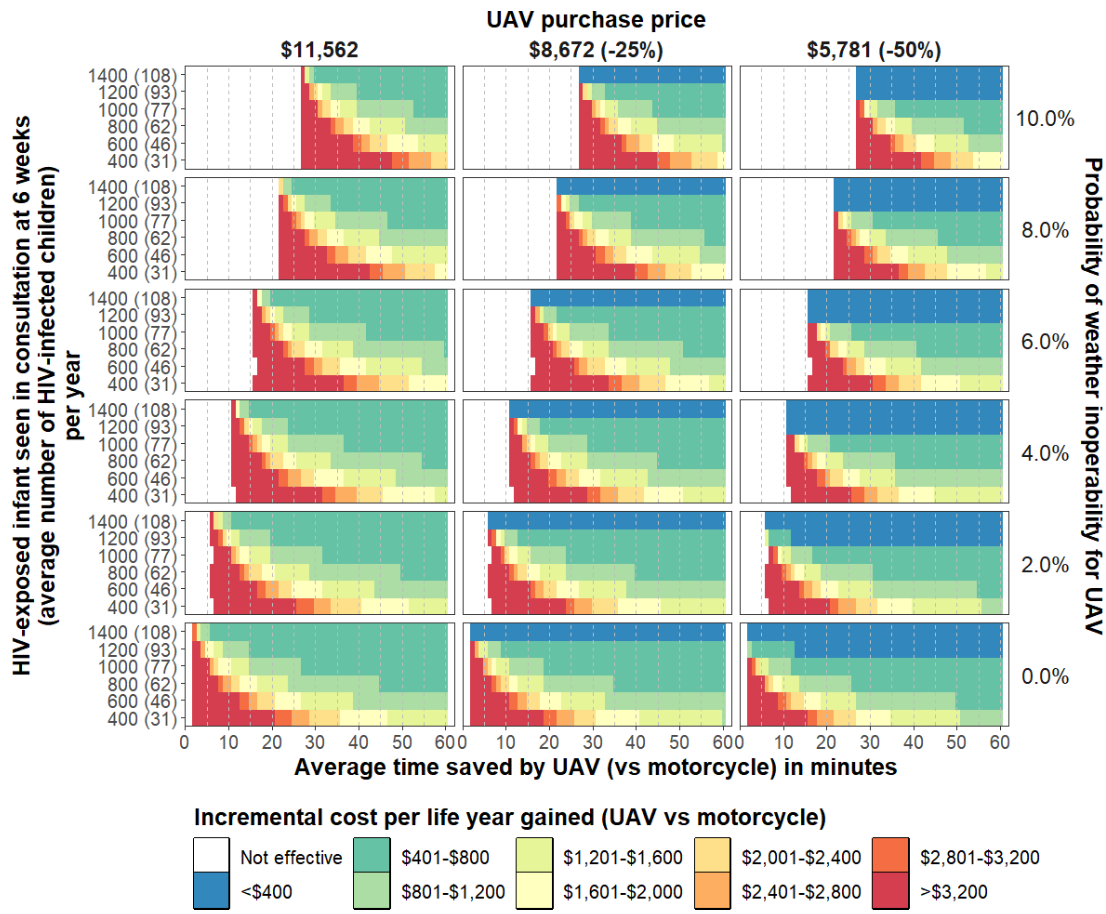

Figure 4 Cost-effectiveness of blood samples transportation by UAV versus motorcycle depending on main parameters. Note 1: Results obtained by modelling the overall cost and the number of life-years gained by the average time saved using linear regressions. Note 2: For comparison, in Conakry region, an estimated 778 HIV-exposed infants (with 60 HIV-infected) were seen in postnatal consultations in 2021, 2.7% of UAV inoperability due to bad weather and the average time saved per UAV was estimated to be about 35.8 min. UAV, unmanned aerial vehicle.

a more affordable and effective solution for the transport of urgent blood products in the foreseeable future.

Our results showed that UAV cost-effectiveness could be increased if a greater number of HIV-exposed children benefitted from this strategy. Such improvement would be possible by increasing the currently low postnatal consultation rate (64.4%) or by including a higher number of health centres, enabled by a higher operational range of the UAV. The current development of hydrogen batteries has recently made it possible to extend the flight times before recharging to more than 12 hours for a UAV model similar to the one used in our simulations, suggesting that micro UAV will soon be able to reach more distant centres.[41] Furthermore, considering the high down time in our simulations, UAV could be used for other health related emergencies, such as transporting tranexamic acid or blood for transfusion in the case of postpartum haemorrhage, which is the leading cause of maternal death in sub-Saharan Africa.[42 43]

The cost-effectiveness of the UAV strategy was highly dependent on weather conditions. In Conakry, these conditions seem rather favourable, as only 2.7% of the UAV trips were cancelled due to bad weather, well below the 10% threshold assumed by another study in a nearby country.[14] It is possible that this difference is due to specific local weather contexts, the UAV's longer travel distance (increasing its exposure to areas with frequent tropical rainfall), or the characteristics of the deployed UAV. Nevertheless, the consideration of weather conditions remains an important factor in the viability of a UAV transport strategy, often omitted in other studies.[15–17 20]

Our study addresses several gaps in the existing literature on UAVs in low-income countries. First, it highlights the potential of UAV use in congested urban environments, which is a persistent issue in developing countries.[23 25] Similar to other studies, we found that the use of a UAV significantly reduces travel times in congested traffic environments,[15 20] supporting the idea that UAVs can be a relevant solution for emergency transport in these contexts. Second, our analysis is among the first to include the life-saving cost benefits of UAV transportation in a low-income country.[14 16 17 20] To date, we have identified only one study that has explored the lifesaving cost benefits of UAV transportation in the Global South. This study investigated the use of UAVs for improving tuberculosis screening in a remote region of Madagascar.[21] However, their analysis has several limitations, such as the omission of important factors such as weather conditions, the strong assumptions in their model regarding the effect of the UAV on the likelihood of being tested for TB, and a lack of description of the comparative transport in the standard of care. Therefore, our results contribute another piece of evidence to the literature indicating that UAVs can be cost-effective for urgent medical transport, even in resource-constrained environments.

Our analysis has some limitations. We assumed that samples would be tested shortly after they were received at the central laboratory. However, this assumption might not hold if the POC platform at the central laboratory is allocated for other analyses besides paediatric HIV diagnostics, or if the laboratory's internal organisation does not prioritise paediatric diagnosis. Although our interview with the head of the central laboratory confirmed that paediatric diagnosis is a priority, it may not necessarily be reflected in practice. In such a scenario, the delay in returning results back to the health centres could potentially exceed the timeframes calculated for the UAV and motorcycle strategies. Data not available for Conakry were assumed from other studies conducted in the sub-Saharan context and may not represent the local conditions. We consider a risk of crashing or losing the UAV that can be seen as low in our base case assumptions, although we did conduct sensitivity analysis on this parameter. The risk of loss or accident for 'small' UAVs remains insufficiently documented overall.[14] Military UAV data suggested an accident risk of less than 5 per 100 000 flight hours, with human error explaining the majority of these accidents.[44] In all our simulations, the use of the UAV never exceeds 3000 flight hours over the 5-year programme. We considered a UAV model with autopilot systems that enable it to perform entire missions autonomously, eliminating the need for manual remote control and thus reducing the likelihood of human errors. Several improvements are also now available to limit flight accidents such as the equipment of sensors to avoid unexpected obstacles.[45]

As our results primarily rely on data from sub-Saharan African, these findings could be generalised to other African settings with high delay in returning infant HIV testing results and traffic congestion—two salient issues in many countries in West and central Africa.[1 23]

Given that the time taken to convey blood samples or results between various sites and laboratories remains the main factor contributing to delayed ART initiation among HIV-infected infants in many African contexts,[11 12] there is an urgent need for innovative solutions to enhance the turnaround times of emergency transportation.

The transportation of blood samples via UAVs can improve EID, and our simulation suggests that this strategy could be cost-effective in the Region of Conakry. UAV-based blood sample transportation for EID could also be cost-effective in other contexts characterised by high rates of mother-to-child transmission and long turnaround time needed for sample transportation.

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