VOLUME 14 NO 1 PP 70–78 JANUARY 2009

Feasibility of satellite image-based sampling for a health survey among urban townships of Lusaka, Zambia

Sara A. Lowther[1], Frank C. Curriero[2,3], Timothy Shields[4], Saifuddin Ahmed[5], Mwaka Monze[6] and William J. Moss[1,4]

1 *Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA*
2 *Department of Environmental Health Sciences, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA*
3 *Department of Biostatistics, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA*
4 *W. Harry Feinstone Department of Molecular Microbiology and Immunology, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA*
5 *Department of Population, Family and Reproductive Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA*
6 *Virology Laboratory, University Teaching Hospital, Lusaka, Zambia*

Summary

OBJECTIVES To describe our experience using satellite image-based sampling to conduct a health survey of children in an urban area of Lusaka, Zambia, as an approach to sampling when the population is poorly characterized by existing census data or maps.

METHODS Using a publicly available Quickbird™ image of several townships, we created digital records of structures within the residential urban study area using ArcGIS 9.2. Boundaries were drawn to create geographic subdivisions based on natural and man-made barriers (e.g. roads). Survey teams of bio-medical research students and local community health workers followed a standard protocol to enrol children within the selected structure, or to move to the neighbouring structure if the selected structure was ineligible or refused enrolment. Spatial clustering was assessed using the *K*-difference function.

RESULTS Digital records of 16 105 structures within the study area were created. Of the 750 randomly selected structures, six (1%) were not found by the survey teams. A total of 1247 structures were assessed for eligibility, of which 691 eligible households were enroled. The majority of enroled house-holds were the initially selected structures (51%) or the first selected neighbour (42%). Households that refused enrolment tended to cluster more than those which enroled.

CONCLUSIONS Sampling from a satellite image was feasible in this urban African setting. Satellite images may be useful for public health surveillance in populations with inaccurate census data or maps and allow for spatial analyses such as identification of clustering among refusing households.

keywords satellite imagery, geographic information systems, sampling, health survey, Zambia

Introduction

The potential to use remotely sensed data to assess demographic and health characteristics of populations will increase as satellite imagery becomes more available. Satellite imagery has been used by demographers to monitor urban growth (United Nations Statistics Division 2004) and to study poverty and growth in informal urban settlements in Africa (Barry & Rüther 2001; Turkstra & Raithelhuber 2004). Satellite images also have been used to monitor the consequences of natural disasters and humanitarian emergencies, such as tsunami-affected areas in Indonesia, Thailand and India (National University of Singapore 2007), and the spread of refugee camps in Darfur, Sudan (United States Agency for International Development 2007). Satellite imagery has been used in epidemiological research, particularly in studies of vector-borne diseases (Sudhakar *et al.* 2006; Rotela *et al.* 2007). In Pakistan, data from satellite images were merged with other geographic and health data to monitor household health and health system utilization (Ali *et al.* 2004). While the merging of data from satellite images and geographic information systems (GIS) with routinely collected data on health and disease can provide important public health information, community surveys will continue to be necessary for epidemiological surveillance.

Survey methods based on probability sampling require household listings, often derived from household census data. Independent collection of household listings for surveys can be expensive. With census data typically collected every 5–10 years, census data may not be sufficiently accurate for epidemiological sampling, particularly in resource-poor settings with unplanned urban sprawl, illegal dwellings and squatter settlements. As a consequence, standard sampling methods are of limited use when the population of interest is not well-characterized by existing census data or maps. Several alternative sampling methods have been developed, such as simplified cluster survey methods (Henderson & Sundaresan 1982), lot quality assurance sampling (LQAS) (Lanata *et al.* 1990), or variations of these methods. Typically, these alternatives are based on administrative census data and community maps.

The increasing availability of digital satellite imagery may provide an opportunity to construct sampling frames where existing census data or maps are inadequate. However, there are few reports of the use of satellite images to establish sampling frames for health surveys. Our study was conducted with the intention of using a satellite image as an alternative to sampling designs commonly used in resource-poor settings. We describe our experience using a satellite image to construct a sampling frame for a prevalence survey of immunity to measles virus among children 9 months to 5 years of age within residential, urban townships of Lusaka, Zambia. Furthermore, while other sampling designs rely on administrative subdivisions and adjust for correlations within subdivisions, satellite images and GIS data can be used to define the distributions of potential clusters. We illustrate a spatial analysis based on the locations of enroled households and households that refused enrolment.

Materials and methods

Description of the study area

The study area was a densely populated, permanent, peri-urban townships within Lusaka, the capital city of Zambia in southern Africa, with a mixture of formal neighbourhoods and informal settlements. Dwellings are single-story structures, with both single- and multi-family households. Maps and census data were not sufficiently accurate to construct a sampling frame for a household-listing based survey.

Obtaining the satellite image

A publicly available 25 km^2 image of the townships of interest from a Quickbird™ satellite (date of image acquisition 13 April 2005) was downloaded within one day of requesting the image from DigitalGlobe Services, Inc (Denver, CO) at the cost of $350. QuickBird is a high-resolution satellite owned and operated by DigitalGlobe™. The image was panchromic, Ortho Ready Standard with a projection of UTM WGS84 (M) zone 35 S and ground sample distance of 0.64 m. Two archived images of the study area were available, with the preferred image obtained during the dry season when cloud cover was minimal.

Constructing the sampling frame and random sampling of potential households

Using ArcGIS 9.2, locations of all structures within the study area were identified from the Quickbird™ satellite image. All structures that appeared to be of adequate size (i.e. larger than a vehicle) and of regular polygonal shape (e.g. rectangular) were digitized and identified as potential residences. Structures were enumerated manually by placing a marker on the centroid of each potential residence, creating an attribute table containing unique identifiers and geographic coordinates for each structure. The enumerated structures potentially included both non-residences and residences, the latter consisting of single or multiple family households. Although structures were typically rectangular, irregularities in the shape and spacing of structures made manual digitization preferable to an automated algorithm.

Sample size calculations prior to the survey indicated 600 households were required to have sufficient power to test the study's hypothesis that the proportions of children with and without measles virus antibodies differed by HIV antibody status. Given potential non-response and potential challenges in using a novel sampling design, a list of 750 structures was randomly generated without replacement using R statistical computing software. This list of randomly selected structures was merged into a data table in ArcGIS 9.2, allowing for the visualization of sampled and non-sampled structures. The process of digitizing the satellite image and selecting structures took approximately 2 weeks.

Shapes of unusual size or configuration were identified as landmarks (e.g. markets, football fields) and used as reference points. Boundaries were drawn to create geographic subdivisions to facilitate survey logistics, based on natural and man-made barriers (e.g. roads), with approximately equal numbers of digitized locations within each subdivision. Subdivisions of the satellite image were printed for survey teams to use as hand-held maps to help them identify selected structures.

Pilot exercise to identify sampled structures using satellite images

Prior to the survey, a pilot exercise was conducted with community health workers (CHWs) and survey interviewers to assess the feasibility of identifying the selected structures using the satellite image. The pilot exercise was conducted in three subdivisions with different characteristics including household density and distance from the starting location. As part of the exercise, the survey teams collected information on whether or not the identified structure was found, the type of structure (e.g. residence), and, if a residence, how many children younger than 5 years of age resided in the home. The pilot exercise demonstrated that sampled residences could be found by the study team using printed satellite images.

Survey implementation

Survey teams were comprised of seven biomedical research students and 21 local CHWs. Training of study staff included provision of health information and review of the study protocol, the informed consent process, ethical responsibilities and administration of the study questionnaire. During the survey, the teams met with study staff in a centrally located public health clinic to receive their assignment and review the location of the study households on a large printed satellite image (3 x 5 feet) of the study area. CHWs were assigned to study teams based upon their knowledge and familiarity of the local communities.

After locating each selected structure using the printed hand-held subdivision map of the satellite image, the survey team evaluated the eligibility of the household. If a selected building was ineligible (e.g. not a residence or a residence without children), the team moved to the building to the right and again determined eligibility. If the structure was a multi-residential building, the team moved to the next household within the same structure before moving to a new structure. If after three attempts no building was found to be eligible or the household declined participation, the team continued to the next selected structure on the list. To document their activities, the survey team traced their movements on the printed satellite image and documented household eligibility on a standardized form. These images were then used to record the locations of the households visited and enroled and this information was entered into the ArcGIS 9.2 database.

The spatial distributions of the enroling and non-enroling households were displayed and potential clustering was assessed. In this context, clustering describes the characteristic that households (enroled or not enroled) tend to be closer together than expected given the spatial distribution of all structures. Clustering was identified by visual inspection and formally by the *K*-function, a spatial statistical tool used to quantify clustering behaviour of spatial point pattern data over a range of spatial scales. The *K*-function is defined as the expected number of events (households) within a specified distance of an arbitrarily chosen event, divided by a scaling factor related to the total number of events and the study area (Waller & Gotway 2004). In practice, the *K*-function is estimated for a range of distances (usually up to one-third the maximum length of the study region) and plotted as a function of these distances. Larger values of the *K*-function support clustering behaviour. To assess whether households refusing to enrol tend to cluster more than those agreeing to enrol, we considered the difference in estimated *K*-functions (*K*-function of those refusing to enrol minus the *K*-function for those agreeing to enrol). Under the null hypothesis of no difference in clustering, the *K*-function difference is zero. Monte Carlo techniques were used to gauge significant departures from zero. Specifically we employed the random labelling scheme, randomly permuting the refusing and agreeing to enrol labels among all the households, calculating *K*-functions and their differences for each permuted set, and then for each distance plotted the minimum and maximum *K*-function difference for 1000 of these permuted sets. This provided simulated envelopes to estimate what would be expected under the null hypothesis of no clustering (Waller & Gotway 2004).

Data analysis and the list of randomly selected households without replacement was performed using the R statistical computing software (R Development Core Team 2008) with specialized functions for the analysis of spatial point patterns (*K*-function analysis) provided by the contributed package *splancs* (Rowlingson *et al.* 2007).

The study was approved by the Johns Hopkins Bloomberg School of Public Health Institutional Review Board and the University of Zambia Research Ethics Committee.

Results

Within the study area, 16 105 structures were identified and digitized (Figure 1) in 110 geographic subdivisions (e.g. Figure 2). The household survey was conducted during July and August 2006 and took 3 weeks to complete. Of the 750 randomly selected structures, six (1%) were not found by the survey teams. A total of 1242 structures were assessed for eligibility, of which 691 structures were enroled as eligible households that agreed to participate (Table 1). The majority of enroled households were those structures initially selected (51% of 691) or the direct neighbour (42% of 691) of the selected structure. The most frequent explanation for not enroling the selected structure was the absence of children between 9 months and 5 years of age (15% of 1242), no one present at the time of the survey (6% of 1282) or refusal to participate (11% of 1282).

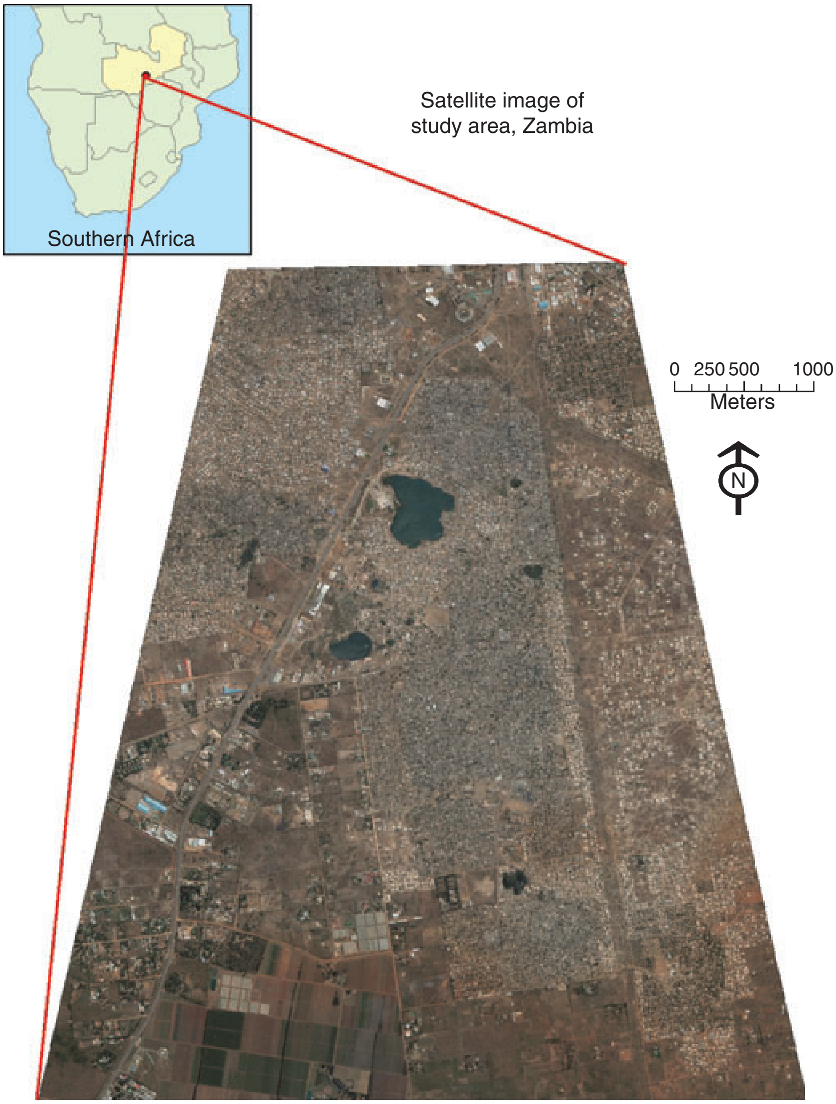

Figure 1 Satellite image of study townships, Lusaka, Zambia, 2005.

The spatial distributions of the enroling (n = 691) and refusing (n = 144) households (Figure 3), show clustering of refusing households. As demonstrated by observed values extending beyond the simulated upper envelope for the K-function difference, clustering was more common among refusing households (up to 1.2 km) (Figure 4). As the definition of the K-function includes division by a scaling factor related to the total number of events and the study region area, the y-axis of the K-function plot is not readily interpretable. Rather, as in this case, the focus is on the relative behaviour of the K-function difference (K-function of those refusing to enrol minus the K-function for those agreeing to enrol) in relation to the zero value and simulated envelopes (under the null hypothesis of no clustering).

Discussion

We described the feasibility of using a publicly available satellite image to construct a sampling frame for a health survey in densely populated urban townships of Lusaka, Zambia. We further illustrated the potential for spatial analyses using satellite images. In this example, we showed that households that refused enrolment tended to cluster more than households that enroled, suggesting the possibility of underlying similarities among these refusing households and the potential for a less representative sample from some geographic locations. During the survey, interviewers noted that households tended to refuse participation if they witnessed neighbours refusing participation.

Figure 2 Detailed satellite image from part of study township, Lusaka, Zambia, 2005, showing locations of digitized locations (yellow points), selected locations (red points), area boundaries (blue lines), roads (red lines), paths (green lines).

The prior existence of an available, archived satellite image allowed for immediate use. If the image has not yet been acquired, the satellite must be manoeuvred to obtain the desired image and time required is dependent on season, cloud-cover, and the area of the selected area. Manually digitizing the study area can easily be performed by a data manager with minimal training in Arc-GIS 9.2. The accuracy of the spatial coordinates of selected structures could have been validated by a handheld Global Positioning System (GPS). GPS validation of spatial coordinates could be performed concurrently with the survey; however handheld GPS devices would add additional cost. In our study, printed maps were sufficient guides for the CHWs familiar with the study area; however if survey teams are unfamiliar with the area, GPS validation may important.

In our study, residential and non-residential structures were not distinguishable on the satellite image. Of the 1242 locations assessed, 48 (3.8%) were non-residential. Some structures that were smaller than typical residences were public toilets, while others that were larger and more irregularly shaped were schools. Other non-residential structures tended to cluster in specific geographic areas (e.g. shops along roads). However, broad inclusion of all

Table 1 Details of enrolment using random selection from a digitized satellite image

Characteristic						Total
Total structures digitized						16 105
Randomly selected structures						750
Structures not found						6
Selected structures identified						744
Enrolment following survey protocol*		Initial	Attempt 1	Attempt 2	Attempt 3	Attempt 4–5†
Not a residence	48 (4%)	40	5	3	0	0
Residences	1194 (96%)	692	374	88	28	12
No one home	78 (6%)	67	8	3	0	0
No children under 5 years of age	192 (15%)	151	31	7	3	0
No parent present	36 (3%)	27	5	2	2	0
Child unavailable at time of visit	12 (1%)	7	3	0	2	0
Refused	144 (11%)	70	40	22	8	4
Not enroled, reason unknown	41 (4%)	21	17	2	1	0
Household with children enroled	691 (55%)	349	270	52	12	8
Total structures assessed	1242 (100%)					

*If the location selected was not enroled due to lack of eligibility or refusal, interviewers were instructed to move to the household to the immediate right and continue for up to three attempts to identify an eligible household.

†Although the survey teams were instructed to make only three attempts to enrol eligible households, in a few instances they made more than the recommended number of attempts.

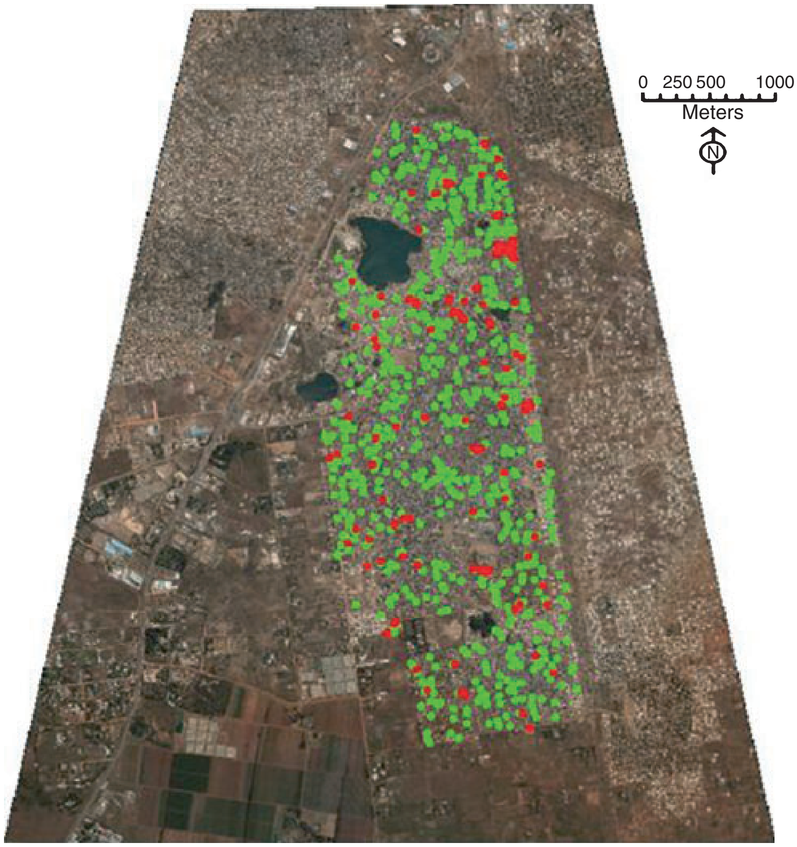

Figure 3 Distribution of enroled households (green) and households that refused enrolment (red) during measles immunization survey, Lusaka, Zambia, 2006.

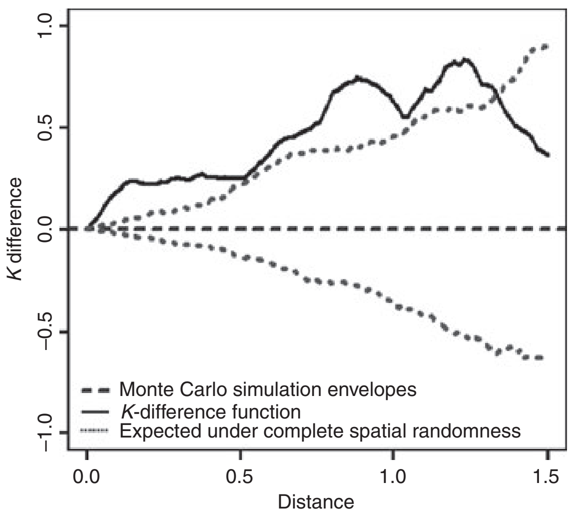

Figure 4 Estimated K-function for the households refusing to enrol (n = 144) minus the estimated K-function for the enroled households (n = 691). Expected K-function difference under the hypothesis of complete spatial randomness (horizontal line at 0) and Monte Carlo simulation envelopes to gauge significant departures.

structures allowed for enrolment of respondents living in unusual housing structures. This may be important when sampling children, a population that is subject to undercounting in population census data (West & Robinson 1999). Extending this methodology to other settings would require local familiarity and recognition of what structures should be marked as potential residences. The applicability may vary between rural *vs.* urban settings, and with the distance between structures.

Digital satellite image-based sampling can be compared to other sampling designs commonly used for surveys in resource poor settings, which often rely on existing census data and accurate area maps (Table 2). One commonly used technique is the '30 cluster 7' survey method, a modified two-stage cluster sampling method developed by WHO to estimate vaccination coverage among children under the Expanded Programme on Immunization (EPI) (Henderson & Sundaresan 1982; Bennett *et al.* 1991). The EPI cluster survey method is inexpensive and only requires a list of clusters but has lower precision than simple random sampling and estimates within clusters are unreliable. An alternative method is LQAS, in which samples

Table 2 Comparison of commonly used sampling designs in resource poor settings

	Cluster survey (e.g. EPI '30 cluster 7' immunization)	Compact segment	Systematic random sampling	Lot quality assurance sampling	Random sampling from a satellite image
Sampling design	2-stage cluster sample	2-stage cluster sample	Systematic random sample	Stratified random sample	Random sample
Selection	Probability proportionate to size according to most recent census	Probability proportionate to size according to most recent census	Probability proportionate to size based on population estimates	Random sampling from listing of all population units available	Random sampling from enumerated locations on digitized satellite image
Sampling frame	None in 2nd stage	None in 2nd stage	Estimated	Need listing of all sample elements	Created based on satellite image
Procedure	Interviewer 'randomly' selects household in centre of study area. Does not require census of selected clusters	All clusters segmented and all households in selected segments used to get probability	Surveyor visits randomly selected households	Surveyor enrols randomly selected households within small 'lot' following protocol; may enrol more if lot does not meet *a priori* defined level	Entire area digitized and enumerated; Interviewers visit selected households
Mapping	No	Yes	Yes	No	Yes
Spatial distribution	Clusters selected; design effect present	Selection not spatially clustered	Entire cluster canvassed based on estimated sampling interval	'Lots' can be small areas but randomly selected; no design effect; no spatial data collected	Random selection; can detect spatial clusters
Probability of selection	Equal but unknown probability of selection	Estimated from enumerated segments	Equal	Equal	Equal and estimated probability of selection
Bias	Prone to bias from similarity of respondents and influence from choice of starting point and subsequent houses	Assumes segments applicable to whole study area	Equal probability of selection spread throughout cluster	May miss locations not on unit listing	Possible if digitizing image and following enrolment protocol inconsistent
Sample size	Depends on survey estimate objectives (set for EPI 30 clusters with 7 subjects per area)	Depends on population and level of risk	Depends on population and level of risk	Depends on population and level of risk	Depends on survey estimate objectives
Geographic boundaries	Need to be defined	Need to be defined, hand drawn	Need to be defined	Defined by surveyor, population listings	Defined and illustrated
Time requirements	Described as time consuming to identify first household. Subsequent houses easy to visit and enrol	Additional time and preparation needed to draw rough sketch map and visit all households in segment	Described as simple to start from edge of defined area, but canvassing area depends on size and density	Described as difficult to travel to enrol only few numbers of households; if "defect" found may need to enrol more so difficult to plan logistics	Preparation and initial digitizing take time and resources; pilot test for feasibility advisable
Computer	Not needed	Not needed	Not needed	Not needed	Computer and printer needed

are drawn from batches or lots of non-overlapping subpopulations to determine if the lot is 'acceptable' or 'unacceptable' (Lanata & Black 1991; Hoshaw-Woodard 2001). This method requires an enumerated sampling frame.

To improve the accuracy of estimates using the EPI cluster sampling method, the selection of several clusters for complete enumeration has been suggested (Brogan *et al.* 1994). In 'compact segment sampling', selected clusters are mapped at the level of individual households. The process of selecting clusters to individually map and enumerate removes bias arising from the interviewer's selection of households and allows the sampling probability to be calculated without requiring a complete household listing (Turner *et al.* 1996). Attempts have been made to reduce selection bias and correlation resulting from selection of the nearest neighbour during the second stage of the EPI sampling procedure. Sampling from a superimposed geographic grid was found to be the fastest and easiest alternative method for the second stage sampling process (Grais *et al.* 2007).

Digitizing a satellite image is superior to simpler methods using sketch maps or geographic grids and allows for the creation of digital records of dwellings. Our method used a simple random sampling for enrolment, which facilitates statistical analyses and eliminates bias from interviewer selection of households. Furthermore, our data collection includes spatial coordinates, allowing for the exploration of spatial clustering. Alternative designs using satellite images could permit stratified sampling based on spatial information such as population density. Formal comparisons of satellite images with other sampling designs common in poor settings would further characterize the differences between the various methods and highlight their strengths and limitations. However, our experience with simple random sampling and survey implementation using a satellite image demonstrates the advantages of this sampling method.

Acknowledgements

This work was supported by a grant from the Thrasher Research Fund (02818-9) to W.J.M. S.A.L was supported by the National Eye Institute Training Grant (EY 07127), pre-doctoral Clinical Trials Training Program in Vision Research, National Institutes of Health, Department of Health and Human Services. We thank Dr Greg Glass for his expertise and support. We thank Mr. Peter Musonda, Ms Chansa Mawonde and Mr David Muonde for their logistical expertise in conducting the survey. We thank the Tianjane Community Theater Group for their creative and motivational performances as part of the community sensitization activities.

Author contributions

TS guided the technical aspects of obtaining and using the satellite image. FC guided the spatial analyses. MM contributed to the survey implementation. SA provided technical guidance on sampling design. WJM participated in all steps of the design and implementation of the survey, and in the writing of the manuscript. SAL designed and coordinated the survey, carried out the analyses, and drafted the manuscript. All authors read and approved the final manuscript.

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Corresponding Author Sara Lowther, Centers for Disease Control and Prevention, Epidemic Intelligence Service assigned to the Minnesota Department of Health, Atlanta, GA 30333, USA. E-mail: SGL6@cdc.gov

