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Comparing sampling approaches for assessing sub-national vaccination coverage: a pilot study in Central African Republic and the Democratic Republic of Congo

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ABSTRACT

Vaccination coverage surveys (VCS) are essential for monitoring program performance, especially where administrative data are unreliable. While national and sub-national estimates are common, district-level data remain limited despite their value for local planning and equity monitoring. This study compared three alternative sampling approaches (ASAs)—Kinshasa School of Public Health VCS (KSPH-VCS), Geographic Information System (GIS)-based sampling, and Lot Quality Assurance Sampling (LQAS)—to the WHO Vaccination Coverage Cluster Survey (WHO-VCCS) in terms of validity and precision among children aged 12–23 months at the health district (HD) level.

A cross-sectional study was conducted in five HDs (urban and rural) in the Central African Republic (CAR) and the Democratic Republic of Congo (DRC). All four approaches were applied simultaneously. For 17 vaccination indicators per HD, comparability to WHO-VCCS was assessed using four metrics: (i) absolute difference in percentage points (pp) between each ASA and the WHO-VCCS estimates, (ii) inclusion within WHO's 95% confidence intervals (CIs), (iii) CI width ratio, and (iv) proportion of estimates outside WHO CIs. Survey-adjusted logistic regressions, design effects (DEFF), and intra-cluster correlation coefficients (ICC) were analyzed. Aggregated results at regional/national levels were also simulated.

GIS showed the highest concordance (49.3% of estimates within 5 pp.; 41.2% within WHO CIs) but had the widest CIs (median width ratio relative to WHO-VCCS: 2.2). KSPH-VCS had narrower CIs (1.7) and moderate validity (22.4% within 5 pp), while LQAS had the highest proportion of estimates outside WHO CIs (median: 18.5 pp). KSPH-VCS and GIS were statistically comparable to WHO-VCCS in 3 of 5 HDs; LQAS in 4. At aggregated levels, all ASAs performed similarly.

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KSPH-VCS and GIS offer viable options to WHO-VCCS, especially for producing aggregated estimates with acceptable precision. Further studies should assess cost, feasibility, and adaptability across settings.

1. Introduction

Vaccination can prevent between 3.5 and 5 million deaths worldwide annually [1–3]. Specifically, the Vaccination Agenda 2030 (IA2030) set out to reach 90% vaccination coverage (VC) of routine vaccines in all signatory countries [4–9]. Therefore, system-wide interventions tailored to local contexts informed by high quality data are needed [10–14]. However, in low- and middle-income countries (LMICs) such as the Central African Republic (CAR) and the Democratic Republic of Congo (DRC), administrative data tends to overestimate VC given denominators derived from out-of-date censuses, registration errors in health facilities, and gaps in data transmission between health systems [12,13,15–17]. In DRC for instance, the most recent national census was conducted in 1984 [18,19], while CAR conducted the fourth General Population and Housing Census in 2021 [20,21]. Therefore, household surveys can be a critical tool in the monitoring of VC in LMICs [16].

In low- and middle-income countries, vaccination coverage estimation has relied on a combination of periodic national household surveys and more operationally focused survey strategies. While large-scale surveys provide robust population-based estimates, their cost and infrequent implementation often limit their usefulness for routine program monitoring at decentralized levels [4,16]. In response, a range of alternative approaches has been applied across LMICs to support more timely subnational assessments, including probability-based cluster surveys adapted from WHO recommendations [22–24], rapid classification-oriented designs such as Lot Quality Assurance Sampling (LQAS) [23,25], and more recent geographically explicit sampling frameworks developed to address outdated census frames [14,26,27]. These experiences highlight recurring trade-offs between statistical precision, representativeness, feasibility, and operational usefulness in resource-limited settings.

Prior to 2015, the World Health Organization (WHO) Expanded Program on Vaccination (EPI) cluster survey was the recommended approach to assess VC. The method consisted of sampling 210 children from 30 selected clusters – seven randomly selected children per cluster. However, this quota sampling was not a probability approach and results were often misinterpreted [22–24,26,28]. Therefore, initially in 2015 as a working draft and then in 2018, the WHO published a revised EPI cluster survey approach using probability-based sampling, the WHO Vaccination Coverage Cluster Survey (WHO-VCCS) [4,16]. Although the revised WHO guidelines provide additional tools to help researchers tailor sampling approaches (SA) to specific contexts, achieving precise district-level estimates may still be challenging in many African settings. In sparsely populated areas, the large number of clusters required can make implementation costly, time-consuming, and labor-intensive, and may increase clustering effects. Therefore, adaptations of the WHO-VCCS may be more appropriate and feasible in LMICs.

In CAR and DRC, large-scale national surveys such as the Demographic and Health Survey (DHS) [25,29–31] and the Multiple Indicator Cluster Survey (MICS) [32,33] are conducted every three to five years. While, these surveys gather extensive health and social data, and include vaccination modules, they are not conducted annually due to their complexity and cost and do not explore reasons for non-vaccination. In addition, these surveys are most often stratified at regional or provincial levels, and typically do not provide estimates at health district (HD) level—typically the operational unit of the health system. Thus, more rapid and practical surveys at the operational level are needed to ensure more accurate timely and precise data. Since 2021, to monitor routine vaccination, the DRC has been conducting annual country-wide vaccination coverage surveys (VCS) using an adaptation of the WHO-VCCS, developed by the Kinshasa School of Public Health (KSPH-VCS) [34–37]. This approach provides precises estimates at the national and provincial level, yet estimates at the HD level have been challenged due to the inclusion of fewer clusters per HD, leading to wide confidence intervals (CI) and an unclear sense of their ability to capture heterogeneity.

Based on the WHO-VCCS recommendations to include more small clusters within strata and considering budget constraints in resource-limited countries, using adaptable yet standardized approaches is essential for rigorous VC assessments. An evaluation in Pakistan comparing the compact segment and grid-based geographical information system (GIS), two alternative sampling approaches (ASA) for assessing VC, found that estimates were similar between these ASA and the traditional EPI cluster survey [27].

In this study, we compared three alternative VCS approaches with the WHO-VCCS at the HD level, focusing on the comparability and precision of the estimates. Alternative approaches assessed include: the KSPH-VCS, a gridded population-based GIS approach and a clustered Lot Quality Assurance Survey (LQAS).

2. Methods

2.1. Study locations and implementation

This study was conducted from April 1 to 17, 2023, in two provinces of DRC and from April 26 to May 13, 2023, in two regions of CAR. In DRC, the study was implemented in N'djili (urban HD) in Kinshasa province and in Boko (rural HD) in Kwango province. In CAR, the study was implemented in Bangui II (urban HD) and Bégoua (peri-urban HD) in region 7, and Bossembele (rural HD) in region 1.

Both CAR and DRC have three-level health systems, within which routine vaccination services are delivered through the Expanded Programme on vaccination (EPI), organized in a pyramidal structure from the central level to health facilities. The central level is responsible for developing and implementing national health policy. The intermediate level serves as a liaison between the central and operational levels; it comprises seven Health Regions (HR) in CAR and 26 Provincial Health Divisions (PHD) in DRC. The operational level is responsible for implementation of primary health care strategies, including routine vaccination. At this level, health districts (HD) constitute the core operational unit for vaccination delivery, including microplanning, vaccine distribution, supervision of health areas, and data consolidation, while health facilities conduct fixed, outreach, and mobile vaccination sessions and ensure last-mile cold chain maintenance. It includes 35 HD in CAR [38,39], and 519 HD in DRC. Each HD in DRC is subdivided into health areas (HA). Each HA provide primary health care to a population of 5000 to 10,000 inhabitants [40]. In CAR, however, at the time of the survey, HD were not subdivided into clearly defined HA, instead, each HD consisted in health centers, each of them serving a population of 5000 to 10,000 in a geographic area [38,39]. For the purposes of this study, the term “HA” is used for both countries.

2.2. Sample size

Sample size calculation for each of the four SAs is presented in the Table 1. For both countries, we considered an expected proportion of 41.5% of children 12 to 23 months fully vaccinated based on the 2021 VCS in DRC, as CAR coverage was notably lower during their most recent MICS at 15.1% (MICS-2019). We used the following formula to

Table 1
Statistical parameters used to calculate the sample size for each survey sampling approach.

Parameters	Approaches			
	WHO-VCCS	KSPH-VCS	GIS	LQAS
Number of HD (A)	5	5	5	5
Expected threshold(p)	0.42	0.42	0.42	0.42
Accuracy required	± 0.10	± 0.10	± 0.10	± 0.10
Alpha (α)	0.05	0.05	0.05	0.05
k ($0.3 \leq p \leq 0.7$) = 1	1	1	1	NA
Confidence coefficient ($Z_{(1-\alpha/2)}$)	1.96	1.96	1.96	1.96
Effective sample size (ESS)(B)	103	103	103	95
Minimum number of respondents per cluster (m)	10	30	30	19
Number of segments per cluster	NA	6	NA	NA
Number of households by segment	NA	5	NA	NA
Intra-cluster correlation coefficient (ICC)	0.33	0.017*	0.017*	NA
Design effect (DEFF) = {[1 + (m − 1)*ICC]*(1 + CVw2)} (C)	4	1,5	1,5	NA
Coefficient of variation (CV_w)	0	0	0	0
Number of households to find an eligible child (D)	5	5	5	NA
Non-response rate (%)	0.15	0.15	0.15	NA
No answer inflation rate (E)	1.18	NA	NA	NA
total completed interviews needed (N_{cs}) = (A x B x C)	2060	750	750	95
Total households to visit ($N_{HH\ to\ visit} = N_{cs}$* D * E)	≈ 12,300	NA	NA	NA
Number of households to be visited per HD = $N_{HH\ to\ visit}$ /A	2460	NA	NA	NA
Number of clusters per HD = (B*C)/m	≈ 41	10	10	5
Number of households per cluster = D*E*m	≈ 60	30	30	19
Total number of clusters = A*B*C/m	≈ 205	50	50	25

NA: Not applicable.
k: "In the WHO-VCCS sample size equation (Equation B2-1, WHO-IVB-18.09), the parameter k represents an adjustment constant that modifies the effective sample size according to the expected coverage proportion (p) and desired precision (d). When p lies between 0.3 and 0.7, k = 1. Outside this range, k varies according to Table K in the WHO manual, to maintain the specified confidence-interval width. When p is unknown, a conservative value k = 1 is recommended."
* : The ICC for the KSPH-VCS and GIS approaches was calculated using the formula Deff=={[1 + (m − 1)*ICC]*(1 + CVw2)}, with m = 30, Deff = 1.5 and CV_w = 0 (minimal variability), yielding an ICC of 0.017.

estimate the effective sample size per HD for WHO-VCCS, KSPH and GIS approaches [16].

$$n \geq \frac{kZ^2_{\left(1-\frac{\alpha}{2}\right)}}{4d^2} + \frac{1}{d} - 2Z^2_{\left(1-\frac{\alpha}{2}\right)} + \frac{Z_{\left(1-\frac{\alpha}{2}\right)} + 2}{k}$$

For the LQAS approach, the sample size was calculated by using the following formula:

$$n \geq \frac{Z^2_{\left(1-\frac{\alpha}{2}\right)} p(1-p)}{d^2}$$

To account for clustering, we applied a design effects (DEFF) to the effective sample size to get the minimal required sample size for each approach, except the LQAS as the latter was designed to classify lots rather than estimate coverage. Based on the WHO recommendations, we used a DEFF of 4 for the WHO-VCCS approach, based on an intra-class correlation coefficients (ICC) of 0.333 and 10 households per cluster [34]. For KSPH-VCS and GIS approaches, we used a DEFF of 1.5, assuming minimal cluster heterogeneity in coverage based on the KSPH-VCS-2021 study report [34]. The final sample size per HD was therefore 95 for LQAS, 410 for WHO, 150 for KSPH and GIS approaches. We divided the required number of households per HD by the size of cluster to get the number of clusters needed for each approach. The cluster size was 10 households for WHO-VCCS, 19 for LQAS and 30 for both KSPH and GIS approaches. Therefore, 41 clusters for WHO, and 5 for LQAS, KSPH-VCS and GIS approaches were needed per HD.

Note that for KSPH-VCS and GIS, the number of clusters were doubled to 10 to assess the impact of cluster variation through simulations. Except in Begoua HD, results are presented for only five randomly selected clusters in this study. We generated combinations of ten numbers taken five at a time. Once all possibilities were mapped, a random number generator was used to select which permutation of five clusters would be selected for analysis. In CAR, we excluded six GIS clusters in Bossembele due to incorrect site selection, retaining four valid clusters.

The target population for the study was children aged 6–23 months, however, the analyses focus on children aged 12–23 months to follow standard vaccine coverage estimates.

2.3. Sampling strategy

2.3.1. WHO-VCCS approach

Each selected HD was considered as a distinct survey domain or stratum in which household were selected through a two-stage SA. In the first stage, the central coordination team randomly selected 41 clusters within each study HD. In CAR, clusters were defined as enumeration areas (EA) from the most recent national census. In contrast, in DRC, due to outdated census data, each study HD was divided into 64 segments by drawing eight equidistant vertical and horizontal lines, and 41 segments were randomly selected.

In the second stage, within each selected cluster, data collectors consecutively enumerated 60 households through a complete household listing to identify those with at least one child aged 6–23 months. When more than 10 eligible households were identified, supervisors systematically selected 10 using a fixed sampling interval based on the order of listing; if exactly 10 were identified, all were included. If fewer than 10 eligible households were found, data collection was extended to the nearest adjacent area to complete the sample." In each selected household, all children aged 6 to 23 months were included in the study – this was the same for all four methods.

2.3.2. KSPH-VCS approach

The KSPH-VCS used a three-stage sampling design [34–37]. First, 10 clusters or HA per HD were randomly selected from the District Health Information Software 2 (DHIS2) database. Both CAR [41] and DRC [42]

maintain a functional National Health Information Systems (NHIS) using DHIS2 for data collection and analysis. Second, each HA was divided into 16 segments, and six were randomly selected to ensure geographic dispersion. Segmentation was done by drawing three vertical and three horizontal equidistant lines on the map of the HA by the coordination team. Two more segments were randomly selected as a back-up by the coordination team to replace uninhabited or unsecured ones. Third, households in each segment were enumerated until 18 eligible households were found; five eligible households were then systematically selected, leading to a total of 30 selected eligible households per HA. If the selected segment had less than five eligible households, the next segment was included.

2.3.3. GIS approach

The GIS sampling approach used population density data and settlement extent from Geo-Referenced Infrastructure and Demographic Data for Development(GRID3) [15] as inputs. For each HD and within the human settlement boundary (habitable zones), we randomly generated ten points, proportionate to the population size, as reflected in each population density grid. A 100-m buffer in urban areas and a 500-m buffer in rural areas was established around each point and defined as clusters. Within each cluster, data collectors located the geographical center of the buffer and went from household-to-household, using an open-access GPS application, SW Maps, until they surveyed 30 eligible households.If the required number of 30 eligible households was not reached within the primary buffer, an additional 150-m buffer in urban areas and a 1-km buffer in rural areas was applied.

2.3.4. LQAS approach

The LQAS approach used a three-stage sampling approach. First, each HD was divided into five supervision zones (strata) and one HA (cluster) was randomly selected per stratum. The supervision areas correspond to the supervision axes defined by the HD teams. When there were more than five axes, only five were selected at random. Second, within each selected HA, a village or avenue was randomly selected and all eligible households were enumerated. Third, in each selected village or avenue, 19 eligible households were systematically selected. If the sample size was not met, the team moved to the closest village or avenue. In large villages (>95 households), supervisors divided them into smaller segments of at least 95 households (assuming one eligible child per five households) and randomly selected one.

2.3.5. Variables and indicators

This study used WHO's Vaccine Coverage Quality Indicators (VCQI) [43] to calculate the main indicators. Sociodemographic characteristics of mothers/guardians included the respondent's type, age, marital status, education level, and religion. Household socioeconomic status was assessed using information on household assets, housing characteristics, and access to basic utilities, which were used to construct a wealth index.

2.4. Data collection

Interviewers used electronic tablets with SurveyCTO Collect questionnaires to record vaccination data from vaccination cards when available or, if missing, from mother/guardians recall and health facility records. In this analysis, only data from cards and mother/guardians recall are presented. Interviewers, males and females were recruited based on their previous experience with data collection, and completed four days of training, which included two days on general survey approaches and two days on approach-specific procedures, with random team assignments and separate sessions for each SA.

The number of field teams in each HD varied by approach, the WHO-VCCS had teams of one supervisor and six interviewers; LQAS had teams of one supervisor and two interviewers; while KSPH-VCS and GIS each had two teams of one supervisor and four interviewers.In each HD, all teams collected data simultaneously and independently, leading to 123 households being surveyed by teams from at least two different approaches. However, we assumed this overlap did not introduce bias in coverage estimates, as each approach was analyzed separately and households were alerted to this possibility and could have refused participation at any time.

2.5. Data analysis

We conducted data analysis using Stata 18 (StataCorp, College Station, TX) and Excel, accounting for the sampling design. Tables and figures were created using Microsoft Excel 2016. During data cleaning, we removed incomplete surveys ($n = 2$), duplicate entries ($n = 64$), and ineligible children based on age ($n = 8$).

To assess household socioeconomic status (SES), we applied principal component analysis (PCA) to household assets, housing characteristics, and utility access. The first principal component which explained 38% of the total variance, generated a wealth index, that we categorized into quintiles from 1 (lowest) to 5 (highest) for interpretation. We analyzed key vaccination indicators, including fully vaccinated children, zero-dose children, and never-vaccinated children. A child was classified as fully vaccinated if he received one dose of Bacillus Calmette-Guérin (BCG), Inactivated Poliovirus Vaccine (IPV), measles (VAR), and yellow fever (YF) vaccines, along with three doses of - Pentavalent (diphtheria-tetanus-pertussis-hepatitis B and *Hemophilus influenzae* type b), -Pneumococcal conjugate vaccine (PCV), and -oral polio vaccine (OPV). We excluded rotavirus (DRC) and meningococcal A vaccine (CAR) doses since these vaccines were not universally recommended in both countries. We defined zero-dose children as those who had not received at least one dose of the pentavalent vaccine [44], and never-vaccinated children as those who had not received any vaccine. We accounted for the cluster sample design in coverage estimates and calculated 95% confidence intervals (95%CI) using the Wilson method [45].

In order to compare the different approaches, we evaluated the width of the 95%CIs, bearing in mind that the wider the 95%CI, the lower the precision of the estimates [46,47] and we also looked at the overlap of the 95%CIs of each ASA with those of the standard WHO-VCCS, noting that while overlap does not necessarily imply a lack of significant difference, it can be useful for visual comparison [48,49].

To further assess the comparability of the ASAs, we evaluated their validity and precision by comparing their estimates to those obtained from the WHO-VCCS across 17 vaccination indicators in five HDs, totaling 85 comparisons per SA. The indicators included BCG, OPV1–3, Penta1–3, PCV1–3, VAR, IPV, YF, fully vaccinated status, never-vaccinated status, zero-dose status, and possession of a vaccination card. We calculated the absolute difference in percentage points (pp) between each ASA and the WHO-VCCS estimates, categorizing these differences as $\leq$5 pp., 6–10 pp., 11–15 pp., or $>$ 15 pp. We also determined whether the ASA estimates fell within the 95% CI of the WHO-VCCS and expressed the width of the ASA's CI as a ratio relative to that of the WHO-VCCS. Additionally, we quantified the extent to which the ASA's CI extended beyond the bounds of the WHO-VCCS's CI. Given the non-normal distribution of these measures, medians and interquartile ranges (IQRs) were used for description. This comprehensive analysis aimed to assess the validity of ASA estimates, their relative precision, and their potential to mislead data users.

We then compared fully vaccine coverage (FVC) among children aged 12–23 months according to the four SAs by performing survey-adjusted logistic regression analyses [50] at the individual level, treating each child as the unit of analysis and using the WHO-VCCS as the reference category in each HD. The dependent variable was fully vaccination status, coded as “yes” [1] for fully vaccinated children and “no” (0) for others, while the SA served as the independent variable. This model estimated the odds of FVC for KSPH-VCS, GIS, and LQAS relative to WHO-VCCS. We assessed, in all HDs, whether the survey-adjusted

Table 2
Description of weighting process for each approach.

Approach	PSU	SSU	TSU	TP	Weight
WHO-VCCS	# AD selected/ total # AD	# eligible HH/# Total HH	# HH selected/# eligible HH	PSU x SSU x TSU	1/**TP**
KSPH-VCS	# clusters / total # HA	# segments selected/# Total segments	# HH selected/# eligible HH	PSU x SSU x TSU	1/TP
GIS	# clusters / total # AD	# HH selected/ total # HH	–	PSU x SSU	1/TP
LQAS	1/# HA in supervision zone	1/# Total village or avenue in HA	# HH selected/# eligible HH	PSU x SSU x TSU	1/TP

PSU: Primary Sampling Unit.
SSU: Secondary Sampling Unit.
TSU: Tertiary Sampling Unit.
AD: Enumeration Area.
HA: Health Area.
HH: Household.
TP: Total probability.

logistic regression showed similar estimates of FVC between each ASA and the WHO-VCCS. The number of districts where no significant difference was observed was then reported. We also compared survey-derived DEFF and ICC, estimated using svy post-estimation commands, considering that a high DEFF and ICC are associated with a decrease in the validity of estimates [27].

To assess simulated coverage at the regional and national levels, we aggregated data from the two HDs in the DRC into a simulated province and data from the three HDs in the CAR into a simulated region. Data from the five HDs were then combined to represent a simulated country. We conducted similar analyses at each simulated geographic level.

We also examined whether the SAs ranked HDs similarly based on estimated vaccination coverage to assess consistency and variability.

2.6. Data weighting by sampling approach

For each approach, sampling weights were calculated as the inverse of the probability of selecting a household. This probability was determined by multiplying the selection probabilities of each sampling unit, as detailed in Table 2.

2.7. Ethical considerations

This study was approved by the ethics committees of KSPH (RDC N°: ESP/CE/028/2023), University of Bangui (RCA N°_9_/UB/FACSS/ lPB /CES/023) and University of California Los Angeles (UCLA) (IRB No. 23000393). Prior to interview start, verbal informed consent was obtained from participants. Only study personnel had access to the collected data and all databases were anonymized prior to analysis.

3. Results

3.1. Sample description

The study included 5209 households: 2993 in CAR and 2216 in DRC. Interviewers surveyed 5255 mothers/guardians of 5332 children aged 6

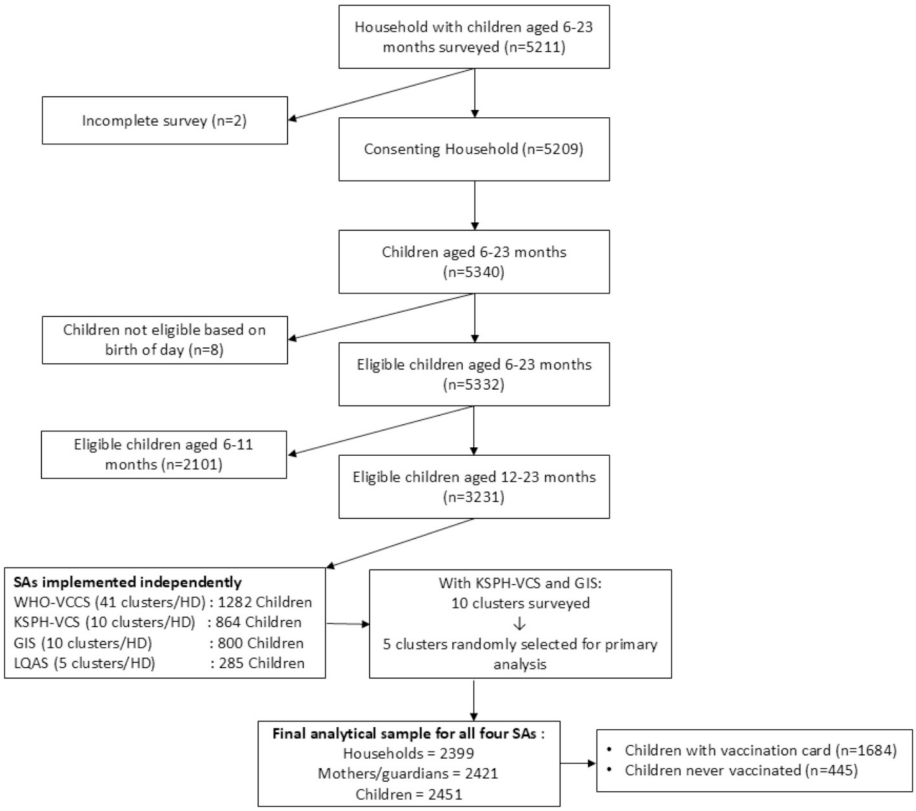

Fig. 1. Flow chart of participation in the comparative survey of sampling approaches in the evaluation of vaccination coverage in CAR and DRC, 2023.

Table 3
Distribution of respondent type by District and by sampling approach in CAR and DRC during the Comparative survey of vaccine coverage assessment sampling approach -2023.

Health Zone/ Health District	Approach	Households	Mother (%)	Father (%)	Guardian (%)
CAR-Bangui II	WHO-VCCS	240	94.6	2.9	2.4
	KSPH-VCS	103	98.0	2.0	0.0
	GIS	79	93.6	4.9	1.5
	LQAS	53	97.8	0.0	2.2
CAR-Begoua	WHO-VCCS	265	93.2	3.4	3.4
	KSPH-VCS	88	97.6	2.4	0.0
	GIS	93	87.2	7.5	5.3
	LQAS	61	95.4	1.6	2.9
CAR-Bossembele	WHO-VCCS	254	89.7	9.1	1.2
	KSPH-VCS	88	83.4	14.9	1.7
	GIS	65	87.2	9.5	3.3
	LQAS	55	95.7	2.6	1.7
DRC-Boko	WHO-VCCS	244	78.4	16.1	5.4
	KSPH-VCS	88	65.5	25.4	9.2
	GIS	92	88.0	6.9	5.1
	LQAS	52	71.9	16.7	11.4
DRC-Ndjili	WHO-VCCS	251	95.5	1.3	3.2
	KSPH-VCS	88	95.5	0.0	4.5
	GIS	84	96.0	0.9	3.2
	LQAS	56	95.2	0.0	4.8

to 23 months. Among these children, 3231 were aged 12 to 23 months and 2101 were aged 6 to 11 months. As shown in Fig. 1, comparative analyses were conducted on a final analytical sample derived after approach-specific cluster selection, comprising 2399 households, 2421 mothers/guardians, and 2451 children aged 12–23 months. Within this final analytical sample, 1684 children had a vaccination card (1050 in CAR and 634 in DRC) and 445 had never been vaccinated (211 in CAR and 234 in DRC) (Fig. 1).

3.2. Socio-demographic characteristics

The primary respondents were mothers of eligible children (Table 3), although in Bossembele and Boko, fathers accounted for a notable share of respondents (≈ 15–25%), particularly under the KSPH-VCS approach. With regard to socio-economic status (SES), the distribution of wealth quintiles varied by area and sampling approach. In N'djili and Bangui II, the majority of households were in the higher to highest quintiles across all approaches, while in Bossembele households were predominantly distributed across the lower wealth quintiles, regardless of SA. In Begoua and Boko, households were mainly concentrated in the lower to middle quintiles, with variations according to SA (Table 4). The distribution of religious affiliations varied between approaches and HDs. In Bangui II, Protestants and Catholics were the majority under WHO-VCCS and KSPH-VCS, while GIS and LQAS recorded higher proportions of Muslims (>39%). In Begoua and Bossembele, Protestants were in the majority with all approaches, particularly LQAS (>75%). WHO-VCCS captured a significant presence of revival and independent churches in these two HDs. In Boko, membership was diverse, with a significant proportion of revival and independent churches in all approaches, especially GIS (≈ 39%). In N'djili, independent churches were the majority (>50% in all approaches), with little variation between approaches (Table 5).

Differences between SAs influenced the representation of the educational level of mothers or guardians. WHO-VCCS and GIS generally captured higher proportions of mothers/guardians with secondary or higher education particularly in Bangui II, Begoua, and Boko, while KSPH-VCS and LQAS tended to include more mothers/guardians no

Table 4
Distribution of household by socioeconomic status. District and. Sampling approach in CAR and DRC during the Comparative survey of vaccine coverage assessment sampling approach -2023.

			Wealth quintile				
Health Zone/Health District	Approach	Household	Lowest (%)	Lower (%)	Middle (%)	Higher (%)	Highest(%)
CAR-Bangui II	WHO-VCCS	240	1,6	14,5	17,5	29,5	36,9
	KSPH-VCS	103	3,0	6,0	19,6	38,2	33,3
	GIS	79	2,1	11,5	28,0	31,0	27,5
	LQAS	53	7,9	15,2	31,2	20,8	24,8
CAR-Begoua	WHO-VCCS	265	11,3	20,5	32,3	18,4	17,5
	KSPH-VCS	88	20,9	23,7	31,2	13,0	11,2
	GIS	93	18,7	23,8	36,3	15,6	5,5
	LQAS	61	12,5	34,8	42,6	10,0	0,0
CAR-Bossembele	WHO-VCCS	254	26,1	33,1	30,1	10,0	0,8
	KSPH-VCS	88	14,2	32,8	39,9	12,4	0,7
	GIS	65	17,7	39,1	32,2	9,1	1,8
	LQAS	55	26,8	28,8	34,8	7,8	1,8
DRC-Boko	WHO-VCCS	244	63,4	21,2	12,4	3,0	0,0
	KSPH-VCS	88	67,8	29,0	0,9	2,2	0,0
	GIS	92	60,1	26,3	10,9	2,6	0,0
	LQAS	52	77,6	14,6	5,2	2,6	0,0
DRC-Ndjili	WHO-VCCS	251	1,8	1,3	5,9	41,4	49,6
	KSPH-VCS	88	0,8	1,8	5,3	43,8	48,3
	GIS	84	0,0	3,5	2,5	44,4	49,6
	LQAS	56	0,0	0,0	11,2	34,5	54,3

Table 5
Distribution of mother/guardian religion by district and sampling approach in CAR and DRC during the Comparative survey of vaccine coverage assessment sampling approach -2023.

Health Zone/ Health District	Approach	Mother/ Guardian	Animist/No religion (%)	Catholic (%)	Protestant (%)	Kimbanguism (%)	Muslim (%)	Revival church/ Independent (%)	Others (%)
CAR-Bangui II	WHO-VCCS	245	0.0	31.1	36.2	0.8	25.0	4.2	2.6
	KSPH-VCS	103	1.0	32.4	35.6	0.0	24.9	5.3	1.0
	GIS	80	0.0	15.2	35.8	0.9	44.4	3.8	0.0
	LQAS	54	0.0	12.2	52.5	0.0	35.3	0.0	0.0
CAR-Begoua	WHO-VCCS	269	0.8	23.9	56.6	0.0	0.4	1.4	16.9
	KSPH-VCS	89	1.8	32.5	53.9	0.0	0.0	3.1	8.8
	GIS	93	0.0	19.0	66.7	0.0	0.0	4.9	9.4
	LQAS	61	0.0	15.5	83.7	0.0	0.8	0.0	0.0
CAR-Bossembele	WHO-VCCS	258	10.9	18.0	46.6	0.0	2.0	19.8	2.7
	KSPH-VCS	89	0.0	17.7	61.6	0.0	4.6	5.9	10.2
	GIS	65	0.0	10.9	76.2	0.0	0.0	10.1	2.8
	LQAS	57	0.9	17.8	76.8	0.0	0.0	0.0	4.5
DRC-Boko	WHO-VCCS	245	2.6	23.6	26.6	6.1	1.2	37.7	2.1
	KSPH-VCS	89	0.0	32.6	20.5	4.9	0.9	30.4	10.8
	GIS	92	0.0	16.4	27.8	3.5	0.0	37.7	14.5
	LQAS	52	0.0	23.1	47.0	5.0	0.0	10.7	14.2
DRC-Ndjili	WHO-VCCS	251	0.0	9.8	8.3	3.2	0.7	68.2	9.8
	KSPH-VCS	88	0.0	11.0	21.4	3.9	1.4	62.4	0.0
	GIS	84	0.9	12.4	11.3	0.9	0.0	70.6	3.8
	LQAS	57	0.0	6.8	21.9	2.0	2.0	65.8	1.5

formal education or only primary education, notably in Bossembele and Boko. In N'djili, all the approaches revealed a high level of education with little variation (Table 6).

Table 6
Distribution of mother/guardian education by District and by sampling approach in CAR and DRC during the Comparative survey of vaccine coverage assessment sampling approach -2023.

Health Zone/Health District	Approach	Mother/Guardian	Never went to school (%)	Primary (%)	Secondary (%)	Superior (%)	Others (%)
CAR-Bangui II	WHO-VCCS	245	17.5	21.9	53.6	7.0	0.0
	KSPH-VCS	103	18.6	24.3	54.1	3.0	0.0
	GIS	80	11.9	40.2	43.6	4.3	0.0
	LQAS	54	23.3	24.9	49.6	2.2	0.0
CAR-Begoua	WHO-VCCS	269	7.7	40.0	49.0	3.3	0.0
	KSPH-VCS	89	13.2	39.7	39.1	1.8	6.2
	GIS	93	10.7	57.0	31.3	1.0	0.0
	LQAS	61	24.6	48.9	25.7	0.0	0.8
CAR-Bossembele	WHO-VCCS	258	25.8	58.1	15.5	0.2	0.4
	KSPH-VCS	89	46.6	46.9	6.5	0.0	0.0
	GIS	65	22.5	70.6	6.8	0.0	0.0
	LQAS	57	34.8	41.8	21.8	0.0	1.6
DRC-Boko	WHO-VCCS	245	16.9	48.5	33.4	1.3	0.0
	KSPH-VCS	89	34.6	23.3	40.1	2.1	0.0
	GIS	92	21.2	28.1	50.7	0.0	0.0
	LQAS	52	20.5	24.9	52.0	2.6	0.0
DRC-Ndjili	WHO-VCCS	251	0.3	3.4	73.6	22.7	0.0
	KSPH-VCS	88	0.0	7.5	77.3	14.2	1.0
	GIS	84	0.0	5.4	78.5	15.2	0.9
	LQAS	57	0.0	3.6	76.9	19.5	0.0

3.3. Vaccination coverage estimates, HD rankings, and 95%CI by sampling approach

In both CAR and DRC, FVC was generally low. In all HDs, the 95%CIs for fully vaccination estimates were narrowest for WHO-VCCS, followed by KSPH-VCS, GIS, and then LQAS. Across HDs, FVC estimates remained higher in Bangui II and N'djili across all approaches. In contrast, Bossembele and Boko, showed lower coverage with GIS and LQAS displaying wider 95%CI (Fig. 2).

Estimates of zero-dose children followed a pattern similar to FVC in terms of CI width. However, zero-dose prevalence was highest in Bossembele and Boko, with greater disparities and wider intervals, particularly for GIS and LQAS approaches. In contrast, N'djili, Bangui II and Begoua showed lower zero-dose and more consistent estimates (Fig. 3). A similar pattern was observed among children who had never received any vaccine dose (Fig. 4).

We ranked the HD according to their point estimates of fully vaccinated children estimated by each SA. There was variability in the rankings according to each SA used (Fig. 5). N'djili consistently emerged as the best performing HD in all approaches, with the GIS approach reporting the highest coverage (77.7%). Bangui maintained a stable second position, demonstrating a relatively consistent performance between approaches. Begoua and Boko displayed variable rankings. In particular, Bossembele systematically underperformed, although the LQAS approach slightly improved its ranking.

3.3.1. Observed DEFF and ICC at HD level and at simulated region and country including their vaccination coverage and 95%CI

Observed DEFFs were generally close to, or lower than the values used for sample size calculation. This was particularly evident with

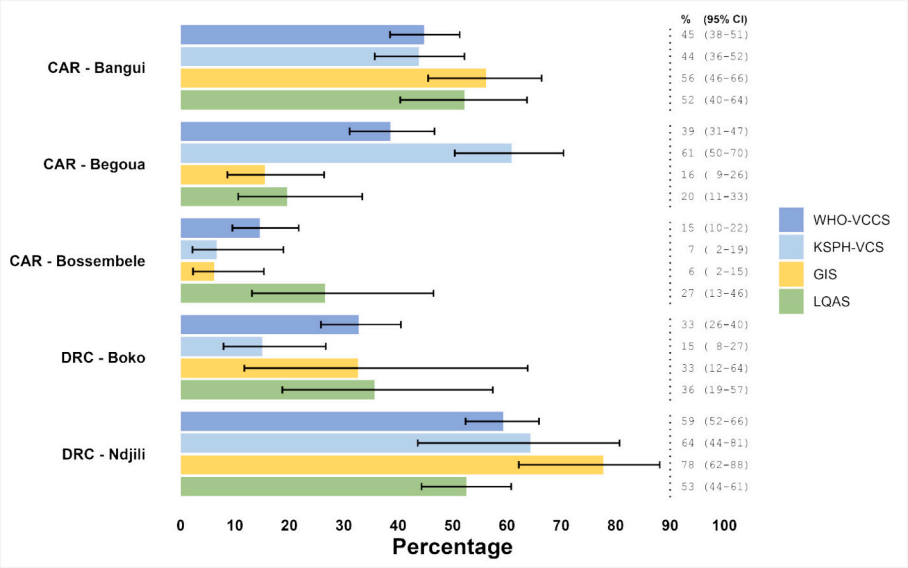

Fig. 2. Proportion of children aged 12–23 months fully vaccinated in pilot study HD in DRC and CAR, 2023.

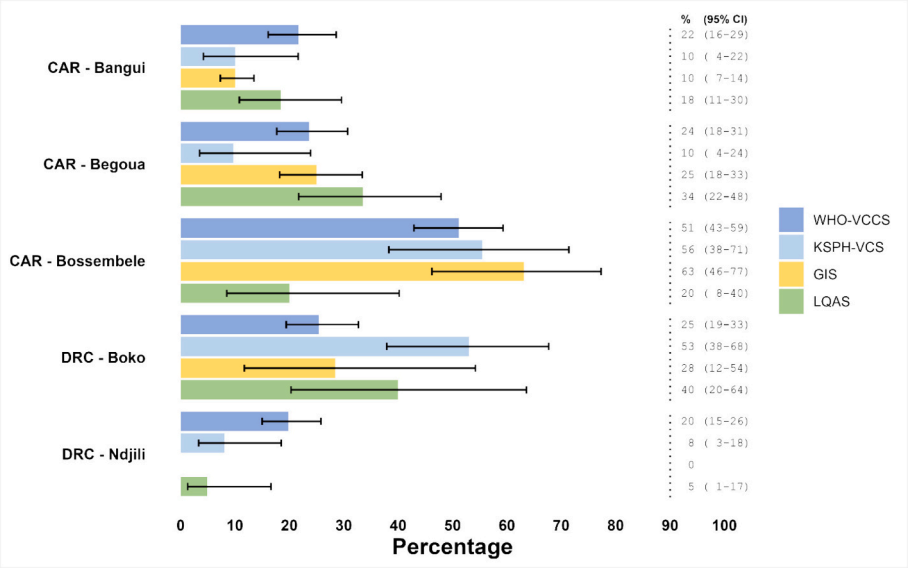

Fig. 3. Estimates of "zero-dose" children aged 12–23 months by HD and vaccine coverage assessment sampling approach, 2023.

KSPH-VCS in Bangui, Begoua and Boko, and with GIS in Bangui, Begoua and Bossembele. WHO-VCCS recorded moderate DEFFs and low but positive ICCs. Overall, KSPH-VCS showed low to intermediate DEFF, but a DEFF of 3.85 and the highest ICC (0.10) among approaches were observed in N'djili. GIS had the highest DEFF in Boko (8.88) and an ICC of 0.29. LQAS gave intermediate DEFFs, except in N'djili with the lowest DEFF (0.42) and a negative ICC (−0.03) (Table 7).

At the simulated aggregated levels, data smoothing reduced district-level variation and narrowed the 95%CI. WHO-VCCS and KSPH-VCS consistently provided moderate coverage estimates with the narrowest 95% CI. GIS showed higher coverage (around 40–42%) but with wider CI, while LQAS had variable estimates (31–42%) with the widest 95%CI. For DEFF and ICC, GIS recorded the highest values overall, especially in the DRC simulated region (DEFF = 7.49, ICC = 0.22) and in the simulated country (DEFF = 8.12, ICC = 0.25) (Fig. 6).

3.3.2. Comparative analysis of alternative sampling methods: validity and precision metrics

Validity of Estimates: The GIS demonstrated the highest concordance with the WHO-VCCS standard, with 49.3% of its estimates exhibiting an absolute difference of ≤5 pp. In contrast, KSPH-VCS and LQAS showed lower concordance rates of 22.4% and 28.4%, respectively. Furthermore, GIS had the lowest proportion of estimates deviating by more than 15 pp. (16.5%), compared to 35.3% for KSPH-VCS and 32.9% for LQAS (Table 8).

Precision of Estimates: In terms of precision, GIS had the widest CIs, with a median width ratio of 2.18 relative to the WHO-VCCS (IQR: 1.43–3.00). KSPH-VCS and LQAS had median width ratios relative to WHO-VCCS of 1.74 [1.29–2.12] and 2.07 [1.53–2.92], respectively. The median proportion of the ASA CIs extending beyond the WHO CIs was 17.2 pp. [7.88–24.06] for GIS, 14.4 pp. [11.01–22.30] for KSPH-VCS, and 18.5 pp. [12.53–31.19] for LQAS (Table 8).

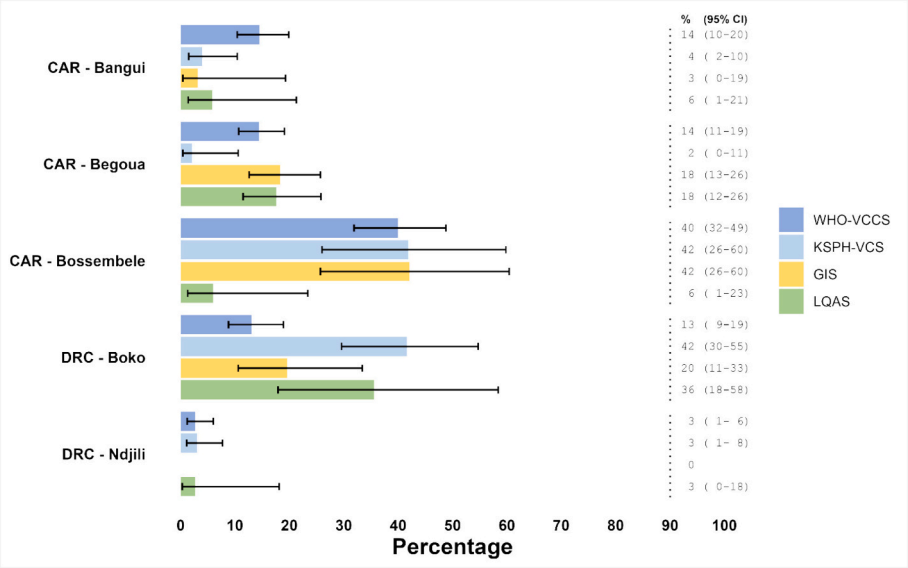

Fig. 4. Estimates of "never vaccinated" children aged 12–23 months by HD and vaccine coverage assessment sampling approach, 2023.

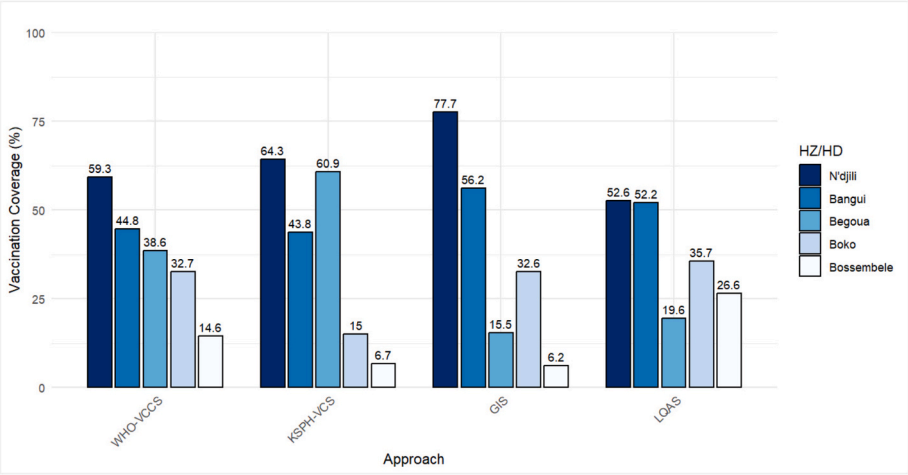

Fig. 5. Ranking of HD based on point estimates of fully vaccinated children coverage according to sampling approaches.

3.3.3. Percentage of 95% CI for which a formal statistical hypothesis test of comparison of proportions failed to reject the null hypothesis of equality

In the survey-adjusted logistic regression, the estimates from KSPH-VCS and GIS did not significantly differ from those of WHO-VCCS in three out of five districts, while LQAS yielded comparable results in four out of five districts. Significant differences compared to the WHO-VCCS were observed for KSPH-VCS in Begoua (OR = 2.47; $p < 0.01$) and Boko (OR = 0.36; $p < 0.05$), for GIS in Begoua (OR = 0.29; $p < 0.01$) and N'djili (OR = 2.39; $p < 0.05$), as well as for LQAS in Begoua (OR = 0.39; $p < 0.05$) (Table 9). In general, the LQAS and GIS approaches tend to produce more variable estimates, particularly in Bossembele and Boko.

At the simulated regional and national levels, no significant differences were found between approaches.

4. Discussion

This study aimed to compare three ASAs, KSPH-VCS, GIS and LQAS to the standard WHO-VCCS to estimate routine vaccination coverage in children aged 12 to 23 months, at the HD level, with a focus on the precision and validity of the estimates. The four approaches were successfully implemented in urban and rural settings in the DRC and CAR, demonstrating their operational feasibility in real-world field conditions.

We observed variations in point estimates between ASAs and the WHO-VCCS within the same district. Although all HDs recorded FVC below the 90% threshold recommended by the WHO, the rankings of the HD according to the point estimates were relatively consistent between the approaches. N'djili systematically occupied the first rank, while Bossembele remained in last position in most cases. However, the variations in the ranking of Begoua and Boko, particularly with LQAS, underline the influence of the methodological choice on the classification of performances. This calls for cautious interpretation that considers not only the point estimates but also the specific characteristics of each SA and the study area.

The comparative analysis of ASAs against the WHO-VCCS reference across 17 vaccination indicators in five HDs amounting to 85 comparisons per approach, revealed distinct performance profiles. The GIS demonstrated the highest concordance with WHO estimates, with nearly half (49.3%) of its estimates falling within a 5 pp. margin and 41.2% within the WHO's 95% CIs. However, this level of validity was associated with broader CIs, as shown by a median width ratio relative to the WHO-VCCS (ratio of the 95% CI width of each ASA to that of WHO-VCCS) of

Table 7
Observed design effects and ICC from the pilot survey comparing alternative approaches to the WHO-VCCS approach across HD.

HD	Approaches	DEFF observed	ICC observed
CAR-Bangui	WHO-VCCS	1.09	0.01
	KSPH-VCS	0.82	−0.01
	GIS	0.95	0.00
	LQAS	0.82	−0.01
CAR-Begoua	WHO-VCCS	1.86	0.09
	KSPH-VCS	1.09	0.00
	GIS	1.48	0.02
	LQAS	1.29	0.02
CAR-Bossembele	WHO-VCCS	2.04	0.11
	KSPH-VCS	2.09	0.04
	GIS	1.01	0.00
	LQAS	2.27	0.08
DRC-Boko	WHO-VCCS	1.70	0.08
	KSPH-VCS	1.57	0.02
	GIS	8.88	0.29
	LQAS	2.37	0.07
DRD-N'djili	WHO-VCCS	1.37	0.04
	KSPH-VCS	3.85	0.10
	GIS	2.14	0.04
	LQAS	0.42	−0.03

2.18 [IQR: 1.43–3.00], suggesting reduced precision. Conversely, the KSPH-VCS produced the narrowest CIs (median ratio relative to the WHO-VCCS: 1.74 [1.29–2.12]) but showed reduced external validity, with 35.3% of its estimates deviating by more than 15 pp. from WHO values and only 16.5% falling within the WHO's CIs, raising potential concerns about external validity. LQAS presented an intermediate profile, with 28.4% of its estimates within a 5 pp. margin and a median CI width ratio of 2.07 [1.53–2.92], yet it exhibited the highest median deviation, defined as the median absolute difference in percentage points between estimates from each ASA and those from the WHO-VCCS (18.5 pp. [12.53–31.19]) beyond the WHO's intervals. These findings highlight the inherent trade-offs between external validity and statistical precision across ASAs and underscore the need to align methodological choices with specific evaluation objectives and contextual considerations. Our findings align with prior comparisons of sampling approaches for vaccination coverage, which reported broadly similar point estimates across probability-based designs but notable differences in precision and design effects [22–27]. Applications of LQAS and GIS-based sampling similarly emphasized trade-offs between operational feasibility and statistical precision rather than systematic bias. The simultaneous implementation of all four approaches within the same health districts in this study further strengthens the comparability of our results.

Overall, survey-adjusted logistic regressions models showed that the ASAs produced coverage estimates statistically comparable to those of the WHO-VCCS approach in three out of five districts for KSPH-VCS and GIS, and in four out of five districts for LQAS. When looking for at the simulated regional or national data, all approaches were similar. These results suggest that these approaches can provide estimates that are not significantly different from the WHO-VCCS reference, indicating an acceptable level of agreement and possible interchangeability in certain contexts. At the health-district level, independent sampling and limited sample sizes can result in small fluctuations around the reference estimate, leading to odds ratios pointing in different directions without indicating systematic differences across approaches.

In terms of precision, the WHO-VCCS approach systematically generated the narrowest 95%CIs, confirming its stability as the reference approach for estimating VC at the HD level [16]. The KSPH-VCS approach showed similar results in several areas, although with somewhat wide 95%CIs compared to WHO-VCCS at the HD level. On the other hand, GIS and LQAS approaches produced wider 95%CIs in several areas, particularly in rural settings such as Bossembele and Boko. The wide 95% CIs observed for LQAS in Bossembele and for GIS in N'djili reflect context-specific reductions in statistical precision associated with elevated design effects (DEFF >2), rather than systematic differences related to rural or urban settings [46,47].

Geographical disparities in coverage were evident across districts. Rural areas like Bossembele and Boko consistently showed higher proportions of zero-dose and never-vaccinated children, irrespective of the SA. These gaps appear more related to local sociodemographic factors such as poverty and maternal illiteracy than to the approaches themselves. In contrast, urban areas like N'djili and Bangui II had more favorable profiles. These findings align with UNICEF and WHO reports identifying poverty, low maternal education, and remoteness as key zero-dose determinants [8,51]. Our results underscore the value of locally disaggregated data for uncovering and monitoring inequities, guiding targeted strategies, and advancing the IA2030 equity agenda [10]. Additionally, unlike simple random sampling, the approaches used

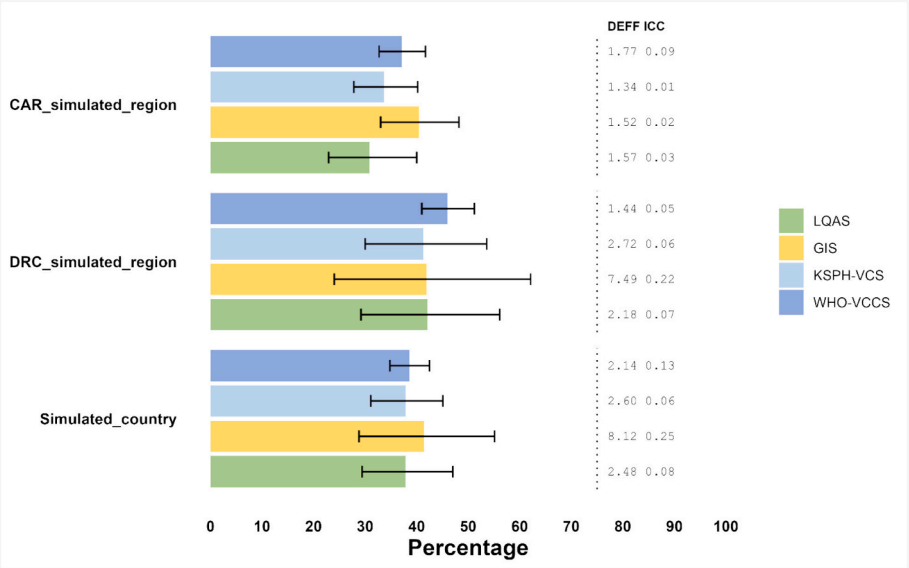

Fig. 6. Full vaccination coverage, observed design effects and ICC from the pilot survey comparing alternative approaches to the WHO-VCCS approach, based on combined data from two HDs forming a simulated region in the DRC and three HDs forming a simulated region in the CAR, as well as on all data aggregated into a simulated country.

Table 8
Comparison of Alternative Sampling Approaches Against WHO Reference Estimates: Accuracy and Precision Indicators.

Evaluation criterion	GIS	KSPH-VCS	LQAS
% of estimates within ≤5 pp. of WHO-VCCS	49.3%	22.4%	28.4%
% of estimates 6–10 pp. from WHO-VCCS	32.7%	29.1%	38.2%
% of estimates 11–15 pp. from WHO-VCCS	32.7%	39.3%	27.9%
% of estimates >15 pp. from WHO-VCCS	16.5%	35.3%	32.9%
% of ASA estimates within WHO-VCCS CI	41.2%	16.5%	24.7%
CI width ratio ASA/WHO-VCCS (median [P25–P75])	2.2 [1.4–3.00]	1.7 [1.3–2.1]	2.1 [1.5–2.9]
Portion of ASA CI outside WHO-VCCS CI (median [P25–P75])	17.2 [7.8–24.1]	14.4 [11.0–22.3]	18.5 [12.5–31.2]

pp: percentage point

may be sensitive to pocket effects, whereby nearby households share similar vaccination status [27,37].

Aggregating data at the regional or national level reduced the variability observed between HDs and produced more stable estimates [16], with narrower 95%CIs, particularly for the KSPH-VCS approach. This suggests that the KSPH-VCS approach could be used appropriately to estimate VC at aggregate levels, particularly regional or national, when the 95%CIs at the HD level remain too wide and should be interpreted with caution for decision-making.

However, this aggregation has a significant limitation: it can mask significant local disparities, reducing the ability of decision-makers to target more specific interventions at the operational level. Thus, at the local level, ASA such as LQAS can remain useful for ranking HDs according to their performance, while aggregate estimates provide a more representative overview with better statistical precision. The experience of the DRC, which has been using the KSPH-VCS approach in VCS since 2021, is a good illustration of this dual logic and data from the 2021–2023 [34–36] surveys have informed the WHO/UNICEF Estimates of National Immunization Coverage (WUENIC). At the national level, KSPH-VCS data are increasingly relied upon by the EPI program, Ministry of Health, and technical and financial partners to inform the planning and evaluation of vaccination strategies [37].

Analysis of the observed DEFF and ICC revealed additional differences in precision between approaches. WHO-VCCS and KSPH-VCS had moderate DEFFs and low ICCs, while GIS had the highest DEFF (8.88) and ICC (0.29) in Boko, indicating high intra-cluster homogeneity. LQAS showed greater variability, including a negative ICC in N'djili, probably due to the small sample size and the small number of clusters. Observed differences in DEFF across SAs likely reflect, in part, differences in household selection methods and within-cluster clustering, as well as contextual heterogeneity in vaccination coverage.

Key strengths of this study include the simultaneous implementation of the approaches in each HD made it possible to limit temporal biases that could be introduced by interviewers improving timeliness and

Table 9
Adjusted* odds ratios with 95% CI from logistic regression models comparing sampling approaches for fully vaccination coverage.

	Fully vaccinated	Odds Ratio	*P*-value	95%CI	
	Approach				
Bangui	WHO-VCCS	1.00			
	KSPH-VCS	0.96	0.85	0.62	1.48
	GIS	1.58	0.08	0.95	2.64
	LQAS	1.34	0.30	0.77	2.34
Begoua	WHO-VCCS	1.00			
	KSPH-VCS	2.47	0.00	1.43	4.28
	GIS	0.29	0.00	0.14	0.62
	LQAS	0.39	0.02	0.17	0.87
Bossembele	WHO-VCCS	1.00			
	KSPH-VCS	0.42	0.19	0.12	1.54
	GIS	0.39	0.10	0.12	1.21
	LQAS	2.12	0.14	0.77	5.85
Boko	WHO-VCCS	1.00			
	KSPH-VCS	0.36	0.02	0.16	0.82
	GIS	0.99	0.99	0.26	3.88
	LQAS	1.14	0.78	0.44	2.98
N'djili	WHO-VCCS	1.00			
	KSPH-VCS	1.23	0.64	0.50	3.04
	GIS	2.39	0.04	1.06	5.42
	LQAS	0.76	0.23	0.49	1.19
Simulated_region_CAR	WHO-VCCS	1.00			
	KSPH-VCS	0.86	0.39	0.62	1.21
	GIS	1.15	0.46	0.79	1.67
	LQAS	0.76	0.22	0.48	1.18
Simulated_province_DRC	WHO-VCCS	1.00			
	KSPH-VCS	0.82	0.47	0.49	1.40
	GIS	0.84	0.69	0.36	1.97
	LQAS	0.85	0.60	0.47	1.55
Simulated_country	WHO-VCCS	1.00			
	KSPH-VCS	0.97	0.86	0.69	1.36
	GIS	1.12	0.69	0.63	2.00
	LQAS	0.97	0.88	0.64	1.46

* : All models adjusted for survey design using the Stata svy command with clusters as PSUs.

accuracy of conducting questionnaires as they become more familiar with the survey tool. The teams received joint training, interviewers were randomly assigned to the teams, and the tools were pre-tested in both countries, thus reinforcing the methodological rigor and internal validity of the study by minimizing selection and information biases. More than 85 interviewers in the CAR were mobilized, which constitutes a strategic investment for future surveys.

However, certain limitations must be taken into account: while all approaches were operationally feasible, some implementation challenges were noted. For GIS, inconsistencies in the delimitation of HDs, particularly in the DRC, led to the exclusion of an incorrectly assigned cluster. The limited number of clusters in LQAS could have contributed to the instability of the estimates. In addition, the obsolescence of census data in the DRC [18,19] required manual segmentation of the clusters, unlike in CAR, which benefited from more recent structured enumeration units [20,21]. The application of each approach according to its original specifications introduced variability in statistical parameters (DEFF and ICC) and differences in the sampling structure (number of clusters, PSUs), which may limit the direct comparability of the statistical outputs. The limited number of HDs included ($n = 5$) limits the generalizability of the results. Differences in experience between country teams, implementation errors for GIS, and the exclusion of certain data may also have affected the estimates. A common limitation for all approaches is the low percent of cards available to transcribe dates of vaccination, having to rely on maternal/guardian recall, which is known to result in information bias, notably for indicators such as FVC [52]. Finally, for an operational choice, the dimensions of cost, feasibility and acceptability not addressed in this manuscript must be taken into account.

Despite these limitations, this study provided critical insights into the comparative strengths and weaknesses of ASAs for VCSs in resource-constrained settings. While the WHO-VCCS remains the most accurate and standardized option, GIS stood out for its strong concordance with WHO estimates, reinforcing its utility where external validity is a key priority. Conversely, KSPH-VCS offered greater statistical precision, particularly at aggregated levels, despite weaker alignment with WHO intervals. LQAS demonstrated a mixed profile, performing well in certain settings but showing wider variability. These observations highlight the necessity of aligning methodological choices with specific evaluation objectives and contextual realities—be it enhancing representativeness, statistical confidence, or logistical feasibility.

Future research should explore these approaches in a wider variety of epidemiological and programmatic contexts, and examine other dimensions such as cost, feasibility, acceptability and the ability to detect inequalities. Testing hybrid models that combine the advantages of several approaches could also improve the validity and usefulness of VC assessments.

5. Conclusion

This study has shown that the three ASAs included KSPH-VCS, GIS, and LQAS demonstrated the capacity to produce vaccination coverage estimates that were generally comparable to the WHO-VCCS standard. Each approach showed distinct performance characteristics: GIS excelled in aligning with WHO estimates, KSPH-VCS delivered greater statistical precision at broader scales, and LQAS offered a flexible compromise. These findings support the strategic adoption of alternative methodologies based on the evaluation goal, resource availability, and operational context, and underscore the potential for more adaptable and context-sensitive vaccination coverage assessments in low-resource settings.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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