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SPATIAL DISTRIBUTION AND EPIDEMIOLOGICAL INSIGHTS INTO WANING MEASLES IMMUNITY AMONG VACCINATED CHILDREN IN LUSAKA, ZAMBIA

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Abstract:
Background: Waning immunity to measles poses a significant public health challenge, particularly in low-resource settings. Understanding the spatial distribution of waning immunity among vaccinated children is crucial for designing targeted interventions. This nested study within a prospective cohort explored the geographic patterns of waning measles immunity in Lusaka, Zambia. **Objective:** To examine the spatial distribution of waning measles immunity among vaccinated children receiving care at the University Teaching Hospital (UTH) in Lusaka, Zambia, using Geographic Information Systems (GIS). **Methods:** This study utilized data from a prospective cohort of 200 children, focusing on 99 participants with waning immunity. Immunity status was determined using IgG testing, and the geographic coordinates of participants' residences were geocoded. A shapefile of Zambia's administrative boundaries was used to create maps in QGIS. The distribution of waning immunity was mapped, and areas with higher concentrations of cases were identified visually. Demographic data were analyzed using Bayesian regression to identify predictors of waning immunity. **Results:** Hotspot analysis highlighted urban areas with the highest prevalence of waning immunity. Bayesian regression indicated that the majority of the selected children who were residing in Lusaka had an increased odd of waning immunity (OR = 2.5, 95% CI: 1.4–4.5) was significantly associated with waning immunity. **Conclusion:** This nested study

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highlights the spatial distribution of waning measles immunity, with hotspots concentrated in Lusaka's urban areas. Integrating geospatial analysis with epidemiological data provides valuable insights for targeted interventions, including booster vaccination campaigns and enhanced cold chain management in high-risk areas. The findings emphasize the importance of incorporating GIS into immunization strategies to optimize resource allocation and improve immunity coverage in low-resource settings.

Keywords: measles, spatial analysis, geographical distribution

1. Background

Measles is one of the most contagious vaccine-preventable diseases, posing a persistent public health challenge globally. While the introduction of the measles vaccine has significantly reduced morbidity and mortality, waning immunity among vaccinated individuals remains a concern. Ideally, robust immunization programs, with well-maintained cold chain systems and timely booster vaccinations, ensure sustained immunity and prevent outbreaks. However, in low-resource settings like Zambia, systemic challenges may compromise vaccine efficacy and long-term protection, leading to immunity gaps even among vaccinated populations (World Health Organization [WHO], 2023).

In Zambia, the measles-rubella (MR) vaccine is routinely administered through the Expanded Program on Immunization (EPI). Despite high reported vaccine coverage, sporadic outbreaks and evidence of waning immunity have been observed, particularly in densely populated areas such as Lusaka Province (Ministry of Health Zambia, 2022). These outbreaks suggest that geographic and demographic disparities may contribute to gaps in immunity. Addressing these disparities requires a detailed understanding of where waning immunity is most prevalent and the associated risk factors.

Spatial analysis using Geographic Information Systems (GIS) provides a powerful method to explore the geographic distribution of immunity. By integrating geocoded data with spatial visualization techniques, GIS can identify hotspots of waning immunity and highlight areas where targeted interventions are needed. However, in Zambia, research on the spatial distribution of measles immunity remains limited. Most studies have focused on national vaccine coverage and epidemiological trends, with insufficient attention to localized geographic patterns and their implications for immunization strategies.

This study focuses on the spatial distribution of waning measles immunity among vaccinated children in Lusaka, Zambia. It uses data from a prospective cohort conducted at the University Teaching Hospital (UTH) in Lusaka between April and July 2024. Out of 200 children in the parent study, 99 were identified with waning immunity based on measles-specific IgG levels below the protective threshold. Geographic coordinates of participants' residential locations, merged with administrative boundary data, were analyzed in QGIS to map and visualize areas with high concentrations of waning immunity. The study aims to identify geographic clusters of immunity loss and provide actionable insights for strengthening immunization programs.

By leveraging spatial analysis, this study fills a critical gap in understanding the geographic distribution of waning immunity in Zambia. Its findings will inform targeted interventions such as booster vaccination campaigns, improved cold chain management, and enhanced surveillance systems in high-risk areas. The integration of spatial data into immunization strategies has the potential to optimize resource allocation and advance measles elimination efforts in Zambia and similar low-resource settings.

2. Materials and Methods

2.1 Study Design and Setting

This study utilized part of the data from a prospective cohort conducted at the University Teaching Hospital (UTH) in Lusaka, Zambia, between April and July 2024. The parent cohort assessed measles immunity among vaccinated children aged 2–15 years. For this analysis, the focus was on the spatial distribution of waning measles immunity among 99 participants identified with waning immunity, extracted from a total cohort of 200.

2.2 Study Population

The study included participants with serological evidence of waning immunity, defined by IgG levels below the protective threshold. The inclusion criteria were:

a) Receipt of at least two doses of the measles-rubella (MR) vaccine.
b) No history of confirmed measles infection within six months prior to enrollment, verified through self-reports and medical records.
c) Availability of geocoded residential addresses for spatial analysis.
d) Participants without waning immunity or with incomplete geocoding information were excluded from this analysis.

2.3 Data Collection

Demographic and clinical data were collected as part of the parent cohort study using a structured questionnaire.

2.3.1 Serological Testing

Blood samples were analyzed using Origene quantitative test kits to measure measles-specific IgG antibody levels. Waning immunity was classified based on IgG levels below the protective threshold.

2.3.2 Geographic Data Collection

Residential locations were geocoded using GPS devices, with coordinates recorded in decimal degrees (latitude and longitude). A publicly available shape file of Zambia's administrative boundaries, including provinces and districts, was obtained for integration into the spatial analysis.

2.3.3 Spatial Analysis

Spatial analysis was performed using Geographic Information Systems (GIS) tools to map and visualize the geographic distribution of waning immunity. The workflow included the following steps:

2.4 Data Preparation

Participant data, including geographic coordinates and waning immunity status, were compiled in Microsoft Excel. A shape file of Zambia's administrative boundaries was prepared for mapping.

2.4.1 Data Import and Integration

The Excel file and Zambia shape file were imported into QGIS (version 3.22). Participant geocoded data were merged with the shape file, linking waning immunity data to administrative areas.

2.5 Mapping and Visualization

Spatial data were displayed as point layers overlaid onto Zambia's administrative map. Choropleth maps were created to illustrate the spatial distribution of waning immunity across Lusaka Province. District-level aggregations highlighted geographic patterns of immunity.

2.6 Interpretation

The maps identified specific areas with a higher concentration of waning immunity cases. Spatial patterns were interpreted in relation to administrative boundaries and contextual factors, such as population density and proximity to healthcare facilities.

2.7 Software

All spatial analyses and mapping were conducted using QGIS (version 3.22).

2.8 Ethical Considerations

Ethical approval for this study was obtained from ERES Converge IRB (REF: 2020-feb-025). Written informed consent was secured from parents or guardians, and assent was provided by children. Participant data were anonymized and securely stored to ensure confidentiality.

3. Results

The table provides a breakdown of individuals across districts, categorized by sex, with percentages calculated as a proportion of the total population (99 individuals).

Chawama and Kanyama emerged as the districts with the highest number of participants, contributing 39 (39.39%) and 43 (43.43%) individuals, respectively. Females represented the majority in these districts, highlighting a gender imbalance in participation.

Table 1: Participant Characteristics

Characteristic	Female	Male	Grand Total
Chadiza	1 (1.01%)	0 (0.00%)	1 (1.01%)
Chawama	21 (21.21%)	18 (18.18%)	39 (39.39%)
Chibombo	2 (2.02%)	0 (0.00%)	2 (2.02%)
Kafue	1 (1.01%)	1 (1.01%)	2 (2.02%)
Kanyama	25 (25.25%)	18 (18.18%)	43 (43.43%)
Katete	0 (0.00%)	1 (1.01%)	1 (1.01%)
Livingstone	0 (0.00%)	1 (1.01%)	1 (1.01%)
Mansa	0 (0.00%)	1 (1.01%)	1 (1.01%)
Monze	0 (0.00%)	1 (1.01%)	1 (1.01%)
Mumbwa	2 (2.02%)	3 (3.03%)	5 (5.05%)
Petauke	1 (1.01%)	0 (0.00%)	1 (1.01%)
Samfya	1 (1.01%)	0 (0.00%)	1 (1.01%)
Sibuyunji	1 (1.01%)	0 (0.00%)	1 (1.01%)
Grand Total	**55 (55.56%)**	**44 (44.44%)**	**99 (100.00%)**

In contrast, districts such as Chibombo, Kafue, and Mumbwa showed low representation, each contributing less than 5% of the total population. Similarly, minimal participation was recorded in districts like Livingstone, Mansa, Monze, Samfya, and Sibuyunji, with only one individual (1.01%) from each of these regions.

Table 2: Measles Waning Immunity by Province Using Bayesian Regression

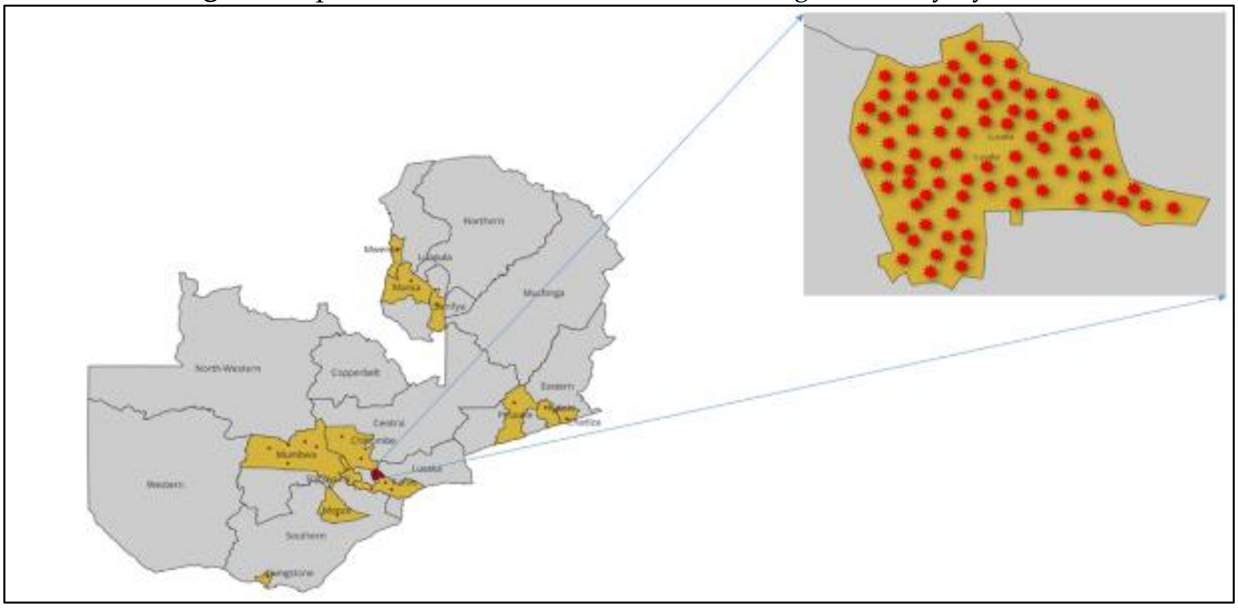
Factors (Reference)	**Odds Ratios**	**95% Credible Interval**	
		2.5% Quantiles	**97.5% Quantiles**
(Intercept)	0.493	0.233	1.045
Age Category			
Age 2-4 years	Ref [1]		
Age 5-9 years	0.688	0.303	1.563
Age 10-15 years	4.028	1.834	8.849
Sex			
Females	Ref [1]		
Male	0.906	0.499	1.645
Education Levels			
Not in School	Ref [1]		
Primary	1.276	0.540	3.013
Secondary	1.366	0.564	3.312
Tertiary	1.627	0.6391652	4.144
Place of Residence			
Outside Lusaka	Ref [1]		
In Lusaka	3.291	1.190	9.100

Gender disparities were also notable across districts. Females were completely absent in Katete, Livingstone, Mansa, and Monze, while males were absent in Chadiza, Chibombo, Petauke, Samfya, and Sibuyunji. These patterns reveal both regional and gender-based variations in the distribution of participants.

The odds ratio (OR) for the intercept was 0.49 (95% Credible Interval [CI]: 0.23–1.04), representing the baseline odds of the outcome when all other factors were at their reference levels. Since the credible interval included 1, this suggests that the baseline odds were not significantly different from 1. Regarding age categories, children aged 2–4 years served as the reference group. For children aged 5–9 years, the odds of the outcome were lower (OR = 0.69; 95% CI: 0.30–1.56) compared to the reference group, but the credible interval included 1, indicating no statistically significant difference. Conversely, children aged 10–15 years had significantly higher odds of the outcome (OR = 4.03; 95% CI: 1.83–8.85), suggesting they were over four times more likely to experience the outcome than the youngest age group.

Sex was also examined, with females as the reference category. Males had slightly lower odds of the outcome (OR = 0.91; 95% CI: 0.50–1.65) compared to females, but the credible interval included 1, showing no significant difference between sexes. Education levels were analyzed using "not in school" as the reference group. Children with primary education had slightly higher odds (OR = 1.28; 95% CI: 0.54–3.01) compared to those not in school, but this difference was not statistically significant. Similarly, secondary education was associated with higher odds (OR = 1.37; 95% CI: 0.56–3.31), and tertiary education increased the odds further (OR = 1.63; 95% CI: 0.64–4.14). However, none of these associations were significant, as the credible intervals for all education categories included 1.

Figure 1: Spatial Distribution of Measles Waning Immunity by Place



Finally, place of residence showed a significant association with the outcome. Those living outside Lusaka were used as the reference group, while individuals residing in Lusaka had significantly higher odds of the outcome (OR = 3.29; 95% CI: 1.19–9.10). This finding indicates that living in Lusaka was strongly associated with increased odds of the outcome.

5. Results

5.1 Spatial Distribution of Waning Measles Immunity

Figure 1 illustrates the geographic distribution of waning measles immunity among vaccinated children in Zambia, with a focus on Lusaka Province. A total of 99 cases of waning immunity were identified, representing 49.5% of the cohort sampled from the prospective study. Spatial mapping revealed distinct patterns of waning immunity across the country, with Lusaka Province showing the highest concentration of cases.

The national distribution of waning immunity cases revealed that multiple provinces, including Central, Eastern, Luapula, and Southern Provinces, reported cases, with Lusaka Province accounting for the majority. Within Central Province, districts such as Mumbwa and Chibombo recorded notable cases, though these numbers were lower compared to Lusaka. In Lusaka Province, intense clustering of waning immunity was evident within the urban and peri-urban areas of Lusaka District. The inset map of Lusaka Province highlighted this clustering, with a significant number of cases concentrated in densely populated neighborhoods. These areas, marked by red star points on the map, suggested a potential correlation between urban density and waning immunity.

Geographically, peri-urban districts like Kafue and Chibombo exhibited moderate levels of waning immunity, while rural districts, such as Petauke in Eastern Province and Mansa in Luapula Province, reported sparse cases. This distribution might indicate a lower prevalence of waning immunity in these areas or possibly underrepresentation in the sampled cohort. Overall, Lusaka Province dominated the distribution with 80 cases, followed by fewer cases in districts like Mumbwa (5 cases) and Chibombo (2 cases). This spatial distribution underscores the concentration of waning immunity in densely populated urban and peri-urban settings, with relatively lower prevalence in rural areas.

6. Discussion

This study identified urban hotspots of waning measles immunity, highlighting the role of spatial analysis in guiding immunization strategies. Spatial analysis using GIS revealed significant clustering of waning immunity in Kanyama and Chawama districts, which are characterized by high population density and poor healthcare infrastructure. These findings are consistent with previous research demonstrating that urban overcrowding exacerbates disparities in vaccine efficacy due to logistical challenges in vaccine delivery and storage (White et al., 2018; Sserwanja et al., 2021).

Spatial analysis offers critical insights for public health. It provides a framework for identifying and addressing disparities in vaccine coverage and efficacy. For instance, hotspot identification enables the allocation of additional resources, such as immunization outreach programs, to high-risk areas. Such targeted interventions have been shown to significantly reduce the risk of outbreaks (Khetsuriani et al., 2020; Moeti et al., 2021).

The findings also support the integration of GIS into public health planning. GIS facilitates data-driven decision-making by mapping vulnerable populations and assessing spatial correlations with health outcomes. Studies have shown that spatially informed interventions are more effective in addressing vaccine-preventable diseases than non-spatial approaches (Dinleyici et al., 2021; Molla et al., 2022). For example, using GIS to enhance cold chain monitoring in hotspot areas could mitigate vaccine degradation and improve efficacy.

Community-level interventions are another critical implication of this study. Public health campaigns tailored to specific clusters can address localized issues such as vaccine hesitancy or access barriers. For instance, Hartigan-Go et al. (2020) demonstrated that hotspot-focused educational programs significantly improved vaccine uptake in urban settings. Similarly, enhanced surveillance in identified hotspots can ensure early detection and rapid response to waning immunity.

The findings align with the Sustainable Development Goal (SDG) 3, which aims to ensure healthy lives and promote well-being for all ages. By identifying spatial clusters of waning immunity, this research contributes to global efforts to eliminate measles and other vaccine-preventable diseases. It underscores the importance of adopting spatial epidemiology as a standard tool in immunization programs, particularly in low-resource settings where challenges such as urbanization and healthcare inequities are prevalent (WHO, 2021; Bloom et al., 2021).

Future research should expand on the socio-environmental determinants of waning immunity. Factors such as migration patterns, urban planning, and socioeconomic disparities warrant further investigation. Additionally, longitudinal studies incorporating genomic data could provide deeper insights into the immunological mechanisms driving waning immunity. Expanding GIS-based studies to rural settings could also reveal unique spatial patterns that differ from urban areas (Datta et al., 2018; Kretsinger et al., 2019).

Spatial analysis revealed significant clustering of waning measles immunity in urban districts, emphasizing the need for targeted interventions. These findings highlight the utility of GIS in optimizing public health strategies and addressing immunization challenges, thereby contributing to improved health outcomes and disease prevention in vulnerable populations.

7. Public Health Implications

The results identified Lusaka Province as a significant hotspot for waning immunity, particularly in urban areas. Densely populated regions such as Kanyama and Chawama sub-districts of Lusaka exhibited the highest concentration of cases. This finding aligns with evidence from previous studies, which demonstrate that urbanization, population density, and healthcare access inequities exacerbate immunity loss risks (Moss, 2017; Mutembo et al., 2023). The clustering of waning immunity in urban areas underscores the importance of tailoring immunization strategies to the unique challenges densely populated settings face.

7.1 Implications for Public Health Practice

A. Enhanced Outreach Programs

By strengthening community outreach, immunization programs can address barriers to vaccine uptake, reduce disparities in access, and ensure that no child is left unprotected. This approach not only enhances immediate vaccination efforts but also builds long-term trust in healthcare systems, contributing to sustained measles immunity and overall public health resilience.

B. Enhanced Cold Chain Systems

Strengthening vaccine cold chain infrastructure is critical to ensuring vaccine potency. Similar studies in sub-Saharan Africa have shown that poor cold chain systems compromise vaccine effectiveness, leading to immunity loss (Graham et al., 2019). Investments in cold chain monitoring systems, including real-time temperature trackers, could mitigate this issue.

C. Community Engagement

Awareness campaigns emphasizing the importance of timely vaccinations and booster doses should be prioritized in high-risk communities. Community-based health workers could play a pivotal role in identifying children who missed vaccinations or require boosters.

D. Policy Recommendations

- **Incorporating Spatial Data into Immunization Strategies.** The use of GIS to map immunity levels should be integrated into Zambia's national immunization programs. By identifying hotspots like Lusaka, policymakers can allocate resources more effectively and target interventions to areas of greatest need.
- **Surveillance System Strengthening.** Strengthened measles surveillance systems that integrate spatial and epidemiological data can improve the early detection of immunity gaps and inform timely interventions.

7.2 Research Implications

A. Integration of Socioeconomic and Health Infrastructure Data

Further research should examine how socioeconomic factors, healthcare access, and cold chain performance contribute to geographic patterns of waning immunity. Integrating these variables into spatial models would provide a more comprehensive understanding of the drivers of immunity loss.

B. Expanding Geographic Scope
This study focused primarily on Lusaka Province. Future research should investigate waning immunity in rural and remote areas to identify additional clusters that may have been overlooked due to limited surveillance.

C. Evaluating Vaccine Potency and Cold Chain Effectiveness
Investigating the efficacy of vaccines stored in different regions and under varying cold chain conditions would provide insights into potential systemic weaknesses.

D. Public Health Practice and Policy in Context
The identification of Lusaka as a hotspot for waning immunity has direct implications for public health practice and policy. Urban areas often serve as hubs for disease transmission due to high population densities, frequent human interactions, and resource constraints. Policies that focus on improving vaccination coverage, introducing booster doses, and enhancing healthcare infrastructure in urban settings are critical for achieving long-term measles control.

From a practical standpoint, this study emphasizes the need for localized, data-driven immunization strategies. The integration of GIS tools into Zambia's immunization program would allow for real-time monitoring of immunity gaps, resource optimization, and evidence-based decision-making. Furthermore, public health campaigns targeting peri-urban and rural areas could address disparities in vaccine access and education.

8. Conclusion

This study provides evidence of spatial clustering of waning measles immunity in Lusaka Province, with significant public health implications. By integrating spatial data into immunization strategies, policymakers can enhance vaccine delivery systems, strengthen surveillance, and target booster campaigns in high-risk areas. The findings contribute to a growing body of evidence supporting the need for innovative, location-specific approaches to measles elimination in low-resource settings. Future research should focus on addressing systemic vulnerabilities and expanding the geographic scope of analysis to fully understand the national burden of waning immunity.

Conflict of Interest Statement
The authors declare no conflicts of interest.

About the Author(s)
Priscilla Nkonde Gardner is currently a Specialist in Vaccine Preventable Diseases at the Zambia National Public Health Institute. She is also a PhD candidate at the University of

Zambia, focusing on epidemiology and public health. Her research interests include vaccine immunogenicity, particularly HIV-infected populations, adolescent sexual and reproductive health, and factors influencing child and adolescent health outcomes. She is actively involved in public health research and has co-authored studies on early childbearing among schoolgirls in rural Zambia. Her academic profiles can be accessed on platforms like ORCID (https://orcid.org/0000-0001-8937-3142) and ResearchGate.

Jimmy Hangoma is a lecturer at the University of Zambia, specializing in health economics and policy analysis. He has been involved in research projects assessing the economic impact of health interventions and policies in Zambia. His work includes evaluating the cost-effectiveness of health programs and analyzing health financing mechanisms to improve resource allocation in the healthcare sector. Mr. Hangoma's contributions aim to inform policy decisions that enhance the efficiency and equity of health services in Zambia.

Nosia Mhango Mwila is a researcher specializing in Clinical Pharmacology and vaccine-preventable diseases. She holds a Bachelor's and a master's degree in clinical pharmacology and is pursuing a PhD in Epidemiology and Public Health. Her expertise in pharmacology provides a unique perspective on understanding immunological mechanisms and enhancing vaccine efficacy. She is co-authoring a paper on measles, contributing to research aimed at addressing immunity gaps and improving vaccine strategies.

Isaac Fwemba is a lecturer in the Department of Epidemiology and Biostatistics at the University of Zambia. He holds a PhD in Public Health with a concentration in Biostatistics from the University of Ghana. His expertise lies in Bayesian modeling, systematic reviews, meta-analysis, and survival analysis. Dr. Fwemba has contributed to research on HIV prevalence estimation and the impact of socioeconomic factors on fertility among adolescents. He is a member of the International Society for Clinical Biostatistics and has an ORCID profile accessible at https://orcid.org/0000-0002-9179-0946.

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Appendix vii: National Health Research Authority Approval

NATIONAL HEALTH RESEARCH AUTHORITY
Paediatric Centre of Excellence, University Teaching Hospital, P.O. Box 30075, LUSAKA
Chalala Office Lot No. 18961/M, Off Kasama Road, P.O. Box 30075, LUSAKA
Tell: +260211 250309 | Email: znhrasec@nhra.org.zm | www.nhra.org.zm

REF:NHREB008/01/04/2024 **Date: 1st April 2024**

Principal Investigator,
Priscilla Nkonde Gardner,
P.O. Box 32639
Lusaka,

Dear Ms Gardner,

Re: Request for Authority to Conduct Research

The National Health Research Ethics Board (NHREB) is in receipt of your request for authority to conduct research titled **"Modelling efficacy and immunogenicity of measles vaccinations in vaccinated HIV infected and HIV-non-infected children utilizing Bayesian network structures at University Teaching Hospital - Lusaka Province, Zambia."** Version 1.0 dated 15th March 2024

I wish to inform you that following submission of your request to the Board, its review and in view of the ethical clearance, this study has been **approved** on condition that:

1. **A Material Transfer Agreement is obtained and cleared by the National Health Research Ethics Board should there be any need for samples to be sent outside the country for analysis;**
2. The relevant Provincial and District Medical Officers where the study is being conducted are fully appraised;
3. Progress updates are provided to the NHRA Bi-annually from the date of commencement of the study;
4. The final study report is cleared by the NHRA before any publication or dissemination within or outside the country;
5. After clearance for publication or dissemination by the NHRA, the final study report is shared with all relevant Provincial and District Directors of Health where the study was being conducted, and all key respondents.

Yours sincerely,

Dr Fusya Goma
Vice Chairperson
National Health Research Ethics Board

Appendix viii: University Teaching Hospital (UTH) Data Collection Permision Letter

Telephone: (260) 211 253947
Fax: (260) 211 250305
Email: info.childrens@uth.gov.zm

In reply please quote:
No:.........................

REPUBLIC OF ZAMBIA

MINISTRY OF HEALTH

OFFICE OF THE SENIOR MEDICAL SUPERINTENDENT
UNIVERSITY TEACHING HOSPITAL
CHILDREN'S HOSPITAL
PLOT NO. 3541, NATIONALIST ROAD
PRIVATE BAG RW 1X
LUSAKA, ZAMBIA

4th April, 2024

Priscilla Nkonde Gardner
PhD Student
Public Health Department
UNIVERSITY OF ZAMBIA

Dear Priscilla Nkonde Gardner,

RE: PERMISSION TO CONDUCT RESEARCH: YOURSELF

Reference is made to your letter dated 8th April, 2024 in which you are seeking permission to conduct research entitled "***Modelling Immunogenicity of Measles Vaccinations in HIV Infected and HIV – Non-Infected Children Utilising Bayesian Network Structures at the University Teaching Hospitals – Children's Hospital,* Lusaka**".

Having obtained the necessary ethical approvals, I am pleased to inform you that permission has been granted.

You may proceed with commencement of data collection in accordance with the terms outlined in your ERES CONVERGE IRB approvals.

Wishing you all the best in your research.

Yours faithfully

Dr M. Mwenechanya
Senior Medical Superintendent
University Teaching Hospitals –Children's Hospital