Quantifying exposure to respiratory hazards in sub-Saharan Africa: planning your study

G Okello, K Mortimer, H Lawin and S Semple

Abstract

Quantification of exposure to respiratory hazards is important for those involved in public health, epidemiology and advocacy work in Africa. This guidance offers an introduction to the topic of exposure assessment for the non-expert and explores the many challenges to performing such work in resource-limited settings. Questions about which pollutants to measure, in what manner, among which population groups and for how long, are explored before consideration is also given to potential practical problems and logistical difficulties that can be experienced. Issues such as battery life, instrument range, the need for a physical sample and/or temporal resolution of exposure data, budget and instrument security are examined with reference to real-life examples. The importance of suitable methods of handling acquired data is also highlighted. While acknowledging the rapid pace of technological advance in instrumentation, a brief options appraisal of some frequently used instruments is also provided.

Keywords: exposure assessment; household air pollution; monitoring; sensors

This brief guidance document is intended for those involved in public health, epidemiology and advocacy work on respiratory hazards in Africa. It is not a review of the literature nor is it intended to be a comprehensive options appraisal of all methods available. Some examples of these are provided elsewhere.[1-5] Instead it is designed to act as a primer or introduction to the topic of exposure assessment for those without a scientific background in air pollution but who find themselves involved in the design or execution of research involving some quantification of exposure to air pollutants. The focus is on considering exposure to Household Air Pollution (HAP) – an exposure responsible for 4 million early deaths per annum[6] – but many of the concepts and considerations are valid for occupational exposure assessment and outdoor air pollution studies. There is an appendix [A] based on a review of studies to measure HAP in low and middle-income countries between 2003 and 2015[7] that offers an options appraisal of some of the main instruments and devices available (though with an acknowledgement that sensors and technologies are developing quickly) and a summary checklist [appendix B] of broad questions to consider when planning a study to assess exposure in resource poor settings.

Our intention is that this is a very practical document and the checklist can be used at an initial project planning stage. It aims to highlight some of the real-life challenges and logistical issues that may be experienced and to prevent simple but costly mistakes in over-reaching beyond what local conditions and circumstances may permit. Many of the observations and thoughts contained herein are the result of first-hand experience measuring HAP and outdoor air pollution in sub-Saharan African countries such as Uganda, Ethiopia,[8] Malawi [9] and Benin.[10]

Gabriel Okello: African Centre for Clean Air, Kampala, Uganda. Kevin Mortimer: Liverpool School of Tropical Medicine, Liverpool, UK. Herve Lawin: Unit of Teaching and Research in Occupational and Environmental Health, Faculty of Health Sciences, University of Abomey-Calavi (UAC), Cotonou, Benin; Institut Régional de Santé Publique, UAC; EcoHealth Chair, UAC. Sean Semple: Institute for Social Marketing & Health, Faculty of Health Sciences and Sport, University of Stirling, Scotland. Correspondence: sean.semple@stir.ac.uk; Tel: +44 1786 466 505

Scope

Assessing exposure to air pollutants

When thinking about exposure assessment of air pollutants there are three main method options. These can be broadly defined as direct measurement of a chemical or material either in the air or through some biomarker in the body or bodily fluids; indirect methods typically use questionnaires or some types of proxy of exposure such as distance to a highway or type of fuel use; and estimation or modelling uses predictive models based on data and the resulting statistical relationships to examine determinants of exposure. The focus of this guidance is on direct measurement methods but consideration of indirect and modelling methods should be given before deciding to embark on direct measurement. Examples of each are given in Table 1.

What is the point of measuring air pollution?

Why are you measuring? What question are you trying to answer? Are there any secondary benefits to measuring?

Make sure you have a clear research question in your mind. You are maybe looking to find out if exposure to biomass fuel smoke is associated with symptoms of eye irritation or pneumonia in children. You may be interested in evaluating an intervention – does one type of stove reduce exposure compared to another. Or you may be looking to quantify exposure to household air pollutants in homes to see how they compare to other countries or to health-based guidance levels. There could be secondary benefits of quantifying exposure such as using the information for the purposes of advocacy to engage with

Table 1: Examples of main types of exposure assessment strategies

Strategy	Examples	Advantages	Disadvantages	Example studies
Direct	Air concentration; concentrations of blood lead or carbon monoxide in exhaled breath.	Can provide data specific to an individual; data on the material of interest; how much has been inhaled.	Costly, labour intensive, subject to issues around the time or duration of sample collection.	Refs 8-12
Indirect	Questionnaires gathering data on proxies for exposure (e.g. use of particular cooking fuel; proximity to a main road).	Simple to use and low cost in comparison to direct and modelling methods.	Assumes all those using a particular fuel, stove or living at a set distance from a road have similar exposures. Translation problems.	Refs 13-14
Modelling	Land use regression methods to estimate air concentrations at given points: often reported with a resolution of 1km x 1km.	No need for expensive chemical analysis or use of equipment. Often desk-based methods using pre-existing databases of measurement data.	Assumes those living in similar area or conditions experience similar exposures. Doesn't take account of individual behaviours that can influence exposures.	Refs 15-16

policymakers and others to bring about changes in terms of fuel use, a cookstove program or provision of healthcare services. Write down your research question – you should come back to this at the end of the planning process to make sure that the design of your measurement strategy will provide answers to the question.

Do you really need to measure? From a public health perspective can you simply say that concentrations are too high and some type of well-known, effective control measures should be applied to reduce the exposure. This is often the case when considering occupational exposures and it is clear and apparent that workers are being exposed to respiratory hazards that are extremely high and need to be controlled using well-recognised industrial practices such as elimination, substitution, ventilation or the use of personal protective equipment.

Can you estimate, model or use a proxy of exposure instead of measuring? So, for example, you may want to know if there is a relationship between a particular health outcome (e.g. the presence of cataracts) and exposure to biomass fuel smoke, and depending on the design of your study you may be able to simply use a questionnaire such as the IMPALA questionnaire for Lung Health in Africa across the Life Course (available at https://github.com/jipp3r/IMPALA_QuestionSet) to identify those who have lived in homes where an open fire was used as the primary means of cooking food.

Coupled to duration and/or some questions about the household this may be a sufficiently good proxy or indicator of exposure to allow you to differentiate between exposed and non-exposed individuals. Or you may be able to do some more complex modelling of exposure by identifying the determinants of the exposure to the hazard. This may involve collecting information on how much fuel is used in the home each day, the volume of the kitchen area, how long cooking takes place, who is involved in the cooking process and if there is a chimney or ventilation system. Using proxies or models to estimate the exposure will be much less costly and time consuming but will inevitably be less accurate.

Do you really need to measure? Have others done very similar work recently? Is there existing exposure data? Are there others with more experience that can do the work for you? This may be the case where you are looking at occupational exposures or want to access data on ambient air pollution from government sources? Search the literature and ask around relevant environmental, governmental agencies or local research and scientific organisations to see what information exists. (For outdoor air pollution data there are some useful websites that show information in real-time and often have access to archived data – see www.aqicn.org)

What to measure?

What hazard, substance or material do you want to measure? What are the alternatives? For HAP the main pollutants are particulate matter (PM) and carbon monoxide (CO). There are others but they tend to be in much lower concentrations and are thus technically more difficult to measure. Most previous epidemiological work on HAP has used PM and CO[7] and there are World Health Organisation health-based concentration guidelines for these.[17]

Be aware that there are different size fractions of PM. The most commonly measured are PM10, PM2.5 and Respirable

fraction (equivalent to PM4). These numbers refer to cut-points in microns (μm) and so PM2.5 is particulate matter smaller than 2.5 microns in diameter. The WHO guidance for PM2.5 is 25 μg of material in each cubic metre of air (μg/m3) averaged over a 24-hour sampling period; and 10 μg/m3 averaged over an annual period.[17] CO is a gas and can have more acute effects on the body. The WHO guidance value for CO varies by the averaging time and is 100 mg/m3 for 15 minutes, 35 mg/m3 for 1 hour, 10 mg/m3 for 8 hours and 7 mg/m3 for 24 hours.[17] Many devices report CO concentration in parts per million (1ppm = 1.15 mg/m3). It is also worth noting here that from PM to CO we have switched from talking about micrograms per cubic metre (μg/m3) to milligrams per cubic metre (mg/m3) – and that 1mg = 1000 μg.

How long do you need to measure?

If you were measuring someone's exposure to ultraviolet light from the sun then taking a spot measurement over a 10-minute period at 3am would tell you very little. It is the same for measuring exposure to air pollution and so you need to think about temporal variability. How does the exposure change over the course of a day? Cooking periods may lead to high concentrations in the home and this may be especially true for morning or evening cooking when windows and doors may be closed. Use of oil or paraffin-based lighting at night can also influence the amount of PM or CO in the home. Similarly, you need to consider if there is much variability between days and whether there is a marked seasonal effect perhaps linked to the ability to cook on a veranda or outside during drier months.

The balance to this is how long your devices can operate in terms of battery life, filter saturation and/or data recording. For most instruments battery life will be the rate limiting issue and, unless your project can arrange repeat visits, then a 24-hour period is a good compromise though it does leave your study open to criticism of a Hawthorne effect where people alter their behaviour during the time they are being studied. Periods shorter than 24 hours should be treated with caution. A device capable of operating for about 12 hours measurement installed at 8am (so collecting data from 8am-8pm) is likely to provide completely different HAP exposure data to one installed at 3pm in the afternoon (measuring 3pm-3am) making comparison impossible. To a lesser extent this is also true for devices that are installed for periods slightly longer than one day – so comparing the average value from a measurement carried out for 28 hours and including two breakfast cooking periods compared to a 24-hour sample that measured just one breakfast event should be avoided. This links to the logistics of being able to return to collect instruments as close to the same time of day as they were installed.

Where data logging devices are used, it is possible to exclude data from these time over-runs and in terms of reducing a Hawthorne effect, the influence of being involved in a study on normal behaviours,[18] it may be best to consider excluding data from a first period (e.g. 60 mins) to allow the device to 'bed-in' and to discount the data collected during the installation visit and a short time after when householders grow used to the device, perhaps picking it up, blowing on it and other activity. Such data discounting is possible with devices that record temporal data – often every minute – but is not possible where sampling is carried out to gather a physical sample such as the mass of PM on a filter.

Achieving a 24-hour measurement can be difficult with instruments that use a pump to perform active sampling (as opposed to 'passive' or diffusive methods). Many devices are designed to collect a work-shift sample and so have battery capabilities that cover 8-12 hours. Where this is the case then external power supply is required to gather 24 hours of data. Technology has improved hugely in this area and cheap power banks can help extend the battery life of some instruments. These should be considered in terms of budget and logistics (they will themselves require re-charging). The extra weight and wearability of these power banks should also be explored in any pilot work.

It is also important to consider aligning the duration of your measurement with any health based guidance or regulation values. For example the WHO guidance on PM2.5 is given as a 24-hour average concentration. Guidelines for Carbon Monoxide exist for both long-term exposure (8-hour) and for acute exposure (1-hour, 30-minutes and 15-minutes).

3. Measurement

Personal or static exposure monitoring?

The ideal measurement is one that is gathered by a device within the breathing zone (30cm of the nose/mouth) of the person. Personal sampling is particularly important when the distance between the individual and the source varies considerably over the course of the day[19] – and even more so when the individual may spend periods in close proximity to the emission source as is the case when lighting a fire or tending a stove. Think of a woman who boils water in the morning, then spends several hours walking to a forest to collect firewood and then a period lighting a fire and preparing a meal. An instrument left in the home for the whole day may overestimate the concentrations she is exposed to whereas a device attached to her upper body will provide a more accurate idea of the respiratory hazard concentrations she has inhaled. The breathing zone is a concept used by Occupational Hygienists and is defined as a position within 30cm of the nose or mouth. Typically, it involves attaching a measurement instrument to a person's shirt lapel.

When setting up personal sampling it is worth thinking about the usual clothing worn by study participants and to have belts and pouches to facilitate the attachment. When attaching instruments to people clear explanation should be provided and cultural and religious beliefs should be respected. The study team may need to include both men and women to ensure that householders are comfortable with the process. Other beliefs should be respected and/or addressed. For example, instrument flashing lights in the night may be considered bad luck or to attract bad spirits. Instrument lights can be easily covered with black tape, while misconceptions that some equipment can cause impotence due to the humming sounds can be explained.

Study participants are generally less keen on wearing instruments than having something placed in the home and so it is important to explain the importance of gathering measurements on what they breathe in. It is also important to provide informa-

tion on what they should do with the devices when bathing or sleeping (generally remove the device and leave it positioned on a table or chair close by), and to explain clearly that the device does not record sound or pictures to allay privacy fears.

Where personal sampling is not possible for practical reasons then static sampling can be combined with some form of time-activity diary to capture information on how long the participant spends in one or more areas where a measurement device is used. Diaries have many problems and completion rates tend to be poor. Simple is best and a matrix with broad periods (2h as a minimum) and a small number of location or task options will help to ensure maximal data collection.

Do you need a physical sample of the pollutant?

When we are measuring PM there are two main ways of doing this and for simplicity we will call these gravimetric and optical method. Gravimetric is the 'gold-standard' and involves collecting the PM on a pre-weighed filter for a set duration with a set flow-rate of air. The increase in mass at the end of the period is simply divided by the volume of air sampled and we produce a concentration (µg or mg per cubic metres of air). This is labour intensive and complex in terms of filter handling and having a balance capable of detecting very small changes in mass. Gravimetric filters require weighing before and after use and this also involves 'conditioning' so that the weighing process takes place in near identical conditions of humidity and temperature (filters can absorb moisture and this can impact on their weight). Obtaining a balance with sufficient sensitivity and a laboratory environment where humidity and temperature can be controlled can be difficult in low and middle income countries and so it may be necessary to have this part carried out by a laboratory in Europe, the USA or Australia. Field and laboratory blanks are also required for this process to identify and correct for any contamination.

The alternative is to use optical particle counters that count how many particles are in the air flow and estimate the average density of these particles to provide an estimate of the concentration. These secondary methods don't provide a physical sample and their estimates of density require calibration to the aerosol being measured.[20] Particles from burning wood may have a different density to particles generated from diesel exhaust or road dust. It is usually necessary to calibrate the data from the optical instruments and this can be done in two ways. If possible then gathering contemporaneous data from gravimetric and optical instruments in the location where you are sampling and comparing the data from your physical sample with your optical derived estimates is best.[21] An alternative is to carry out the calibration procedure in a controlled environment such as an exposure chamber where wood or charcoal can be burned in a manner similar to that found in the homes. The frequency of calibration will depend on the instrument, the manufacturer guidance and the concentrations the instrument is being used to measure. For many low-cost devices guidance on calibration is not available and calibration at the beginning, middle and end of the study is recommended to enable identification and correction of any sensor drift.

Gravimetric sampling tends to require more battery power as the pump has to draw air through a filter with high resistance. This can further complicate the process in terms of gathering 24-hour measurement data. Our recommendation is to carry out side-by-side gravimetric sampling with optical instruments on a sub-sample of participants to provide relevant calibration data. It is also worth exploring the literature and/or discussing with the manufacturer the existence of any calibration factors relevant to your particular scenario. It is worth remembering that gravimetric or filter based methods will only provide data on the average concentration over the entire measurement period and will not provide detail on temporal changes. However, it is worth noting that there are some integrated optical/gravimetric devices (e.g. the MicroPEM (RTI International, NC, USA)) that can measure for 24 hours or more and also provide detail on temporal changes.

Instrument range and accuracy

The range of concentrations likely to be encountered over a measurement period will be considerable. For PM2.5 the concentrations may be as low as 2-3 µg/m3 at night time but as high as 1000-10,000 µg/m3 during some cooking periods. The dynamic range of many instruments can be swamped by these changes and optical counters may struggle with such high concentrations. Will they be overloaded by the concentrations encountered during cooking periods? How important is it if concentrations exceed the maximum limit of detection for an instrument for very short periods (say 5-10 minutes per day; <1%). How accurate do you need to be? If you are classifying study participants into broad exposure categories of high, medium and low then is it worth using a much more expensive instrument with the ability to measure to 0.1 µg/m3 as opposed a cheaper more robust device with resolution of 1 µg/m3?

Similarly if we think about the lower limit of detection and consider two models of a CO measuring instrument: one with a range of 3-1000 ppm and the other with a range of 0.5 to 300 ppm, if we know that most 1-minute concentrations over the course of a day will be <3 ppm and we wish to use this data to model PM2.5 exposures then we should select the device that has better resolution at lower concentrations.

Calibration, maintenance, servicing and quality control

We've already thought about calibrating optical particle counters against gravimetric measurements. Other instrument types may require calibration and you need to read the manufacturer's guidance on this. There may also be a requirement to service the instrument annually and to do regular in-field maintenance and cleaning. This could simply involve cleaning and greasing an impactor head or opening up a device to use 'canned' or compressed air to remove any deposits of particulate matter. Quality control is important and good record keeping of the use of each instrument and what cleaning, servicing and calibrations schedules have taken place is essential.

Collecting the data or sample

It is important that you obtain any relevant ethical approvals before starting your study – something beyond the scope of this document except in so much as the guidance here will help

inform your decisions on what you will require to explain in your participant information sheet, consent forms and application to your local ethics committee.

You'll then have recruited your participant and obtained informed consent to include them in your study. You've attached your personal sampler or positioned your static/fixed sampler in the main living area of the home (typically at about 1 metre height from the ground and at least 1 metre away from any direct sources of emission like a fire or lamp). You've gathered your contextual information and recorded the instrument ID number on your record sheet/app. You've noted the time the device was switched on, recorded the flow rate if applicable and made sure the device is in 'logging mode' or the equivalent to ensure that it is functioning as planned. You should now arrange a time for the return visit and check that someone will be present to enable collection of the instrument. You may want to leave a quick 1-page guide 'What to do if…' to overcome any problems and a study contact mobile number if any urgent queries arise. Be courteous and thank all in the household for their time and help.

Remember that what can go wrong will go wrong and so you should have equipment spares where possible. Strong tape is a good thing to carry to help secure instruments to stands, tables or shelves.

When you return to collect the devices you should first enquire about any problems or difficulties. Was the device switched off at all? Did anything unusual occur? You may be able to download the data there and then and depending on your further commitments you may be able to clean/service the instrument and replace batteries. Or you may need to recover the device to a logistics base (a vehicle or back to your accommodation or office) to re-charge and extract your data. If you are collecting a physical or gravimetric sample then these are best removed from the sampling head in a clean, stable area usually back in an office or laboratory in order to avoid contamination. Having a clear and simple Standard Operating Protocol (SOP) for the sampling and measurement process is essential to ensure uniform data collection that minimises any variability or bias from the fieldworkers gathering measurements.

4. Analysis and reporting

Gathering contextual information

So you're now about to measure in a home or other location. You'll have collected information about the location of the home and the participant during the recruitment process. Clearly there is a lot of contextual information that can also be gathered to make sense of the measurement data you gather. For example, you almost certainly want to know the type of fuels used in the home and the stove or cooking arrangements. Details of the size of the home, presence of a chimney, windows, separated cooking area, where fuel is stored, whether animals are also kept in the home can all influence the concentrations of PM measured and may help you identify homogenous exposure groups and think about exposure variability. Think about the type of information you will analyse and what you may look back on and wish you'd collected. At the same time, you are ethically bound not to collect information that will not be used – and remember that shorter questionnaires or forms will be easier to administer and process.

4.2 Data handling

Working with a statistician to determine sample size and analysis plans at an early stage is important. This will give you some early ideas about budget, study duration and how realistic your plans are. At the outset of the study, and before any data collection, it is essential to write a comprehensive data management and analysis plan so that you know how you will handle your data and what you'll do with incomplete data: will you, for example, attempt to repeat sampling if you discover that a device has failed in a particular home?

Temporal data has many advantages when measuring exposure to air pollution. It allows you to see how concentrations and exposures change over the course of a day and with many logging devices offering resolution of 1-minute you can see the timing of peaks linked to activities like lighting a fire or blowing out a lamp. In addition to being able to generate a 24-hour average it also allows metrics about thresholds to be considered: how much of the day was the exposure above 250 μg/m3. The downside is that such instruments produce a lot of data. For each minute there can be several elements – date, time, temperature, humidity, large particle number, all particle number, calibration factor applied, derived PM2.5 concentration. Multiply these data pieces by 1440 minutes per day and the number of participants and it is easy to see how a database of several million items of information can be generated even from quite small studies. A robust data entry and storage procedure is required to ensure that the exposure information is kept intact and can be traced through the various protocol steps for quality assurance purposes.

A method for handling incomplete data should be devised prior to collection. What will you do with data from instruments that were switched off for a short period or where battery life failed after 23 hours. What limits will you set on these values? Will you impute missing values or will you simply 'average' for the period collected?

4.3 Making sense of your findings

Create a data analysis plan. You will need to summarise your data – remember why you measured in the first place. It may be that you simply want to report on changes to average exposure levels before and after an intervention. Or maybe you want to see if there is a change in the percentage of time participants are exposed to concentrations above a particular threshold. Or if peaks of exposure are much lower than before. Perhaps you want your data for advocacy purposes to convince a policymaker that there is a need for changes to protect people from exposure. Think how best to present your data in a simple, easily digestible manner that remains faithful to your findings, doesn't exaggerate and presents a route to improvement.

You may want to compare your findings to health-based guidance or limit values from the WHO or regulatory bodies in other countries and/or place your measurements in context of other studies in neighbouring or nearby countries. All of these can help to simplify your message and provide motivation to improve conditions. Think about recommendations and

future interventions. Are there any local or specific measures that you think can be applied nationally or internationally? Perhaps you saw a new way of lighting a fire or cooking in a village in southern Malawi that could help reduce personal exposure to HAP across the globe?

Remember too that it isn't just your data. Think about the benefits of building in feedback to those who participated in the study. Can you easily provide feedback at the time of data collection or at a later date. This may be at an individual level or at the level of the group or village: numerical feedback about individual exposure conditions can be a powerful tool to help generate behaviour change.

Acknowledge the weaknesses of your study – so you compromised and didn't measure everyone's exposure to every respiratory pollutant every day and so your knowledge is incomplete, but so long as what you've gathered is likely to be representative, reliable and reasonably accurate then it is of use.

Finally, share your experience and learning about the exposure assessment process. Help others avoid making the same mistakes you've encountered or toiling to re-invent the same wheel that you've perfected. Think about writing an 'exposure paper' for your study - it doesn't have to subsumed in to the health paper and buried in a couple of paragraphs with minimal detail. Exposure assessment is an important piece in the public health jig-saw and you should make sure others know about what you achieved.

5. Logistics

5.1 What population will you measure?

The choice of measurement population has implications in terms of logistics and should be considered carefully. There are likely to be big differences in exposure by age, gender, job title, socio-economic circumstances and other factors. Do you need to measure everyone in your study or can you identify 'homogenous exposure groups' who carry out activities and live comparable lifestyles that lead to similar exposure to the hazard being measured? Are there data available that show that variability between people in those groups is small – and if so then the number of measurements you need to take to get a representative picture of the population will also be small. Think about reviewing the variability in exposure measurements at an early or pilot stage. If you find that many adult women or all children have a very similar measured exposure then you may not need to expend a lot of time and resources measuring more, but if you find that exposures vary between households then individual assessment is required.

5.2 Practicalities

The logistics of acquiring exposure data are not to be underestimated. There can be many issues such as the need for reliable and safe transport to/from the site; accommodation for the research team; translation services; gender-appropriate teams for local cultural norms; access to electric power to charge up instruments and replacement battery packs; availability of spares and replacements for servicing equipment; local weather conditions and political unrest. Shipping equipment and samples to the country where the work will take place also requires some thought and planning. Equipment containing lithium-ion batteries has special rules for air-freight and may, even when in accordance with those rules, be wrongly rejected by couriers. Customs and import duties may be applied and can lead to several weeks of delay to get appropriate equipment to a study site. An accompanying letter signed by a senior member of the study team explaining the equipment is to be used for medical research and will not be re-sold in the receiving country can help to expedite the process.

As explained above, gravimetric samples involve transportation of pre-weighed filters and it is important that these are not directly handled by couriers or customs officials. You may want to make one 'example' sample available and again provide an accompanying letter explaining the nature of the filters and samples.

Gaining access to homes should also be considered. In some cultures, it is necessary to wait for the head of the household to return before the research team can enter the home even if another adult is already present. It is worth checking in advance and scheduling sufficient time for unexpected delays when setting up and collecting instruments.

The Hawthorne effect has been mentioned previously.[18] Broadly this is the impact of the study visit to the home on household behaviour and it is possible to think of it in several ways. The visit by the team and installation of instruments can lead to increased local interest by neighbours and relatives. As a result, perhaps the participant will have more visitors that evening and will cook more or for longer duration leading to an atypical exposure measurement. Alternatively, the participant may decide not to cook as usual due to the desire to have a 'low reading' or 'not to damage the equipment with the smoke'. It is important to explain that participants should go about their usual daily activities as normal and to try to ignore the presence of the instrument.

5.3 Budget

The primary cost of your fieldwork is likely to be cost of the researchers' time visiting homes and collecting data. Equipment is also costly and can range from low-cost CO logging instruments ($100) through to robust optical instruments like the TSI Sidepak AM510 Personal Aerosol Monitor (TSI Inc, MN, USA) capable of measuring PM2.5 ($4000). Low-cost particles monitors like the Dylos DC1700 (Dylos Corporation, CA, USA), ($450) can help reduce costs. Pumps ($1000) are re-usable but filters to collect a physical sample ($10 each) and other consumables such as batteries, cleaning materials, belts, pouches, storage boxes and locks etc should also be factored in. Equipment, good quality batteries and power packs can sometimes be difficult to source in sub-Saharan African countries and shipping costs can be substantial. You should also budget for data handling especially when you have large sets of temporal data.

5.4 Security of instruments, tampering and safety of population

People are inevitably interested in new technology, particularly when they are asked to wear a device or it has been placed in their home. This can lead to tampering, instruments being

accidentally switched off or loss of data. Where possible the device may have buttons locked off either through software methods or using physical locks and barriers. Locked storage boxes can be used for static devices or button barriers on instruments such as the Dylos if they are worn to assess personal exposure. Spending time with the participant to explain how the device works and how it measures their exposure can be beneficial for reducing the rate of tampering.

Measuring children's exposure can be particularly difficult with safety considerations for infants and young children in terms of small parts, batteries and glass. Older children can be more likely to tamper with equipment, press exposed switches and buttons and perhaps use the devices as toys. For very young children it may be best to measure the mother's exposure and assume infants spend nearly all their time in close proximity to their mother.

Some participants may express concerns about the safety of those in the household as a result of having expensive equipment located in their home. Where participants express such fears that wearing devices or siting the instrument in their house could increase the risk of attack, theft or violence then this should be discussed and/or the participant removed from the study. The study risk assessment should take this in to account.

Conclusions

Quantifying exposure to respiratory hazards presents many challenges but can also provide those involved in public health, research and advocacy work with powerful objective evidence of the need for change or for the effectiveness of interventions that have been developed. Knowing what can be achieved and identifying some of the common pitfalls can help the research team make the best use of limited resources and stay within project budget. Technological advances are making the collection of real-time personal exposure data increasingly realistic for a range of air pollutants and these exciting developments are likely to open opportunities for future studies to identify new methods to improve the air quality that people in sub-Saharan Africa breathe within their home, outdoors, at work and in other indoor spaces.

Acknowledgement/declaration

Author contributions: Conceptualisation, SS, GO and KM; writing—original draft preparation, SS and GO; writing—review and editing, SS, GO, HL and KM; funding acquisition, KM.

Funding: We thank the NIHR Global Health Research Unit on Lung Health and TB in Africa at LSTM - "IMPALA" for helping to make this work possible. In relation to IMPALA (project reference 16/136/35) specifically: IMPALA was funded by the National Institute for Health Research (NIHR) using UK aid from the UK Government to support global health research. The views expressed in this publication are those of the author(s) and not necessarily those of the NIHR or the UK Department of Health and Social Care. The work was also supported by the 'Biomass Reduction and Environmental Air Towards Health Effects in Africa - BREATHE partnership (MR/L009242/1)' which was jointly funded by the UK Medical Research Council (MRC) and the UK Department for International Development (DFID) under the MRC/DFID Concordat agreement. The options appraisal work described in appendix A does not seek to endorse or approve or recommend any single instrument and has been carried out based on our own experiences and judgment. We have no financial links with any of the companies that produce or sell any of these devices.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Koehler, K.A.; Peters, T. New Methods for Personal Exposure Monitoring for Airborne Particles. Curr Environ Health Rep 2015, 2, 399–411. doi:10.1007/s40572-015-0070-z.
2. Loh, M.; Sarigiannis, D.; Gotti, A.; Karakitsios, S.; Pronk, A.; Kuijpers, E.; Annesi-Maesano, I.; Baiz, N.; Madureira, J.; Fernandes, E.; Jerrett, M.; Cherrie, J. How Sensors Might Help Define the External Exposome. Int. J. Environ. Res. Public Health 2017, 14, 4, 434.
3. Balakrishnan, K.; Thangavel, G.; Ghosh, S.; Shupler, M.; Sambandam, S.; Mukhopadhyay, K.; Rohani, H.; Bruce, N.; Smith, K. The Global Household Air Pollution Database 2018 (Version 5.0). http://www.who.int/airpollution/data/Background_Global_HAP_Db_v5_2018.pdf (accessed 26 September 2018).
4. Carter, E.; Norris, C; Dionisio, K.; Balakrishnan, K.; Checkley, W.; Clark, M.; Ghosh, S.; Jack, D.; Kinney, P.; Marshall, J.; Naeher, L.; Peel, J.; Sambandam, S.; Schauer, J.; Smith, K.; Wylie, B.; Baumgartner, J. Assessing Exposure to Household Air Pollution: A Systematic Review and Pooled Analysis of Carbon Monoxide as a Surrogate Measure of Particulate Matter. Environ. Health Perspect. 2017, 125, 076002. doi: 10.1289/EHP767.
5. Larkin, A.; Hystad, P. Towards Personal Exposures: How Technology Is Changing Air Pollution and Health Research, Curr Environ. Health Rep 2017, 4, 463–471.
6. Gordon, S.B.; Bruce, N.G.; Grigg, J.; Hibberd, P.L.; Kurmi, O.P.; Lam, K.B.; Mortimer, K.; Asante, K.P.; Balakrishnan, K.; Balmes, J.; Bar-Zeev, N.; Bates, M.N.; Breysse, P.N.; Buist, S,.; Chen, Z.; Havens, D.; Jack, D.; Jindal, S.; Kan, H.; Mehta, S.; Moschovis, P.; Naeher, L.; Patel, A.; Perez-Padilla, R.; Pope, D.; Rylance, J.; Semple, S.; Martin, W.J 2nd. Respiratory risks from household air pollution in low and middle income countries. Lancet Respir Med. 2014, 2, 823-60. doi: 10.1016/S2213-2600(14)70168-7.
7. Jaglowska, K. Measuring biomass fuel exposure in homes in developing countries. Master's Thesis, University of Aberdeen, Scotland, 2013.
8. Okello, G.; Devereux, G.; Semple, S. Women and girls in resource poor countries experience much greater exposure to household air pollutants than men: Results from Uganda and Ethiopia. Environ. Int. 2018, 119, 429-437.
9. Fullerton, D.G.; Semple, S.; Kalambo, F.; Suseno, A.; Malamba, R.; Henderson, G.; Ayres, J.; Gordon, S. Biomass fuel use and indoor air pollution in homes in Malawi. Occup. Environ. Med. 2009, 66, 777-83. doi: 10.1136/oem.2008.045013
10. Lawin, H.; Fanou, A.L.; Hinson, V.; Wanjiku, J.; Ukwaja, N.K.; Gordon, S.B.; Fayomi, B.; Balmes, J.R.; Houngbegnon, P.; Avokpaho, E.; Sanni, A. Exhaled carbon monoxide: a non-invasive biomarker of short-term exposure to outdoor air pollution. BMC Public Health 2017, 17, 320. doi: 10.1186/s12889-017-4243-6.
11. Rumchev, K.; Spickett, J.T.; Brown, H.L.; Mkhweli, B. Indoor air pollution from biomass combustion and respiratory symptoms of women and children in a Zimbabwean village. Indoor Air. 2007,17,468-74.
12. Zhou, Z.; Dionisio, K.L.; Arku, R.E.; Quaye, A.; Hughes, A.F.; Vallarino, J.; Spengler, J.D.; Hill, A.; Agyei-Mensah, S.; Ezzat,i M. Household and community poverty, biomass use, and air pollution in Accra, Ghana. Proc Natl Acad Sci USA. 2011,108:11028-33. doi: 10.1073/pnas.1019183108
13. Olaniyan, T.; Dalvie, M.A.; Röösli, M.; Naidoo, R.; Künzil, N.; de Hoogh, K.; Parker, B.; Leaner, J.; Jeebhay, M. Asthma-Related Outcomes Associated with Indoor Air Pollutants among Schoolchildren from Four Informal Settlements in Two Municipalities in the Western Cape Province of South Africa. Indoor Air. 2018 Oct 19. doi: 10.1111/ina.12511.
14. Akinyemi, J.O.; Adedini, S.A.; Wandera, S.O.; Odimegwu, C.O. Independent and combined effects of maternal smoking and solid

fuel on infant and child mortality in sub-Saharan Africa. Trop Med Int Health. 2016, 21(12):1572-1582. doi: 10.1111/tmi.12779
15. Lin, H.; Guo, Y.; Kowal, P.; Airhihenbuwa, C.O.; Di, Q.; Zheng, Y.; Zhao, X.; Vaughn, M.G.; Howard, S.; Schootman, M.; Salinas-Rodriguez, A.; Yawson, A.E.; Arokiasamy, P.; Manrique-Espinoza, B.S.; Biritwum, R.B.; Rule, S.P.; Minicuci, N.; Naidoo, N.; Chatterji, S.; Qian, Z.M.; Ma, W.; Wu, F. Exposure to air pollution and tobacco smoking and their combined effects on depression in six low- and middle-income countries. Br J Psychiatry. 2017,211:157-162. doi: 10.1192/bjp.bp.117.202325.
16. Saucy, A.; Röösli, M.; Künzli, N.; Tsai, M.Y.; Sieber, C.; Olaniyan, T.; Baatjies, R.; Jeebhay, M.; Davey, M.; Flückiger, B.; Naidoo, R.N.; Dalvie, M.A.; Badpa, M.; de Hoogh, K. Land Use Regression Modelling of Outdoor NO_2 and PM2.5 Concentrations in Three Low Income Areas in the Western Cape Province, South Africa. Int J Environ Res Public Health. 2018,15. pii: E1452. doi: 10.3390/ijerph15071452.
17. WHO guidelines for Indoor Air Quality. http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf?ua=1 (accessed 26 September 2018).
18. Schwartz, D.; Fischhoff, B.; Krishnamurti, T.; Sowell, F. The Hawthorne effect and energy awareness. Proc Natl Acad Sci U S A 2013, 110, 15242-6. doi: 10.1073/pnas.1301687110.
19. Cherrie, J.W. Personal and static sample measurements are related. Occup Environ Med 2004, 61(4):374.
20. Jiang, R.T.; Acevedo-Bolton, V.; Cheng, K.C.; Klepeis, N.E.; Ott, W.R.; Hildemann, L.M. Determination of response of real-time SidePak AM510 monitor to secondhand smoke, other common indoor aerosols, and outdoor aerosol. J Environ. Monit. 2011, 13, 1695-702. doi: 10.1039/c0em00732c.
21. Kurmi, O.P.; Semple, S.; Steiner, M.; Henderson, G.D.; Ayres J.G. Particulate matter exposure during domestic work in Nepal. Ann Occup. Hyg. 2008, 52, 509-17. doi: 10.1093/annhyg/men026.
22. Semple, S.; Ibrahim, A.E.; Apsley, A.; Steiner, M.; Turner, S. Using a new, low-cost air quality sensor to quantify second-hand smoke (SHS) levels in homes. Tob Control. 2015,24:153-8. doi: 10.1136/tobaccocontrol-2013-051188.
23. Loffredo, C.A.; Tang, Y.; Momen, M.; Makambi, K.; Radwan, G.N.; Aboul-Foutoh, A. PM2.5 as a marker of exposure to tobacco smoke and other sources of particulate matter in Cairo, Egypt. Int J Tuberc Lung Dis. 2016, 20:417-22. doi: 10.5588/ijtld.15.0316
24. Chartier, R.; Phillips, M.; Mosquin, P.; Elledge, M.; Bronstein, K.; Nandasena, S.; Thornburg, V.; Thornburg, J.; Rodes C. A comparative study of human exposures to household air pollution from commonly used cookstoves in Sri Lanka. Indoor Air. 2017, 27:147-159. doi: 10.1111/ina.12281.
25. Pillarisetti, A.; Allen, T.; Ruiz-Mercado, I.; Edwards, R.; Chowdhury, Z.; Garland, C.; Hill, L.D.; Johnson, M.; Litton, C.D.; Lam, N.L.; Pennise, D.; Smith, K.R.; Small, Smart, Fast, and Cheap: Microchip-Based Sensors to Estimate Air Pollution Exposures in Rural Households. Sensors (Basel). 2017, 1. pii: E1879. doi: 10.3390/s17081879
26. Whitehouse, A.; Miyashita, L.; Liu, N.; Lesosky, M.; Flitz, G.; Ndamala, C.; Balmes, J.R.; Gordon, S.B.; Mortimer, K.; Grigg, J. Use of cleaner-burning biomass stoves and airway macrophage black carbon in Malawian women. Sci Total Environ. 2018, 635:405-411. doi: 10.1016/j.scitotenv.2018.04.125.
27. Wang, Y.; Yang, W.; Han, B.; Zhang, W.; Chen, M.; Bai, Z. Gravimetric analysis for PM2.5 mass concentration based on year-round monitoring at an urban site in Beijing. J Environ Sci (China). 2016, 40:154-60. doi: 10.1016/j.jes.2015.09.015.
28. Devakumar, D.; Semple, S.; Osrin, D.; Yadav, S.K.; Kurmi, O.P.; Saville, N.M.; Shrestha, B.; Manandhar, D.S.; Costello, A.; Ayres, J.G. Biomass fuel use and the exposure of children to particulate air pollution in southern Nepal. Environ Int. 2014, 66:79-87. doi: 10.1016/j.envint.2014.01.011.
29. Bartington, S.; Bakolis, I.; Devakumar, D.; Kurmi, O.P.; Gulliver, J.; Chaube, G.; Manandhar, D.S.; Saville, N.M.; Costello, A.; Osrin, D.; Hansell, A.L.; Ayres, J.G. Patterns of domestic exposure to carbon monoxide and particulate matter in households using biomass fuel in Janakpur, Nepal. Environ Pollut. 2017, 220(Pt A):38-45. doi: 10.1016/j.envpol.2016.08.074.
30. Chen, C.; Zeger, S.; Breysse, P.; Katz, J.; Checkley, W.; Curriero, F.C.; Tielsch, J.M. Estimating Indoor PM2.5 and CO Concentrations in Households in Southern Nepal: The Nepal Cookstove Intervention Trials. PLoS One. 2016, 11:e0157984. doi: 10.1371/journal.pone.0157984
31. Dionisio, K.; Howie, S.; Fornace, K.; Chimah, O.; Adegbola, R.; Ezzati, M. Measuring the exposure of infants and children to indoor air pollution from biomass fuels in The Gambia. Indoor Air. 2008, 18:317-27. doi: 10.1111/j.1600-0668.2008.00533.x.

Appendix B: Checklist when planning exposure assessment strategy

Why are you measuring? What purpose will your results serve? Is there a scientific question you wish to answer?

Are there likely to be any secondary benefits to having measurement data?

Do you really need to measure?

Would an estimate or modelled value of exposure be sufficient?

Do you really need to measure?

What pollutant(s) will you measure?

How long do you need to measure for?

Do you need personal exposure measurements or will static/fixed site data do?

Do you require a physical sample for laboratory analysis?

What population or sub-group do you want to measure?

How similar are particular groups of people? Can you identify 'homogenous exposure groups'?

What practical issues will you encounter?

How accessible is the location where data will be collected?

Are there issues gaining access to homes/participants?

Budget?

How safe will your instruments be?

Can participants tamper with the equipment?

Will siting the instruments in homes put householders at risk of attack or theft?

What range of concentrations will be encountered? Does your device handle both low and high concentrations?

How accurate do you need your results to be?

What calibration, servicing and quality control measures will be required? Can these be carried out in the field or do they require equipment to return to base?

Battery life? Power supply for re-charging? Availability of good quality batteries with-in country?

Do you have a plan for handling large amounts of contextual and temporal data on exposure?

How will you share your findings? Will you provide personal feedback to participants?

Appendix A: Options appraisal for various methods

HAP	Device	Method	Cost (size/ weight)	Power
PM	Dylos Dc1700	Laser-based optical particle counter with two size bins (>0.5µm and >2.5µm)	$400 (18cm x 12cm x 8cm 1100g)	5-6h on internal battery; can run on an external 20,000mAh powerbank for ~24h
PM	TSI Sidepak AM510/20 Personal Aerosol Monitors	Laser-based optical particle counter (size selective impactors for 1/2.5/10µm)	$4000 (13cm x 10cm x 8cm 620g)	20h with a 5400mAh Lithium-ion battery pack
PM	RTI Micro Personal Exposure Monitor (MicroPEM)	Both optical and gravimetric	$2000 (10cm x 5cm x 4cm 240g)	Up to 40 hours on three AA batteries
PM+CO	Particle and Temperature Sensor (PATS+)	Laser-based particle counter and electrochemical CO monitor	$600 (10cm x 5cm x 4cm 250g)	Up to 80 hours on internal battery; extendable with external battery
PM/CO	Aprovecho IAP Meter	Laser-based optical particle coun-ter (PM2.5) and electrochemical cell for CO	$2500 (20cm x 13cm x 8cm 860g Back-pack arrangement)	Internal battery can operate for 3-30 days depending on sampling frequency
PM	Gravimetric sampling	Traditional filter-based methods using a pump (e.g. Casella Apex), tubing and a size selective head to gather PM on a filter (PVC, glass fibre, mixed cellulose ester).	$1000 plus filter ($10) costs (Pump 13cm x 8cm x 5cm (500g) plus tubing and size selective head)	Battery life depends on filter type and flow rate (1-2 lpm) but typically 12-16 hours with good quality batteries.
CO	Lascar CO Logger	Electrochemical sensor changes resistance when exposed to CO – concentration logs to internal memory	$100 (12cm x 3cm x 3cm 100g)	½ AA battery can last for 3 months – dependent on concentrations but can easily measure multiple participants for 24h
CO	Diffusive tubes	Diffusion tube with chemical reaction and onward analysis in laboratory	$40-50 plus laboratory analysis costs ($50 per sample) (10cm x 3cm x 3cm when inside protective covering <100g)	No power requirements

From a recent review of the literature we identified the main methods used to quantify HAP in low and middle-income countries. While a small number of studies quantified pollutants such as Nitrogen Oxides, Sulphur Dioxides, Formaldehydes, and Benzene, most studies focused on PM or CO to quantify exposure. Given the technical difficulties with measuring these lower concentration pollutants our options appraisal focuses on methods measuring PM or CO.

Advantages	Disadvantages	Studies
Low-cost; low noise; temporal resolution (1min); can log 9056 mins in internal memory; can be modified to provide real-time data over internet; maintenance and servicing simple; two size bins can help fingerprint sources.	0-1000µg/m3; poorer response above this; bulky for personal sampling; requires calibration. Serial output can lead to download problems.	[8,22]
Designed for personal sampling; temporal resolution (1s upwards); excellent range (1µg/m3 to 100mg/m3); well supported with good software	High cost; pump is noisy – very noticeable at nights in homes in rural settings. Requires expensive annual servicing and calibration.	[21,23]
Has both gravimetric and optical options for measuring PM; lightweight (<240g) and small – wearable. Low noise.	Complex. Training is required to use the device; Additional cost for filters.	[24]
Low cost; small and portable; temporal resolution; Data logging of up to several gigabytes (SD card); Optional carbon monoxide sensor; Logging intervals can be specified by the user; PM detection limit is 10-50,0000µg/m3 and 0-500ppm CO. Also records temperature and movement which can help specify microenvironments.	Poor at low concentrations; requires 15 minutes at the beginning and end of sampling for a zeroing procedure in a clean safe area out of direct sun-light. Software complex.	[25]
Low noise – operates via fan.; temporal data for both PM and CO. Wide range 0-60,000µg/m3 for PM2.5 and 0-1000ppm CO	Bulky and obtrusive. Poor resolution 25µg/m3 for PM2.5 and 1ppm for CO. RS-232 output can lead to download problems.	[26]
Gold standard for calibration of other secondary particle counting methods	Only provides average over the sampling time; pumps can be noisy; requires careful filter handling and additional costs of filters and transport to lab for conditioning/ weighing.	[27-28]
Low cost. Small and wearable. Simple to use – plug and play. No noise. Robust and unobtrusive. Temporal data (10s-5min). Can store 32,000 readings; sensor life ~4y. Re-usable	Accuracy only +/- 5ppm; CO often not well correlated with PM concentrations particularly at lower concentrations	[29-30]
Low cost, small and wearable. No noise. No power requirements. Only provides average concentration over sampling period.	Single use; usually a glass tube so needs to be inside plastic protective cover; requires chemical analysis and careful storage and transport.	[31]

Note: other options are available but this listing provides the main types of devices used in research on HAP in resource poor settings in the past 10-15 years based on personal experience of the authors and the Masters thesis 'Systematic review: Measuring biomass fuel smoke exposure in homes in developing countries' written by Jaglowska at the University of Aberdeen which summarized data collection methods from 36 papers from 17 countries [7]. There may be alternatives to the devices listed here provided by the same manufacturer; we have provided an appraisal of the device that we consider most suited for HAP measurement from the available suite of instruments. Costs and dimensions are approximations. Battery life can vary considerably by the age of the device, temperature, filter used and many other factors – figures provided here are indicative only. Summary advantages and disadvantages are personal observations of one or more of the authors.