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Multi-level determinants of timely routine childhood vaccinations in The Gambia: Findings from a nationwide analysis

Oghenebrume Wariri [a,b,c,*], Chigozie Edson Utazi [d,e], Uduak Okomo [a,f], Winfred Dotse-Gborgbortsi [d,e], Malick Sogur [g], Sidat Fofana [g], Kris A. Murray [h,1], Chris Grundy [b,1], Beate Kampmann [a,c,i,1]

[a] Vaccines and Immunity Theme, MRC Unit The Gambia a London School of Hygiene and Tropical Medicine, Fajara, the Gambia
[b] Vaccine Centre, London School of Hygiene and Tropical Medicine, London, United Kingdom
[c] Department of Infectious Disease Epidemiology, London School of Hygiene and Tropical Medicine, London, United Kingdom
[d] WorldPop, School of Geography and Environmental Science, University of Southampton, Southampton, United Kingdom
[e] Southampton Statistical Sciences Research Institute, University of Southampton, Southampton, United Kingdom
[f] MARCH Centre, London School of Hygiene and Tropical Medicine, London, United Kingdom
[g] Expanded Programme on Immunization, Ministry of Health and Social Welfare, The Gambia, Banjul, the Gambia
[h] Centre on Climate Change and Planetary Health, MRC Unit The Gambia at The London School of Hygiene and Tropical Medicine, Fajara, the Gambia
[i] Centre for Global Health, Charité Universitatsmedizin Berlin, Germany

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ABSTRACT

Introduction: Achieving the ambitious goals of the Immunisation Agenda 2030 (IA2030) requires a deeper understanding of factors influencing under-vaccination, including timely vaccination. This study investigates the demand- and supply-side determinants influencing the timely uptake of key childhood vaccines scheduled throughout the first year of life in The Gambia.

Methods: We used two nationally-representative datasets: the 2019–20 Gambian Demographic and Health Survey and the 2019 national immunisation facility mapping. Using Bayesian multi-level binary logistic regression models, we identified key factors significantly associated with timely vaccination for five key vaccines: birth dose of hepatitis-B (HepB0), first, second, and third doses of the pentavalent vaccine (Penta1, Penta2, Penta3), and first-dose of measles-containing vaccine (MCV1) in children aged 12–35 months. We report the adjusted Odds Ratios (aORs) and 95 % Credible Intervals (95 % CIs) in each case.

Results: We found that demand-side factors, such as ethnicity, household wealth status, maternal education, maternal parity, and the duration of the household's residency in its current location, were the most common drivers of timely childhood vaccination. However, supply-side factors such as travel time to the nearest immunisation clinic, availability of cold-storage and staffing numbers in the nearest immunisation clinic were also significant determinants. Furthermore, the determinants varied across specific vaccines and the timing of doses. For example, delivery in a health facility (aOR = 1.58, 95 %CI: 1.02–2.53), living less than 30 min (aOR = 2.11, 95 %CI: 1.2–8.84) and living between 30 and 60 min (aOR = 3.68, 95 %CI: 1.1–14.99) from a fixed-immunisation clinic was associated with timely HepB0, a time-sensitive vaccine that must be administered within 24 h of birth. On the other hand, children who received Penta1 and Penta2 on time were three- to five-fold more likely to receive subsequent doses on time (Penta2 and Penta3, respectively). Finally, proximity to an immunisation facility with functional vaccine cold-storage was a significant supply-side determinant of timely MCV1 (aOR = 1.4, 95 %CI: 1.09–1.99).

Conclusions: These findings provide valuable insights for programme managers and policymakers. By prioritising interventions and allocating scarce resources based on these identified determinants, they can maximize their impact and ensure children in The Gambia receive timely vaccinations throughout their first year of life, contributing to IA2030 goals.

* Corresponding author at: Vaccines and Immunity Theme, MRC Unit The Gambia a London School of Hygiene and Tropical Medicine, Fajara, the Gambia.
E-mail address: Oghenebrume.Wariri@lshtm.ac.uk (O. Wariri).
[1] Co-senior authors.

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1. Introduction

While the World Health Organization's (WHO) Expanded Programme on Immunisation (EPI) has achieved remarkable success in improving routine vaccine coverage globally, inequalities in the uptake of childhood vaccines persist [1,2]. Furthermore, vaccine-preventable diseases (VPDs) still claim the lives of approximately 1.5 million children annually [3]. The persistence of VPDs despite high vaccine coverage underscores the importance of understanding vaccination not only in terms of coverage but also in terms of timeliness [4]. The growing consensus is that focusing solely on high vaccination coverage, a simple measure of the proportion of vaccinated individuals, is no longer adequate, as timely vaccination also plays a crucial role in disease prevention. Achieving global eradication of measles demands a minimum of 95 % immunity in every birth cohort, rather than an average coverage of 95 % across the entire population [5]. This emphasises the importance of timely vaccination, which involves ensuring that children receive their doses at the recommended time to provide maximum protection [6]. Unfortunately, timely vaccination has not been a priority in many low- and middle-income countries (LMICs). In The Gambia, despite relatively high routine vaccination coverage similar to that achieved in many high-income countries [7,8], multiple studies [9–11], including our previous research [12,13], have revealed significant gaps in the timeliness of children's vaccinations. It is evident that a high coverage does not necessarily ensure the timely administration of vaccines. This suggests that, while achieving high vaccination coverage rates is important, it is equally crucial to ensure timely vaccinations.

Launched by the WHO, the Immunisation Agenda 2030 (IA2030) is an ambitious global strategy for the next decade to ensure everyone, everywhere has equitable access to life-saving vaccines [2]. To achieve this, immunisation programme managers and policymakers need a comprehensive understanding of the factors influencing non-vaccination and under-vaccination, including vaccination timeliness. Although extensive research has explored the determinants of vaccination coverage in LMICs [14–17], studies on the determinants of timeliness remain limited in scope and depth [18,19], creating a substantial blind spot. While numerous studies, including systematic reviews, have established links between various individual, household or community-level factors and vaccination coverage in different LMIC settings [15–17,20], research on drivers of vaccination timeliness lags. Most existing studies have focussed on child, maternal, and household sociodemographic characteristics [21–25], neglecting the influence of broader, multi-level quantitative supply-side factors. To our knowledge, only few studies have examined community-level factors such as access to vaccination services [26] or immunisation system barriers to timely childhood vaccinations [19]. The existing research on timeliness often focuses on limited number of vaccines and vaccination timepoints [27,28], neglecting the diversity of vaccines administered at various periods throughout the first year of life. There is evidence to suggest that determinants of effective vaccination may differ depending on the timing of the dose [29], with birth being a particularly vulnerable period and coverage in later infancy potentially influenced by different factors. Furthermore, no in-depth quantitative studies have yet attempted to measure the determinants of vaccination timeliness based on a robust theoretical model such as a conceptual framework. This lack of a comprehensive theoretical foundation hinders an understanding of the complex interplay between various factors and their potential impact on timely vaccination.

To ensure timely childhood vaccinations, addressing the identified knowledge gaps is crucial. By conducting research that encompasses broader quantitative factors, diverse vaccines given during infancy, and utilising robust theoretical frameworks, we can better understand the complex dynamics that influence timely childhood vaccination. In this study, we examined the determinants of timely routine childhood vaccines in The Gambia, focusing on those scheduled within the first year of life (i.e., birth, 2, 3, 4, and 9 months). Specifically, we included the birth-dose of hepatitis-B vaccine (HepB0), the first, second, and third doses of the pentavalent (i.e., Diphtheria, Pertussis, Tetanus, Hepatitis B and *Haemophilus influenzae* type B) vaccine (Penta1, Penta2, and Penta3), and the first dose of the measles-containing vaccine (MCV1). We examined broader, multi-level quantitative factors that determine the recognition of the need for vaccination or demand-side factors. We also examined quantitative factors that impact a household or community's ability to access immunisation facilities and the readiness of facilities to deliver timely vaccinations (i.e., supply-side factors).

2. Methods

2.1. Conceptual framework and included variables

Our analysis was based on the integration of two complementary frameworks: the 'three-delays model' proposed by Thaddeus and Maine [30], to understand drivers of maternal mortality, and the framework developed by Philips et al. [14] to examine determinants of effective vaccine coverage. Both frameworks propose three levels of factors influencing the receipt of care/vaccination: those determining the intention or recognition of the need for care/vaccination (i.e., *level 1 factors*); those impacting a household's ability to access health facilities (i.e., *level 2 factors*); and those that determine the readiness of health facilities to deliver appropriate and timely services (i.e., *level 3 factors*). Philips et al. [14] further classifies the *level 1 factors* as demand-side factors, while the *level 2 and level 3 factors* are considered supply-side factors (Fig. 1).

Level 1 factors typically include socioeconomic and demographic variables. Variables such as travel time to health facilities, perceived distance to the facility, and ownership of a motorized vehicle are considered *level 2 factors*. *Level 3 factors* include the organization of the clinics, scheduling of services, staffing numbers, and the population within the catchment area of a facility, which can impact waiting times for services as shown in literature [31,32]. This combined framework allowed us to comprehensively analyse the drivers of timely vaccination at the individual, household, and community/cluster levels.

The inclusion of variables in this analysis was guided by evidence from the literature on drivers of timely or effective vaccination [14–16,18–20], expert knowledge, and data availability. The complete list of included explanatory variables and their coding are provided in Fig. 1 and Table S1 of the supplementary appendix respectively.

2.2. Data sources and data collection

The two main data sources utilised in this study are the 2019–20 Gambia Demographic and Health Survey (GDHS) [33], and the national immunisation facility mapping conducted by The Gambia EPI programme in 2019. Detailed descriptive summaries of both datasets, specifically the number of children with available information and the completeness of variables in the dataset, are provided in the supplementary appendix.

For each child aged 12–35 months in the 2019–20 GDHS [33], we extracted and processed data on the outcome variables—timely HepB0, Penta1, Penta2, Penta3, and MCV1—and all the variables related to *level 1 factors*. We also extracted and processed variables related to *level 2 factors* and the geographical coordinates (latitude and longitude) of the selected cluster from the 2019–20 GDHS. Detailed information about the methodology of the 2019–20 GDHS is available in the supplementary appendix.

To estimate the geographic accessibility of immunisation facilities (*level 2 factors*) and the factors influencing their readiness to deliver appropriate and timely services (*level 3 factors*), we utilised data from the national immunisation facility mapping conducted by The Gambia EPI programme in 2019 (see supplementary appendix for further details). This comprehensive dataset, temporally aligned with the 2019–20 GDHS, included: geospatial data (latitude and longitude) of all

immunisation sites; category of facility (fixed or outreach site); ownership of functional vaccine cold storage; and population within the facility catchment area, defined using a travel-time least-cost-path model. To ensure we had data on other *level 3 factors* not already captured, we collaborated with The Gambia EPI to update the national immunisation facility mapping dataset with additional variables, including the number of times each facility is open per month and staffing levels for service provision. Detailed information about how each child and DHS cluster were linked to the nearest facility is provided in the supplementary appendix.

2.3. Defining and computing the outcome variables

We assessed vaccination timeliness based on established windows in The Gambia's routine vaccination schedule, which includes five appointments in the first year (birth, 2, 3, 4, and 9 months) [34]. For each vaccine, we calculated the age of the child at vaccination (in days) by subtracting their birth date from the date they received the vaccine. Timely HepB0, Penta1, Penta2, Penta3, and MCV1 was defined as vaccination within 24 h of birth, between 61 and 90 days (i.e., 2 months), 91–120 days (i.e., 3 months), 121–150 days (i.e., 4 months) and 271–300 days (i.e., 9 months) respectively, in accordance with the national vaccination schedule in The Gambia [34]. Any vaccination outside these windows was classified as untimely, regardless of whether it was received too early or too late. To evaluate a child's ability to consistently receive the multi-dose Penta vaccine (i.e., Penta1, 2 and 3) according to the recommended schedule, we created a timely "All Penta" variable. This composite variable indicates whether all three Penta doses were received within the recommended timeframe. Any child receiving at least one dose outside the window was considered untimely for this composite variable.

2.4. Estimating geographic accessibility

Travel time from each 2019–20 GDHS cluster to the nearest fixed immunisation clinics was employed as the primary indicator for assessing geographic accessibility. Travel time was chosen as it encompasses various factors, including elevation, barriers, road network, and travel speed, which collectively influence geographic accessibility more accurately than Euclidean or straight-line distances [35]. Travel times were modelled as the least cost path over an impedance surface. Motorized and walking speeds on roads were assigned conservatively using calibrated speed limits (S3 Table), based on travel time studies conducted in similar African context [36,37]. Travel time was generated at 1 km resolution and extracted using the corresponding cluster locations from the 2019–20 GDHS. Median travel times were extracted within 5 km and 2 km buffer zones for rural and urban clusters, respectively, to account for the deliberate displacement of cluster locations applied in the DHS methodology to ensure respondents' confidentiality [38,39]. Detailed information about the modelling approaches and data sources used in the process is shown in the supplementary appendix.

2.5. Bivariate and multivariate multi-level modelling of the determinants of timely vaccination

We began with bivariate analyses, fitting simple binary logistic regression models, for each outcome with one variable (covariate) at a time. These "reduced" models mirrored the full, multi-level model but included only the individual level. This simplified analysis allowed us to understand the independent association of each covariate on the outcome without interference from other covariates.

To address multicollinearity in the multivariate analyses, we computed generalized variance inflation factors (GVIFs) [40] for each covariate/outcome combination. We excluded variables with high GVIFs (>2, ensuring comparability across covariates as recommended by Fox & Monette [40]) or those showing inconsistent significant associations between the bivariate and multivariate analyses (a common sign of undetected multicollinearity). For these preliminary analyses, we used the traditional frequentist approach.

For the full multivariate analysis, we employed a Bayesian multilevel random intercept logistic regression model to estimate the relationships between timely vaccination and the covariates, accounting for individual, household, cluster and stratum-level variations. The

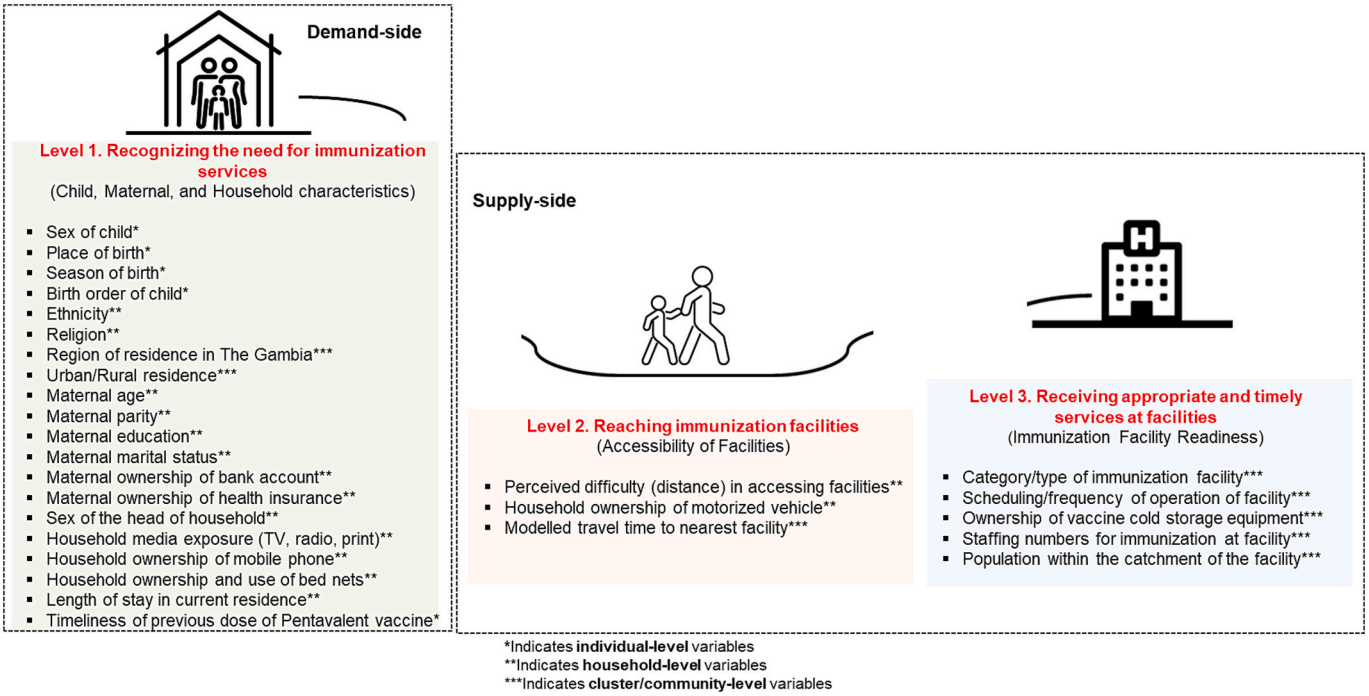

Fig. 1. Outcome variables and groups of level 1, level 2 and level 3 factors considered in the study, classified according to the conceptual frameworks adopted [14,30].

multi-level random intercept logistic regression model used in the multivariate analysis is described as follows. Let y_{ijkl} denote the binary response, representing vaccination timeliness (HepB0, Penta 1, Penta 2, Penta 3, All Penta, or MCV1) for the ith child in household j, cluster k and stratum l, and p_{ijkl} the corresponding probability of timely vaccination. The model is given by

$$y_{ijkl} \sim \text{Binomial}\left(1, p_{ijkl}\right), i = 1, \ldots, n_{jkl}, j = 1, \ldots, n_{kl}, k = 1, \ldots, n_l, l = 1, \ldots, L,$$

$$\text{logit}\left(p_{ijkl}\right) = \beta_0 + \sum_{p=1}^{r_1} \beta_p^{ind} x_{pijkl} + \sum_{p=1}^{r_2} \beta_p^{house} x_{pjkl} + \sum_{p=1}^{r_3} \beta_p^{clust} x_{pkl} + \delta_{jkl}^{house} + \delta_{kl}^{clust} + \delta_l^{strat},$$

$$\delta_{jkl}^{house} \sim N\left(0, \sigma_{house}^2\right), \delta_{kl}^{clust} \sim N\left(0, \sigma_{clust}^2\right), \delta_l^{strat} \sim N\left(0, \sigma_{strat}^2\right), \quad (1)$$

Here r_1, r_2 and r_3 represent the numbers of individual, household, and cluster-level covariates (see Fig. 1), respectively. β_0 is the overall intercept and β_p^{ind}, β_p^{house} and β_p^{clust} are regression coefficients or fixed effects corresponding to the covariates x_{pijkl}, x_{pjkl} and x_{pkl} respectively. δ_{jkl}^{house}, δ_{kl}^{clust} and δ_l^{strat} are the household, cluster and stratification random effects with variances σ_{house}^2, σ_{clust}^2 and σ_{strat}^2 respectively. The inclusion of clustering and stratification as random effects in the model aims to account for the complex design used in DHS surveys [41]. This approach is an alternative to incorporating survey weights directly into the model. Notably, no interaction terms were included in the model.

In the bivariate and multivariate analyses, we calculated crude (unadjusted) and adjusted odds ratios (cORs and aORs) respectively as the exponentiated estimates of the fixed effects, along with their corresponding 95 % confidence intervals (CIs) or credible intervals (CIs) to assess the significance of the covariate-timely vaccination associations. In both analyses, covariates with 95 % CIs not containing the value 1 were considered to have significant associations with timely vaccination. Data cleaning, validation and analysis were carried out using the R programming language [42], and the R-INLA package [43].

2.6. Model estimation and evaluation of predictive ability

We placed a non-informative prior $N\left(0, 10^{-3}\right)$ on all regression coefficients and an informative Gamma$(0.1, 0.1)$ prior with a mean of 1 and variance 10, on the precisions of the random effects. This choice ensured they were well-estimated, especially σ_{house}^{-2} whose estimation can often be affected by small sample sizes at this level [44]. We tested different prior specifications for the variance parameters in model (1) but observed no significant changes in the estimated fixed effects. Similarly, including or excluding the household level in the model didn't meaningfully alter the fixed-effect estimates.

To assess the models' abilities to predict timely vaccination, we calculated the area under the receiver operating characteristic curve (AUC). This metric is defined by plotting sensitivity against 1 minus specificity (sensitivity and specificity in our context relate to the proportions of timely vaccination and untimely vaccination correctly classified by the fitted models). AUC scores close to 1 indicate excellent discrimination, with 0.5 representing chance performance [45]. Furthermore, we used variance partitioning coefficients (VPC) to examine how much of the total variance in the outcome variable (after accounting for the effects of covariates) can be attributed to different levels of the model's hierarchy.

2.7. Role of the funding source

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

3. Results

In the bivariate analysis, all variables were significantly associated with the timely receipt of at least one of the vaccine-dose considered, except six level 1 variables (ownership of bed nets, sex of household head, maternal health insurance, maternal age, child's birth order, and season of birth). This finding further justifies the decision to include all the variables in our analysis. The figures showing the unadjusted ORs and corresponding 95 % CIs from the bivariate analyses can be found in the supplementary appendix as Figs. S6–S11. The adjusted ORs observed in the multivariate analyses are presented below. Please refer to Table S3 of the supplementary appendix for the reference categories of all the covariates in both the bivariate and multivariate analyses.

3.1. Determinants of timely receipt of HepB0 and MCV1

The aORs and corresponding 95 % CIs from the multivariate analyses for determinants of timely HepB0 and MCV1 are plotted in Fig. 2. For timely HepB0 vaccination, variables that had significant positive associations (i.e. significantly increased the odds of timely vaccination) were; place of birth, region of residence, maternal parity, household size, length of stay in current residence, and travel time to the nearest fixed health facility. On the other hand, household wealth status and ownership of vaccine cold storage at nearest facility were the variables that had significant positive associations with timely MCV1.

Children born in a health facility had 58 % (aOR = 1.58, 95 %CI: 1.02–2.53) higher chance of receiving timely HepB0 compared to those born at home. Compared to children from "other regions" (Kuntaur, Janjanbureh & Basse), those in Greater Banjul, Brikama and Kerewan were 281 % (aOR = 3.81, 95 %CI: 1.13–13.86), 275 % (aOR = 3.75, 95 %CI: 1.20–11.80) and 386 % (aOR = 1.58, 95 %CI: 1.02–2.53) more likely of receiving timely HepB0 respectively. Children born to mothers with 1–3 previous births (parity) were 62 % more likely to receive timely HepB0 compared to those born to mothers with 4 or more previous births (aOR = 1.62, 95 %CI: 1.02–2.55). Additionally, children from households who had resided in their current home for 1–3 years were 143 % more likely to receive timely HepB0 compared to those who had lived there for less than a year (aOR = 2.43, 95 %CI: 1.02–6.52). Children who lived less than 30 min and those who lived between 30 and 60 min from a fixed health facility had a 111 % (aOR = 2.11, 95 %CI: 1.2–8.84) and 268 % (aOR = 3.68, 95 %CI: 1.1–14.99) higher chance of receiving timely HepB0, respectively, compared to children who lived more than 60 min away (Fig. 2).

Compared to children from poor households, children from middle-income households had a 23 % higher likelihood (aOR = 1.23, 95 %CI: 1.02–1.57) of receiving timely MCV1 vaccination (Fig. 2). Similarly, children from wealthy households had a 37 % higher likelihood (aOR = 1.37, 95 % CI: 1.06–1.76) of receiving timely MCV1 vaccination. Children living near an immunisation facility equipped with a functional vaccine cold store had a 40 % higher chance (aOR = 1.4, 95 %CI: 1.09–1.99) of receiving timely MCV1 vaccination compared to children whose closest facility lacked a cold store.

3.2. Determinants of timely receipt of Penta1, Penta2, Penta3 and "All Penta"

Determinants of timely multi-dose pentavalent vaccination uptake varied across doses. The following variables had significant associations with timely Penta1 vaccination: ethnicity and length of stay in the current residence. For timely Penta2 vaccination, the variables that showed significant associations were timeliness of receiving Penta1 and staffing numbers providing services in the nearest immunisation facility. Similarly, the variables that had significant associations with timely Penta3 were timeliness of receiving Penta2, ethnicity, maternal parity, maternal education, and household wealth status (Fig. 3). Children belonging to specific Gambian ethnic groups were significantly more

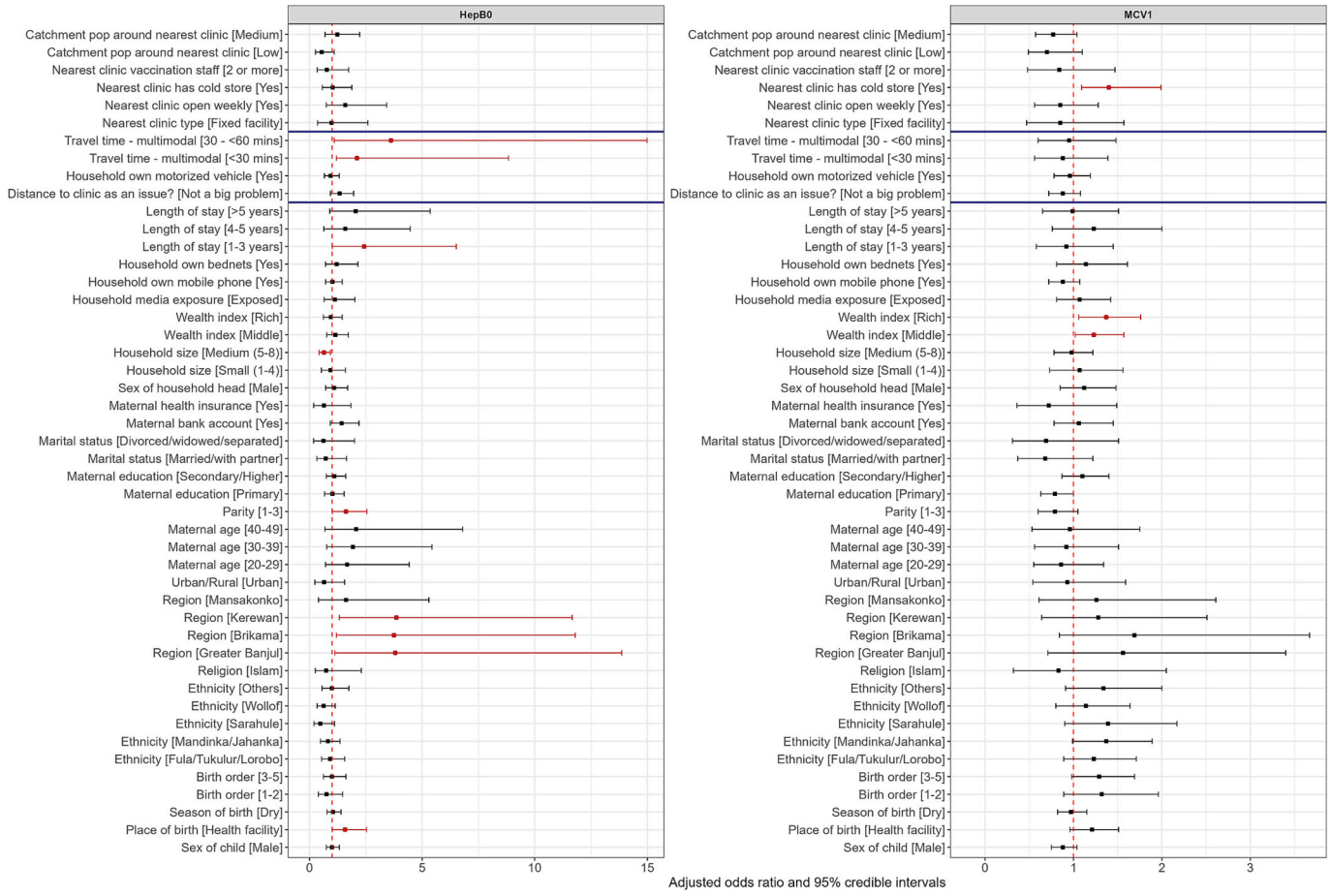

Fig. 2. Adjusted odds ratio and corresponding 95 % credible interval plots for determinants of timely birth-dose of hepatitis B (HepB0) and first-dose measles containing vaccine (MCV1).

Note: The vertical dashed red lines mark the odds ratio of 1. Red dots and lines show the aORs and 95CIs of variables that have significant associations with vaccination. Dark blue horizontal line separates the covariates in level 1, 2 and 3 factors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

likely to receive timely Penta1 vaccination compared to non-Gambian children. Notably, Mandika/Jahanka children had a 59 % higher chance, followed by Fula/Tukular/Lorobo (70 %), Wollof (73 %), and Sarahule (102 %). Additionally, children residing in their homes for 1–3 years were 77 % more likely, while those residing for 4–5 years were 138 % more likely to receive timely Penta1 compared to those who had lived there for less than a year.

Similar to the pattern observed in Penta1, children of Fula/Tukular/Lorobo ethnicity were 44 % more likely to receive timely Penta3 compared to non-Gambian children. The timeliness of receiving previous doses of the pentavalent vaccine played a crucial role in determining the likelihood of receiving subsequent doses on time. Children whose Penta1 was timely were significantly more likely to receive timely Penta2, with more than threefold higher chance (354 %) compared to those with untimely Penta1 (aOR = 4.54, 95 %CI: 3.49–6.1). This pattern was further amplified for Penta3, where children with timely Penta2 demonstrated a fivefold (539 %) increase in the likelihood of timely Penta3 uptake compared to those with untimely Penta2 (aOR = 6.39, 95 % CI: 5.73–7.12) (Fig. 3). Beyond the crucial influence of previous pentavalent vaccine timeliness, several level 1 factors (i.e., demand-side) emerged as significant predictors of timely Penta3. Children born to mothers with 1–3 previous births (parity) compared to those with four or more children, those whose mothers had secondary or higher education compared to those with no formal education and those from middle-income families compared to those from poor households had 62 %, 31 % and 57 % significantly higher chance of timely Penta3 respectively.

All covariates that determined a child's ability to consistently receive all three doses of pentavalent vaccine (i.e., Penta1, 2 and 3) in a timely manner, were *level 1 factors* (Fig. 4). Male children, children whose mothers had a secondary or higher education, those with Gambian parents, and those from middle-income families had a higher chance of receiving timely "All Penta" compared to female children, those whose mothers had no formal education, those born to non-Gambian parents and those from poor households. Specifically, male children had a 19 % higher chance (aOR = 1.19, 95 % CI: 1.01–1.4), children whose mothers had a secondary or higher education had a 24 % higher chance (aOR = 1.24, 95 % CI: 1.08–1.56), and children from middle-income families had a 49 % higher chance (aOR = 1.49, 95 % CI: 1.17–1.9).

3.3. *Summary of determinants of timely vaccination and predictive ability of the models*

The summary of the estimated relationship between the covariates and timely vaccination for all the vaccines examined is shown in Fig. 5. Level 1 factors were the commonest determinants across all the vaccines, however, level 2 and 3 factors were also significant. Ethnicity (Penta1, Penta3 and All Penta) and household wealth status (Penta 3, MCV1 and All Penta) were significant across three of the vaccines each compared to maternal parity, maternal education and length of stay in current residence which were significant across two vaccines. The timeliness of previous Pentavalent vaccine was a significant predictor

Fig. 3. Adjusted odds ratio and corresponding 95 % credible interval plots for determinants of timely first, second and third dose of pentavalent vaccine (Penta1, Penta2 and Penta3).

Note: The vertical dashed red lines mark the odds ratio of 1. Red dots and lines show the aORs and 95CIs of variables that have significant associations with vaccination. Dark blue horizontal line separates the covariates in level 1, 2 and 3 factors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for all subsequent doses. The plots of predictive ability of the models (AUC) and the proportion of the total residual variation attributed to different levels of the model's hierarchy (VPC) are shown in supplementary appendix (Figs. S4 and S5). the AUC scores for the six vaccines examined range between 0.76 and 0.90, showing that all the fitted models had good discriminatory power.

4. Discussion

Our study examined the factors that influence timely routine childhood vaccination in The Gambia. To achieve this, we utilised two complementary conceptual frameworks that provided a comprehensive theoretical foundation: we examined various quantitative factors that determine the recognition of the need for vaccination from a broader, multi-level perspective (level 1 or demand-side factors). Additionally, we examined the quantitative factors that affect a household or a community's ability to reach immunisation facilities and the ability of these facilities to provide timely vaccinations (level 2 and 3 or supply-side factors). The most common drivers of timely childhood vaccination were demand-side factors such as ethnicity, household wealth status, maternal education, maternal parity, and the duration of the household's residency in its current location. Nonetheless, supply-side factors such as travel time to immunisation facilities, availability of functional vaccine cold storage and staffing numbers in facilities were also significant determinants. Our analysis showed that most demand-side factors were significant for two or more of the vaccines examined. We also found that the determinants of timely vaccination varied across specific vaccines and the timing of doses, which aligns with existing evidence [29].

For HepB0, a time-sensitive vaccine that must be administered within 24 h of birth, delivery in a health facility significantly increased timely uptake. Similar findings have been reported in neighbouring Senegal [46,47], and elsewhere [29]. The increased likelihood of timely HepB0 in facility births can be attributed to immediate access to health professionals who can administer the vaccine within the recommended 24-h window, unlike in home births. While the 2019–20 GDHS data shows a promising rise in facility deliveries to 84 % from 63 % in 2013, a concerning 15 % of births still occur at home in The Gambia [33]. This translates to missed opportunities for timely HepB0 vaccination. To bridge any remaining gaps and optimise timely HepB0 uptake in The Gambia, further efforts are needed to increase facility deliveries, implement postnatal home visits for timely HepB0 administration, and ensure infants born at home are brought to health facilities promptly, as recommended by the WHO [48].

Our study also found that shorter travel time to a fixed immunisation facility increased the chances of timely HepB0 vaccination. This is likely because fixed immunisation facilities in The Gambia frequently double as Reproductive and Child Health (RCH) clinics, offering delivery services. As a result, women in close proximity and who give birth at these facilities have access to HepB0 for their newborns. This finding is consistent with previous research in The Gambia [11] and elsewhere [49,50], that has established a link between geographic proximity to

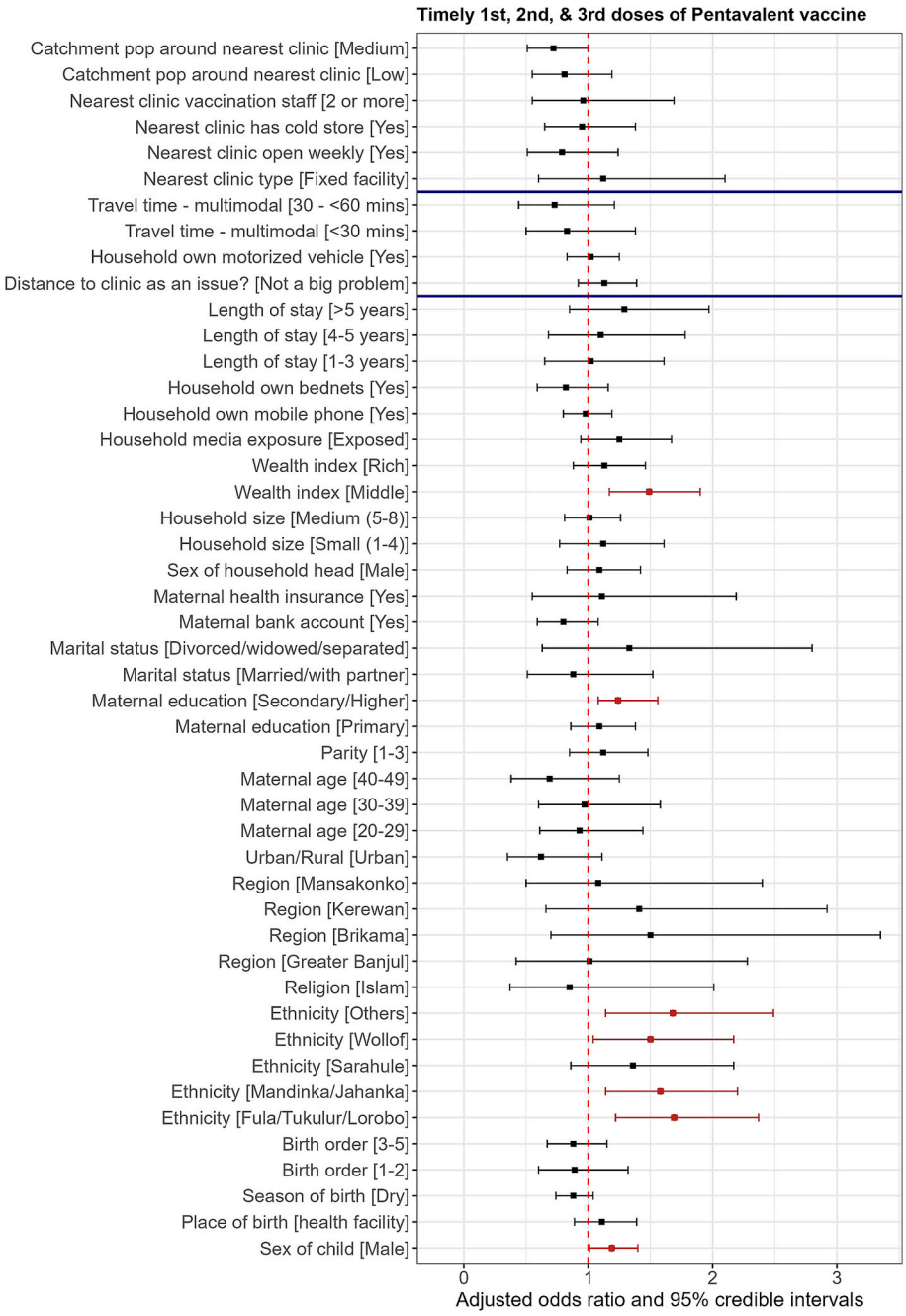

Fig. 4. Adjusted odds ratio and corresponding 95 % credible interval plots for determinants of consistent timely all doses of pentavalent vaccine (i.e., Penta1, Penta2 and Penta3).

Note: The vertical dashed red lines mark the odds ratio of 1. Red dots and lines show the aORs and 95CIs of variables that have significant associations with vaccination. Dark blue horizontal line separates the covariates in level 1, 2 and 3 factors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vaccination services and the uptake of routine childhood vaccines. However, our results differed from those reported by Moisi et al. in Kenya, who found that travel time to a vaccination clinic did not affect vaccination coverage or timeliness [51]. This difference in finding could be explained by differences in focus. Our analysis examined travel time to fixed immunisation facilities and its influence on the timeliness of various doses given throughout infancy, specifically analysing it's effect on HepB0, given it's unique time-sensitive nature. Moisi et al. [51], on the other hand, examined the effect of travel time on vaccines administered later in infancy but did not examine it's affect on HepB0. This further underscore the importance of considering vaccine-specific factors when investigating drivers of timely vaccination.

A key measure of a successful immunisation programme is its ability to consistently reach children on time with multiple doses of the same antigen, like the pentavalent vaccine. Our study revealed that timely administration of subsequent doses of the multi-series pentavalent vaccine is strongly associated with timely receipt of the prior doses. Children who received Penta1 and Penta2 on time were three to five times more likely to receive subsequent doses of Penta2 and Penta3 on time, respectively. This is consistent with previous studies in The Gambia and other contexts that have highlighted the "domino effect," where delays in earlier doses increase the likelihood of delays or non-uptake of later ones [9,10,52,53]. This has important programmatic implications - prioritising interventions that improve the timeliness of

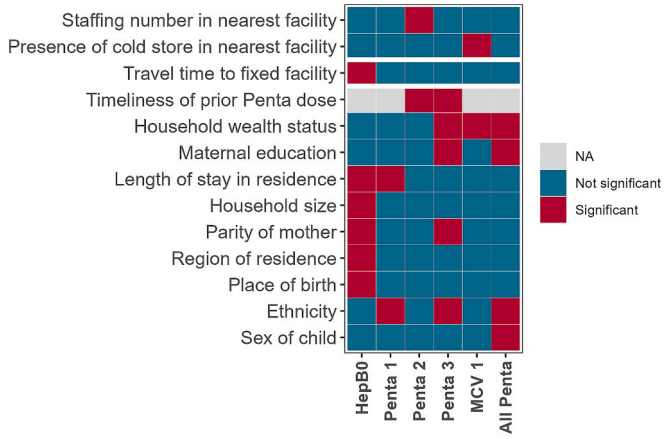

Fig. 5. Summary of the estimated relationships of the predictors of timely vaccination in the multivariate analyses. Only variables found to be significant for at least one vaccine are shown.

the earlier doses of multi-series vaccines could significantly boost overall vaccination timeliness. Based on our findings, programme managers and service providers should focus their efforts on overcoming any barriers that hinder the timely administration of the first doses in multi-series schedules.

We also found that ethnicity significantly influenced timely pentavalent vaccine uptake. Children from non-Gambian households were substantially less likely to receive Penta1, Penta3, and "All Penta" on time compared to those of specific Gambian ethnic groups. This finding highlights potential barriers to equitable access to vaccination services for non-Gambian children. These barriers could stem from their limited understanding of the immunisation system or other obstacles. Our findings align with past research that has established a connection between ethnic minority status and lower timely vaccination rates [29,53,54]. Given that approximately 10 % of The Gambia's population are non-Gambians [33], these results highlight the urgent need for the EPI programme to prioritise equitable access to vaccination for ethnic minorities in the country. However, a cautious interpretation of this finding is warranted, as ethnicity may be correlated with other factors such as maternal education and household wealth. Additionally, the ethnicity of health facility staff could influence vaccination uptake, with caregivers potentially willing to travel long distances to have their children vaccinated by staff of their own ethnicity. Ethnicity may also be linked to socioeconomic factors like wealth status. Ensuring that all children, regardless of their background, enjoys the full benefits of vaccination is crucial for achieving improved health outcomes and preventing VPDs, aligning with the "Everyone, Everywhere" vision of the IA2030 agenda [2].

Measles control serves as a crucial indicator of a strong immunisation system and an important marker of equity within that system. Our study found a significant association between household wealth and timely MCV1 uptake. Children from middle and high-income families were more likely to receive MCV1 on time, aligning with findings from elsewhere [18,19]. While immunisation services in The Gambia are free, indirect costs like transportation and potential income loss from seeking services might deter vaccination, particularly for the poorest households. Moreover, these households often face multi-dimensional poverty, which is a complex problem that goes beyond income [55]. This encompasses various deprivations like limited education, living in urban slums, lack of empowerment in healthcare decisions, and time constraints, all of which can hinder timely vaccination uptake.

Our study identified proximity to an immunisation facility with functional vaccine cold storage as a key factor influencing timely MCV1 uptake. However, limited cold-storage is a persistent challenge in many developing countries. The 2014 WHO multi-dose vial policy, advising on minimizing wastage while ensuring safety, recommends discarding opened vials within six hours unless specific conditions are met [56]. This can lead to "batching" in facilities lacking functional cold-storage, where healthcare workers wait to accumulate enough children before opening a vial to avoid waste. This, unfortunately, can delay vaccinations, especially for children attending outreach clinics without functional cold-storage facilities. Interestingly, research in The Gambia has shown that over 70 % of healthcare workers are willing to open multi-dose vials even if the batching threshold is not met, suggesting potential to optimise vaccination visits and reduce delays [57]. Another promising solution lies in accelerating the implementation of single-use technologies like measles vaccine micro-needle patches [58]. These innovations could reduce reliance on functional cold-storage and, potentially, improve timely vaccination, particularly in outreach settings.

There are some limitations to the design, dataset, and analytical approach used in this study. Due to the cross-sectional design of our study, we cannot establish causality between the examined predictive factors and the observed outcomes. Instead, we can only suggest an association, and thus, our findings should be interpreted with caution. However, cross-sectional surveys are the only feasible method for exploring these associations, as it would be unethical to observe and follow up children until untimely vaccinations are realised. Additionally, many factors associated with untimely vaccination existed well before the children in the study were born, suggesting that temporality is likely present for most observed relationships. We recognise that we did not consider contextual and qualitative factors such as vaccine hesitancy, beliefs, social norms, rumours, overall trust in government and the immunisation system that can affect a family's decision to vaccinate their children. However, our study concentrated on quantifiable determinants, utilising two robust and complementary conceptual frameworks. In our analysis of geographic accessibility and facility-level factors that determine timeliness, we assumed that households received vaccination services from the nearest clinic. This might not always be true, as individuals may bypass closer facilities due to perceived service quality issues [59–61], or service managers may assign communities to specific clinics based on geographic boundaries or operational efficiency, even if they are not the nearest. Additionally, we assumed a constant travel speed in our model and did not account for potential variations in travel time resulting from seasonal changes in travel speed due to weather conditions.

To refine future analysis on travel time models and how facility factors impact uptake of timely vaccination, it may be possible to collect information about the specific clinic where services are received using electronic immunisation registers or demographic surveillance systems. It is also important to note that our travel time estimates may have been biased by the random displacement of DHS cluster locations. However, we mitigated this by extracting median travel times within 5 km and 2 km buffer zones for rural and urban clusters, respectively [39]. Additionally, using the complete census of all Gambian immunisation facilities, instead of a limited sample, significantly enhanced the robustness of our travel time models by minimizing potential misclassification errors [62].

Despite these limitations, our study has several strengths. First, we utilised modelled travel time as a supply-side determinant of timely vaccination, an improvement over reported travel times or distances used in previous studies [11,19]. Second, our two main datasets, the 2019–20 GDHS and the data from the national immunisation facility mapping conducted by The Gambia EPI programme in 2019, were temporally aligned. This improves the quality of our estimates compared to previous studies that have relied on combining facility dataset from databases which may be out of date with population data such as DHS datasets [63,64]. Third, our collaboration with the Gambia EPI improved the facility data with relevant additional variables such as staffing and service scheduling, further enhancing the analysis. Lastly, our study examined broader quantitative factors, diverse vaccines scheduled during different timepoints in infancy, and utilised robust

theoretical frameworks to gain a deeper understanding of the complex factors that influence timely childhood vaccination.

In conclusion, our study, guided by robust conceptual frameworks, has provided insight into the key factors that drive timely childhood vaccination in The Gambia. While demand-side factors influencing households' recognition of the need to seek immunisation services were the most prominent determinants, supply-side factors like travel time to facilities, cold chain availability, and staffing levels also played a significant role. It's important to note that these determinants varied depending on the specific vaccine and timing of doses. This detailed analysis provides valuable information for immunisation programme managers and service providers. By prioritising interventions and allocating scarce resources based on these identified determinants, they can maximize their impact and ensure children receive timely vaccinations throughout their first year of life.

Ethics approval

The Gambia Government and MRC Unit The Gambia at LSHTM Joint Ethics Committee granted ethical approval for this study (Project ID/Ethics ref.: 22786; Date: 16 January 2021).

Patient consent for publication

Not applicable.

Patient and public involvement

Patients and/or the public were not involved in the design, conduct, reporting, or dissemination plans of this research.

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CRediT authorship contribution statement

Oghenebrume Wariri: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Chigozie Edson Utazi:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Uduak Okomo:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Winfred Dotse-Gborgbortsi:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Malick Sogur:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Sidat Fofana:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Kris A. Murray:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Chris Grundy:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Beate Kampmann:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Oghenebrume Wariri reports financial support was provided by European and Developing Countries Clinical Trials Partnership. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available to anyone for further analyses on reasonable request through the corresponding author, after securing approval from The Gambia Government and MRC Unit The Gambia at LSHTM Joint Ethics Committee.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vaccine.2024.126500.

References

[1] Lai X, Zhang H, Pouwels KB, Patenaude B, Jit M, Fang H. Estimating global and regional between-country inequality in routine childhood vaccine coverage in 195 countries and territories from 2019 to 2021: a longitudinal study. EClinicalMedicine 2023:60.
[2] World Health Organization. Immunization Agenda 2030 - a global strategy to leave no one behind. Geneva. 2021.
[3] World Health Organization. Embrace the facts about vaccines, not the myths. https://www.who.int/news-room/commentaries/detail/embrace-the-facts-about-vaccines-not-the-myths. [Accessed 17 January 2024].
[4] World Health Organization. Harmonizing vaccination coverage measures in household surveys: A primer. Geneva, Switzerland: WHO; 2019.
[5] World Health Organization. Measles vaccines: WHO position paper, April 2017–recommendations. Vaccine 2019;37(2):219–22.
[6] MacDonald SE, Russell ML, Liu XC, et al. Are we speaking the same language? An argument for the consistent use of terminology and definitions for childhood vaccination indicators. Hum Vaccin Immunother 2019;15(3):740–7.
[7] Wariri O, Edem B, Nkereuwem E, et al. Tracking coverage, dropout and multidimensional equity gaps in immunisation systems in West Africa, 2000-2017. BMJ Glob Health 2019;4(5).
[8] Wariri O, Nkereuwem E, Erondu NA, et al. A scorecard of progress towards measles elimination in 15 west African countries, 2001–19: a retrospective, multicountry analysis of national immunisation coverage and surveillance data. Lancet Glob Health 2021;9(3):e280–90.
[9] Scott S, Odutola A, Mackenzie G, et al. Coverage and timing of children's vaccination: an evaluation of the expanded programme on immunisation in the Gambia. PLoS One 2014;9(9):e107280.
[10] Odutola A, Afolabi MO, Ogundare EO, et al. Risk factors for delay in age-appropriate vaccinations among Gambian children. BMC Health Serv Res 2015;15:346.
[11] Miyahara R, Jasseh M, Gomez P, et al. Barriers to timely administration of birth dose vaccines in the Gambia, West Africa. Vaccine 2016;34(29):3335–41.
[12] Wariri O, Utazi CE, Okomo U, et al. Mapping the timeliness of routine childhood vaccination in the Gambia: a spatial modelling study. Vaccine 2023;41(39):5696–705.
[13] Wariri O, Utazi CE, Okomo U, et al. Timeliness of routine childhood vaccination among 12-35 months old children in the Gambia: analysis of national immunisation survey data, 2019-2020. PLoS One 2023;18(7):e0288741.
[14] Phillips DE, Dieleman JL, Lim SS, Shearer J. Determinants of effective vaccine coverage in low and middle-income countries: a systematic review and interpretive synthesis. BMC Health Serv Res 2017;17(1):681.
[15] Bosch-Capblanch X, Banerjee K, Burton A. Unvaccinated children in years of increasing coverage: how many and who are they? Evidence from 96 low-and middle-income countries. Trop Med Int Health 2012;17(6):697–710.

[16] Santos TM, Cata-Preta BO, Victora CG, Barros AJ. Finding children with high risk of non-vaccination in 92 low-and middle-income countries: a decision tree approach. Vaccines 2021;9(6):646.
[17] Rainey JJ, Watkins M, Ryman TK, Sandhu P, Bo A, Banerjee K. Reasons related to non-vaccination and under-vaccination of children in low and middle income countries: findings from a systematic review of the published literature, 1999–2009. Vaccine 2011;29(46):8215–21.
[18] Masters NB, Wagner AL, Boulton ML. Vaccination timeliness and delay in low- and middle-income countries: a systematic review of the literature, 2007-2017. Hum Vaccin Immunother 2019;15(12):2790–805.
[19] Wariri O, Okomo U, Kwarshak YK, et al. Timeliness of routine childhood vaccination in 103 low-and middle-income countries, 1978–2021: a scoping review to map measurement and methodological gaps. PLOS Global Public Health 2022;2(7):e0000325.
[20] Utazi CE, Pannell O, Aheto JMK, et al. Assessing the characteristics of un- and under-vaccinated children in low- and middle-income countries: a multi-level cross-sectional study. PLOS Global Public Health 2022;2(4):e0000244.
[21] Choudhary M, Solomon R, Awale J, Dey R. Demand-side determinants of timely vaccination of oral polio vaccine in social mobilization network areas of CORE Group polio project in Uttar Pradesh, India. BMC Infect Dis 2018;18(1):222.
[22] Gibson DG, Ochieng B, Kagucia EW, et al. Individual level determinants for not receiving immunization, receiving immunization with delay, and being severely underimmunized among rural western Kenyan children. Vaccine 2015;33(48):6778–85.
[23] Gram L, Soremekun S, At Asbroek, et al. Socio-economic determinants and inequities in coverage and timeliness of early childhood immunisation in rural Ghana. Trop Med Int Health 2014;19(7):802–11.
[24] Mutua MK, Mohamed SF, Kimani-Murage EW, et al. Complete and on-time routine childhood immunisation: determinants and association with severe morbidity in urban informal settlements, Nairobi, Kenya. Ann Hum Biol 2020;47(2):132–41.
[25] Akmatov MK, Mikolajczyk RT. Timeliness of childhood vaccinations in 31 low and middle-income countries. J Epidemiol Community Health 2012;66(7). e14-e.
[26] Dejene H, Girma D, Geleta LA, Legesse E. Vaccination timeliness and associated factors among children aged 12-23 months in Debre Libanos district of North Shewa Zone, Oromia Regional State, Ethiopia. Front Pediatr 2022;10:867846.
[27] Mvula H, Heinsbroek E, Chihana M, et al. Predictors of uptake and timeliness of newly introduced pneumococcal and rotavirus vaccines, and of measles vaccine in rural Malawi: a population cohort study. PLoS One 2016;11(5):e0154997.
[28] Périères L, Marcellin F, Lo G, et al. Hepatitis B vaccination in senegalese children: coverage, timeliness, and sociodemographic determinants of non-adherence to immunisation schedules (ANRS 12356 AmBASS Survey). Vaccines (Basel) 2021;9(5).
[29] Mansour Z, Said R Br, et al. Factors affecting age-appropriate timeliness of vaccination coverage among children in Lebanon. Gates Open Res 2018;2:71.
[30] Thaddeus S, Maine D. Too far to walk: maternal mortality in context. Soc Sci Med 1994;38(8):1091–110.
[31] Graham B. Population characteristics and geographic coverage of primary care facilities. BMC Health Serv Res 2018;18(1):398.
[32] Wagenaar BH, Gimbel S, Hoek R, et al. Wait and consult times for primary healthcare services in Central Mozambique: a time-motion study. Glob Health Action 2016;9:31980.
[33] Gambia Bureau of Statistics (GBoS) and ICF. The Gambia demographic and health survey 2019–20. Maryland, USA: Banjul, The Gambia and Rockville; 2021.
[34] World Health Organization. Vaccination schedule for Gambia. https://immunizationdata.who.int/pages/schedule-by-country/gmb.html?DISEASECODE=&TARGETPOP_GENERAL=. [Accessed 29 January 2023].
[35] McLafferty SL. GIS and health care. Annu Rev Public Health 2003;24(1):25–42.
[36] Dotse-Gborgbortsi W, Tatem AJ, Matthews Z, Alegana VA, Ofosu A, Wright JA. Quality of maternal healthcare and travel time influence birthing service utilisation in Ghanaian health facilities: a geographical analysis of routine health data. BMJ Open 2023;13(1):e066792.
[37] van Duinen AJ, Adde HA, Fredin O, et al. Travel time and perinatal mortality after emergency caesarean sections: an evaluation of the 2-hour proximity indicator in Sierra Leone. BMJ Glob Health 2020;5(12):e003943.
[38] Burgert CR, Colston J, Roy T, Zachary B. Geographic displacement procedure and georeferenced data release policy for the Demographic and Health Surveys. Icf International; 2013.
[39] Perez-Heydrich C, Warren JL, Burgert CR, Emch ME. Influence of demographic and health survey point displacements on raster-based analyses. Spatial Demogr 2016;4:135–53.
[40] Fox J, Monette G. Generalized collinearity diagnostics. J Am Stat Assoc 1992;87(417):178–83.
[41] Snidjers TAB, Bosker RJ. Multilevel analysis. 2nd ed. London: SAGE Publications Ltd; 2012.
[42] R Core Team. A language and environment for statistical computing. Vienna, Austria. 2021.
[43] Rue H, Martino S, Lindgren F, Simpson D, Riebler A. R-INLA: Approximate Bayesian inference using integrated nested Laplace approximations. Trondheim Norway. 2013.
[44] Adeyinka DA, Muhajarine N, Petrucka P, Isaac EW. Inequities in child survival in Nigerian communities during the sustainable development goal era: insights from analysis of 2016/2017 multiple Indicator cluster survey. BMC Public Health 2020;20(1):1613.
[45] Hosmer DW, Lemeshow S, Sturdivant RX. Applied logistic regression. 3rd ed. Hoboken, New Jersey: John Wiley & Sons, Inc; 2013.
[46] Bassoum O, Ba MF, Sougou NM, Sow A, Seck I. Determinants of timely administration of the birth dose of hepatitis B vaccine in Senegal in 2019: Secondary analysis of the demographic and health survey. PLOS Global Public Health 2024;4(8):e0002734.
[47] Bassoum O, Sougou NM, Ba MF, et al. Vaccination against tuberculosis, polio and hepatitis B at birth in Podor health district, Northern Senegal: cross-sectional study of vaccination coverage and its associated factors. BMC Public Health 2022;22(1):1–13.
[48] World Health Organization. Practices to improve coverage of the hepatitis B birth dose vaccine. Geneva, Switzerland: World Health Organization; 2012.
[49] Blanford JI, Kumar S, Luo W, MacEachren AM. It's a long, long walk: accessibility to hospitals, maternity and integrated health centers in Niger. Int J Health Geogr 2012;11:24.
[50] Metcalf CJ, Tatem A, Bjornstad ON, et al. Transport networks and inequities in vaccination: remoteness shapes measles vaccine coverage and prospects for elimination across Africa. Epidemiol Infect 2015;143(7):1457–66.
[51] Moïsi JC, Kabuka J, Mitingi D, Levine OS, Scott JA. Spatial and socio-demographic predictors of time-to-immunization in a rural area in Kenya: is equity attainable? Vaccine 2010;28(35):5725–30.
[52] Kiely M, Boulianne N, Talbot D, et al. Impact of vaccine delays at the 2, 4, 6 and 12 month visits on incomplete vaccination status by 24 months of age in Quebec, Canada. BMC Public Health 2018;18(1):1364.
[53] Suffel AM, Walker JL, Williamson E, McDonald HI, Warren-Gash C. Timeliness of childhood vaccination in England: a population-based cohort study. Vaccine 2023;41(39):5775–81.
[54] Tiley KS, White JM, Andrews N, Ramsay M, Edelstein M. Inequalities in childhood vaccination timing and completion in London. Vaccine 2018;36(45):6726–35.
[55] Bourguignon F, Chakravarty SR. 337Chapter 18 Multidimensional Poverty Orderings: theory and applications. Arguments for a Better World: Essays in Honor of Amartya Sen: Volume I: Ethics, Welfare, and Measurement. Oxford University Press; 2008. p. 0.
[56] World Health Organization. WHO policy statement: Multi-dose vial policy (MDVP): Handling of multi-dose vaccine vials after opening. World Health Organization; 2014.
[57] Usuf E, Mackenzie G, Ceesay L, Sowe D, Kampmann B, Roca A. Vaccine wastage in the Gambia: a prospective observational study. BMC Public Health 2018;18(1):864.
[58] World Health Organization. Measles and rubella strategic framework 2021–2030. Geneva, Switzerland: World Health Organization; 2020.
[59] Amoro VA, Abiiro GA, Alatinga KA. Bypassing primary healthcare facilities for maternal healthcare in North West Ghana: socio-economic correlates and financial implications. BMC Health Serv Res 2021;21(1):1–14.
[60] Makacha L, Makanga PT, Dube YP, et al. Is the closest health facility the one used in pregnancy care-seeking? A cross-sectional comparative analysis of self-reported and modelled geographical access to maternal care in Mozambique, India and Pakistan. Int J Health Geogr 2020;19(1):1–10.
[61] Dotse-Gborgbortsi W, Dwomoh D, Alegana V, Hill A, Tatem AJ, Wright J. The influence of distance and quality on utilisation of birthing services at health facilities in Eastern Region, Ghana. BMJ Glob Health 2020;4(Suppl. 5):e002020.
[62] Skiles MP, Burgert CR, Curtis SL, Spencer J. Geographically linking population and facility surveys: methodological considerations. Popul Health Metrics 2013;11(1):14.
[63] Ouma PO, Malla L, Wachira BW, et al. Geospatial mapping of timely access to inpatient neonatal care and its relationship to neonatal mortality in Kenya. PLOS Global Public Health 2022;2(6):e0000216.
[64] Joseph NK, Macharia PM, Ouma PO, et al. Spatial access inequities and childhood immunisation uptake in Kenya. BMC Public Health 2020;20(1):1407.