Evaluation and application of prototype air quality monitors for household air pollution exposure assessment

by

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Submitted by	Aaron Birch	in partial fulfillment of the requirements for
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Abstract

Household air pollution (HAP) from burning of low-quality fuels is a significant contributor to global burden of disease, particularly in low- and middle- income countries. Epidemiological studies of HAP have been hampered in their ability to collect quantitative exposure measurements from a lack of affordable, durable and easily usable air quality monitors. New devices offer potential to overcome these obstacles but must be tested in real world conditions before deployment. This study's goal was to evaluate the performance of three prototype monitors compared to two reference monitors and their applicability for use in a prospective cohort epidemiologic study. Prototype monitors tested included a filter-based monitor, and two particle counters. Simple linear regression models of HAP exposure were constructed using questionnaires and observational data.

55 households were recruited for HAP monitoring in two villages in India in 2015. Monitors were placed in the household kitchens for 24- and 48-hour sample periods. Male and female household residents were recruited for personal fine particle ($PM_{2.5}$) exposure monitoring using the filter-based prototype monitor. All filter samples were analyzed for $PM_{2.5}$ mass concentrations and particle light absorbance.

Successful filter samples collected with the V1.0 Ultrasonic Personal Aerosol Sampler (UPAS, Access Sensor Technologies, Fort Collins, CO), were obtained in 81% of homes with successful reference measurements. Fewer successful samples were collected with prototype particle counters, (43% and 75%). Personal monitoring with the UPAS succeeded in 54% of attempts. There was a high level of agreement between prototype filter and reference monitor ($R^2 = 0.85$ and slope = 0.98 for $PM_{2.5}$ and $R^2 = 0.88$ with slope = 1.63 for absorbance). Neither prototype particle counter performed well enough for subsequent analyses.

The best performing models of HAP exposure were for individual communities with a broad pool of predictors; including multiple types and amounts of fuels and cooking times, versus models combining communities with a narrower set of predictors. Using a broader variable pool improved adjusted R^2 values by as much as 0.35.

Recommendations were made for improvements for the UPAS sampler. An updated (V2.0) UPAS sampler was selected by the PURE AIR study of HAP.

Lay Summary

Billions of persons worldwide are exposed to harmful air pollution inside their own homes from burning poor quality fuels for cooking, heating and lighting. This type of pollution is called household air pollution (HAP) and it is known to be a leading risk factor for death, disease and disability in the world.

Until recently it has been very difficult to extensively measure the amount of HAP in the homes of affected people, in part because the equipment needed to do this has been too expensive and complicated.

In this paper three prototype air quality monitors were tested in real-world conditions in India to determine if they could be used by large scale study of HAP called the PURE AIR project. We found that one monitor, called the Ultrasonic Personal Aerosol Sampler (UPAS) worked very well and should be used by the PURE AIR project.

Preface

The work described in this thesis was a part of the PURE AIR study directed by Drs. Michael Brauer, The University of British Columbia, and Perry Hystad, Oregon State University. PURE AIR is funded by the Canadian Institutes of Health Research and the US National Institutes of Health. PURE AIR was a sub-study of the Prospective Urban and Rural Epidemiological study (PURE), directed by Drs. Salim Yusuf and Koon Teo, McMaster University.

This thesis received ethical approval under the PURE AIR study from the University of British Columbia Behavioural Research Ethics Board (H15-01268 and H14-02982).

This thesis is the work of Aaron Birch and was conducted under the supervision of Drs. Michael Brauer and Hugh Davies of the University of British Columbia and Perry Hystad of Oregon State University.

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List of Abbreviations

ALRI	Acute lower respiratory tract infections
CART	Classification and regression trees
CVD	Cardiovascular disease
COPD	Chronic obstructive pulmonary disorder
CRA	Comparative risk assessment
DALY	Disability adjusted life years
GBD	Global burden of disease
mg/m^3	Milligrams per cubic meter of air
$\mu g/m^3$	Micrograms per cubic meter of air
IER	Integrated exposure-response function
LPM	Liters per minute
LIC	Lower-income country
LMIC	Lower-middle-income country
mAh	Milliampere hour
MIC	Middle-income country
OC	Organic carbon
PGI	Postgraduate Institute of Medical Education and Research (a.k.a. PGIMER)
$PM_{2.5}$	Airborne particulate matter with an aerodynamic diameter smaller than 2.5 micrometers
PTFE	Polytetrafluoroethylene (PTFE), a synthetic fluoropolymer of tetrafluoroethylene commonly used in aerosol filter membranes
PUWP	Portable University of Washington Particle monitor
SES	Socioeconomic status
SEV	Summary exposure value
SRI	St. John's Research Institute
TRAP	Traffic related air pollution
UPAS	Ultrasonic Personal Aerosol Sampler
HAP	Household air pollution
WHO	World health organization

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1 Introduction

Globally billions of persons are exposed to high levels of household air pollution (HAP) from burning solid (biomass and coal) and low-quality liquid fuels (kerosene) for cooking, heating and lighting. These exposures represent one of the leading environmental determinants of morbidity and mortality in low- and middle-income countries (LIC, and MIC), yet they remain comparatively understudied due, in part, to the difficulty in gathering good quality quantitative measurements of household and personal HAP exposures (1,2). Epidemiological studies of the health impacts of HAP exposures would benefit from improved measurement capabilities such as those promised by newly developed air quality monitors (1,3,4).

To date, the collection of sufficient quantitative HAP measurements to support large cohort epidemiological studies of respiratory and cardiovascular diseases (CVD) has been considered impractical due to cost, time, and logistical constraints (1). The development and deployment of new $PM_{2.5}$ (particulate matter with an aerodynamic diameter at or below 2.5 µm) measurement devices could help overcome these obstacles by enabling large-scale sampling campaigns.

A large body of research work has conclusively shown that HAP levels in homes in LIC and MIC are typically many times above the world health organization (WHO) air quality guidelines (AQGs) (1). HAP exposures in LIC and MIC accounts for the majority of human exposure to particle air pollution (5–7). HAP exposures from solid and low-quality liquid fuel burning in the home are functions of a combination of factors, including; the types of fuels burned; where in the home they are burned; the presence of ventilation features; the time spent in proximity to emission sources(5,6,8–10).

The health impacts of HAP exposure have been severe, but trends in global exposure are positive. A 2016 Global Burden of Disease report attributed roughly 2.6 million deaths to HAP exposure, making HAP the #2 environmental risk factor and the #10 overall risk factor (11). The health impacts of HAP exposure have been highly biased; geographically towards LIC and MIC, gender biased towards women; and age biased towards young children (7,12,13). Over the last 25 years there has been a significant reduction in the risk contributed by HAP to the global disease burden; globally HAP exposures have dropped by 43% (40.7 – 45.6%) in this time period (14). HAP's ranking as a risk factor has also fallen in the same period, from the #3 and #4 risk factor for mortality and morbidity (in DALYs) in 1990 to the #8 and #10 risk factors in 2016 (15). Despite this positive trend HAP exposure remains the second leading environmental risk factor for disease burden, after outdoor ambient particulate matter air pollution.

Roughly three billion people, a third of the global population found primarily in LIC and MIC, rely on solid and low-quality liquid fuels for cooking and heating (16,17). The proportion of the world's population reliant on solid and low-quality liquid fuels has trended downwards in the last 25 years (7,17,18). Globally, the majority of the HAP associated disease burden has fallen on LIC and MIC, some of which are also the world's most populous (China, India, Bangladesh, Nigeria and Pakistan) (7,13). HAP associated disease burdens in the growing but currently less populated countries of sub-Saharan Africa are also very high.

People in poor, rural communities in LIC and MIC have been most highly exposed to HAP. An estimated 75% of rural populations cook with solid fuels in traditional stoves or open fires (7,13). Women and children within these communities have been at particular risk due to gender specific household roles associated with high exposure levels (19,20).

While there has been increased attention paid to the global health impacts of outdoor air pollution in the last quarter century, HAP associated health impacts have remained comparatively understudied in LIC and MIC compared to research carried out in high income countries (HIC), where HAP exposure is a minor component of disease burden (5,21). As a result, the health impacts of HAP exposure on CVD remains unclear in LIC and MIC.

Where research into the health effects of HAP exposure in LIC and MIC has taken place, it has focused largely on chronic obstructive pulmonary disease (COPD), lung cancer and acute lower respiratory infections (e.g. pneumonia), building in large part on the extensive body of work investigating the health effects of tobacco smoke exposure. HAP exposure levels in LIC and MIC often exceed typical second-hand tobacco smoke exposures in HIC (22). The integrated exposure-response (IER) functions developed from combining information from outdoor air pollution, HAP, second-hand smoke and active tobacco smoking research have been foundational to HAP exposure research (1).

The connection between HAP exposure and respiratory diseases, like COPD, has been well established in research, but the relationship between HAP and CVD remains less well established (23–25). Comparatively few studies have looked at the link between HAP and CVD, those studies have typically relied on national survey data of the types of fuels used in households to serve as indicators of HAP exposure, substituting for in-home exposure measurements (13,26). The use of categorical predictors in the absence of exposure measurements has been problematic; HAP exposures are complex functions of a host of factors, such as fuel type, cookstove type, ventilation features, cooking time, seasonality, and time spent in proximity to the emissions source (1), and thus studies relying on categorical predictors which lack measurement verification risk significant errors in assigning HAP exposures in epidemiological models (27).

The lack of quantitative HAP exposure data has arisen, in part, from the difficulty with collecting HAP measurements. Firstly, there are significant logistical difficulties to be overcome when conducting a large-scale epidemiological study in any locale: participant recruitment, researcher and equipment transportation; sample handling, to name a few. These obstacles can be magnified when the communities of interest are in parts of the world where access is challenging. Secondly, the equipment used to take HAP measurements must be accurate, consistent, robust, and affordable; it must also be able to collect data in a wide variety of environments with minimal maintenance and recalibration.

To date, much of the equipment used for HAP exposure measurement was originally designed for occupational hygiene work in mining, manufacturing, and agricultural workplaces in HIC. In the past this has usually been gravimetric air quality monitors, consisting of a diaphragm pump connected via tubing to a filter in a sampling head with a size selective inlet configured for inhalable, respirable or $PM_{2.5}$.(28). While this equipment has good precision and accuracy it also tends to be expensive, heavy, noisy, requires frequent calibration and can require skilled operators.

There has recently been a proliferation of hardware developers showing proposed or prototype next generation air quality monitors that promise a level of performance close to established monitors, but at a lower cost. Most of these new devices use an established air quality measurement principle, gravimetric filter-based devices or light scattering particle counters, for example. Hardware developers promise new air quality monitors that are cheaper and easier to use by leveraging new, or newly available, components together with the computing power of modern smartphones. Some new devices have been developed as consumer air quality monitors, for example the Dylos monitor (29), which allow users to measure their personal environments. Other devices have been developed more specifically for the research community, such as the Portable University of Washington Particle monitor (PUWP).

This present study aims to evaluate the real-world performance of a prototype gravimetric monitor and two potentially complementary light-scattering particle counters against established reference devices in a pilot-scale HAP field sampling project.

1.1 Household air pollution background

Modern epidemiology's focus on the health effects of air pollution was largely brought about by historically significant air pollution events in urban centers, notably the famous "London Fog" of 1952 where thousands of deaths were attributed to exposure to a toxic mix of fog and smoke from homes and factories burning coal in London, England (9). The response to this incident included some of the first legal and public health initiatives aimed specifically at understanding and controlling air pollution.

Until the 1980s most of the attention epidemiologists paid to the health effects of air pollution concentrated on outdoor air pollution in HIC. The general consensus held that the main sources of public exposure to air pollution came from industrial sources and primarily took place in the urban outdoor environment (30).

The effects of indoor air pollution on health received more attention in the 1980s as ideas like total exposure assessment became more widespread in hygiene and epidemiology. This idea holds that the population level effects of a pollutant are determined by its toxicity and the duration, frequency and magnitude of exposure (6,30). This led to early work in HAP research looking at who was exposed, to what, for how long and how often.

This early work concluded that (30):

- The majority of person hours were spent indoors, and thus that the majority of a person's exposure also occurred indoors. Despite this, the majority of air pollution research at that time had focused on ambient outdoor air pollution.
- Indoor air in rural communities was frequently more polluted than in urban areas, especially in LIC and MIC.
- The main source of indoor air pollution in rural communities in LIC and MIC was from burning solid fuels, primarily biomass and coal, for domestic energy needs.

Currently, nearly all studies of HAP in LIC and MIC agree that exposure levels in household reliant on solid fuels greatly exceed, often by orders of magnitude, standards for air quality set by the WHO and other organizations (1). Conversely, much of what is understood of the HAP to CVD dose/response function has been based on the comparatively low levels of exposures to outdoor air pollution found in North America and Europe. The dramatic difference in expected HAP exposure levels between households in HIC versus LIC and MIC has led to uncertainty over the extent to which air pollution research from the former can be applied to the latter.

Until quite recently there has been a lack of quantitative data for household HAP levels and personal exposures in households in LIC AND MIC where there is a high reliance of solid and low-quality liquid fuels (1,5,16,26,31–34); this has resulted in uncertainty over the HAP vs CVD dose/response function.

There has also been a general lack of data concerning how exposures vary: by location, gender, age, cooking behaviour and fuel type (35–37). The lack of quantitative HAP exposure measurements has led to some studies using exposure proxies such as national level surveys of household fuel use. This practise is problematic as it tends to ignore the complex ways in which a host of household characteristics and behaviors interact to determine HAP levels and personal exposures (38).

1.2 Household air pollution health impacts

Globally the health impacts of HAP exposure have been severe but have begun to decline in the last few years. HAP exposure were responsible for 4.3 million premature deaths globally in 2012, according to the WHO; HAP also caused roughly 7.7% of global mortality, more than AIDS, malaria, and tuberculosis combined (39). However, according to the most recent GBD report HAP has declined as a risk factor for disability adjusted life years (DALY) over the past 25 years; from the #1 to the #2 environmental risk factor and from the #4 to the #10 overall risk factor (15). The GBD uses a summary measure of exposure, the risk-weighted prevalence of an exposure called a summary exposure value (SEV) to express the percentage of a population exposed to a risk factor. For HAP exposure this has fallen from 34% to 19%, a decline of 43% (11). The GBD states there has been a similar decline in HAP's rank as a risk factor for mortality over the same time period. Based on estimates of solid fuel use for cooking the WHO estimates that HAP exposure is responsible for 33% of all deaths from COPD in LMICs, 25% of all deaths from stroke, 17% of all lung cancer deaths and 15% of all ischemic heart disease deaths globally (39).

The burden of disease from HAP exposures has not been evenly distributed globally, the great majority of HAP attributed deaths and DALYs occur in LICs and LMICs, with particular concentrations in sub-Saharan African countries, India, China and their Southeast Asian neighbours (39). Significant economic progress in China and India over the past 25 years may have been responsible for improving the HAP attributed disease burden situation in those countries. However, there may be cause for concern for the future. Expected growth in many African countries could result in a significant rise in the HAP associated disease burden if not coupled with proportional economic growth and/or significant public health interventions (40).

HAP exposures may put specific groups at greater risk of negative health outcomes. Children and women are likely more at-risk due to social roles that predispose them to higher exposures and particular biological vulnerabilities and susceptibilities. For example, women and children frequently have higher HAP exposures than men due to gender roles in household duties, specifically cooking and childcare, in many parts of the world (41).

The health impacts of HAP exposure have not been studied as thoroughly as the impacts from ambient air pollution and fossil fuel combustion (42). However, research on the health impacts of HAP has pointed towards mechanisms of disease similar to ambient air pollution exposure, including increased arterial stiffness, higher inflammatory cytokines and reactive oxygen species and higher blood pressure in studies of exposed populations (42).

It is difficult to reconcile the severity of the health impacts associated with HAP exposure with the current low level of attention and resources directed towards HAP research and interventions, especially given the resources directed towards HIV/AIDS, malaria, and other communicable diseases. This in turn reinforces the sense of urgency surrounding the need for improved HAP research tools.

1.3 Household air pollution characteristics and sources

The bulk of indoor air pollution in households in LIC and MIC with high HAP exposure levels have come from burning solid and low quality liquid fuels for cooking and heating (1,2,41). These fuels are also often burned in simple stoves or open fires in homes with poorly ventilated kitchens, which results in higher exposure levels (43). When these types of fuels are burned they release a large amount of a complex mixture including nitrogen and sulphur oxides, carbon monoxide and volatile organic compounds (VOCs), compared to the usable amount of heat generated. The pollutants most associated with health impacts are aerosols and carbon monoxide(44). Aerosols, small liquid or solid particles suspended in air, associated with HAP are formed by incomplete combustion, and are mostly carbon, with small amounts of other chemicals and elements adsorbed onto their surface. Aerosols are the most commonly measured HAP indicator for the purposes of health research (39,43).

Households have typically relied on low quality fuels when they cannot afford or access superior fuels (10,45), though cultural practices also play an important role in fuel selection. Electricity is usually regarded as the highest quality energy source, as it produces essentially no air pollution within the home environment, though ambient air quality in a community can be adversely affected by nearby electricity generation. Liquid and gas phase petroleum products, like LPG and natural gas, produce much smaller amounts of particulate matter compared to other fuels (44). Kerosene can be significantly more polluting than other more refined petroleum products, depending on its composition, as kerosene is available in many different grades. Its quality as a fuel also depends on how it is burned, e.g. under pressure or not (46). The broad range of potential exposures from a single type of fuel points to a broader problem in HAP research where using overly broad categorical predictors for exposure can lead to misclassification or very imprecise estimates (38).

Solid fuels most commonly used in HAP exposed households are biomass fuels, typically wood, (usually unprocessed though sometimes in pellets), crop residue, charcoal, and animal dung (44). These fuels can be used alone, or in combination, depending on their availability or traditional household practises. Households relying on biomass fuels may switch between fuel types, depending on local availability. For example, in Bangladesh households alternate between different types of crop residue (rice husks, straw, jute, sugar cane) depending on which crop has been harvested most recently (19). Fuel use can also vary by season, but there has been a lack of research data concerning how HAP exposures vary seasonally within a given household. This is likely due to the costs and logistical difficulty of gathering exposure data prospectively. Likewise, there also appears to be a lack of data concerning how season affects some predictive household level variables, such as fuel type, ventilation, and time spent cooking. Ventilation of the cooking area is an important determinant of HAP exposure levels in a home, yet it is very difficult to assess the performance of ventilation features in a home, such as the air flow rate through a chimney. Some HAP studies have dealt with this problem by assigning a protection factor to ventilation feature. For example, assigning a value of zero for perfect ventilation through to a value of one for no ventilation to homes and rooms in homes. While this technique is not perfect it works well enough on sufficiently large sample sizes (6). Other studies have used fieldworker's qualitative assessment of a household's ventilation, from poor to moderate to good (43).

Cooking location within, or outside, the home can account for significant variation in HAP levels. Cooking location, including outside the home, can account for up to an eight-fold difference in HAP levels (1,19,43). Other factors can also have an impact on HAP levels in a home. These include primary food types; some foods require longer to cook, some are cooked in pots while others are roasted over an open fire, others require frequent tending. These factors can increase emissions from duration and disturbance of a fire or exposure from time spent in close proximity (16,17,47). Weather and climate also play an important role, cold regions require more fuel for heating. Availability of fuel types can also change seasonally or from inclement weather (19). Rainy conditions can also increase the moisture content of biomass fuels, affecting combustion efficiency (20). Finally, Socio-Economic Status (SES) and intra-familial status: Personal HAP exposure is highly dependent on social norms concerning who performs cooking and heating tasks in a household (17). SES is also a powerful predictor of HAP exposure, though the relationship between changes in SES and HAP is likely very complicated.

1.4 Household air pollution exposures

Essentially all estimates of HAP exposure to date have clearly shown that in households that rely on solid fuels HAP exposures exceed acceptable levels, often by orders of magnitude (41). A WHO systematic review of HAP focused studies estimated global mean $PM_{2.5}$ kitchen area concentrations in households relying on solid fuels to be 972µg/m^3, which led to an estimated 24-hour personal exposure of 267 µg/m^3 and 219 µg/m^3 for women and children, respectively. While there was considerable variability in the methods used by the studies to evaluate HAP exposure levels, the evidence showing extreme exposure levels was considered unequivocal (46). There was also evidence to show that exposures for women and children were very high, and higher than exposures for men, largely due to gendered household roles where women and children spent more time indoors and in close proximity to stoves and fireplaces while cooking and burning takes place (46,48). In comparison, the mean 24-hour kitchen area $PM_{2.5}$ concentration was estimated to be 148 µg/m^3 in households relying on gas, electricity or kerosene (46). These estimates were generated from a meta-analysis of work published prior to 2012. These exposure levels, for either solid or liquid fuels, were far above WHO guideline levels for $PM_{2.5}$ exposures of 25µg/m^3 for 24-hours and 10µg/m^3 annually. (21).

A recent study by Shupler et al employed a hierarchical Bayesian approach to model kitchen area and personal HAP exposure using data from an updated WHO global database. They found mean kitchen area HAP $PM_{2.5}$ concentrations, broken down by fuel types, ranged from as low as 104 µg/m^3 for gas/electric stoves to 958 µg/m^3 for animal dung. This study also estimated that the ratio of a female's personal exposure to their household exposure was 0.4, globally (49).

Balakrishnan et al is one study which has collected measurements of HAP levels for different fuel types in an attempt to build an exposure model (43). This study examined HAP exposures versus fuel types, kitchen design, ventilation features in 420 households in rural India. They found statistically significant differences in HAP levels for different fuel types. For 24-hour kitchen area $PM_{2.5}$ concentrations animal dung was found to produce the highest pollution levels (732 µg/m^3) followed, in order, by wood (500 µg/m^3), kerosene (203µg/m^3) and finally LPG (73µg/m^3). The differences between the fuel types were consistent for different kitchen types/locations.

There has been a general consensus that HAP exposures vary significantly by region, for example amongst LIC globally there have been higher exposures in SE Asia versus Latin America though some questions remain about the degree of variation (50). Conversely, there has also been a general consensus that HAP exposures do not vary significantly by region for HIC. Fuel use can also vary significantly between rural and urban areas within the same country (38).

Models of regional HAP exposure have used survey data on the types of fuels selected and the amounts of fuels consumed to infer exposure; the advantage of this method was that solid fuel use could be estimated with more confidence than HAP exposure itself (6). Regional estimates of percent of population exposed to HAP, based on solid fuel use as of 2016 were (18):

1. Eastern Sub-Saharan Africa (94%)
2. Central Sub-Saharan Africa (83%)

3. Western Sub-Saharan Africa (79%)
4. Oceania (69%)
5. South Asia (49%)
6. Southeast Asia (38%)
7. East Asia (31%)
8. Southern Sub-Saharan Africa (28%)
9. Caribbean (27%)
10. Andean Latin America (19%)

It had been estimated 2010 that the absolute number of people relying on solid fuels has been declining globally, except in the eastern Mediterranean (where numbers remained relatively stable) and Africa (where high population growth rates have substantially increased numbers exposed) (51).More recent data from 2010 to 2016 shows mixed effects; with rapid declines in exposed populations in South, Southeast and Eastern Asia; and stable to slight declines in African regions, except for Southern Sub-Saharan Africa (18).

1.5 Household air pollution measurement

Data on indoor air pollution has been relatively scarce compared to outdoor air pollution, especially for rural households in LIC and MIC. This is largely due to the costs and logistical hurdles associated with gathering quality quantitative HAP measurements (1,2). Where epidemiological studies of HAP exposure have taken quantitative measurements, they have typically been smaller samples, (n<100), of kitchen area $PM_{2.5}$ mass concentrations. Very rarely have studies taken personal exposure measurements or made more than a few hundred measurements of any type. However, recently the WHO has compiled the results of many quantitative studies into the WHO Global HAP Database, which in total has about 1100 measurements from 53 countries (49). HAP studies have traditionally employed either gravimetric pump and filter monitors or, more recently, light scattering or ion depletion instruments. Both types have their advantages but either method requires careful planning.

Quantitative studies of HAP have often relied on area sampling using gravimetric (filter and pump) measurement methods. Gravimetric devices are very robust and reasonably straightforward to operate in the field, and usually less expensive than more sophisticated air quality monitors, like optical particle counters. Gravimetric monitors also take physical samples, which allows for later analysis, such as mass-spectroscopy, and for independent verification of measurements. Gravimetric monitors, especially larger versions suitable for both indoor and outdoor sampling, are well suited to sampling in high pollution environments as they do not foul or jam easily, and they are usually easy to service in the field. Optical particle counters, on the other hand, can be difficult to clean and can malfunction if their delicate sensors become contaminated.

A disadvantage of gravimetric monitors has been that because they take physical samples they require a large, and sometimes expensive, supply of filters for samples and blanks. Filters must be carefully weighted before and after sampling, which requires delicate and expensive equipment, and skilled technicians working in environmentally controlled laboratories. The combined costs of equipment and labour has usually raised the per data point cost of gravimetric samples above that of electronic devices (52). Until very recently these requirements made large scale filter-based sampling campaigns impractical for many epidemiological studies; however, the recent arrival of automated filter weighing scales has made large-scale gravimetric studies more practicable (53).

Studies using gravimetric monitors have also had to account for higher shipping costs and risks, loss or damage to a filter meant the loss of a household measurement and all the work that went into collecting that sample. Alternately other sampling methods, like optical particle counters, generate electronic data, which can be duplicated and transmitted with much less risk. More recently studies of HAP exposure have used optical particle counters to measure household HAP levels (1). These air quality monitors have several advantages that have made them attractive to researchers; first being their ability to record real-time changes in HAP levels which is very useful for assessing exposure events and placing them in temporal context, (e.g. that morning cooking times may be shorter but more intense than mid-day cooking events). Secondly, some usually more expensive optical particle counters can simultaneously measure multiple particle size categories, PM_{10} and $PM_{2.5}$, at the same time which could be useful for determining the sources of HAP. Information on particle sizes may also be useful for determining the potential health impacts of HAP exposure since smaller particles tend to deposit deeper in the lungs.

The disadvantages of optical particle counters are that they have usually been quite expensive, and especially for devices capable of size selective measurements. Optical particle counters must be calibrated against gravimetric samples for each distinct $PM_{2.5}$ mixture. Particle counters infer mass from known particle characteristics (size, composition), but there can be a great deal of variation in particle characteristics depending on the type of fuel burned, the combustion conditions, and so on. Reliance on lab generated particles to infer mass from field data can produce significant error in derived measures of mass concentration. For a multi-country epidemiological study this could require a significant number of gravimetric samples, and the costs and logistical difficulties in collecting those samples may overwhelm whatever advantages particle counters had over gravimetric samples in the first place.

HAP studies have typically employed area monitors to measure $PM_{2.5}$ mass concentrations inside the home. Area sampling has at least three advantages versus personal sampling. First, area sampling monitors do not need to be as compact as personal monitors; an area sampler can be larger and heavier than a personal monitor, it only needs to be light enough to be carried short distances and small enough so as not to interfere with normal household activity once in place. Secondly, area monitors can be powered by an electric outlet, or by a large portable battery. Personal monitors must be battery powered, and they must be light enough to carry comfortably for long periods, which are difficult goals to achieve simultaneously.

A significant limitation of area monitoring in HAP research has been that it does not measure personal exposure; which is problematic because the health outcomes epidemiologists study are more closely related to personal exposure. Studies using area monitors have tried to address this limitation through different means, for example by inferring personal exposure from recording or estimating the time spent by a person in proximity to a cooking fire and measuring HAP levels in that exposure micro-environment.

In the late 1990s improved equipment allowed some studies to measure personal exposure using direct reading instruments, such as optical particle counters, personal monitors, or a combination of techniques (37). Earlier studies were somewhat limited in the sizes of particulate matter they could accurately measure with the equipment available. While studies before 1990 mostly looked at total suspended particulates, researchers have better able to directly measure $PM_{2.5}$ since 2000 (8).

Proponents of personal exposure measurements have asserted that area measurements are vulnerable to misclassification and do not capture the full range of exposures present in the cooking space (36). Stationary air quality monitors in a cooking area are also unable to capture the heterogeneity of HAP concentrations throughout the home environment, and thus are vulnerable to misclassification of exposure (17). HAP levels can vary significantly within small distances, horizontally and vertically, away from the cookstove or fireplace emission source. Studies of HAP have found that personal exposures varied greatly according to time spent in discreet spatial micro-environments inside the home. These environments could be very small (<0.5m) and were delineated by proximity to the main emissions source, a cooking fire or stove. Personal exposures were a function of time spent in the different micro-environments and activity in those environments (37,54).

There is good evidence to show that gender and HAP exposure are highly correlated (55,56). Time spent in specific micro-environments, specifically those with highest $PM_{2.5}$ concentrations nearest the cooking fires and stoves, are highly correlated with female gender roles of cooking and childcare. Up to 75% of a woman's HAP exposure can come from time spent in these areas, while almost none of a male's exposure burden came from same source. Exposures could also vary significantly when starting or tending to a fire (4,16,37). These results would not normally be captured by single stationary area samples or by proxy measurements of exposure.

However, until very recently the prospect of conducting large-scale quantitative measurements of personal exposure were dismissed as not practical due to costs and logistical constraints (1,5,17,30,37). Some have pointed to specific issues with how different types of personal monitors work; for example, gravimetric monitors are time integrating and so cannot detect discreet high emission events (16). Conversely, given the highly heterogeneous nature of HAP, optical particle counters require gravimetric reference measurements for calibration in nearly every combination of household characteristic, a burden which could make using these types of monitors impractical. Others have pointed out that most personal exposure monitors were developed for occupational exposure assessments, and so were not well suited to HAP exposure research in LIC and MIC where exposure levels could be very high and sample periods much longer than those typically found in occupational settings (17). Other older studies dismissed personal exposure monitoring as impractical due to the technical complexity of available monitors, and the skilled staff required to operate the equipment (17,35). Despite, or perhaps because of, these perceived obstacles many studies have called for the development of lighter, cheaper, easier to operate air quality monitors which could be used for both area and personal exposure monitoring (55,57).

Despite the advances in air quality monitor technology there is no monitoring technology or solution on the horizon that would allow census level sampling. Even if future epidemiological studies are able to collect thousands of samples there will always be a need to develop models of exposure at the population level.

1.6 Household air pollution modelling

A major difficulty facing an epidemiological study of the health effects of HAP exposure is the lack of quantitative measurements. The costs and logistical constraints associated with gathering good quality measurements of HAP in communities that are frequently difficult to access and work in has meant that there is a relatively small pool of data compared to the populations of interest.

Researchers looking at HAP have in many cases chosen not to measure particulate matter (PM) directly; instead they modeled estimates of exposure from other sources of data, like national survey data, or using combined regional research results (46,51). Various methods have been used to do this for large-scale cohorts, including:

1. Cross-national regression analysis, where the exposure-response relationship in one country is used to derive exposure for another working backwards from health outcomes data (8). This technique relies on all causes of mortality, which include indirect effects, and thus tends to overestimate health impacts.
2. Multiple surrogates for direct exposure measurements; for example using outdoor air pollution measurements with measures of SES or location (16).
3. Fuel based approach to model burden of disease from HAP exposure which uses relative risk estimates from health outcomes associated with HAP from solid fuel use. This is more of a bottom-up method, and it tends to use a binary classification of fuels (dirty versus clean). This approach has the advantage of using a large number of health outcome data from countries with high levels of solid fuel use. This technique has been used by the WHO's comparative risk assessment (CRA).

The advantage of the exposure proxy approach has been that it allowed rapid and inexpensive modelling for large populations. Using exposure proxies, like clean versus dirty fuels, also had the advantage of fitting with the available epidemiological results, which used the same metrics (1). The disadvantage of this approach has been that it had difficulty explaining how the assessed variables, such as fuel types selected and SES, combined to produce the observed outcomes (4). Furthermore, using broad categorical, and sometimes binary, predictors derived from national level survey data to model HAP exposure could lead to misclassification; HAP exposures are the complex products of the combination of many factors, factors that are not necessarily captured by exposure proxies.

Epidemiologists studying HAP exposure have in some cases addressed the misclassification problem by taking quantitative measurements of household and personal exposures together with observations of predictive variables, like types and quantities of fuels used, the presence or absence of ventilation features, and so on (1). Researchers have used these models to estimate HAP exposures at multiple levels, from the regional down through progressively more specific levels to the household and finally the personal, where each increasingly detailed level of exposure model requires correspondingly more specific predictors of exposure (43).

The barrier to building more specific models of HAP exposure then becomes the costs associated with collecting data on predictive exposure factors. Fortunately, these data can come from other health studies, and can be assembled from multiple sources. While this can be tedious, it has been cheaper and faster than gathering actual exposure measurements.

As one important example, Balakrishnan et al, 2004 (43) and 2013 (1) modeled HAP in rural Indian households according to household characteristics available from large national surveys. Balakrishnan's 2004 objectives were to measure HAP levels, specifically $PM_{2.5}$, in rural Indian households relying heavily on solid fuels for domestic energy, model those levels using questionnaire responses, and to use time/activity data at the household level to estimate the personal exposure of different household members (43).The Balakrishnan study also collected categorical data for potential proxies of HAP exposure. The study used Indian census data and questionnaires to collect information from study participants (43). Variables assessed are shown in table 1, below. Fuel type was assessed for cooking, heating water, and heating separately. Balakrishnan also questioned participants about household practices related to HAP, such as cooking times and durations, and smoking (43). The variables assessed by Balakrishnan are shown in table 1.

Table 1: Predictive variables of HAP exposure assessed by Balakrishnan et al

Variable	Values
Fuel Type	Wood, Crop residue, Dung, Coal, Charcoal, Kerosene, Electricity, LPG, Bio-gas, Other
Fuel Amount	Mass of solids or volume of liquids and gasses
Kitchen Type	Indoor with or without partition, Detached building, Open air
Kitchen Ventilation	Poor, Moderate, or Good
Roof Materials	Bio-material, Tiles, Corrugated metal, Asbestos sheet, Brick, Stone, Concrete, Other
Wall Type	Bio-material, Mud, Brick (cured or not), Wood, Metal sheet, Stone, Concrete, Ekra
Floor Type	Mud, Wood, Bamboo, Brick, Cement, Tile, Other

Collected data was analyzed using a combination of linear regression modeling followed by logistic regression and classification and regression trees (CART) using binary dependent variables. The study used a binary exposure classification system to maximize the applicability of their results, despite the loss of statistical power this method entailed. Predictive household variables were selected using univariate linear regression with an exclusion criterion of $p > 0.25$ and a stepwise selection method. Interaction between predictor variables was screened for using two-way ANOVA (43). The 2013 study used ANOVA models of each dependent/independent variable combination, predictors with significant F-test results were included in the final multiple regression model (1).

1.7 PURE and PURE AIR studies

The Prospective Urban and Rural Epidemiological (PURE) study is a very large scale prospective cohort study of a broad range of environmental, social, economic, and biological factors that contribute to global morbidity and mortality from CVD and other chronic diseases (58–61). PURE has enrolled more than ~250,000 participants, aged 35 – 70, in 628 communities from 26 countries, including many communities with high rates of low quality fuel use. PURE has a planned duration of more than 10 years, and to date it has a very high (≥90%) retention rate (58). PURE has collected comprehensive direct measures of health, including lung function, blood pressure and medical history, from these participants as well as a rich observational data set of many factors that can be used to model HAP. PURE selected participating countries in order to capture a mix of communities with a broad range of economic development levels, both between and within selected countries. Communities, defined in PURE as discreet groups each with a common identity in a defined area, were selected to facilitate enrolment, engagement, retention and follow-up. Individuals, aged 35-70, were recruited to achieve a broadly representative sample of their communities, and with consideration given to retention and access for follow up (58).

The PURE study's comprehensive cohort presents a unique opportunity to study HAP related health outcomes across a very broad array of household settings in LICs and MICs with high rates of low quality fuel use. PURE did not originally collect any measurements of HAP, at the household or personal exposure levels. Nested within PURE, the PURE AIR study is a multi-country epidemiological study of the association between respiratory and cardiovascular diseases and exposure to both outdoor and household air pollution (62). A primary objective of this study is to address the current uncertainties surrounding the global impact of HAP on cardiopulmonary health by conducting thousands of detailed $PM_{2.5}$ exposure measurements from PURE enrolled households. Specifically, the PURE AIR study measures $PM_{2.5}$ concentrations in the kitchen areas of selected households, and personal breathing space measurements in a subset of those selected households. PURE AIR is a complimentary study to PURE and leverages that larger study's data to:

- Assign outdoor air pollution exposures to PURE enrolled communities.

- Assign indoor air pollution exposures to PURE enrolled participants, quantify independent and joint associations between indoor and outdoor air pollution with respect to CVD and COPD.
- Investigate the exposure-response function of HAP in the non-linear region between ambient outdoor pollution levels and exposure levels associated with smoking.

These household $PM_{2.5}$ exposure measurements are collected from ~5,000 PURE participating households. PURE AIR also collects personal $PM_{2.5}$ exposure measurements for the primary male and female residents from a subset of ~10% of sampled households for an additional ~1,000 personal exposure measurements. Participating households were selected from communities in ~10 LIC and MIC with significant use of solid fuels for cooking and heating. Measurements were targeted to PURE partner institutions in countries with a high level of solid fuel use in rural communities: primarily China, India, Pakistan, Bangladesh, Tanzania, Zimbabwe, South Africa, Chile and Colombia. This constitutes one largest quantitative measurements of HAP ever attempted.

PURE AIR provides equipment and technical support to the PURE partner institutions in their respective countries who will then carry out fieldwork with their own staff. This remote support and administration approach is a departure from previous projects in LIC and MIC where either foreign academic carried out fieldwork directly, using local researchers as assistants, or from projects were academics from LIC and MIC carried out their research work without assistance from outside technical support. PURE AIR's approach represents a new and more equitable approach to global scale research work, and if successful could serve as a template for future collaborative research projects.

The PURE AIR study also applies a detailed questionnaire to participants in households selected for sampling; this questionnaire is based largely on the baseline enrolment questionnaire issued to participants in the PURE study. Responses to the questionnaire will illuminate household conditions and behaviours thought to influence $PM_{2.5}$ levels; responses will also be used to gauge the degree of change in households from their enrolment in PURE to their current state. The PURE AIR study will combine the household and personal $PM_{2.5}$ exposure data with the results of the simultaneously issued questionnaire of observable household factors to produce new quantitative models of HAP exposure at the community and household level. Previously models of HAP exposure had only been attempted at the state and national level (1). The PURE AIR study will also explore the viability of modelling personal $PM_{2.5}$ exposure.

The work in this thesis was conducted to support the exposure assessment strategy deployed in PURE AIR, details of which are provided elsewhere (63).

1.8 Rationale

HAP exposures are a significant, and preventable, contributor to global morbidity and mortality. Despite this the ways in which HAP exposure contribute to the incidence and progression of specific diseases, such as CVD, is not well understood; more so in countries where a significant portion of the population relies on low quality fuels, solid and liquid, for their domestic energy needs. Most studies agree that there has been a general lack of data concerning how HAP exposures vary by cooking location in the home, types of fuels used, and if there are seasonal variations in HAP levels (35–37). There has also been a general assumption that pollution characteristics for a given fuel type are the same across all regions. For example, it was assumed that emissions from burning crop residue are the same in India and Tanzania even though the crops in questions are different. While the soundness of this assumption has been in doubt (64), there do not appear to be any studies of HAP exposure which specifically address variability in emissions for a given fuel type across multiple regions.

Much of the uncertainty surrounding the connection between HAP exposure and disease has arisen in large part from the use of proxy measures of exposure, and even second order proxy measures, by global disease burden analyses (38). Such studies have used high level proxy indicators, such as measures of socio-economic status, to derive which fuels were used at the household level, which in turn inferred HAP emissions. The result has been an association between indicators of fuel use and health outcomes gathered at the national or sub-national level. It seems very likely that such remote proxies for HAP exposure are vulnerable to misclassification and imprecision. Rectifying these deficiencies requires an epidemiological investigation with sufficient HAP measurement data to identify significant predictive factors of HAP exposure. These would include fuels used, cooking location within a home, ventilation features and more. This in turn requires the ability to gather good quality quantitative measures of HAP exposure in a sufficiently large sample size to then confidently predict exposures.

Collecting such HAP measurements requires affordable equipment that can be deployed with minimal training and supervision. While such equipment does not need to be as precise and sensitive as monitors designed for use in medical research or industrial compliance monitoring it still must be reasonably accurate and, more importantly, consistent across many thousands of samples in very different environments. The development of new monitors together with the validation of good predictive household variables will make large scale HAP sampling campaigns possible, which in turn will enable the development of superior exposure models. Such exposure models will be indispensable in more accurately identifying the portion of the global disease burden specifically attributed to HAP exposure, and in evaluating the effectiveness of interventions. Both of which will eventually support the reduction in HAP exposure and associated suffering

To this end, this work recruited households and individuals enrolled in the PURE study to participate in HAP measurement in order to meet the following objectives:

- Compare the performance of a prototype filter based gravimetric monitor against a reference gravimetric monitor in measuring household HAP levels in PURE enrolled households.
- Compare the performance of 2 prototype light scattering particle counters against a reference particle counter and a reference gravimetric monitor in measuring household HAP levels in the same PURE enrolled households.
- Evaluate the performance of the same prototype filter based gravimetric monitor in measuring personal HAP exposure for both the primary male and primary female resident of each PURE enrolled household.
- Test the suitability of the PURE household environment questionnaire as a basis for predictive exposure modelling by combining the results with the HAP measurements

from the filter-based reference device to build a simple predictive model of household HAP exposure. Also, determine if any additional household characteristics would improve such a model by making additional observations and combining the results with the simple predictive statistical model.

- Develop a field sampling protocol for the UPAS monitor in support of the PURE AIR project.

2 Methods

2.1 Overarching study

The specific aim of this study was to measure HAP in the kitchen areas of 60 households, split evenly between two villages in rural India, with reference and prototype monitors. The performance of the prototype monitors was evaluated by evaluating success in 24- or 48-hour sample collection and by comparing measurements successfully taken by the prototype monitors to those by the reference monitors. In addition, personal HAP exposures were measured for the primary male and female residents in each household using the prototype gravimetric monitor. Personal HAP exposure measurements were compared between genders and to matching household measurements. Simple linear regression models of kitchen area HAP were made using measurements taken from both villages and observations of household characteristics based together with responses to a questionnaire comprised of questions from the original PURE baseline questionnaire and additional questions drawn from other studies.

2.2 Location selection

The PURE project has spent more than a decade building a very large prospective cohort for its research. PURE's selection of study countries, communities, households and participants is detailed elsewhere (58). The PURE AIR project has leveraged this extensive cohort for its investigation of the links between HAP exposure and CVD. As a pilot project in support of the PURE AIR project this work made use of the same PURE cohort and PURE member research institutions. The PURE AIR study secured the cooperation of the St. John's Research Institute (SRI) of Bangalore, and the Postgraduate Institute of Medical Education and Research (PGI) from Chandigarh, India. At the request of PURE AIR, both SRI and PGI agreed to facilitate fieldwork by providing two English speaking staff members to act as community liaisons. Both institutions also arranged food, lodging and transportation to and from participating communities.

Staff from both institutions recruited households and individuals in each of their selected communities such that the households selected represented the baseline PURE fuel use characteristics of their respective communities with a slight oversampling of households using solid fuels. The rationale behind oversampling these households was that there was an expectation that there would be little difference in HAP levels in households relying exclusively on gas or electricity for cooking, and thus a larger sample pool of these households would not add meaningful power to the model of HAP exposure.

2.3 Participant recruitment

Through local PURE partner institutions this study sought to recruit the primary male and female members of each household for personal exposure monitoring. Primary male was defined as the most senior male member of the household; primary female was defined as the most senior female household member responsible for cooking during the sample period. Recruitment of households and persons was handled by local staff from SRI and PGI. Potential participants were approached opportunistically according to the field staff's understanding of availability and willingness to participate. Participants were contacted initially several days before sampling and again one to two days in advance. In some cases where a participant household could not participate on the day scheduled for sampling they were rescheduled, and an alternate household was contacted by SRI or PGI staff and asked if they could participate immediately. In either case participants were asked for consent according to the standard practise set out by the authorizing institutional review board.

2.4 Ethics approvals

All persons recruited for this project were already enrolled in the PURE project. The PURE project had not previously sampled household or personal HAP exposure. It had, however, taken detailed information on each participant at their enrolment and had also conducted medical examinations and tests with participants, specific tests and examinations varying by location and local partner. The PURE project had also secured ethics approvals for its work from all concerned review boards. Likewise, the PURE AIR project had also secured ethics approval for its work. The fieldwork for this project was covered under PURE AIR ethics approvals. Specifically, the protocol for this study was approved by the UBC behavioural research ethics board (BREB) (H15-01268 and H14-02982). Approvals for the fieldwork component of this study were also granted by the equivalent research ethics boards at SRI and PGI.

2.5 Prototype devices

Previously, the PURE AIR study had identified the UPAS from Access Sensors as potential monitor to use in its survey of HAP in thousands of PURE enrolled households. PURE AIR also identified two other devices, the Tzoa and the PUWP, that could potentially augment the gravimetric UPAS with the ability to measure the duration and magnitude of exposure events in the household environment. The UPAS prototype tested in this study was the same device described by Volkens et al. (28) (who refer to it as a serial prototype) and became known as version one (V1.0) of the UPAS, as referred to in Arku et al. (38). The Tzoa and PUWP device tested did not have model number designations, but the Tzoa tested here was the first field operable device produced by Misty West contract engineers (65).

This work focused on evaluating the performance of these three prototype air quality monitors for use in the PURE AIR study, either as the primary measurement instrument in the case of the UPAS, or as a supplemental device, in the case of the Tzoa and the PUWP. Testing these prototypes in PURE enrolled households enhanced the applicability of the results to the PURE AIR study.

The PURE AIR study had a number of requirements from a potential monitor:

1. Reliability: Any air quality monitor used by the PURE AIR study would need to be very durable and robust. A suitable monitor would need to be able to take dozens, perhaps hundreds, of measurements between service intervals. For household $PM_{2.5}$ HAP measurements, the monitor would need to be able to operate in very hot and humid conditions where $PM_{2.5}$ concentrations would potentially be high (>500µg/m^3) over a 24- to 48-hour sample period, and very high (>2,000µg/m3) for short periods. Personal

monitoring would additionally stress the device by exposing it to vibration, small impacts, precipitation and perspiration.

2. Endurance: The ability to capture multiple days of cooking cycles was a key feature for the PURE AIR project. Sample durations of 48-hours help to reduce the influence of atypical cooking events on time integrated $PM_{2.5}$ measurements. A suitable monitor could employ duty cycles to extend its run time, but the cycles would have to be very short, preferably less than minute, so as not to miss short but intense personal exposures that can occur when starting or tending to a fire.
3. Consistency: A suitable monitor must be able to consistently and accurately measure both high and low HAP levels.
4. Data security and redundancy: A suitable monitor must be able to securely retain whatever electronic record of a sample it creates, such as air-flow rate in a filter-based device or particle counts with attendant environmental conditions. This would reduce the possibility of lost data if a monitor were lost or damaged.
5. Ease of use: Monitors designed for use in industrial or medical applications can have complicated calibration and/or operating instructions. A central goal of the PURE AIR project was to have field staff from local partners conduct sampling in PURE enrolled households. Overly complex devices could be a barrier to quick training and sample collection and would require overly complex instruction manuals.
6. Low cost: Air quality monitor designed for use in industrial and medical settings in North America and Europe can be very expensive. The high cost of these devices precluded their use in PURE AIR.
7. Compact and lightweight: Extended duration personal exposure samples requires monitors which are small and light enough to be worn comfortably by a participant for up to 48-hours, except when sleeping.

The PURE AIR project selected three devices for evaluation. While each device was at a different stage in its respective development, they were each thought to be far enough along that they could be tested in the field with a reasonable expectation of success. The performance of the selected prototype monitors was evaluated by deploying them simultaneously with reference monitors during HAP measurement fieldwork in India in the summer of 2015. The performance of the prototype monitors was assessed by comparing the number of samples collected successfully and their measurements against reference monitor results from the same households.

2.5.1 UPAS

The Ultrasonic Personal Aerosol Sampler (UPAS) by Access Sensor Technology of Fort Collins, Colorado is a very compact, lightweight and durable gravimetric monitor designed to be suitable for both stationary indoor air quality measurements and personal exposure measurements. The UPAS evaluated here (V1.0), while still a prototype, was in a more advanced state of development than the Tzoa and PUWP monitors. Ten UPAS monitors were provided for evaluation. The UPAS used a novel solid-state piezoelectric micro-pump to pass air through a cyclone pre-filter and then a sample filter. In this case the UPAS was set to a 1 lpm flow rate and used a 37mm Teflon coated glass fiber filter, 2µm pore size (fiberflow, PALL corporation). The pump's design made it very quiet, durable, compact and energy efficient. An integrated mass-flow sensor coupled with air temperature, pressure and humidity sensors allowed the UPAS to maintain a stable flow rate over time, as flow resistance increased from mass deposition on the sample filter. The UPAS units evaluated had an integrated light sensor capable of detecting if the devices were indoors or outdoors, as well as accelerometers and GPS capabilities, (the GPS units were not enabled during evaluation). The UPAS bodies were made from machined injection molded plastic with integrated handles for nylon webbing.

The evaluated UPASs used two cellphone batteries which usually allowed units to run for up to 35-hours continuously without duty cycling, external batteries were used to augment the UPASs for longer 48-hour samples. These units were restricted to simple on/off operation and were not programmable for airflow rate, run time, duty cycling, or pre-programmed start/stop times. The UPAS monitors recorded detailed run logs, including mass flow rate, air temperature and humidity, cumulative volume sampled, GPS (disabled in this case), accelerometer and machine state parameters to a .txt log file at 10 second intervals. These data were recorded on to removable microSD cards in each device. Volckens et al. tested an earlier development version of the UPAS, similar to the units evaluated here, against reference devices, an EPA federal reference configured URG cyclone and a SKC PEM; the UPAS measurements were found to correlate very strongly with both reference device in a series of laboratory tests (R^2>0.96) (24).

One issue of note with the UPAS monitor evaluated here was its use of glass fiber filters (PALL fiberflow), which are rare compared to the PTFE membrane filters used in most gravimetric monitors and consequently were difficult to acquire. These glass fiber filters were known to be vulnerable to adsorbing semi-volatile aerosols, which could lead UPAS measurements to overestimate particulate mass concentrations. The glass fiber filters were also very fragile and required very careful handling.

2.5.2 Tzoa

PURE AIR selected the Tzoa, a consumer-oriented particle counter, for evaluation as a complimentary air quality monitor. The Tzoa was designed for both in-home and personal air quality monitoring. The version evaluated here was a first-generation prototype fabricated by Misty West engineering in Vancouver, BC. Six Tzoa monitors were provided for evaluation.

This monitor was the smallest and lightest devices evaluated, about the size of a hockey puck and about 150 grams. The Tzoa used a laptop cooling fan to pull air through a maze-like passage, which acted as a kind of pre-filter impactor, and then through the path of an infra-red laser, without focusing lenses, and 90-degree side scatter light sensor mounted to a custom printed-circuit board. The Tzoa also had a built-in relative humidity sensor, but no other sensors. The Tzoa units evaluated were powered by a 2,880-milliamp hour (mAh) cellphone battery and could be augmented by an external battery for extended run times. The Tzoa's onboard computer analysed feedback from the light sensor for intensity and duration and then derived a particle count, based on the device's factory calibration against a reference particle counter using a common exposure. The evaluated Tzoa monitors were calibrated against salt-particle aerosols with a TSI DustTrak desktop monitor by Misty West prior to fieldwork; it was not possible to calibrate Tzoa monitors in the field. The monitors recorded total particles counted over five second intervals and wrote that sum to a .CSV file together with relative humidity for the time interval. The Tzoa recorded data as a .CSV file to a removable microSD card. Recently a study has evaluated a newer version of the Tzoa monitor, the Tzoa-R, which has more advanced features like duty cycling (66).

2.5.3 PUWP

PURE AIR selected the Portable University of Washington Particle (PUWP) sensor for evaluation as a complimentary air quality monitor. The PUWP was developed by Dr. Edmund Seto of the University of Washington as a low-cost, compact, portable aerosol monitor for use in urban traffic pollution studies. The PUWP was intended to be significantly cheaper than established aerosol monitors, like the TSI DustTrak, and thus a better option for researchers who do not need the TSI's advanced feature set, like simultaneous measurement of size-segregated mass fractions (67,68). A very early development version of this device was included in this work's fieldwork trials in India in the summer of 2015.

This device used a Shinyei sensor, a recently available mass-produced low-cost optical aerosol sensor in place of more expensive sensors. This sensor uses a resistor to heat air, which then passes through a light bean from an infrared LED, a photodiode detector mounted at a 45-degree angle captures scattered light with a single focusing lens. Onboard electronics process the signal from the light sensor, first filtering out small signals with a pass-band filter and then measuring the duration of the remaining signals; in effect, the Shinyei measures the opacity of the sampled air stream (69). The PUWP, as evaluated, had a flexible internal configuration; different augmenting sensors and features could be added as required, including GPS, temperature and relative humidity sensors, though none of these were equipped in the evaluated devices. The evaluated PUWP monitors had the capacity to run on battery power from 4 AA batteries and/or on an external power source. PUWP devices have been used alongside reference particle counters (TSI DustTrak with $PM_{2.5}$ impactors) to measure traffic pollution in China (67). In this case there was very good agreement with the reference devices (R^2 >0.86), in conditions with high aerosol levels. However, in this case there was also substantial disagreement between PUWP devices exposed to the same conditions, necessitating frequent co-calibration.

2.6 Reference devices

The Harvard impactor (HI) was selected as the primary reference device for measuring $PM_{2.5}$ HAP. It is a well-established monitor, having been used in the well-known Harvard Air Pollution Health Study. The same, or a similar, device has been used in many other air pollution studies (70). Briefly, the HI is a gravimetric air filter with a size selective inertial impactor driven by an external air pump. Air is drawn into the HI at a fixed 10 liters per minute (LPM) and then first through a sharp cut impactor with an oiled sintered metal impactor plate, which removes particles larger than 2.5 microns from the air stream, before passing through a filter mounted in a plastic adaptor in the base of the impactor (71). In this case the filters used were 37mm PTFE filters, 2μm pore size, with plastic support rings (Teflo, PALL corporation). The HI's advantages were its simple and durable construction, ease of maintenance, it requires no adjustments, and that it can be assembled and disassembled without tools. The disadvantage of this particular monitor, and other similar designs, were that the impactor and pump together were quite large, (both impactor and pump were housed inside a Pelican 1450 case (37 x 26 x 15.5cm)), and heavy (~5Kg). This made them too heavy to mount to a stand and far too heavy to contemplate for personal exposure sampling. The Leyland Legacy pump (SKC corporation) was selected to power the HI. This pump was a large and robust design and having been used for many years in a variety of applications and it is well-know and widely trusted.

The TSI DustTrak model 8534 was selected as the reference particle counter because it was a well-established and widely used air quality monitor. Its portability and internal battery also made it well suited for use in this project. The DustTrak 8534 is a sophisticated particle counter with the ability to measure the mass of particles in multiple size bins (PM_1, $PM_{2.5}$, PM_{10}, and total PM) simultaneously. It uses an air-sheath system that keeps particles isolated from the internal sensors, (allowing extended operation in high pollution environments without contamination). It can also handle a wide range of aerosol concentrations (0.001 – 150mg/m^3) and aerosol sizes (0.1 – 15μm) (72). The advantages of this device for HAP measurement were its ability to simultaneously measure multiple size fractions and its real-time measurements allow detection of very brief changes in exposure levels. The disadvantages of this device were that it needed to be calibrated against a gravimetric sample to ensure quality mass measurements (this was taken care of in fieldwork as the DustTrak was always collocated with a HI), its high rate of power consumption which limited its endurance, and its expense (~$10,000 US, meaning that only one unit was available to this project).

2.7 Household air pollution modelling

Quantitative measurements of $PM_{2.5}$ HAP were conducted in summer 2015. PURE AIR arranged with SRI and PGI to sample 60 households, split evenly between two PURE enrolled villages in rural India with high rates of solid fuel use. For the purposes of modelling, HAP measurements of kitchen area $PM_{2.5}$ concentrations in each participating household were taken with the reference HI monitor. Household characteristics were assessed by observation of each home's physical features and by local PURE staff completing a short questionnaire with the residents of the household. Questions were given, and answers recorded in the local dialect, then translated to English by PURE field staff. Responses, observations and measurements were then tabulated for each household.

The HI monitors used here were loaded with 37mm PTFE filters, 2µm pore size with plastic support rings (Teflo, PALL corporation). HI monitors were driven by TSI Leyland Legacy pumps running at 10LPM. Assembled HI and pump sampling trains were calibrated with a BIOS DryCal piston type calibrator immediately prior to and following each deployment. $PM_{2.5}$ concentrations were calculated in the normal way following post fieldwork filter weighing and quality controls. For descriptive statistics, the data was left untransformed, for all other statistical tests the data was log transformed.

Predictive variables for the HAP model were drawn from the standard PURE enrolment questionnaire administered to all PURE participants, with additional variables added based on the other HAP research work, primarily Balakrishnan (1,43,73). The PURE enrolment questionnaire asked participants a series of questions about basic household characteristics and activities, such as whether they had access to electricity, owned land, and what their average monthly income was (74). This enrolment questionnaire was not originally designed to investigate HAP, but some of its questions are relevant to HAP modelling. A new questionnaire, specifically for this study with these questions was written for fieldwork (Table 2), (see appendix 2). PURE field staff translated the questionnaire into the local language for each sampled village. The questionnaire was given orally to participants following sampling during equipment collection. Observations were made during monitor placement and collection.

Table 2: PURE baseline variables and expanded variables included in questionnaire

Variable Name	PURE Baseline?	Units	Measurement Method
Electricity	Yes	Yes/No	Interview and observation
Primary fuel type	Yes	Single or mixed fuels*	Interview
Cooking Location	Yes	Inside, outside or both	Interview and observation
Cooking time outside	Yes	Whole months	Interview
Ventilation	Yes	Chimney, exhaust, open window	Observation
Roof Material	Yes	Various	Interview and observation
# Persons in household	Yes	Persons residing primarily in that home	Interview
Secondary fuel type	No	Single or mixed fuels	Interview
Solid fuel amounts	No	Kilograms	Interview
Cooking time	No	Hours	Interview
Total tobacco products	No	Pieces	Interview
Wall Material	No	Various	Interview and observation

Floor Material	No	Various	Interview and observation
Ventilation Rating	No	Poor, fair, good	Observation
Cooking typical	No	Yes/No	Interview
Sensor distance from cooking location	No	Meters	Observation

* Original PURE baseline questionnaire did not allow for mixed fuels

Participating households were assessed for access to electricity, but participants were not asked about the reliability of electricity or the capacity of their connection.

The PURE enrolment questionnaire asked participants what the primary fuel they used for cooking was and allowed for 10 discreet fuel types (see appendix 2) with an 'other' category. Secondary fuel type was added to see if allowing for multiple fuel types could improve the HAP model. In this study, primary fuels were defined as the fuel used most for cooking during the sample period, secondary fuels were defined as the next most commonly used fuel during the same period. Participants were asked what fuel(s) they used and how much of that fuel they used during the sampling period. If participants could not estimate mass or volume, then staff would ask to see examples and then estimate mass or volumes to the best of their ability.

The cooking location question assesses where the household's cooking took place during the sample period. If cooking only took place indoors then the household was assigned indoors as a cooking location, likewise for outdoors. If cooking took place indoors and outdoors to any extent, then the household was assigned indoor and outdoor kitchen status. This assignment does not describe how cooking was split between two locations (e.g. big stove inside, small outside).

The ventilation variable recorded the presence of defined ventilation features in the cooking area of a sampled household. Open windows were counted if they were in sufficient proximity to the primary cooking location to appear to provide some measure of ventilation. Chimneys were assessed as any structure over a cooking stove or fireplace which gathered smoke and channeled it outside the home. Exhausts were any other feature which appeared to provide ventilation, but which were not windows of chimneys, such as a small opening with a fan or wire mesh. The ventilation rating of a home was a subjective assessment of the overall quality of ventilation in the kitchen area of a sampled home. Possible responses were poor, moderate and good. Poor was defined as conditions that were immediately uncomfortable, good was assigned to kitchens with no apparent HAP, and fair was assigned to all other observations. Similar assessments have been used in other HAP studies (43). This variable was included to see if an on-the-spot subjective assessment of air quality would correlate with measurements of $PM_{2.5}$. For homes with exclusively outdoor cooking a response of good was recorded.

The time spent cooking during the sample period was recorded based on the total time spent cooking and tending the cooking fire, including preparing and lighting the fire or stove. This variable was not meant to include time spent preparing ingredients, for example cutting vegetables or grinding spices or flour. The number of months per year a sampled household spent cooking outside was recorded in addition to cooking location. This variable does not count where cooking took place during the sample period. Instead it was recorded as a way of assessing how normal the cooking location was, during the sample period, compared to that household's average practise. If a household cooked exclusively indoors a value of zero was recorded, likewise if a household cooked exclusively outdoors a value of 12 was recorded. Participants, specifically those responsible for cooking, were asked if cooking practises during the sample period were typical or normal. Abnormal conditions were not defined to the participant, if a participant indicated that cooking practices were not typical they were then asked in what way was cooking atypical.

The total tobacco products variable was defined as the total number of discreet tobacco products consumed in the home near the cooking area or kitchen. Originally questions were asked about cigarettes, *beedies* (small hand-rolled cigarettes) and other types of tobacco products separately, but it proved difficult to define the different types of tobacco products in interviews, so the separate categories were collapsed into a single variable.

The original PURE enrolment questionnaire asked only about the roof material in each participating household. This was expanded to include wall and floor materials, both as a way of assessing the SES of a sampled household and as a way of describing the 'tightness' of a home, (the degree to which air inside a home was isolated from air outside the home). Where building materials were not obvious, for example painted surfaces, homeowners or residents were asked about construction materials. The PURE study recorded the number of residents in a participant's home at the time of enrolment. However, because enrolment was many years ago for all households participating in the PURE AIR project these figures needed to be updated. Household size was assessed as part of the standard post-sampling interview with participants. The gender and age of each household resident was also recorded.

2.8 Fieldwork methods

2.8.1 Pre-sampling preparation

Prior to deployment all monitors were charged using the appropriate chargers connected to voltage transformers (India uses 220v power). HI and UPAS monitors were cleaned, inspected and loaded with unused filters. Filter ID #s and monitor numbers were recorded onto daily log sheets (see appendix 3). HI/Leyland Legacy sampling trains were calibrated with a BIOS (now MesaLabs) Defender 510 flow rate meter. UPAS monitors were flow rate checked using a TSI 4100 mass flow meter, (the UPAS monitors did not have adjustable flow rates).

Tzoa and PUWP monitors were zero-calibrated by placing the device in a sealed Ziploc bag and running the device for a short period. Leyland Legacy pumps for the HI monitors were programmed to run on a 90-second on/off duty cycle for either 24- or 48-hour periods prior to activation. All other devices were activated or deactivated manually on deployment or collection, respectively.

Prior to sampling participants were asked for consent in their own language by field staff. Interaction and instruction for personal monitoring of the primary male and female resident in every household were carried out by a field staff member of the same gender, in accordance with local social standards.

2.8.2 Fieldwork travel and logistics

Fieldwork began in Belupalle village (13°10’53.7” North 78°37’10.1” West), Chittoor District in Andhra Pradesh, India on July 11, 2015. 27 households in Belupalle were sampled between July 11 and 31. Belupalle village is located in the southern Indian state of Andhra Pradesh, approximately 125 KM east of the nearest major city Bengaluru, Karnataka. Belupalle lies within a semi-arid climate zone running south to north in the middle of India, the local landscape resembles the American southwest with sparse vegetation and exposed rock and sandy soil. For the first round of fieldwork in Belupalle the field team was based out of the Emmaus Swiss Hospital near Palamaner. The team traveled to Belupalle village, a 30- to 40-minute trip, typically arriving before 6:30am, this allowed household monitoring to begin before cooking began for breakfast and before the male household members left for their fields or other work.

Fieldwork in Kheri village (30°33’53.3” North 76°59’52.0” West), Haryana, India began August 7, 2015 and ran until September 2 when fieldwork concluded; 33 households in Kheri were sampled. Kheri village is located in Haryana state, about 48 Km southeast of the city of Chandigarh in the same state. Kheri village in the north of India lies to the southwest of the Himalayan foothills in a humid sub-tropical climate zone with parklands of alternating stands of trees and open grasslands over rich organic soils. For the second round of fieldwork in Kheri village the field team was based in Chandigarh, Punjab and traveled to Kheri daily, a 90- to 105-minute trip, typically arriving at ~9:00am. This allowed household monitoring to begin after cooking for the morning meal had ended. In Kheri village most male participants were employed in their homes or in the village, so the later start time was not an issue. Male participants working on farms returned home to begin personal monitoring, their farms being located close to the village this was apparently not a hardship for them.

In both villages three households were sampled simultaneously. Sample periods were either 24- or 48-hours; 24-hour samples beginning Tuesday and Thursday, ending and collected on Wednesday and Friday. 48-hour sample beginning Saturday, ending and collected Monday. With either length of sample, it was the goal to begin sampling at a time such that meal preparation and cooking was not interrupted and when both male and female personal monitoring participants were available.

2.8.3 Household air pollution sample collection

In every participating home $PM_{2.5}$ HAP was measured using one HI reference monitor with Leyland Legacy pump and one each UPAS, Tzoa and PUWP prototypes. Some homes had additional Tzoa and PUWP monitors depending on how many functional units were available. Each UPAS, Tzoa and PUWP monitor was connected to an external cellphone battery pack with a micro-USB cable to augment their internal batteries and ensure full run times. A TSI DustTrak reference particle counter was placed in every third home sampled. An external battery was acquired and modified for use with the DustTrak for the Kheri village samples.

Monitors were placed as close to one meter away horizontally one meter above the floor from the primary cookstoves as possible without interfering with normal household activities. Most homes had small kitchen areas, ~2m x ~3m with one fireplace built into an exterior wall and one two-burner LPG stove on a counter or similar surface. Monitors were usually placed on a shelf or flat surface at the same height as the counter tops, or slightly higher. Typical counter heights were 1m – 1.5m above floor level. All monitors were checked for operability when deployed and again when collected; non-operational monitors were noted on the log sheet for the household.

2.8.4 Personal household air pollution exposure sample collection

Personal HAP exposure measurements for the primary male and female resident were taken in every household sampled with UPAS monitors. Each personal sample UPAS monitor was prepared in the same manner as UPAS monitors used for household sampling. Reference personal exposure monitors were not used in conjunction with the prototype UPAS monitors due to cost and logistical constraints, as well as the impracticality of having a study participant wear multiple monitors at the same time.

Male and female participants were instructed in how to wear the UPAS monitor for the sample period; participants were also instructed to remove the monitor for bathing and sleeping and were instructed to keep the monitor close-by while sleeping. UPAS monitors were attached to a section of nylon webbing with a plastic click-buckle and were worn either around the waist or over one shoulder; either method held the monitor close to waist level. Participants were asked if they had any problems or issues with the UPAS monitor on collection.

2.8.5 Household characteristics observations and questionnaire

At the end of every sample period monitors were collected for participating households and a standard questionnaire was issued to the primary female resident of the household sampled when possible, or the person most involved in cooking when not (appendix 2). This questionnaire was based on the original PURE baseline questionnaire given to all participants when they were first enrolled in PURE. The questionnaire was given in participant's native language, and responses were translated to English by field staff.

All households were also examined for the presence of a standard list of features when monitors were collected (appendix 3). These items were not included in the questionnaire, but if the answer was unclear the residents were consulted. The features assessed were:

- Construction materials used in roof, walls and floor of the home. Building materials were assessed based on appearance and by asking residents.
- Electricity?
- Kitchen type: outside, detached building, inside with no partition, inside with partition.
- Ventilation features: chimney, windows, exhaust openings.
- Number of ventilation features in total.
- Presence of separate heating ventilation.
- Subjective assessment of ventilation: poor, moderate, good.
- Distance from monitors to primary cookstove: lateral, vertical.
- Fuel switching? Was more than one type of fuel used during sample period.
- Number of persons living in household during sampling, age and gender of each person.

2.8.6 Post-sampling

At the end of each household and personal sample field staff collected all equipment, made household observations, and conducted the questionnaire with residents. All equipment was then inspected for damage, participants were asked if any equipment, household or personal, was a problem for them during sampling. After returning from either village HI and UPAS devices were flow rate checked, and all monitors and batteries were recharged. HI, Tzoa and PUWP monitors were disassembled and cleaned as much as possible. The intake cyclone on the UPAS monitors were removed and cleaned. The Tzoa monitors were disassembled and cleaned as much as possible with a kim wipe. The PUWP monitors were more difficult to clean, the internal Shinyei sensors were permanently sealed and not accessible. All filters were resealed in petri dishes. Data from each monitor, except the Leyland Legacy pumps, were transferred to an encrypted UBC laptop, and sample logs were copied into the same computer.

2.9 Lab Methods

2.9.1 Filter weighing

Prior to weighing all filters were stored in the UBC microbalance room for at least 72 hours. Microbalance room average conditions were 25.3°C (SD 0.86) and 43.4%RH (SD 2.01). Filters were weighed by hand on a Sartorious M5P scale. Filters were weighed prior to fieldwork in May and June of 2015, post fieldwork weighing took place in September and October of the same year. Post fieldwork, filters of either type were examined for damage or signs of contamination. Any filter with signs of damage or contamination were not weighed post fieldwork, all other filters including blanks were weighed normally. Damaged filters were retained alongside undamaged and weighed filters. Filters were weighed, and mass concentration calculations were performed in the normal way for each successful gravimetric sample. See appendix 4 for details.

2.9.2 Filter absorbance measurements

Light absorbance measurements for all filters were made after filter weighing was complete. All absorbance measurements were made using a Diffusion Systems Model 43 smoke-stain reflectometer using that instruments standard operating instructions (see appendix 4). In brief, the light absorbance of an exposed filter is an indication of the amount of elemental carbon () from combustion deposited onto the filter. Absorbance is a function of the area of the filter over the volume of air passed through the filer multiplied by the natural log of the ratio or the reflectance of an exposed filter over the reflectance of an unexposed blank filter. The formula for this is:

$$a = \frac{A}{2V} \ln\left(\frac{\mathrm{R_F}}{\mathrm{R_S}}\right)$$

Where

- a = absorbance
- A = area of the stain on the filter (m^2)
- V = volume sampled (m^3)
- R_F = average reflectance of the field blank filters
- R_S = reflectance of the sample filter as a percentage of R_0, where R_0 is the clean control filter (set to 100.0)

2.10 Statistical methods

All statistical analyses were performed using JMP version 13 by SAS software.

2.10.1 Successful versus failed household and personal samples

After all undamaged filters were weighed, each household and personal sample was analyzed to determine if the sampled could be deemed successful and considered for further analysis, successful meaning the monitor in question operated as designed, physical samples were undamaged and data from sampling were recorded properly. Filters and data records from all samples, both successful and not, were retained. All samples were evaluated as successful if they met the following criteria:

- Samples must have covered the intended sample time period, either 24- or 48-hours (within a tolerance of +/- 0.5hrs, depending on time of collection). Short samples were deemed not successful.
- HI/Leyland Legacy samples must have flow rate measurements from before and after sampling of 10LPM +/- 0.1LPM
- UPAS sample logs must show average flow rates of 1LPM +/- 0.1LPM with no momentary interruptions or significant deviations.
- All Tzoa and PUWP samples must have data files containing particle count data for the full length of the sample.
- All TSI DustTrak logs must have data files containing particle count data for the full length of the sample period with no error or warning messages.
- All filter-based samples must have a pre- and post-sample weight and a complete associated run log.
- All devices must have successful samples from at least half of all sample locations to be considered for further analysis.

2.10.2 Impute missing measurements

Where prototype measurements of household HAP exposure were not successful, replacement values could be imputed using other data. Missing reference device measurements were not imputed. The pool of measurements was not large enough to reliably derive a missing reference device measurement from household characteristics. It was not logical to impute a missing reference device from a prototype device measurement from the same location, this would defeat the purpose of having a reference device. Imputation was done only within data from a single village. It was expected that measurements would differ significantly by village. The imputed values were only used to compare prototype to reference monitor performance, they were not used in modelling as only reference device measurements were used in modelling.

Missing prototype device measurements were imputed only if both of the following conditions were met:

- The ratio of missing measurements to successful measurements, within a village, was sufficiently small. This was set at 50%.
- The correlation and regression between successful prototype measurements and reference device measurements within the same village was high and significant. This was set at 0.8 for both correlation and regression, with an alpha of 0.05.

Missing measurement data for a single household was calculated from the following formula:

$$P_m = R_h \times \bar{P}_v / \bar{R}_v$$

Where:

- P_m = Prototype missing measurement for a given household
- R_h = Reference measurement for the same household
- $\bar{P}_v$ = Average of all prototype measurements from the same village as the missing measurement.
- $\bar{R}_v$ = Average of reference measurements from all households with a successful prototype measurement.

This technique was simple to apply and understand, and it was sensitive to the overall nature of measurement data from within a village.

This technique was not applied to missing personal HAP measurements for two reasons:

- Personal HAP exposure measurements were not strongly correlated with household HAP exposure measurements
- There were too many missing personal HAP exposure measurements to reliably form an estimate of average personal HAP exposures.

2.10.3 Statistical analysis methods

Observational data of household characteristics were converted into whole nominal values for the JMP software to work with. At the same time, similar characteristics were collapsed and combined into common variables (appendix 1). Lognormal data from $PM_{2.5}$ and light absorption measurements (hereafter absorption) from the reference HI and prototype UPAS monitors were transformed with the natural log (*ln*). Absorbance measurements of some filter samples produced negative values, meaning the sample became more reflective. This was assumed to be an erroneous reading as the material deposited of either type of filter did not make them more reflective. Such samples were assigned an absorbance value of one, indicating no change in absorbance compared to a blank.

In order to assess the performance of prototype monitors $PM_{2.5}$ and absorption measurements were tested with bivariate fit tests, including; graphical plot of x and y variables with regression equation and R^2 value. Correlations between household measurements of $PM_{2.5}$ and absorption were calculated with Spearman's Rho test of ranked values. Regression and correlation analyses were also performed for male:female household $PM_{2.5}$ mass and absorbance, and for male:household versus female:household ratios.

Descriptive statistics for prototype and reference monitor household HI and UPAS $PM_{2.5}$ and absorption measurements were calculated with JMP, including; mean, standard deviation, standard mean error, upper and lower 95% mean confidence intervals, minimum and maximum values and geometric mean. Log normality was tested with Kolmogorov's D test. Descriptive statistics for personal UPAS and household UPAS $PM_{2.5}$ and absorption measurements, for both genders separately, were calculated with JMP, including: mean, standard deviation, standard mean error, upper and lower 95% mean confidence intervals, minimum and maximum values and geometric mean. Log normality was tested with Kolmogorov's D test. To aid interpretation, histograms of male and female HAP measurements were generated for $PM_{2.5\ mass}$ and absorbance. In order to better illustrate the differences in HAP exposure by gender the ratio of male and female personal exposure over their respective household exposures was calculated and then a bivariate fit of the two ratios was performed together with a graphical plot of x and y variables, the regression equation and R^2 value. Correlation between the two ratios was also calculated using Spearman's Rho test of ranked values. Household characteristic observations and questionnaire responses were collected and recoded into nominal variables according to the methods set out in appendix 4. These nominal values were used to make the predictor variables used in this study's statistical models of HAP. The distribution of household characteristics and questionnaire responses were tabulated and one-way fits between nominal predictors and the mean reference HI $PM_{2.5}$ measurement for each predictor value were calculated in JMP. Similarly, the bivariate fit between continuous predictors and reference HI HAP $PM_{2.5}$ measurements were also calculated in JMP.

The suitability of household characteristic variables and questionnaire responses for HAP modelling was assessed by performing pairwise correlation tests between each predictor variable versus *ln* transformed reference $PM_{2.5}$ mass and absorbance measurements. A significant correlation between any individual predictor from a category of predictors was taken to indicate the suitability of the entire category. For example, if a type of wall material was significantly correlated to $PM_{2.5}$ concentrations that would indicate that wall materials as a class were suitable predictors of HAP. This test was run on uncombined factor variables. Possible collinearity within all possible predictive factors for HAP modeling was tested by performing multiple pairwise correlations on all combinations of factors. The threshold for collinearity was set at 0.6 by convention. This test was run on all possible predictors. Some variable combinations were ruled out by their mutually exclusive nature. For example, the primary fuel type used in a household could only be one type of fuel, therefore collinearity between primary fuel types were not considered. Had a variable been collinear with the predictor it would have been excluded, unless a strong argument could be made for retaining it. Had two predictors been collinear with each other the variable with the lower correlation with the predictor would have been excluded.

Observational data of household characteristics and questionnaire responses were converted into whole nominal values for the JMP software to work with. At the same time, similar characteristics were collapsed and combined into common variables. See appendix 1 for details.

Predictor and response variables were log transformed, by the natural log, and then compared with pairwise correlations. The threshold for collinearity between a predictor and the response variable was set at a correlation of 0.6, with an alpha for significance of 0.05. This test was run on uncombined factor variables, this meant that some mutually exclusive factors were tested against each other; such combinations were manually identified and removed.

2.10.4 Linear regression modelling of household $PM_{2.5}$ levels

The secondary objective of this study was to build a simple proof-of-concept statistical model of household $PM_{2.5}$ using measurements from the reference HI monitor together with observations of household characteristics and responses to the questionnaire conducted during fieldwork. Subsequent $PM_{2.5}$ absorbance measurements of the same reference monitor samples allow modeling with that parameter, an approach which may prove useful to the PURE AIR study or other projects. Comparing PM2.5 and models allows for a richer evaluation of the predictive factors selected by the models as well as the overall performance of the models. In this case any linear regression models of HAP could only support four or five factors with a pool of 53 reference device measurements. The small number of supportable factors meant an automated all-possible-models technique was most appropriate. The rules used for building these models are set out in appendix 7.1. In brief, HAP measurement data was checked for errors; qualitative observations were recoded into discreet nominal variables; the response variable, having been found to be lognormal, was transformed with the natural log; and, finally, tests were run to look for collinearity, with a threshold for collinearity set arbitrarily at 0.6, between the predictors and response variables and amongst the predictors. No predictors failed the ($r>0.6$) collinearity test, though some came close, and all predictors were made available to model making process.

To this end twelve linear regression models were constructed, six for household $PM_{2.5}$ mass and absorbance each. For either outcome variable three categories of models were made, one for the results of both villages combined and one each for either village separately. Villages were modeled separately because observed HAP levels and fuels use patterns were so strongly different between Belupalle and Keri villages. For each of these categories two types of models were made, one using only the PURE baseline questionnaire predictors and one using the expanded pool of variables. This was done to determine if the additional predictors would improve models for both villages together and/or for individual villages. The PURE baseline factors and the expanded variable are found in section 2.7 and table 2.

Fit models for both outcome variables used collapsed and combined predictive factors. JMP produced results for models with one to five factors; however, in testing the model making process no lower factor models were found to offer superior results. Model were evaluated with an eye towards balancing regression power with parsimony; models were also judged according to the sensibility of the final factors selected. For example, if a final model had a good explanatory power but used seemingly non-sensible factors, (i.e. floor material + wall material + roof material), it would be rejected in favor of a less powerful, but more sensible, model. The end result was a prediction expression, and raw and adjusted R^2.

The predictor variables were coded such that absent/present conditions were represented as 0 and 1, respectively. Predictors that were continuous variables, such as kilograms of solid fuel used and cooking time in hours, were kept as is. Predictors that represented multiple possible conditions, such as building materials, were coded as described in appendix 7.3.

3 Results

3.1 Monitor performance

3.1.1 Fieldwork conditions

Fieldwork for this study planned to measure HAP $PM_{2.5}$ in 60 different households split evenly between two villages in rural India. During fieldwork, 27 households in Belupalle and 28 households in Kheri gave their consent for sampling. In all five cases of refused consent the field staff present for sampling were not the same staff members who had recruited the households in question, alternate arrangements could not be made.

Fieldwork in Belupalle and Kheri took place in July and August of 2015, respectively, towards the end of the local monsoon season in both locations. However, the Belupalle area was in drought during fieldwork and no significant rainfall occurred during fieldwork. Sporadic heavy rain occurred in the Kheri village area during fieldwork there. As field staff were not continuously present in either location during sampling and no record of local rainfall was available, exact rainfall amounts during sampling were unknown. The prototype UPAS monitors used for household and personal sampling recorded temperature and relative humidity (Table 3). These results show that the UPAS monitors used in household and personal exposure sampling experienced temperatures and relative humidity levels well outside what they might experience in the lab. The other prototype monitors, the Tzoa and PUWP, were collocated with the UPAS household monitors, and so experienced essentially the same conditions. These results also show that the average temperatures and humidity levels experienced by the UPAS monitors used for personal exposure measurements were largely similar to the averages experienced by the household monitors in the same village.

Table 3: Minimum, mean, and maximum average temperature and relative humidity for household and male and female personal exposure samples by village

	Belupalle Village Minimum – mean – maximum	Kheri Village Minimum – mean – maximum
Household average temperature °C	28.9 – 30.90 – 32.8 n=18	30.1 – 32.9 – 36.7 n=25
Household average relative humidity %	34.5 – 40.3 – 60.7 n=18	39.2 – 60.2 – 82.3 n=25
Male personal exposure average temperature °C	25.8 – 31.3 – 35.1 n=15	29.6 – 30.9 – 32.6 n=13
Male personal exposure average relative humidity %	33.0 – 42.3 – 48.4 n=15	61.8 – 65.5 – 86.0 n=13
Female personal exposure average temperature °C	30.6 – 32.1 – 39.8 n=14	29.6 – 31.7 – 33.4 n=14
Female personal exposure average relative humidity %	37.1 – 47.8 – 46.7 n=14	51.6 – 72.2 – 97.0 n=14

3.1.2 Reference monitors: Harvard impactor / Leyland legacy

A single HI reference monitor was deployed in every household sampled. A total of 55 unique households were sampled from July to September in 2015. 53 of the 55 attempts had successful HI measurements. In Belupalle 26 of 27 samples were successful; in Kheri 27 of 28 samples attempted were successful. One of the two failed samples were due to a pump malfunction (a pinched hose between the pump and HI filter), the other was the result of a torn filter.

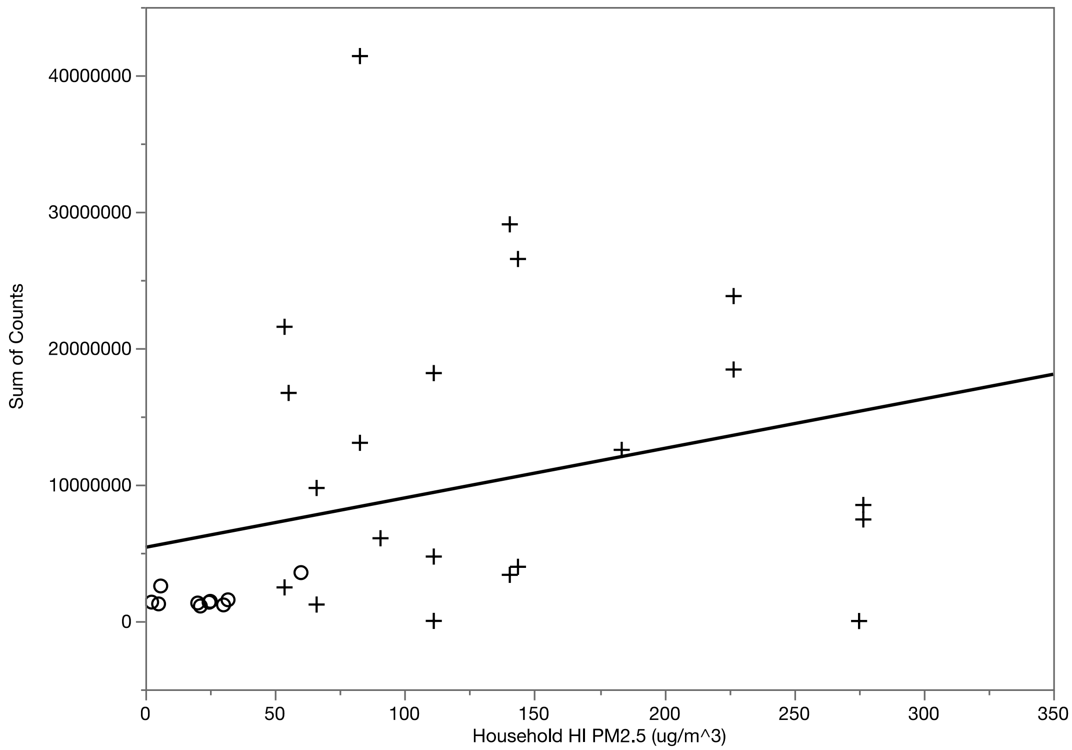
3.1.3 Reference monitors: TSI DustTrak

A single TSI DustTrak monitor was deployed in every third household sampled for a total of 18 sample attempts. The TSI DustTrak's used here had NiCad internal batteries, which, under field conditions, powered the monitor for roughly six hours. it was not possible to source external batteries, nor was it possible to connect the TSI monitor to external power in sampled homes. As a result, the monitor was run on internal power only for the Belupalle phase of fieldwork. no TSI DustTrak samples ran the full 24- or 48-hour intended sample duration.

3.1.4 Prototype monitors: Tzoa

In total there were 75 Tzoa samples attempted in the 53 households with successful reference HI $PM_{2.5}$ measurements; of those 32 were successful, 10 of the 32 were duplicates in the same location. There were 26 Tzoa samples with no data recorded in the sample log file, for unknown reasons. Of the remaining samples with data 17 had early termination, due to loss of power or unknown reasons.

Following the conclusion of fieldwork, a simple *post-hoc* analysis was performed on the 32 successful samples to see if further analysis was warranted. A bivariate fit was run comparing HI reference $PM_{2.5}$ measurements versus the sum of Tzoa particle counts within matching households. The results (figure 1) showed the sum of particle counts were very weakly correlated to $PM_{2.5}$ measurements, with an R^2 of 0.09 and a more than 10-fold variance among particle count sums at ~50μg/m^3.



Sum of Tzoa particle counts = 53953159 + 362389 * Household HI $PM_{2.5}$ ($\mu g/m^3$)

$R^2 = 0.09$

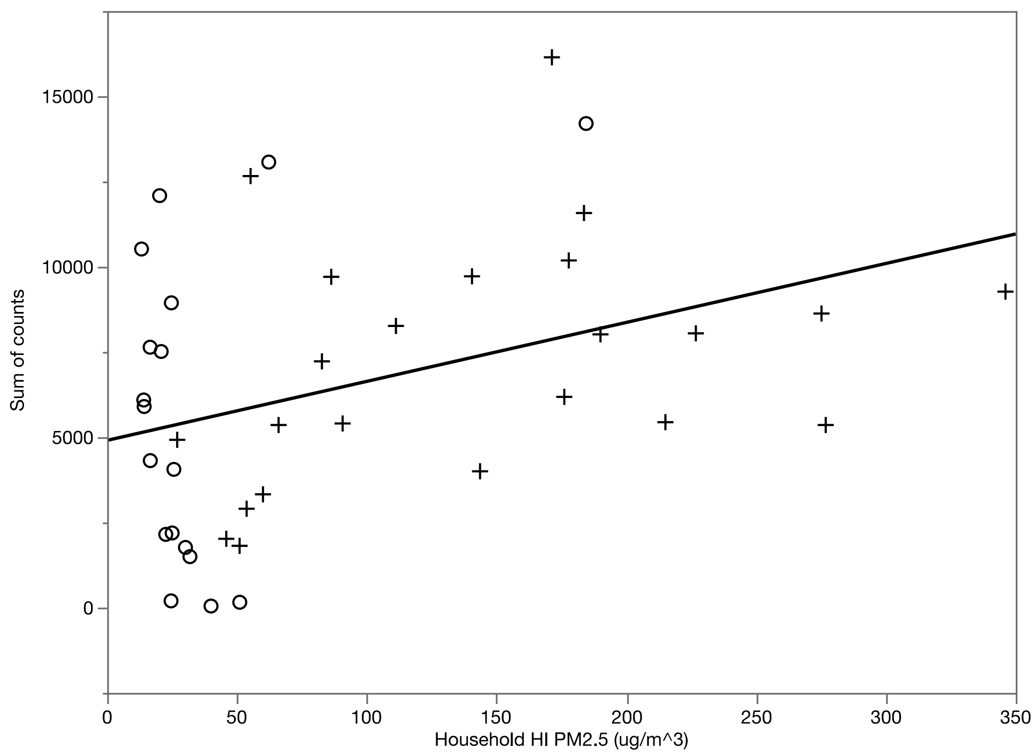
*Circles = Belupalle measurements, Crosses = Kheri measurements

Figure 1: Regression of reference HI HAP PM2.5 measurement versus Tzoa summed particle counts in 32 households in two rural Indian villages

3.1.5 Prototype monitors: PUWP

There were 60 PUWP samples attempted in the 53 households with successful reference HI $PM_{2.5}$ measurements, 9 of those were completely successful. There were 15 failed samples, 4 of the failed samples had no data recorded, a further 11 samples did not run for the full sample length. The remaining 36 samples ran for the full sample period but had unexplained interruptions, instances where the monitor’s cumulative particle counts reset to zero. These interruptions were corrected in post sampling data analysis, as the monitors recorded particle counts continuously during the full sample period. These interruptions remain unexplained, they were not duplicated in post fieldwork lab tests with the PUWP monitors, however, these lab tests did not replicate the temperature and humidity levels encountered in the field.

Again, a *post-hoc* analysis was performed with the PUWP measurements, specifically the 45 measurements including interruption corrected measurements. A bivariate fit was run using HI reference $PM_{2.5}$ measurements versus summed PUWP particle counts among matching households. The results (figure 2) showed weakly correlated measurements, with an R^2 of 0.14 and a six-fold variance in particle count sums at ~50μg/m^3.



Sum of PUWP particle counts = 4907 + 17.3 * Household HI $PM_{2.5}$ (μg/m^3)

R^2 = 0.14

*Circles = Belupalle measurements, Crosses = Kheri measurements

Figure 2: Regression of reference HI HAP PM2.5 measurement versus PUWP summed particle counts in 32 households in two rural Indian villages

3.1.6 Prototype monitors: UPAS household samples

Only one of 10 UPAS monitors failed entirely during fieldwork, a household unit, after 7 samples. (The particular unit would not turn on after charging, possibly due to a defective power button). This unit was replaced with the backup UPAS monitor, which continued to work properly for the remaining fieldwork.

UPAS monitors were collocated with reference HI monitors in all sampled households. UPAS samples were successful in 43 of the 53 households with successful reference HI measurements. Four of the 10 failed UPAS samples were due to damaged filters, the rest were a result of unexplained airflow anomalies, (where the UPAS's airflow dropped from 1LPM to ~0.1LPM), likely due to firmware errors.

3.1.7 Prototype monitors: UPAS personal samples

The UPAS was the only prototype monitor suitable for personal exposure monitoring. The construction of the UPAS prototypes was more robust and durable, the UPAS had a molded and machined glass-fiber reinforced composite body with integrated loops for nylon webbing, where the Tzoa and PUWP had 3D printed plastic shells. No reference personal exposure monitors were used in this study.

Table 4, below, shows successful personal HAP samples by village and by gender.

Table 4: UPAS personal samples by location and gender

	Attempted Samples	Successful Samples	Male Samples	Female Samples
Total	110	60	31	29
Belupalle	54	31	17	14
Kheri	56	29	14	15

Personal $PM_{2.5}$ exposure samples with the UPAS monitor were unsuccessful for a few common reasons. Most commonly UPAS monitors sometimes "jammed" part way through a sample. A jam occurred when there was a drop in the flow rate of air through the UPAS monitor, from a set rate of 1 LPM to, usually, less than a tenth of that. It appeared that covering the intake to the UPAS with clothing or similar materials could cause a malfunction in the UPAS's firmware such that the device would continue to run at a reduced flow rate without self-correcting. The UPAS monitors evaluated here used glass fiber filters, which were very fragile. Despite careful handling these filters could be torn easily, either during handling or by pressure on the filter cap cutting the filter while the UPAS was running. A few samples were lost when small insects were drawn into the UPAS monitor's air intake and then crawled through the cyclone pre-filter and into the main filters where they became embedded on the glass fiber filter, contaminating the sample. Neither the gender of the participant nor the village in which the sample was taken appears to have had an effect on the failure rate of personal exposure samples. Without reference device measurements it is difficult to place the 55% success rate in context. However, this is significantly lower than the ~81% success rate of household UPAS samples, which suggests that there are significant additional stresses involved with personal exposure measurements.

3.2 Regression and correlation analysis of reference HI versus prototype UPAS HAP measurements

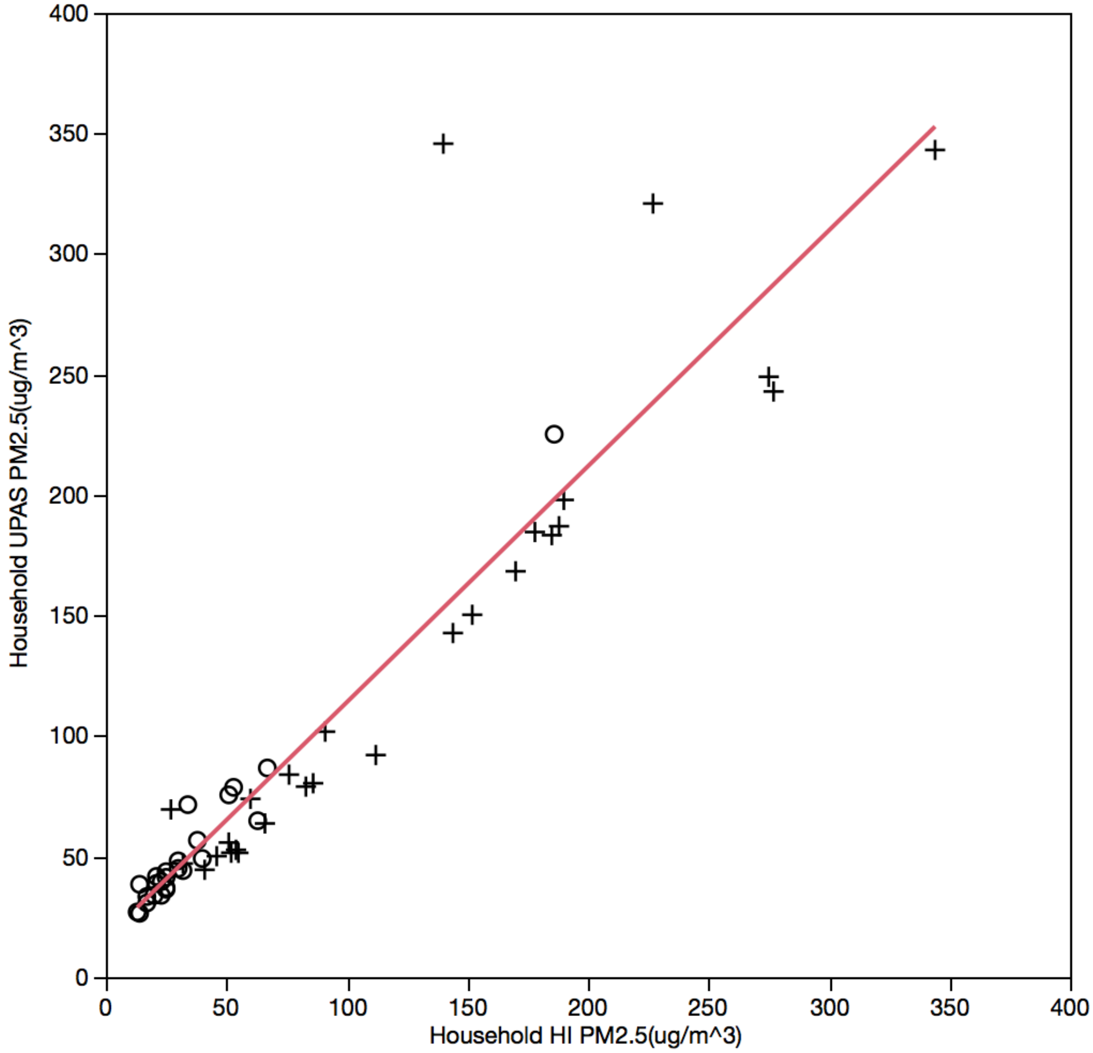
Prototype UPAS monitors were collocated with reference HI monitors in participating households in both villages. Missing UPAS measurements were imputed using reference device measurements as described in section 2.10.2.

A regression analysis was performed in JMP of the prototype UPAS versus reference HI HAP $PM_{2.5}$ mass and absorbance measurements. The analysis was of the 53 successful household measurements made with the reference HI monitor and the matching successful and imputed UPAS measurements. The resulting plots of the bivariate fit between reference HI and prototype UPAS measurements are shown below, with samples from the southern Indian village of Belupalle shown as circles and the northern Indian village of Kheri shown as crosses.

These results, in figures 3 and 4, show greater agreement between the prototype and reference devices at lower HAP $PM_{2.5}$ and absorbance levels in either village, with progressively greater variation as HAP measurements increased. Outlier measurements were not removed from this analysis for two reasons: one, in such a small sample size the subtraction of a single data point has a profound impact on regression and correlation scores. Two, the graphical plot of the bivariate fit clearly shows the direction and magnitude of any outlier's influence.

Despite the presence of one or two outliers the overall agreement between the prototype UPAS and the reference HI monitor are quite strong. The R^2 values for the HAP $PM_{2.5}$ and absorbance comparisons were 0.85 and 0.88, respectively. The slope of the best fit line in the HAP $PM_{2.5}$ was also very close to 1, at 0.98. The slope of the absorbance line of 1.68 is likely due to difference in baseline absorbance between the two different filter materials used by the UPAS and HI monitors.

These results (figure 3) also show a small overestimation bias of $PM_{2.5}$ by the prototype UPAS monitors compared to the reference HI monitors. It is worth noting that the prototype and reference devices used different filters, glass fiber and PTFE, respectively. Moreover, semivolatile aerosols are known to preferentially adsorb to fibrous filters, which can bias measurements made with these filters (28).

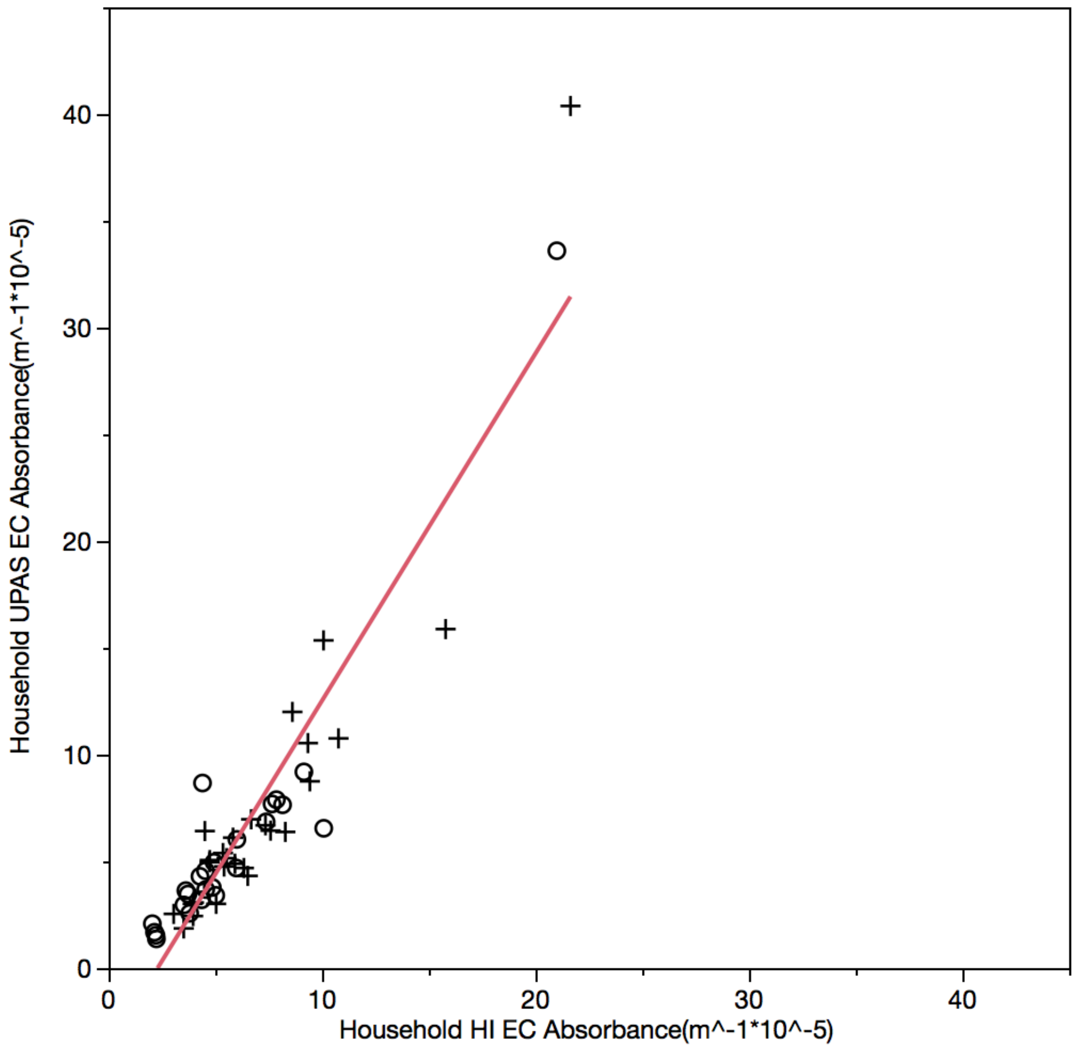


Household UPAS $PM_{2.5}$(μg/m^3) = 16.23 + 0.98 * Household HI $PM_{2.5}$(μg/m^3)

$R^2 = 0.85$

*Circles = Belupalle measurements, Crosses = Kheri measurements

Figure 3: Regression of reference HI versus prototype UPAS HAP $PM_{2.5}$ measurements in 53 households in two rural Indian villages



Household UPAS Absorbance = -3.73 + 1.63 * Household HI Absorbance

$R^2 = 0.88$

*Circles = Belupalle measurements, Crosses = Kheri measurements

Figure 4: Regression of reference HI versus prototype UPAS absorbance measurements in 53 households in two rural Indian villages

3.3 Descriptive statistics of reference HI and prototype UPAS HAP measurements

Descriptive statistics of the results from the household measurements for both devices are in table 5. These results show that, for the overall mean as well as at every distribution point, prototype UPAS monitors measured slightly higher HAP $PM_{2.5}$ levels than collocated reference HI monitors, though the difference appears to be constant across the exposure range. Filters collected from household HAP $PM_{2.5}$ measurements were also analyzed for absorbance. Absorbance measurements can be useful in illustrating the contribution from combustion sources to overall $PM_{2.5}$ levels. These results show more variability between measurements made by either monitor. Again, it is worth noting that each type of monitor used a different filter material and the same treatment to both filter types may not produce identical responses.

Table 5: Descriptive statistics for reference HI and prototype UPAS HAP PM2.5 and absorbance measurements from 53 households in two rural Indian villages

	$PM_{2.5}$ mass		Absorbance	
	HI (μg/m^3)	UPAS (μg/m^3)	HI (/m*10^5)	UPAS (/m*10^5)
Mean	82	96	6.43	6.73
Geo Mean	55	73	5.61	5.13
Standard Deviation	79	84	3.95	6.86
Standard Error Mean	11	12	0.54	0.94
Minimum	13	26	2.05	1.37
Lower 95% Mean	60	73	5.35	4.84
Upper 95% Mean	104	119	7.52	8.62
Maximum	344	346	21.64	40.38

The log normality of measurements of HAP $PM_{2.5}$ and absorbance made with prototype and reference monitors was determined using Kolmogorov's D test. All measurements were found to be lognormally distributed except for UPAS measurements of HAP $PM_{2.5}$, in that case the null hypothesis (H_0 = lognormal distribution) was weakly rejected.

3.4 Descriptive statistics of prototype UPAS personal HAP measurements

Prototype UPAS monitors were used to collect personal HAP $PM_{2.5}$ exposure measurements from the primary male and female residents in every participating household. 53 households had successful reference HI HAP $PM_{2.5}$ measurements, in these households there were 31 successful male personal exposure measurements and 29 successful female personal exposure measurements. Missing UPAS measurements, either from failed or damaged samples, were not imputed as no reference personal monitor was employed alongside the UPAS prototype.

The results from personal exposure monitoring are shown below for both male and female participants. Table 6 shows descriptive statistics for $PM_{2.5}$ measurements for male versus female participants, table 6 also shows absorbance measurements for the same groups. The results show that $PM_{2.5}$ levels had right-skewed lognormal distributions, mean $PM_{2.5}$ were higher for males than females but geomean levels were higher for females. Minimum exposure measurements were quite similar between the genders. Females did have notably higher lower 95% mean exposure levels than males. Outlier measurements were not removed from the analysis.

The results for absorbance measurements show that, while the mean and geomean absorbance measurements for males and females were not very different, the upper 95% mean and maximum absorbance levels for females were notably higher than for males.

Table 6: Descriptive statistics for prototype UPAS personal exposure PM2.5 and absorbance measurements from 53 households in two rural Indian villages

	$PM_{2.5}$ Mass		Absorbance	
	Male n = 31 ($\mu g/m^3$)	Female n = 29 ($\mu g/m^3$)	Male n = 31 ($/m*10^5$)	Female n = 29 ($/m*10^5$)
Mean	106	95	4.3	4.6
Geo Mean	76	85	3.5	2.6
Standard Deviation	160	58	2.9	3.2
Standard Error Mean	29	11	0.5	0.6
Minimum	34	39	0.7	0*
Lower 95% Mean	47	74	3.2	3.9
Upper 95% Mean	165	117	5.3	5.8
Maximum	939	345	12.4	12.9

The lognormality of personal exposure measurements made with the prototype UPAS monitor was determined using Kolmogorov's D test. The HAP $PM_{2.5}$ for either gender measurements were lognormally distributed, but absorbance measurements were more normally distributed.

The correlations for male vs female and male or female vs household personal HAP $PM_{2.5}$ and absorbance measurements were calculated with a Spearman's Rho test. These tests were done to determine how strongly personal exposure were linked with household HAP levels, and how strongly male and female personal exposures were linked in the same household. The results are shown below in table 7, correlation values are shown with their associated probabilities of significance. Note that the correlations between gender to household HAP $PM_{2.5}$ and absorbance for males and females were not drawn from matching households, thus the higher *n* values compared to the male versus female exposure correlation which are drawn from households where both personal exposure measurements and the household measurement were all successful at the same time.

The results of these tests show that, when comparing personal exposure to matching household exposures, HAP $PM_{2.5}$ measurements had weaker and less significant correlations than absorbance measurements from the same samples.

Table 7: Correlation between prototype UPAS measurements of male and female personal HAP exposures and matching reference HI household HAP exposures from 53 households in two rural Indian villages

	Male vs Household n = 31	**Female vs Household n = 29**	**Male vs Female n = 17**
HAP PM2.5	0.26 (p<0.17)	0.39 (p<0.04)	0.52 (p<0.03)
Absorbance	0.53 (p<0.002)	0.80 (p<0.001)	0.86 (p<0.0001)

In order to better illustrate the relationship between household and personal HAP $PM_{2.5}$ exposures the ratio of personal exposure over matching household were calculated for both $PM_{2.5}$ and absorbance measurements.

The results, shown below in table 8, show that average personal HAP $PM_{2.5}$ exposures were roughly 2 to 2.6 times the measured household HAP $PM_{2.5}$ exposure levels within the same household. Conversely the ratios for male over household and female over household absorbance measurements, also in table 8, are much smaller, less than 1, and have less variation within each group. Taken together these results indicate that males and females were exposed to sources of $PM_{2.5}$ with low elemental carbon content, unlike the stationary household monitors.

Table 8: Descriptive statistics for ratio of personal prototype UPAS over household reference HI $PM_{2.5}$ and absorbance exposure measurements from 53 households in two rural Indian villages

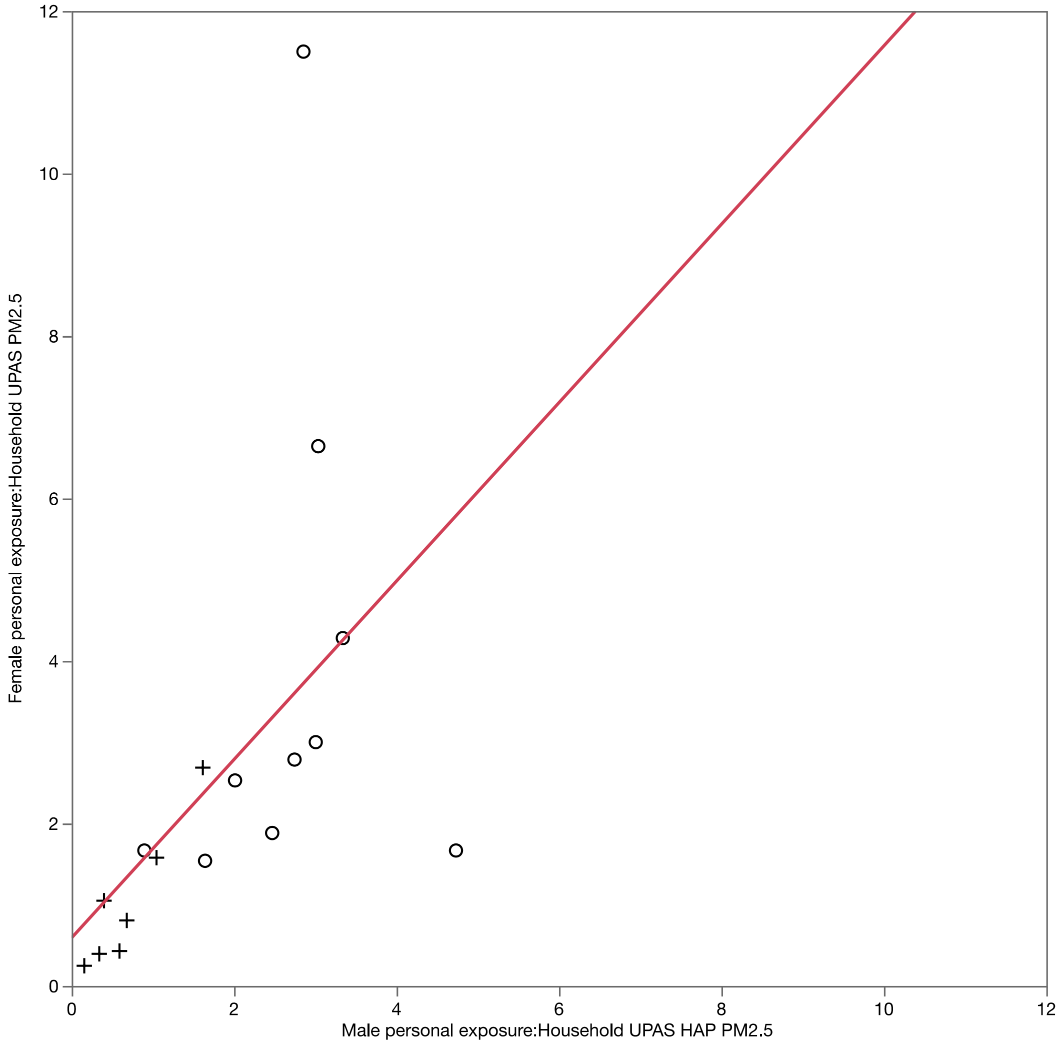
	$PM_{2.5}$ Mass		Absorbance	
	Male/Household n = 31	Female/Household n = 29	Male/Household n = 31	Female/Household n = 29
Mean	2.65	2.07	0.85	0.67
Geo Mean	1.69	1.32	0.69	0.46
Standard Deviation	3.59	2.32	0.47	0.29
Standard Error Mean	0.64	0.43	0.08	0.05
Minimum	0.16	0.24	0.16	0.01
Lower 95% Mean	1.34	1.19	0.63	0.56
Upper 95% Mean	3.97	2.95	0.98	0.78
Maximum	20.41	11.5	2.07	1.30

3.5 Regression and correlation analysis of male versus female ratios of prototype UPAS personal exposure over reference HI HAP measurements

A regression analysis was performed on the ratios of male:household versus female:household HAP $PM_{2.5}$ measurements in households where all three types of measurements were successful. In total 17 of 53 households with successful reference HI monitor measurements met these criteria. The same regression analysis was also performed on absorbance measurements from the same samples. The resulting plots, figures 5 and 6, are shown below, with samples from the southern Indian village of Belupalle shown as circles and the northern Indian village of Kheri shown as crosses.

The results show that, with respect to $PM_{2.5}$ measurements in figure 5, the degree of variability between the two genders to household ratios rose with increasing $PM_{2.5}$ measurements, and measurements from the southern village of Belupalle had less variability than measurements from the northern village of Kheri. It is also worth noting that the slope of the regression line was very close to 1 (1.098), indicating a close relationship between gender over household exposure ratios, and that this relationship is relatively consistent regardless of village.

Conversely the plot of the bivariate fit for absorbance measurements, in figure 6, seem to indicate village had a meaningful effect on gender over household ratios. It would appear that males in the northern village of Kheri had higher elemental carbon exposures than females within the same household.

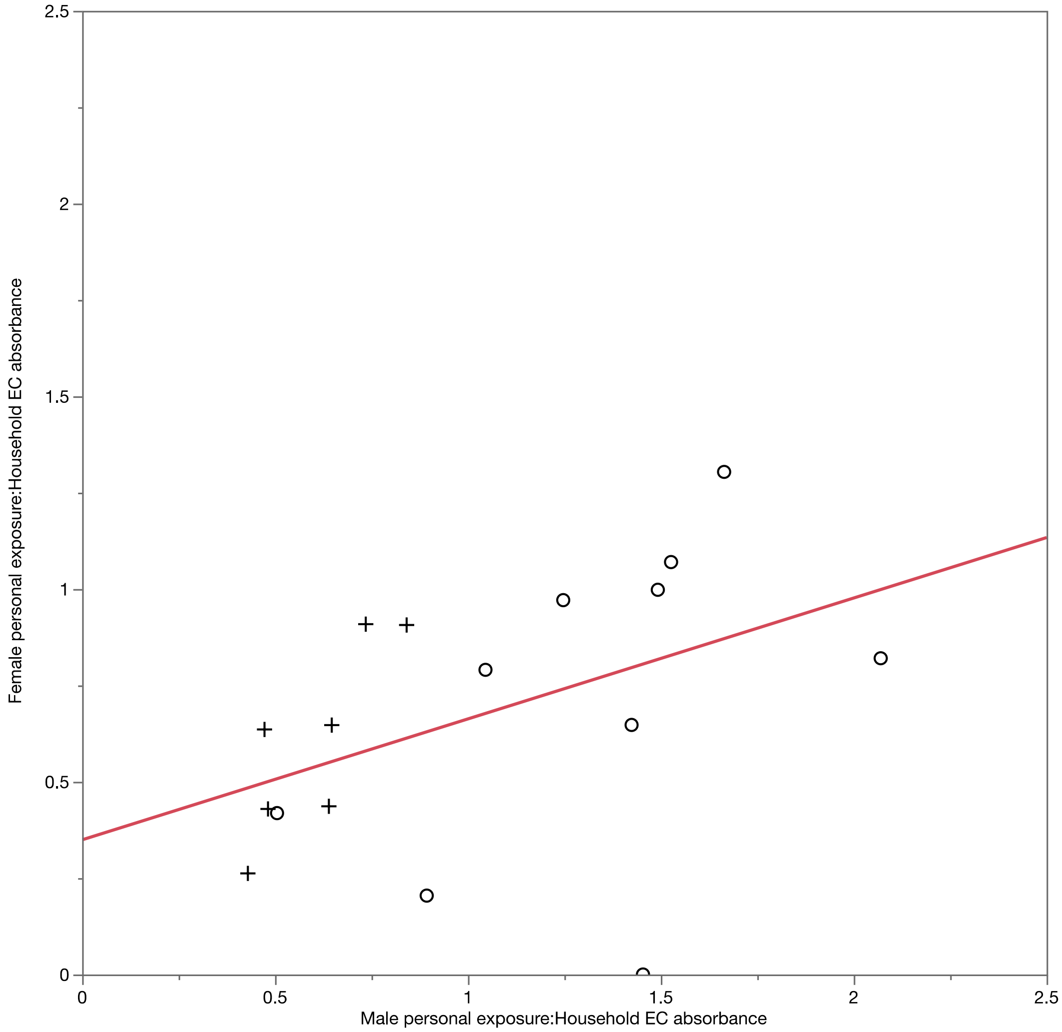


Female personal exposure/household UPAS HAP $PM_{2.5}$ ($\mu g/m^3$) = 0.59 + 1.10 * Male personal exposure/household UPAS HAP $PM_{2.5}$ ($\mu g/m^3$)

$R^2 = 0.27$

*Circles = Belupalle measurements, Crosses = Kheri measurements

Figure 5: Regression of male over household versus female over household HAP $PM_{2.5}$ measurement ratios from 17 households in two rural Indian villages



Female personal exposure/household absorbance ($m^{-1}*10^{-5}$) = 0.35 + 0.31 * male personal exposure/household absorbance ($m^{-1}*10^{-5}$)

$R^2 = 0.21$

*Circles = Belupalle measurements, Crosses = Kheri measurements

Figure 6: Regression of male over household versus female over household HAP absorbance measurement ratios from 17 households in two rural Indian villages

The correlation between the male to household and female to household ratios were also calculated for both HAP $PM_{2.5}$ and absorbance.

Table 9: Correlation between prototype UPAS male over household and female over household HAP measurement ratios from 17 households in two rural Indian villages

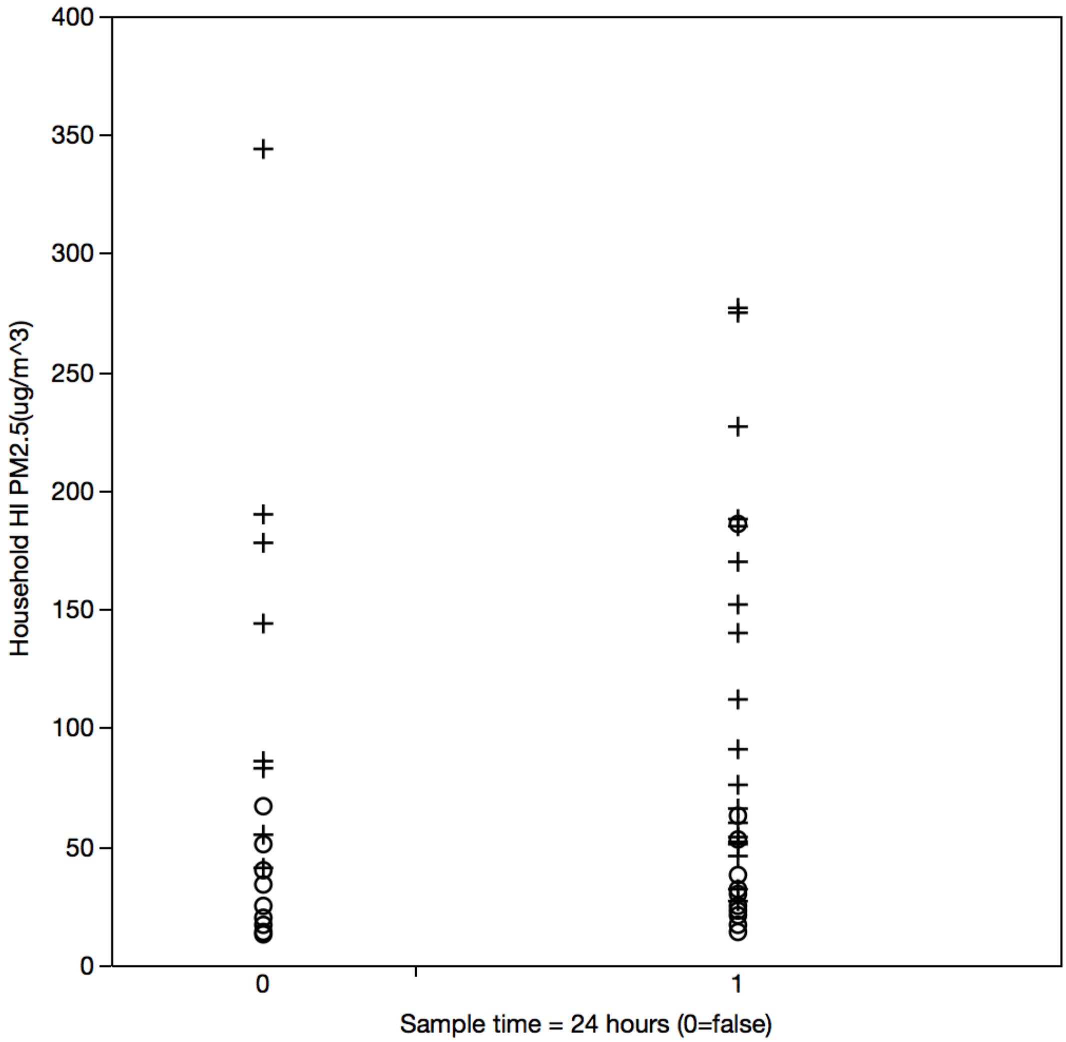
	Male/Household vs Female/Household n = 17
HAP PM2.5	0.84 (p<0.0001)
Absorbance	0.54 (p<0.01)

3.6 Comparison of 24- versus 48-hour HAP measurements

During fieldwork, household and personal exposure measurements were made for 24- and 48-hour periods. This was done in part to determine if 48-hour measurements were superior in capturing within household, day-to-day, variations in HAP levels, compared to 24-hour measurements.

In practise during fieldwork three households were monitored simultaneously, and each week two rounds of 24-hour measurements were made and one round of 48-hour measurements.

Reference HI measurements were sorted according to sample duration and plotted in JMP, shown below in figure 7. As before samples from the southern Indian village of Belupalle shown as circles and the northern Indian village of Kheri shown as crosses. In figure 7 sample time, on the X axis, 48-hour samples are given as 0, and therefore 24-hour samples are given as 1.



*Circles = Belupalle measurements, Crosses = Kheri measurements

Figure 7: Reference HI HAP $PM_{2.5}$ measurements by sample time

The analysis of these time segregated measurement data is shown below in table 10. The results show that the means for the two different sample durations were not significantly different.

Table 10: Comparison of 24- versus 48-hour reference HI HAP $PM_{2.5}$ measurements ($\mu g/m^3$)

	24-hour	48-hour
n	17	36
Mean	82	81
Standard deviation	87	76
Lower 95%	38	56
Upper 95%	127	107
ANOVA	**F Ratio**	**Prob>F**
	0.002	0.97

3.7 Reference HI HAP $PM_{2.5}$ measurements by household characteristic

Household questionnaires and observations were successfully carried out in every PURE enrolled household. The responses and observations for categorical variables were converted into nominal variables, see section 2.11.4 and appendix 7.3 for details, and compared to the reference HI $PM_{2.5}$ measurements for all households with those features. The results are shown below in table 11. Please note that with respect to cooking fuels a household cannot use the same type of fuel for primary and secondary cooking, for example every household using LPG as a primary fuel must have used a solid fuel (wood or wood and dung) as a secondary fuel, if they used more than one type of fuel. Also note that ventilation features were not mutually exclusive nor compulsive, a household may have had all ventilation features or none. It is important to point out that solid fuels used for primary or secondary fuels were exclusive by village. Households in the southern village of Belupalle used only wood as a solid fuel and never the wood and dung mixture used by households in the northern village of Kheri. Some assessed variables are not included here as there was no variation in their response, for example all households participating in this study had electricity, and no households had any heating separate from their cookstoves.

Table 11: Comparison of discreet household characteristics from observations and questionnaire responses to reference HI HAP $PM_{2.5}$ measurements (μg/m^3) from 53 households in two rural Indian villages

Predictor	Level	*n*	Mean (SD) $PM_{2.5}$ (μg/m^3)
Primary cooking fuel	Kerosene	1	82.9
	LPG	37	79.9 (80.7)
	Wood	8	49.9 (57.2)
	Wood and dung	7	136.6 (76.7)
Secondary cooking fuel	None	25	84.0 (93.9)
	LPG	9	69.8 (68.1)
	Wood	8	59.3 (37.1)
	Wood and dung	11	102.8 (75.1)
Cooking location	Inside	40	80.1 (86.0)
	Inside and outside*	12	78.7 (48.4)
	Outside*	1	186
Ventilation	Open window	37	70.7 (80.0)

	Chimney	35	76.7 (79.9)
	Exhaust	18	138.3 (97.7)
Typical Cooking	Yes	50	83.8 (80.9)
	No	3	47.7 (21.2)
Roof material	Cement, Stone	43	85.0 (74.8)
	Tile, Asbestos sheet	5	25.4 (6.8)
	Wood	5	110.4 (132.0)
Wall material	Cement, Tile	50	80.2 (78.4)
	Earth	1	32.0
	Brick	2	146.5 (113.8)
Floor material	Cement, Tile	47	78.9 (80.3)
	Earth	6	104.3 (71.3)
Ventilation rating	Poor	28	93.3 (82.9)
	Moderate	18	79.1 (84.4)
	Good	7	42.9 (26.8)

*It should be noted that in all households with at least some outdoor cooking the placement of the cooking area was within the household's compound or walls and was close to the kitchen area. Unfortunately, the distance to the nearest kitchen area opening was not observed.

3.8 Correlation between observed household characteristics and questionnaire responses versus reference household $PM_{2.5}$ measurements

Before constructing a statistical model of HAP, it was necessary to test for collinearity, both amongst predictors and between predictors and the response reference HI measurement. Predictor variables were drawn from the pool of questionnaire responses and observations of household characteristics. Table 12, below, shows the calculated correlations, with confidence intervals and significance probabilities, for *ln* transformed predictor variables versus reference HI measurements of HAP $PM_{2.5}$ and absorbance. Significant probabilities that reject the null hypothesis, that there is no correlation between the two variables, are highlighted in bold type. Some predictor variables were notably and significantly correlated with each other, but not above the 0.6 collinearity threshold. Most associations would seem to confirm common sense expectations about a given relationship. For example, increased solid fuel use was positively and significantly correlated to increased HAP $PM_{2.5}$ and absorbance levels. In other relationships the connection between $PM_{2.5}$ and absorbance measurements were not clear, despite expectations. For example, increased cooking time was positively and significantly correlated to increased $PM_{2.5}$ measurements, but it was not the case that increased cooking time was significantly correlated to higher absorbance measurements. Some expected correlations were evident, but at low significance levels. For example, LPG fuel use was negatively correlated to HAP $PM_{2.5}$ and absorbance levels, but these correlations were not statistically significant. In other cases, the intuitive correlation between the dirtiest fuel, the wood and dung, and high HAP levels was evident, and at a statistically significant level.

Table 12: Significant correlations between ln transformed household characteristic variables and reference HI HAP $PM_{2.5}$ and absorbance

	By *ln* Household HI $PM_{2.5}$				By *ln* Household HI Absorbance			
Predictor Variable	**Correlation**	**Lower 95%**	**Upper 95%**	**Sig Prob**	**Correlation**	**Lower 95%**	**Upper 95%**	**Sig Prob**
Primary Fuel: Kerosene	-0.14	-0.39	0.14	0.33	-0.08	-0.34	0.20	0.59
Primary Fuel: LPG	-0.03	-0.30	0.24	0.84	-0.26	-0.50	0.01	0.06
Primary Fuel: Wood	-0.21	-0.46	0.06	0.12	0.11	-0.17	0.37	0.43
Primary Fuel: Wood & Dung	0.32	0.05	0.54	**0.02**	0.27	0.003	0.51	**0.05**
Secondary Fuel: None	-0.11	-0.37	0.16	0.41	-0.07	-0.33	0.21	0.63
Secondary Fuel: LPG	-0.08	-0.34	0.20	0.59	-0.05	-0.31	0.23	0.75
Secondary Fuel: Wood	-0.03	-0.30	0.24	0.82	-0.03	-0.30	0.24	0.84
Secondary Fuel: Wood Dung	0.24	-0.03	0.48	0.09	0.15	-0.13	0.40	0.29
Total Solid Fuel Used (Kg)	0.21	-0.07	0.45	0.14	0.40	0.14	0.60	**0.003**
Cooking Location: Inside	-0.17	-0.42	0.10	0.22	-0.12	-0.38	0.15	0.39
Cooking Location: Outside	0.19	-0.08	0.44	0.17	0.36	0.10	0.58	**0.007**
Cooking Location: Outside & Inside	0.12	-0.16	0.37	0.41	0.007	-0.26	0.28	0.96
Months Cooking: Outside	0.17	-0.11	0.42	0.23	0.13	-0.14	0.39	0.34
Ventilation: Open Window	-0.31	-0.53	-0.04	**0.03**	-0.44	-0.64	-0.19	**0.001**

Ventilation: Chimney	-0.12	-0.37	0.16	0.41	0.01	-0.26	0.28	0.94
Ventilation: Exhaust	0.53	0.31	0.70	**<.0001**	0.38	0.12	0.59	**0.01**
Cooking: Typical	0.06	-0.21	0.32	0.67	0.16	-0.11	0.42	0.24
Cooking Time: Hours	0.34	0.07	0.56	**0.01**	0.08	-0.19	0.34	0.56
Total Tobacco: Pieces	-0.11	-0.36	0.17	0.45	-0.20	-0.45	0.07	0.14
Roof Material	-0.04	-0.31	0.23	0.77	0.33	0.07	0.55	**0.02**
Wall Material	0.14	-0.13	0.40	0.31	0.12	-0.16	0.38	0.40
Floor Material	0.19	-0.09	0.48	0.17	0.23	-0.04	0.47	0.10
# Persons Per Household	0.28	0.01	0.51	**0.04**	-0.08	-0.34	0.10	0.59
Ventilation Rating	-0.21	-0.45	0.07	0.14	-0.37	-0.58	-0.11	**0.007**

The calculated correlations with confidence intervals and significance probabilities, amongst *ln* transformed predictor variables were calculated with pairwise correlations in JMP. Predictors were coded in the same way as table 12, as described above. The results for intra-predictor variable correlation showed that no variable was collinear with any other predictor variable, though there were several combinations with high degrees of correlation. The threshold for collinearity amongst predictive variables was set at 0.6, by convention. There were some categories of predictive variables that had high degrees of collinearity. Fuel types were highly correlated with the amount of solid fuels used in a home, with four of seven combinations having correlations above 0.5. Cooking location was also strongly correlated with fuel type used, where households cooked which cooked outside at least some amount where strongly correlated with solid fuel use. Finally cooking time was also strongly correlated, >0.5, with the number of persons per household.

3.9 Linear regression modelling of household $PM_{2.5}$ and absorbance

The development of simple statistical models of HAP levels in PURE participant households was a central goal of this work. These models were to serve, in part, as a proof of concept for the larger PURE AIR study.

The models of $PM_{2.5}$ and absorbance, in tables 14 and 15, respectively, raw R^2 and adjusted R^2 scores are given for the best performing 5 factor models produced by the all-possible-models technique. The prediction expression for each model is also given with the predictors listed in descending order of significance, predictors with an *p* value less than 0.05 are shown in bold type. All models were based on 53 observations of natural log transformed reference HI monitor measurements. Each model had a statistically significant ANOVA F score. The variables available to the model making program are shown in table 13, and are listed by variable class, PURE baseline questionnaire derived variables, or the expanded pool of variables.

Table 13: Potential predictor variables available for statistical models

Variable Name	Units	Variable Class
Community	Belupalle or Kheri	PURE Baseline
Primary fuel type	LPG, Kerosene, Wood, Wood and Dung	PURE Baseline
Cooking Location	Inside, Outside, Both	PURE Baseline
Cooking time outside	Months per year	PURE Baseline
Ventilation	Chimney, Window, Exhaust	PURE Baseline
Roof Material	Cement, Stone, Asbestos sheet, Tile, Wood	PURE Baseline
# Persons in household		PURE Baseline
Secondary fuel type	None, LPG, Kerosene, Wood, Wood and Dung	Expanded Pool

Solid fuel amounts	Kg	Expanded Pool
Cooking time	Hours per day	Expanded Pool
Total tobacco products	Discreet pieces	Expanded Pool
Wall Material	Cement, Earth, Brick	Expanded Pool
Floor Material	Cement, Tile, Earth	Expanded Pool
Ventilation Rating	Good, Fair, Poor	Expanded Pool
Cooking typical	Yes/No	Expanded Pool
Sensor distance from cooking location	Meters	Expanded Pool

Table 14: Raw and adjusted regression scores with prediction expressions for models of reference HI measurements of *ln* transformed HAP $PM_{2.5}$ for combined and individual villages using PURE baseline variables only and with expanded pool of variables

Village	Variable Pool	R^2	Adj R^2	Prediction expression: *ln* PM2.5 =
Both n = 53	PURE	0.68	0.64	4.77 + [0.62 if **community = Kheri**, -0.62 if Belupalle] + [1.34 if **cooking location = outside**, -1.34 if else] + [0.08 * **# persons household**] + [0.27 if **cooking location = inside**, -0.27 if else] + [0.15 if **ventilation feature = exhaust**, -0.15 if else]
	Expanded	0.68	0.64	4.77 + [0.62 if **community = Kheri**, -0.62 if Belupalle] + [1.34 if **cooking location = outside**, -1.34 if else] + [0.08 * **# persons household**] + [0.27 if **cooking location = inside**, -0.27 if else] + [0.15 if **ventilation feature = exhaust**, -0.15 if else]
Belupalle n = 27	PURE	0.58	0.48	3.80 + [1.31 if **cooking location = outside**, -1.31 if else] + [0.07 * # persons household] + [-0.27 if primary fuel = kerosene, 0.27 if else] + [0.21 if cooking location = inside, -0.21 if else] + [0.10 if ventilation feature = chimney, -0.10 if else]
	Expanded	0.72	0.64	4.66 + [0.82 if **cooking location = outside**, -0.82 if else] + [0.30 if **secondary fuel = wood**, -0.30 if else] + [0.28 **typical cooking = true**, -0.28 if else] + [-0.18 if ventilation feature = open window, 0.18 if else] + [-0.14 if primary fuel = LPG, -0.14 if else]
Kheri n = 26	PURE	0.32	0.16	3.90 + [0.13 * # persons household] + [0.32 if cooking location = inside, -0.32 if else] + [0.18 if ventilation feature = exhaust, -0.18 if else] + [-0.10 if ventilation feature = open window, 0.10 if else] + [roof material: -0.12 if solid, 0.12 if sheet, 0 if else]

	Expanded	0.52	0.41	4.01 + [0.52 if **secondary fuel = none**, -0.52 if else] + [**ventilation rating:** 0.60 **if poor**, 0.40 if moderate, -1.00 **if good**] + [0.09 * **# persons household**] + [-0.03 * total tobacco products]

Table 15: Raw and adjusted regression scores with prediction expression for models of reference HI measurements of *ln* transformed HAP $PM_{2.5}$ absorbance for combined and individual villages using PURE baseline variables only and with expanded pool of variables

Village	Variable Pool	R^2	Adj R^2	Prediction expression: *ln* absorbance =
Both n = 53	PURE	0.46	0.41	2.23 + [0.64 if **cooking location = outside**, -0.64 if else] + [0.17 if **ventilation feature = exhaust**, -0.17 if else] + [0.05 * **# persons household**] + [-0.11 if primary fuel = LPG, 0.11 if else] + [-0.12 if ventilation feature = open window, 0.12 if else]
	Expanded	0.55	0.50	2.17 + [0.77 if **cooking location = outside**, -0.77 if else] + [0.19 if **ventilation feature = exhaust**, -0.19 if else] + [0.03 * **total solid fuel** (Kg)] + [0.14 if **ventilation rating = poor**, -0.14 if else] + [0.04 * **# persons household**]
Belupalle n = 27	PURE	0.49	0.36	2.36 + [0.64 if **cooking location** = outside, -0.64 if else] + [-0.14 if primary fuel = LPG, 0.14 if else] + [0.28 if ventilation feature = exhaust, -0.28 if else] + [0.04 * # persons household] + [-0.10 if ventilation feature = open window, 0.10 if else]

	Expanded	0.60	0.51	1.70 + [0.78 if **cooking location = outside**, -0.78 if else] + [0.05 * **total solid fuel** (Kg)] + [0.08 * # persons household] + [0.14 if ventilation rating = poor, -0.14 if else] + [0.16 if secondary fuel = none, 0.14 if else]
Kheri n = 26	PURE	0.42	0.28	1.41 + [-0.19 if **ventilation feature = open window**, 0.19 if else] + {0.06 * # persons household] + [roof material: 0.16 if solid, -0.16 if wood, 0 if else] + [0.09 if cooking location = inside, -0.09 if else] + [0.05 if ventilation feature = exhaust, -0.05 if else]
	Expanded	0.70	0.63	1.25 + [0.07 * **total solid fuel** (Kg)] + [**ventilation rating**: 1 **if poor or moderate**, -1 **if good**] + [-0.25 if **secondary fuel = LPG**] + [-0.03 **months cooking outside**] + [**roof material**: 0.20 **if solid**, -0.20 **if wood**, 0 if else]

With respect to the usefulness of the expanded pool of predictors, the results in tables 14 and 15 show that, for models of $PM_{2.5}$ and absorbance, when both villages are modelled together the expanded pool of predictors do not offer a meaningful improvement in predictive power. The combined village models of $PM_{2.5}$ and absorbance use largely the same predictors, and even have mostly the same significance rankings. The primary difference between the combined village models of $PM_{2.5}$ mass and $PM_{2.5}$ absorbance being the $PM_{2.5}$ model selects community as a predictor, while the absorbance model does not.

However, when the villages were modelled separately the models using the expanded pool of predictors significantly outperform the PURE only models, improving the adjusted R^2 scores by as much as 0.35. This suggests that factors and behaviors that determine HAP exposure vary significantly by village, or perhaps by region as in this study the two villages are from very different regions in India. It is also worth noting that the expanded pool of variables had a greater effect on the models of absorbance, most notably in the village specific models. This result, coupled with the selection of different predictors between the $PM_{2.5}$ and absorbance models, indicates that the expanded variables are valuable to both types of analysis. Specifically, the added variables addressing secondary fuels and the amount of solid fuels used appear to be particularly useful. Secondary fuel was selected as a predictor in three out of four single community models using expanded pool predictors, and total solid fuel (Kg) was selected in every absorbance model using expanded pool predictors.

The most useful PURE baseline predictors are cooking location and the presence of discreet ventilation features, both of which were selected in 10 of the 12 models. Conversely building materials appears to be the least useful predictor, selected in only two of 12 models. Some of the specific terms in the prediction expressions may seem to have unusual values, for example the presence of an exhaust ventilation feature was correlated with an increase in both $PM_{2.5}$ and absorbance levels. Likewise, households with cooking locations outside the home were associated with higher HAP levels.

4 Discussion

This study found that the UPAS prototype performed well enough during fieldwork in two rural Indian villages, an 81% success rate and an $R^2 = 0.85$ with a slope of 0.98 compared to the reference monitor, to warrant the PURE AIR project selecting it for use in that study's large-scale epidemiological fieldwork. The UPAS monitors performed less well at collecting personal exposure measurements, with successful samples in 55% of attempts. However, this study would still to recommend it to the PURE AIR project pending further revisions to improve its reliability.

None of the other prototypes performed well enough to warrant consideration. The Tzoa was successful in 43% of attempted samples, and the PUWP in 75%. However, there was a very high degree of variance in particle counts at a given reference device measured $PM_{2.5}$ concentration, 10-fold and 6-fold for the Tzoa and PUWP, respectively. This indicates that both devices require further development before they can be reliably used by the PURE AIR study.

The simple statistical models of HAP made by this study demonstrated the viability of using observations of household characteristics and questionnaire responses as a modelling database. Furthermore, the performance of the expanded pool HAP models demonstrates the value in collecting additional observation and questionnaire data beyond what is found in the PURE baseline questionnaire.

4.1 Fieldwork

The fieldwork component of this work was successful. 55 of the 60 households recruited by field staff from SRI and PRI for HAP measurement participated in household and personal exposure sampling. Prototype UPAS monitors were successful in 81% (43 out of 53) of HAP measurements, compared to the reference monitors. Questionnaires and observations were successfully completed in all participating households. The success of the reference measurements and the data collected from household observations and questionnaire responses provided a solid foundation for prototype monitor evaluation and for construction of a simple statistical model of HAP $PM_{2.5}$.

4.2 Tzoa and PUWP prototype monitor performance

The two prototype particle counters, the Tzoa and the PUWP, did not perform well during fieldwork in two rural Indian villages in 2015. Both devices had numerous failed samples, (43% and 75% success rates for the Tzoa and PUWP, respectively), problems with endurance, were difficult to maintain, and were not built strongly enough for the stresses encountered. However, both devices were in the very early stages of development. The Tzoa units taken to India were the first prototype units fabricated by their developer, and the PUWP monitors were very early stage proof of concept models that had previously been deployed in traffic air pollution studies (68). More recently Curto et al. tested a newer version of the Tzoa monitor and concluded that that version was also not ready for use in field sampling (66). In contrast, Seto et al. found that the PUWP monitor performed much better, but in lab conditions simulating lower concentrations of traffic related air pollution (68).

The primary problems with both the Tzoa and the PUWP were:

- Both devices had significant problems recording sensor data to their internal memory/ Both the Tzoa and the PUWP used removable microSD cards. This type of memory card is widely used in consumer electronics and is considered reliable, so problems with data retention are probably not attributable to this type of storage.
- Both devices had issues with their batteries. A significant number of failed samples were due to monitors running out of power before the end of the samples period. Both the Tzoa and the PUWP were augmented with external batteries during fieldwork; however, these external batteries also proved unreliable. Neither the Tzoa or the PUWP had “fuel gauges” or other means of determining when the devices were fully charged or how fast they drained their batteries. By comparison the UPAS monitors recorded power and voltage levels, which enabled better device management.
- The Tzoa and the PUWP were difficult to clean internally. Owing to the high pollution conditions the monitors were operating in there were problems with soot and dust

collecting inside the monitors. This presented a problem in the Tzoa as soot and dust would deposit on the lens of the internal laser and the light sensor, which likely interfered with accurate particle counts. With the PUWP dust built up inside the devices in areas that could not be cleaned. This was an issue with calibrating the PUWP monitors, by running the monitor inside a sealed Ziploc bag, as the dust in the monitor would prevent a true zero calibration. Neither the Tzoa or the PUWP were designed to be cleaned, and both devices had to be disassembled and cleaned by hand with Kim wipes and alcohol.

- Both the Tzoa and the PUWP prototypes were made by 3D printing. It appeared that the high temperatures encountered during fieldwork caused plastics to soften and distort, potentially affecting the monitor's operation. It is also possible that the heat from the discharging batteries or some other internal component may have contributed to this problem. Some warping and distortion was noted in either type of device post-fieldwork. Warping was more of an issue for the Tzoa monitors, which used a laser and mirrors fixed to the body of the monitor, thus heat distortion of the shell affected the alignment of the light beam with respect to the optical sensor. The PUWP monitor used a premade Shinyei sensor, which was not affected by warping in the body of the PUWP, but the internal circuitry and battery connection may have been.

The Tzoa and PUWP units did have some positive features. The Tzoa monitors were quite small, about the size of a hockey puck. The small size of the Tzoa monitors made them easy to transport, but these monitors were only used for stationary household measurements where size and weight were less of an issue. The Tzoa monitor could also be powered by an external battery or with a USB charger. (Unfortunately, the homes visited in this study did not have electrical connections in their kitchen areas, so the Tzoa units had to use external batteries which had their own problems).

Based on the fieldwork performance of the Tzoa and the PUWP monitors it was not possible to recommend either monitor to the PURE AIR project.

4.3 UPAS prototype monitor performance

The performance of the UPAS monitor for household sampling was superior the other prototype monitors. Out of 53 successful reference HI monitor samples there were 43 matching successful UPAS monitor samples. Four of the 10 failed UPAS household samples were due to damaged filters, the rest were attributed to hardware problems. Based on the positive fieldwork results the UPAS monitor was judged to be a success and further analysis was performed comparing the UPAS measurements to matching reference HI samples.

The UPAS was the only monitor used for personal exposure sampling. Out of a total of 110 attempted personal samples, two personal samples were attempted in each of the 55 sampled households, 60 were successful, 31 male and 29 female samples. The higher failure rate for personal samples seems to be due to the greater stress placed on the monitor, compared to household samples. It was not possible to determine the exact cause of all the failed personal samples, but analysis of the samples logs seems to indicate that most failed samples involved a sharp drop in airflow rates, from which the monitor did not recover. This was most likely due to the intake of the UPAS being blocked by clothing or some other object. Other samples were lost due to damaged filters or contamination from insects drawn into the UPAS.

When compared to the reference HI monitor the UPAS performed very well in measuring HAP $PM_{2.5}$ and absorbance. A simple bivariate fit of HI versus UPAS measurements in 53 households (including 10 imputed missing UPAS measurements) produced regression scores of 0.851 and 0.877, respectively (figures 3 and 4). With respect to the $PM_{2.5}$ bivariate fit, the slope of the line of best fit was also very close to 1 (0.979), indicating a high degree of agreement between the two devices. The visualizations of these analyses, in section 3.2, show greater agreement at lower $PM_{2.5}$ and absorbance measurements. Both regression formulas had positive Y axis intercepts. In the case of $PM_{2.5}$ measurements this may be due to biased adsorption of VOC molecules to the PTFE coated glass fiber filter material used by the UPAS monitor. However, the slope of the regression line indicates that this bias is relatively consistent across the range of HAP $PM_{2.5}$ measurements.

In the case of absorbance measurements, there is a lingering question over what effect an identical treatment on two different filter materials will have. The regression line formula from the bivariate fit of UPAS over HI absorbance had a negative Y axis intercept (-3.73 in figure 4), which would seem indicate that the PTFE filters used in the reference HI monitor were less absorbent and more reflective than the glass fiber filters used in the UPAS.

The results of personal exposure measurements may contradict the general consensus, based on categorical exposure proxies, in literature that females are exposed to higher levels of HAP than males, due primarily to genders roles which keep women in close proximity to cooking fires (1,38). The results from this study show that males had slightly higher mean $PM_{2.5}$ exposures than women from the same households, 106 $\mu g/m^3$ versus 95 $\mu g/m^3$, respectively. Males also had a higher ratio of personal exposure over household exposure than females for $PM_{2.5}$, 2.65 versus 2.07, respectively, and for absorbance, 0.85 versus 0.67. Conversely, females had a higher geomean personal exposure 85 $\mu g/m^3$ versus 76 $\mu g/m^3$ for males. The results from this study may be a by-product of the small sample size, or they may point to a weakness in proxy-based models of personal exposure. In either case there is a clear need for a more broadly based quantitative assessment of personal exposures and for gender specific models of models of personal exposure (38).

It is also interesting to note that personal $PM_{2.5}$ exposures for males and females were more than double their matching household measurements, while the same samples showed absorbance ratios of 0.85 and 0.67. This would seem to indicate that males and females were exposed to a significant source of respirable particulates with a lower black carbon content than in their matching households. This result also highlights the usefulness of making absorbance measurements on $PM_{2.5}$ samples, in this case as a way of detecting a potential confounding influence on personal HAP exposures that a time-balance derivation of personal exposures from household measurements would likely not have produced.

The strength of any conclusions from the personal exposure measurements from the prototype UPAS monitors are constrained by the small sample sizes for males and females. Only 17 of the 53 households with successful reference HI measurements also had successful male and female

UPAS personal exposure measurements. Despite this it seems reasonable to conclude that personal exposure sampling with the UPAS monitors could provide a valuable source of information for the PURE AIR study, especially given the design changes made to the UPAS after the conclusion of this study.

4.4 Linear regression models of household air pollution

Simple statistical models of HAP for all households combined and for households by village were developed using both the PURE baseline questionnaire and the expanded pool of variables. Models for HAP exposure by village had similar or slightly better explanatory power than the combined model; adjusted R^2 values of 0.64 versus 0.64 and 0.41, for combined and village level models of $PM_{2.5}$ using expanded pool variables, respectively; and 0.50 versus 0.51 and 0.63 for absorbance. The expanded pool of variables added significant explanatory power to the village level models, improving adjusted R^2 from 0.48 to 0.64, and from 0.16 to 0.41, for Belupalle and Kheri villages, respectively.

The predictor variables drawn upon from the PURE baseline questionnaire were broadly similar to the predictors used by Balakrishnan. Likewise, the factors selected by this study's model making process were roughly equivalent to those selected by Balakrishnan. Table 16 shows the factors selected by this study's model compared to Balakrishnan's model.

Table 16: Predictive variables selected by models of HAP $PM_{2.5}$ exposure from this study and Balakrishnan et al (1)

This study	Balakrishnan
Community	Study region
Cooking location	Kitchen type
# Persons per household	Cooking time
Ventilation feature	Ventilation rating*
Fuel type	Fuel type

*Ventilation rating in Balakrishnan was a subjective qualitative appraisal of household ventilation. This study assessed the presence or absence of three classes of ventilation features and also qualitatively assessed ventilation performance.

The factors selected by either model, this study or Balakrishnan, were roughly equivalent. Community in this study is a smaller scale proxy for national region in the Balakrishnan study, especially considering this study's two rural villages were very far apart from each other. The strong differences in HAP related behaviors between villages, and the relative homogeneity within villages, coupled with the clear difference in average HAP levels between villages points to the importance of modelling HAP at the community, or perhaps regional, levels.

Cooking location and kitchen type are also roughly equivalent, Balakrishnan had a more detailed assessment of kitchen layout, and included outdoor kitchens as one possible value of the kitchen type predictor. This study did not measure kitchen dimensions, but all homes with indoor cooking had separate cooking areas. It is also worth noting that this study's model making process selected cooking location as a predictive factor despite the fact that the large majority of households surveyed (40 of 53) cooked indoors exclusively, and only one household cooked outside exclusively. Additionally, and confusingly, outdoor cooking was associated with increased HAP levels in this study's models. This may be the result of increased infiltration of ambient particulates, based on the observation that in the expanded pool absorbance model for Kheri outdoor cooking was associated with lower carbon measurements.

Cooking time, selected as a factor by Balakrishnan, and the number of persons per household, selected in this study, are very closely related. In this study the number of persons per household were positively and significantly correlated with increased cooking time, $r = 0.51$ and $p < 0.0001$, respectively. This study borrowed Balakrishnan's subjective assessment of kitchen area ventilation, (poor, moderate and good), but this study's model making process selected discreet ventilation features as a better predictor.

The exhaust ventilation feature was the most frequently selected in the models generated by this study, but the presence of this feature was associated with a rise in HAP. It seems counter intuitive that a ventilation feature could increase HAP levels; however, this may be because an exhaust was defined as any opening that was not a chimney or an open window or a door. So, the presence of an exhaust feature can be viewed as the lack of a superior ventilation feature.

This study selected fuel type as a predictor of $PM_{2.5}$ levels in the combined villages PURE baseline factors model and in the expanded pool factors individual villages models. Balakrishnan selected fuel type in its general combined model. In this study, most households used LPG as a primary fuel, which may have diminished fuel type as an important class of predictive variable. Despite this, both this study and Balakrishnan show the importance of evaluating the type of fuel used in a household. It is also worth noting that only one home used kerosene as a fuel, so it's association with lower HAP levels in the PURE combined villages model may not be meaningful.

None of Balakrishnan's papers, or apparently and other paper to date, have used household characteristics and features to build a linear regression model of absorbance. This study's results indicate that that the ratio of personal exposure over household $PM_{2.5}$ levels are much larger than the ratio of personal over household absorbance measurements, 2.65 and 2.07 versus 0.85 and 0.67, for males and females respectively. These differences indicate that the persons sampled in this study had a significant source of non-combustion related $PM_{2.5}$ compared to their matching household levels. These differences point to the importance and value in taking absorbance measurements from gravimetric $PM_{2.5}$ samples.

The results from this study show that the questions from the PURE enrolment questionnaire can be used to construct a simple statistical model of HAP, but more importantly they show that there is significant and meaningful additional value in gathering additional observational and questionnaire data, specifically measures of secondary fuels types used and the amounts of fuels used, for building models of HAP exposure. It is not possible to say whether or not a larger study would choose the same variables as selected here, but there does seem to be good reason to collect observational and questionnaire data beyond what is found in the PURE baseline questionnaire. The specific performance metrics of these models of HAP levels are less important than this study's demonstration that functional models can be built using observational and questionnaire data, including variable beyond what are drawn from the PURE baseline questionnaire.

4.5 Strengths and limitations

The primary strength of this study was its leveraging of the PURE cohort to test prototype air quality monitors in conditions very similar to what the PURE AIR project will encounter in its fieldwork, in India, Pakistan and Bangladesh. Testing these prototype monitors against each other and a reference device in a lab would not have been able to duplicate the stresses encountered in fieldwork, especially with respect to the personal exposure measurements taken by this study. Using PURE enrolled participants means the results from this study should be directly applicable to the PURE AIR project. This is most directly relevant in the recommendation of the UPAS monitor for use in the PURE AIR study. Using the PURE cohort also means that the predictive variables drawn from the baseline questionnaire can also be used to retroactively model exposures in those participating households at the time they were enrolled. This may be of value to both the PURE and PURE AIR studies as they examine health outcomes from the PURE cohort. PURE also has additional participant data not used in this study that could be used to construct even better models of HAP exposure.

Another strength of this study was its ability to work with Access sensors to develop subsequent versions of the UPAS monitor. This study was able to pass recommendations regarding monitor design and performance onto the UPAS's developer immediately following fieldwork. This enabled the quick development of two subsequent versions of the UPAS, and the knowledge gained from the fieldwork in this study was instrumental in the formulation of a field sampling protocol for the PURE AIR study. This significantly enhanced the usefulness of this study to the PURE AIR project.

The primary limitation of this study was the small sample size, or more precisely the homogeneity of some of the results. Even though the fieldwork component of this study was successful, the number of households participating were not varied enough to fully explore the power of some predictive household variables' contribution to HAP. For example, every participating household had electricity, so despite assessing this variable the results had no power to predict HAP levels. The much larger Balakrishnan et al study was able capture a more diverse array of responses in its data (1). Even though it assessed a narrower array of predictors compared to this study's expanded pool of predictors that study was still able to generate a good quality model of HAP $PM_{2.5}$, with more confidence in its findings. The sample size limitation in this study will be more than corrected in the PURE AIR study, so whatever shortcomings there are in this study's results should not automatically impair the PURE AIR study.

The problems this study had with field logistics and equipment malfunctions will hopefully not apply to the PURE AIR study either. While the loss of measurement data did impair this study, specifically the inability to put the reference TSI DustTrak to good use, it did not nullify this study's results. The knowledge and experience gained during fieldwork in India in 2015 was put to good use in selecting support equipment and putting together kits of field equipment for the PURE AIR study.

This study's conclusions with respect to modeling HAP levels from observable household characteristics and questionnaire responses are also limited when compared to the models that could have been generated if this study had considered the broader data on PURE enrolled households and participants possessed by the PURE study. The PURE study has a very rich database which includes measures of household income, SES, and other fields.

4.6 Post-fieldwork work in support of PURE AIR

Following the completion of fieldwork in 2015 the results and observations from the evaluation of the UPAS monitor were shared with Access Sensor Technologies. The strengths and weaknesses of the device were discussed, as well as recommendations for design changes for subsequent versions of the UPAS monitor. The recommendations were to:

- Use a different filter material. The Teflon-coated glass fiber filters used by the UPAS in this study (PALL fiberfilm) were very fragile and difficult to acquire. Access was encouraged to find a suitable low-impedance PTFE filter.
- Employ a filter cassette design. Handling the filters required for gravimetric sampling was a significant challenge in the field. Even stronger filters like the PTFE filters used in the reference HI device can be easily damaged or contaminated if not handled correctly. The PURE AIR study aims to use staff from PURE partner agencies who, while very hard-working and motivated, may not be trained and familiar with good sample handling techniques. Placing filters in labeled cassettes would significantly reduce the chances of contaminating, damaging or mishandling a sample.
- Change the design of the UPAS to use a screw-on filter cap. The press fit design of the UAPS monitors used in this study were problematic, too much pressure could damage a sample filter easily and wear and tear from constant use resulted in progressively loser fits over the course of fieldwork. A screw-on cap design, coupled with a filter cassette, would alleviate this problem.
- Enable wireless data transfer and programmable duty cycling. The microSD cards used by the UPAS monitors in this study were reliable, but difficult to insert and remove and could damage the monitor if inserted incorrectly. Enabling wireless data transfer would eliminate the need for constantly removing and inserting the microSD cards. Additionally, the ability to program duty cycles into the UPAS monitor would significantly extend the effective sampling time capabilities of the device, making longer term sampling possible without the need to use an external battery pack.

- Alter the design of the air intake to be more resistant to inhalation of large particles and insects, or occlusion by clothing. Some samples were lost when a UPAS monitor sucked up small insects into the analytical filter chamber, others were likely lost when clothing from personal exposure participants covered the air intake, causing an unrecoverable interruption in airflow.

Access Sensor developed two subsequent versions, V1.2 and V2.0, of the UPAS monitor, the final version, V2.0, was delivered in quantity to the PURE AIR study in the spring of 2017. This version incorporated all of the recommendations made in 2015, plus more features including a smart-app controller, and an integrated receiver socket for attaching the UPAS to a stand for stationary measurements. A more detailed description of the UPAS used in the PURE AIR study is given in Arku et al (38).

This study produced a field sampling protocol for use in the PURE AIR study, together with instructional videos for field staff carrying out household and personal exposure sampling in the PURE AIR study's extensive field sampling campaign (appendix 7.9). The protocol covered all aspects of UPAS operation and support necessary for PURE AIR field staff to prepare, program, operate, and collect data with the UPAS monitor. Additionally, the protocol details sample handling and the transmission of electronic sample logs from each UPAS back to a server at UBC, which allows PURE AIR to quickly detect non-compliant samples and then request resampling. The protocol, based on the results of this study, allows the PURE AIR project to send all the equipment needed for data collection to its partner institutions without the need for expensive in-person training and supervision. Other support documents were also produced including a smartphone setup guide, which instructs PURE AIR staff in how to configure the smartphones used to program the new UPAS monitors, see appendix 7.10.

Based on the lessons learned during fieldwork this study selected the support equipment used in the PURE AIR study. It also assisted the PURE AIR study in developing a data transfer and handling method allowing rapid transfer of the sampling logs generated by the UPAS monitors to be transferred to a central server at UBC where each log could be automatically scanned for errors or other problems. This data transmission and scanning ability allows the PURE AIR study to detect and diagnose problems with field sampling rapidly enough to allow it to direct field staff to resample specific locations and persons when problems arise, which in turn reduces lost sampling results.

4.7 Suggestions for future research

This study was undertaken in support of the PURE AIR study, which has already employed the UPAS monitor in its work, along with the field sampling protocol developed with the knowledge and experienced gained in this study. Hopefully the experience and knowledge gained in that study will inform the design of subsequent versions of the UPAS, and perhaps other monitors. The use of filters, while challenging from a logistics and cost perspective, means that the UPAS could be employed in sampling for a wide variety of pollutants or contaminants. The field sampling protocol developed by this study for the PURE AIR study, and the remote data management and field work support this study assisted in developing, may also be useful to other projects. The ability to send kits of easy to use equipment with simple instructions and procedures means local health care workers or similar support staff can carry out important health research in a faster, more efficient, cost-effective and equitable manner than has previously been possible. Exposure studies in remote areas, or of larger cohorts, would be well served by the UPAS monitor, or similar devices, coupled with the techniques and methods developed for the PURE AIR study.

5 Conclusions

Numerous studies and papers have pointed out the need for relatively low-cost, compact, easy to use and reliable air quality monitoring devices for use in household exposure assessments in developing countries (2,4,5,43). However, the lack of appropriate equipment has hampered studies of HAP exposure until now. This study has shown that the UPAS monitor (Access Sensor Technologies) can be used to measure personal and household HAP $PM_{2.5}$ in communities in LIC and MIC with high levels of indoor air pollution from the use of low-quality liquid and solid fuels. The successful construction of a simple statistical model of HAP exposure should serve as a proof of concept for the PURE AIR study that data collected by the PURE study, and observations of household characteristics, can be used to model HAP exposures in the larger PURE AIR study. Leveraging the PURE cohort, and the generous support of PURE study partner institutions, made this study possible and significantly enhanced its usefulness to the PURE AIR study. The small scale and sample size in this study do limit the power of the model of HAP exposure, however, the model serves as a valid proof of concept.

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Appendices

A Simple Predictive Model Building Steps

Basic steps for building models of HAP are:

1. Clean data
2. Recode and collapse variables
3. Transform outcome variable
4. Spearman’s Rho correlation of all possible predictor variables with outcome variable
5. Test for auto-correlation between predictor variables
6. Use an all-possible-models technique (automatic in JMP) to find best predictor variables from the original PURE questionnaire data set. This will wind up generating a basic predictive model
7. Forced inclusion of expanded variables on to the model produced in step 6. This may result in multiple additional terms being added to the base model.

These steps are described in more detail below:

1. **Clean data:** This step means going through my database and making sure that all the values and responses recorded are as they should be. (e.g. no transposed digits, no misplaced responses).

   I will also remove households without a valid Harvard Impactor (HI) measurement of PM2.5, (it turns out there were only two). I do not believe I can reliably impute missing values for the response variable in a data set this small. No households had missing predictor variable observations
2. **Recode and collapse variables:** In this step I will collapse some unique responses to the next closest response. (e.g. There were types of household materials which were very similar in nature and permeability (cement versus stone covered in cement), these were collapsed into the same category).

I will also recode several binary categorical responses into a single nominal variable. (e.g. Instead of yes/no responses for several independent but related responses I will make a single nominal variable with a unique value for each combination of independent responses).

3. **Transform variables:** This really only applies to the response variable. I can show that HAP concentrations are log-normally distributed, and therefore a simple natural log transformation will make it possible to use further statistical tests.
4. **Correlation (Spearman's Rho) between possible predictors and outcome variable:** The correlation (Rho) from the Spearman's test will show which predictive variables are most strongly connected with HAP concentrations on an individual basis. I'll use Spearman's test as it is better at dealing with non-linear relationships than Pearson's correlation. Because HAP levels are a function of many interacting factors I can't say that any individual factor is monotonic with HAP levels.

   For this step I will test both the recoded categorical variables and the individual variables (eg the ventilation recode variable and each ventilation factor separately). I want to do this to make sure that the recoding process doesn't gloss over or suppress an individually predictive variable.

   I think that if I get even one good connection between a predictor and the response then I should include the entire category, even if the recoded category doesn't show a good connection.
5. **Test for collinearity between predictor variables:** In some of the papers I've read where multiple linear regression (MLR) models were used this step frequently comes after variable selection. In my case I think it's a better idea to test for collinear variables at this step for two reasons:
   - One, I want to look at correlation amongst all of my possible predictor variables, not just the one the variable selection step chooses (I want to be able to evaluate the variables I don't use in my model, as they might prove useful with an expanded data set).

- Two, I want to show collinearity amongst my un-recoded variables, but I will build my model around the recoded variables (eg, in my model I'll use a single variable for fuel type combinations instead of 7 independent variables, one for each possible response). It may be that factor within a category is collinear with another category factor, even if the whole categories are not.

I will take a correlation between two predictor variables above 0.6 to indicate the possibility of collinearity, and I will evaluate each instance myself to see if there really is collinearity at work.

6. **All-possible-models for villages combined and each separately, with PURE and expanded pool variables each:** Due to my small sample size I know I can't support a model with more than 4, or at maximum 5, predictors. This means it's feasible to use an automated model building method. I will run this procedure with all of my collapsed/aggregated predictors and repeat the process with 3, 4 and 5 factor outputs.

   I am not going to set a hard rule for which level model to use if models with different numbers of predictors wind up with the same, or very close, adjusted r^2 values. I think if I do, I will just wind up having to next state that I will look at the resulting model to see if it has useful/meaningful variables. (eg If I say I will always use the lowest factor model I might wind up having to break my own rule if I wind up with "floor material-tobacco-open window").

   It may be the case that each factor level model will include only predictors which I would view as having low real-world predictive power (e.g. a model that uses only tobacco products, floor material and secondary fuel amounts), in which case I would have to conclude that it isn't possible to make a good predictive model with my data, but that's a legitimate outcome (if a disappointing one).

   From general observations and impressions during fieldwork it was obvious that there were significant differences between the two villages. So, to test whether this really was the case I'll model the villages together and again separately. For each village level model, I'll run the PURE factors and the expanded factors. And then for every combination I'll model $PM_{2.5}$ and absorbance.

B Thresholds for Variable Inclusion/Exclusion

Because I am proposing to use an all-possible-model method I don't have to specify a threshold for the inclusion/exclusion of predictor variables.

Despite this I do want to keep an eye on the factors selected by the modeling process, and make sure they have at least a plausible correlation/regression connection to the outcome variable in my pairwise tests, and that they aren't collinear (though I shouldn't let collinear terms in the model in the first place). Balakrishnan et al. used a p factor of 0.25 in their regression model, but then wound up using a different technique in the end.

C Response Variable Selection

There are no rules needed to select a response variable for my simple predictive model of HAP. The only suitable variable is PM2.5 concentrations in micrograms per cubic meter of indoor air.

Household PM2.5 was measured gravimetrically with Harvard Impactors (HI) and UPAS monitors. There are two main reasons why I should base my model on the HI measurements; one, the HI is the reference device and so I have the most confidence in its measurements. Two, the HI had more successful samples (53 of 55 attempts) than the UPAS (47 of 55 attempts).

The entire point of my thesis and the work I've done with assessing and developing new monitors has been to find a better way of understanding exposure to PM2.5. In my thesis I can get into why hygienists, epidemiologists and public health people want to measure PM2.5, versus some other indicator.

Technically the TZOA and the PUWP devices recorded particle counts per time period. My intention was to translate these data into a measure of PM2.5 by comparing the particle counts from these devices with the data recorded by a TSI Dustrak in the same location, and at the same time.

The results from the TZOA and the PUWP device are not what I hoped they would be. Both devices suffered more failed sampling attempts than the UPAS monitors, and many more failed samples compared to the reference HI devices.

To illustrate: with the PUWP devices I attempted a total of 85 samples in 55 households; of these 29 were partially successful in that they recorded data for some of the 24 or 48-hour sample period, another 17 of the 85 samples were fully successful in recording for the entire sample period. With the TZOA devices I attempted a total of 75 samples in 55 households; of these 17 were partially successful, another 32 were fully successful.

D Description of Variables

D.1 Household PM2.5 concentrations (measured by Harvard Impactor)

Type: Continuous

Units: micrograms per cubic meter – $\mu g/m^3$

Mean: 82.66

Minimum: 13.23

Maximum: 346.04

Standard Deviation: 80.43

Number of unique measurements: 53

Transformations: The measurements for this variable are (weakly) log-normally distributed. For descriptive statistics the data is left untransformed, for all other statistical tests the data is first log transformed.

Measured by: Harvard Impactor with a size selective impactor plate, using a 37mm ptfe filter with a 2-micron pore size, run at 10L/minute using a TSI Leyland Legacy pump, calibrated before and after use with a BIOS DryCal piston type calibrator. All equipment property of Occupational and Environmental Hygiene program, School of Population and Public Health, Faculty of Medicine, University of British Columbia.

Description: This is variable is the concentration of PM2.5 in the air of the kitchen area of sampled households. Each concentration was calculated in the normal way for an air filer sample.

Why this variable? The results from the Harvard Impactor are the best response variable for two basic reasons:

1. There are more measurements of PM2.5 HAP from the Harvard Impactor than there are from any other device.
2. The Harvard Impactor was used as a reference device against which the other devices were tested against. Therefore, we can have the highest confidence in these data points compared to any other results.

*Please note:

- All predictor variables were successfully measured in every household sampled, so the number of unique measurements for every predictor is 53.
- No predictor variables have been transformed
- I am using the PURE/International questionnaire from Feb 2012 as my source for which variables that project used.

D.2 Fuel Types: Primary, Secondary

Type: Nominal

Units: NA

Values: LPG, Kerosene, Wood, Wood and Dung, None (2^{nd} only)

Original PURE variable? The original PURE questionnaire only asked for the primary fuel used for cooking, and only allowed a single response (eg no fuel mixing). Mixed fuels as a response and secondary fuel types are part of my expanded set of variables.

Measured by: Interview. Field staff from St. John's Research Institute (Belupalle) and PHRI (Kheri) interviewed participants from sampled households and asked what fuel(s) were used for cooking. Responses were recorded.

Description: Fuel type refers to the basic type of fuel used for cooking in the sampled household. (No sampled households had any provisions for heating). Liquid fuel type was almost exclusively liquefied petroleum gas (LPG) with only one household using kerosene (this household was treated/coded as LPG). Two basic types of solid fuels were observed: Wood and Wood and Dung. These were exclusive by village (Wood only in Belupalle). In both villages wood was sourced from local scavenging/harvesting (eg not purchased from a reseller). Dung in Kheri was sourced from each household's livestock (Cattle and Buffalo)

Primary fuels are the dominant energy source for cooking in the sampled household. The original PURE questionnaire asked for the primary fuel used for cooking and allowed only one response, additionally this didn't allow for multiple fuels used together (eg co-burning wood and animal dung). For my purposes I am allowing fuel mixtures as a response (if I don't then the results for households who used solid primary fuels will be very confused).

Secondary fuels were supplemental fuels also used in the cooking. There is no equivalent for secondary fuels in the original PURE questionnaire. A single fuel type cannot be used as both a primary and secondary fuel. In my observations primary and secondary fuels were mutually exclusive by fuel state (eg solid versus liquid), so if a solid fuel was used as a primary, then the only possible responses for secondary were liquid or none.

How does this connect to the outcome variable? The type of fuel used for cooking is perhaps the most important determinant of exposure. Other household characteristics may either amplify or dampen the amount of pollutant generated, or may protect or expose a person to that pollutant. But the prime factor determining the amount of pollutant generated would seem to be the pollutant itself.

D.3 Fuel Amounts: Total, Primary, Secondary (Solid fuels only)

Type: Continuous

Units: Kg

Values: Any amount greater than zero, recorded to the nearest half-kilogram

Original PURE variable? No, the original PURE questionnaire did not record the amount of fuel used for cooking or heating (solid or liquid fuels)

Mean: Total = 4.91, Primary = 3.69, Secondary = 1.21

Minimum: 0, 0, 0

Maximum: 22, 15, 10

Standard Deviation: 5.22, 4.29, 2.16

Measured by: Interview. Field staff from St. John's Research Institute (Belupalle) and PHRI (Kheri) interviewed participants from sampled households and asked how much solid fuel(s) were used for cooking. There was no reliable way to estimate the amount of liquid fuel used in a sample period. Responses were recorded.

Description: When participants were asked what fuel(s) they used they were also asked how much fuel they consumed during the sampling period, if they used solid fuels.

Some participants gave answers directly in kilograms, others showed the field team the amount (eg three pieces of wood a certain size). In the latter case the field team estimated mass based on the physical samples given. My field notes show that when participants were asked how much fuel they used there was a lot of back and forth between the interviewer and the participant, possibly indicating that participants were unsure themselves how much fuel they used, or were not clear on the question being asked.

How does this connect to the outcome variable? Intuitively the amount of fuel used should be very strongly related to emissions and thus concentration and exposure. However, this is probably not a 1:1 relationship as the operating conditions of the stove change over time, stoves are not equal between homes, and estimates may be inaccurate.

I suspect that in a broader sample this variable would be collinear with cooking time and/or fuel type, but my sample size is small. In my two-way ANOVA test cooking time and total solid fuel have a 0.39 correlation with a p value of 0.0035, this is likely weakened somewhat by the fact that cooking time includes liquid fuel cooking times. If I weed out all the households that only used liquid fuel then cooking time is correlated to total solid fuel at 0.40 with a p value of 0.0178, so it turns out the liquid fuel households had a minimal effect.

D.4 Cooking Location

Type: Nominal

Units: NA

Values: Indoor kitchen (collapsed from separate indoor and common area kitchens), Outdoor kitchen, Indoor and Outdoor kitchen.

Original PURE variable? Yes, the original PURE questionnaire asked where cooking for the household was done. It allowed responses of Inside, Outside, or Both.

Measured by: Observation and interview. I assessed where the main kitchen was and confirmed with the participants via field staff from St. John's Research Institute (Belupalle) and PHRI (Kheri). Responses were recorded.

Description: This variable describes where the household's cooking took place during the sample period. If cooking only took place indoors then the household was assigned indoors as a cooking location, likewise for outdoors. If cooking took place indoors and outdoors to any extent then the household was assigned indoor and outdoor kitchen status. This assignment doesn't describe how cooking was split between two locations (eg big stove inside, small outside)

There really wasn't any possible ambiguity about where participant's cooked, and I don't think the field staff had any trouble getting the answer from the participants.

How does this connect to the outcome variable? Where the food is cooked, and thus where the fuel is burned, is a basic factor of exposure. In my observations liquid fuels were never used in outdoor kitchens, so I believe that this variable's effect is tangled up with fuel type (also the location of a dirty fire affects exposure much more than the location of a clean one). I am not sure if this connection shows up in my data, as fuel types used were also very segregated by village.

D.5 Months per year cooking outside

Type: Continuous

Units: Whole calendar (western/Gregorian) months

Values: 0 through 12

Original PURE variable? Yes, the original PURE questionnaire asked for the average # of months per year spent cooking outside, in whole months except with any time less than a month but more than zero recorded as one full month.

Measured by: Interview. Field staff asked participants (primary female mostly) how many months per year they primarily cooked outdoors. This question was only asked if the participating household had indicated that they did not cook indoors only. Households that cook only indoors were assigned a value of zero.

Description: This covers how many months every year the household uses its outdoor stove/fireplace as its primary cooking location. This does allow for using indoor and outdoor cooking locations simultaneously, so long as most cooking takes place outside. This variable doesn't account for households which used their outdoor stove as an occasional supplement to their indoor stove.

This variable doesn't account for where cooking took place during the sample period.

How does this connect to the outcome variable? This variable serves as a proportional measure of the split between indoor and outdoor cooking in households which used both locations for cooking.

However, so long as this variable has a value less than 12 and more than 0 it can't, by itself, describe where cooking took place during the sample period.

No households were observed to switch cooking locations during a sample period.

D.6 Ventilation

Type: Nominal

Units: NA

Values: Open Window, Chimney, Exhaust

Original PURE variable? Yes, the original PURE questionnaire asked if cooking took place indoors if there were: windows, chimney, exhaust, partially open to outside. In my observations no homes with indoor kitchen had partial openings (which I took to mean an open wall or some opening bigger than a standard door and permanently open).

Measured by: Observation. I assessed each sampled kitchen area for ventilation features. Results were recorded on location log sheets.

Description: Open windows were easy to identify, in fact no homes had glass windows in their kitchen areas. Chimneys were assessed as any structure over a cooking stove which gathered smoke and channeled it outside the home. Exhaust was essentially any other feature which would provide ventilation, but which was not an open window or chimney. These were typically holes cut in ceilings or walls.

How does this connect to the outcome variable? Ventilation features can be thought of as a defense mechanism. These features do not reduce emissions, instead they lower HAP levels by a combination of evacuating contaminated air and supplying (relatively) cleaner outdoor air. It is possible that open windows and exhausts could increase kitchen area HAP levels between cooking events by allowing more polluted outdoor air into the kitchen. A properly functioning chimney (with suction from air passing over the home) should resist this effect.

D.7 Cooking Time

Type: Continuous

Units: Hours, to the nearest half hour

Values: Any number of hours less than 24

Original PURE variable? No, the original PURE questionnaire did not ask for cooking time, or any surrogate for cooking time.

Mean: 3.12

Minimum: 1

Maximum: 6.5

Standard Deviation: 1.08

Measured by: Interview. Field staff interviewed participants from sampled households and asked them, usually the primary female, how many hours per day they spent cooking.

Description: We, the field staff and I, tried to define this as clearly as we could as the total time spent cooking during a sampled day. This included was meant to include the time a cooking fire was lit. However, it turned out that this a more difficult question to answer than we thought. Field staff spent more time with participants on this question than any other. Participants seemed to be unsure about how to divide time spent preparing to cook (eg cutting vegetables) versus time spent cooking (eg food in a pan, pan on the fire).

How does this connect to the outcome variable? Time spent cooking should be directly related to the time a particular stove or fireplace is used. However, in my case there might be a few problems with this:

- I was asking participants to recall/estimate time spent cooking. I should have asked participants to track the time they spent cooking and then report that back to me.

- I may have wrongly assumed that participants would think of all their daily tasks in terms of time, I also did not ask how participants measured time
- I should have asked how long the particular cookstove or fires were lit, not time spent cooking, as the former is more precise and relevant than the latter

Despite these problems I think I can use this variable as a measure of how much time an individual participant spent cooking relative to other households in a particular village, given similarities in diet, cooking methods, etc

D.8 Total Tobacco Products

Type: Continuous

Units: # of tobacco products used per day during sample period

Values: Any whole number

Original PURE variable? No, the PURE questionnaire did not ask about tobacco product use.

Mean: 4.03

Minimum: 0

Maximum: 30

Standard Deviation: 8.02

Measured by: Interview. Field staff asked male and female participants how many tobacco products they used per day during the sample period.

Description: In my questions for participants I asked about cigarettes, beedies (small hand-rolled cigarettes), and other tobacco products separately. However, only 3 households had cigarette smokers, and no households used a product classified as other. Only one household used multiple kinds of tobacco products. As a result, I collapsed the separate responses into a single category

How does this connect to the outcome variable? This variable is difficult to connect to HAP exposure in my data. When I select households with at least some tobacco use and fit # of tobacco products used to PM2.5 levels I get a slight negative correlation (-0.05) with a slight negative R^2 value (-0.08). When I compare Male and Female personal exposure levels to # of tobacco products used I get a negative correlation with a small positive r^2 for males and a small positive correlation with a negative R^2 value for females. These non-significant results are due in large part to the fact that so few households used any tobacco products (14 of 53) that I wind up with very few data points.

D.9 Building Materials (Roof, Walls, Floor)

Type: Nominal

Units: NA

Values: Roof: stone, cement, cement and stone, asbestos sheet, tile, wood, wood and tile – Wall: cement, earth, brick – Floor: cement, tile, cement and tile, earth

Original PURE variable? Sort of, the original PURE questionnaire asked about roof materials (thatch, tiles, reinforced concrete, slate, fibrocement sheets, galvanized iron sheets, asbestos sheets, other). The questionnaire did not ask about other home materials

Measured by: Observation and interview. I made direct observation of roof, wall, and floor materials. Where it wasn't obvious (ie painted surfaces) I asked participants what materials were used.

Description: This variable is pretty simple and straightforward, it's simply what materials were used in the 3 basic parts of the sampled home (roof, walls, floor).

How does this connect to the outcome variable? There are two ways in which building material connect to HAP levels:

1. Building materials are a strong indicator of SES. It is reasonable to assume that a household capable of using superior building materials will also be able to use superior fuels for cooking and heating. Questions then arise around fuel stacking and willingness to pay, and that is why observing this variable may be useful beyond a more direct measure of SES (eg income, savings, etc)
2. Superior building materials may paradoxically be connected to higher HAP levels if they also restrict ventilation (eg a sealed concrete roof has a lower inherent ventilation ability than a thatched or unsealed tile roof). This effect might be seen in homes with different building materials but otherwise similar characteristics having higher than expected HAP levels in superior material homes.

D.10 # of persons in household (Male, Female, Total)

Type: Continuous

Units: # of resident persons in household

Values: Any whole number greater than zero. Recorded for male and female residents, sum equals total persons

Original PURE variable? Yes, probably. The original PURE questionnaire asked how many household members earned money. I believe the PURE teams did record the number of persons living in a household at some point.

Mean: Total, male, female: 5.01, 2.62, 2.39

Minimum: 2, 1, 1

Maximum: 17, 8, 9

Standard deviation: 2.61, 1.34, 1.52

Measured by: Interview. Field staff asked participants how many people were living in the home during the sample period.

Description: This is just what it seems, how many people were living in the home when sampling took place. In reality things were a bit more complicated. I didn't appreciate that members of extended families in the same village would move between their homes as much as I came to understand that they did. This was especially apparent in Belupalle during Ramadan when Moslems would move from home to home during the fasting period. While I believe that my counts of persons in the home at the time of sampling were accurate, they may not reflect the normal size of the household.

How does this relate to the outcome variable? The # of people in a home should be directly related to the time spent cooking and thus the amount of fuel used (either bigger stove/fireplaces used or used for longer). This might not be a directly linear relationship as in some way an economy of scale may exist. Conversely if a family size is too big for a kitchen's capacity it might necessitate more cooking events. Unfortunately, I did not record any measure of capacity (eg stove size, fire size) beyond the amount of solid fuels used.

D.11 Ventilation Rating

Type: Nominal

Units: NA

Values: Poor, Moderate, Good

Original PURE variable? No. The PURE questionnaire did not include an assessment of the quality of home's ventilation

Measured by: Observation. I assessed each sampled home's kitchen area ventilation (indoor only) for overall quality.

Description: This was a completely subjective measure. I looked for a combination of ventilation features, soot buildup, and general "tightness" of the home's construction. I wanted to see if my appraisal of a home's ventilation would match actual HAP measurements. This parameter was also used by some of my reference papers, including the Balakrishnan papers (the published work most similar to my own).

How does this connect to the outcome variable? This variable is an appraisal of the quality of a home's kitchen area ventilation. If it turns out that a subject assessment of ventilation is strongly connected to actual PM2.5 measurements then there may be some point to simply asking field staff in a larger questionnaire campaign to assess the quality of ventilation in a home. This might at least lead to a reliable way of placing a home within categories/ranks of HAP exposure.

D.12 Cooking Typical?

Type: Nominal

Units: NA

Values: Yes, No

Original PURE Variable? No. The original PURE questionnaire did not ask any questions about typical cooking practices as that project did no sampling.

Measured by: Interview, field staff in both villages asked participants if their cooking practices were typical/normal during the sample period.

Description: Atypical practices were not defined to the participant, if the participant indicated that cooking practices were atypical they were then asked to elaborate. Only three households indicated atypical cooking practices during a sample period. All three were at the start of sampling, which coincided with the end of Ramadan in 2015, which all three households indicated as the reason.

How does this connect to the outcome variable? The idea behind asking this question was to be able to identify samples of household and personal exposure which might not be representative of other households with the same characteristics.

D.13 Variable Recoding and Collapsing

In order to use the JMP program to perform statistical analysis of my observations I needed to convert my characteristic responses into nominal values. In general, I assigned each response within a category a number. (eg Zero for no, One for yes). Where a category had multiple levels of response (fuel types can be primary or secondary) I've made a two-digit number for the category with the first digit representing the first level and the second digit representing the second level, and so on.

D.14 Fuel Types

There were four distinct types of fuel used for cooking in all sampled households. As only one household used Kerosene I decided to collapse LPG and Kerosene into a single variable called liquid fuel. No household can use multiple fuel types for primary or secondary fuels. No fuel type can be both primary and secondary in the same household.

D.14.1 *Primary Fuels*

Fuel types	Value
LPG	1
Kerosene	2
Wood	3
Wood and dung	4

D.14.2 *Secondary Fuels*

Fuel Type	Value	Label
None	0	None
LPG	1	Liquid fuel
Wood	2	Wood
Wood and Dung	3	Wood and dung

D.15 Ventilation Features

Any sampled household could possess some, all, or no ventilation features. Each feature has been coded as separate variables with a value of zero, if the feature is absent, or one, if the feature is present.

D.16 Cooking Location

Two of the sampled households had indoor cooking locations in a common living area rather than in a separate kitchen area. Because I didn't separately sample for living area HAP levels I decided to collapse these homes into a single value for indoor cooking.

Cooking Location	Value	Laebl
Central Area	1	Inside
Kitchen	1	
Both	2	Both
Outside	3	Outside

D.17 Home materials

The original PURE questionnaire collected information on what material participant's roofs were made out of, other studies of HAP exposure have also collected information on wall and floor materials. I collected data on roof, wall and floor materials in all homes I sampled.

I collapsed responses for different materials into like groups with similar structural, ventilation, and SES qualities. (eg roofs made of cement, stone, cement and stone were collapsed into a single value for solid impermeable roofs I've called solid tight).

D.17.1 *Roof Materials*

Material	Value	Label
Cement	1	Solid tight
Cement & Stone	1	
Stone	1	
Tile	2	Sheet loose

Asbestos Sheet	2	
Wood	3	Wood loose
Wood and Tile	3	

D.17.2 ***Wall Materials***

Material	Value	Label
Cement	1	Solid tight
Tile	1	
Earth	2	Earth
Brick	3	Solid loose

D.17.3 ***Floor Materials***

Material	Value	Label
Cement and Tile	1	Solid
Cement	1	
Tile	1	
Earth	2	Earth

D.17.4 ***Home Material Combination***

Roof code +	Wall code +	Floor code

D.17.5 Ventilation Rating

Poor	1
Moderate	2
Good	3

D.17.6 Cooking Typical

Yes	1
No	0

E Questionnaire to Implement during Monitor Pick-up:

The majority of these questions are from the household questionnaire completed during PURE study enrollment.

Time and Date of Monitor Collection:

Household ID:

Participant ID:

Household GPS coordinates:

1.) Does the house have electricity?

- No/Yes

2.) Primary fuel used for cooking in the past 48hrs (check only one)

- Kerosene, charcoal, coal, gas, wood, agriculture/crop, gobar gas, electricity, animal dung, shrub/grass, other

3.) Were additional fuels used for cooking?

- Kerosene, charcoal, coal, gas, wood, agriculture/crop, gobar gas, electricity, animal dung, shrub/grass, other

4.) If solid fuel was used, how much was used for cooking

- <1 bucket, 1-2 buckets, 2-4 buckets, >4 buckets (define size of bucket)

5.) Where was cooking for the household done? (check all that apply)

- Inside the house in a separate kitchen, Inside the house in the central living space, outside the house, inside and outside the house

6.) If cooking was conducted inside the house, were there any of the following? (check all that apply)

- Open window, chimney, exhaust, partially opening to outside

7.) In the last 48 hrs was your cooking practices representative of a typical day?

- No/Yes, if no how did they differ?

8.) On average, how many hours do you typically cook per day?

9.) Primary heating source in the past 48hrs (check one only)

- Coal open fie, wood open fire, gas furnace, portable heater, none, electricity, other

10.) # of cigarettes , beedies or other forms of tobacco smoked in the home during the last 48 hrs.

F Sample Log Sheets

Log Sheet #	Date:	Technician:
PURE Community ID#	Household ID#:	Site Name: Palamaner
Sample Location #	Lat:	Long:
Temperature (C):	RH%	Rain (Y/N & Description):

Pre-Deployment (Household)		
SKC Pump #	H.I. #	Filter #
Run Test (Y/N)	Charge Confirmed (Y/N)	Flow Rate Set to:
UPAS #	Filter #	Run Test (Y/N)
Tzoa#:	PUWP#:	Dylos#:
Pre-Deployment (Personal #1)	UPAS #	Filter #
Run Test (Y/N)	Wristband #	
Pre-Deployment (Personal #2)	UPAS #	Filter #
Run Test (Y/N)	Wristband#	

Deployment (Household)	Devices Running (Y?N)	Deployment Time:
H.I. & SKC	Calibrated Rate:	Calibrator:
UPAS:	Calibrated Rate:	Calibrator:
Personal #1	ID#	Deployment Time:
UPAS:	Calibrated Rate:	Calibrator:
Personal #2	ID#	Deployment Time:
UPAS:	Calibrated Rate:	Calibrator:

Collection (Household)		
Collection Time:	SKC & H.I. Running:	UPAS Running:
Tzoa Running:	PUWP Running:	Dylos Running:
H.I. & SKC	Calibrated Rate:	Calibrator:
UPAS:	Calibrated Rate:	Calibrator:
Collection (Personal #1)	Devices Running:	Collection Time:

UPAS:	Calibrated Rate:	Calibrator:
Collection (Personal #2)	Devices Running:	Collection Time:
UPAS:	Calibrated Rate:	Calibrator:

Observation Results	**Household ID#:**
Type of Roof	
Type of Walls	
Type of Floor	
Electricity?	
Primary Cooking Fuel	
Secondary Cooking Fuel	
Primary Heating Fuel	
Secondary Heating Fuel	
Cooking inside or out or both	
Kitchen Type (outside, detached, inside no partition, inside with partition)	
Inside Cooking Ventilation (chimney, window, opening)	
# opening to kitchen (0,1,>2)	
Inside Heating Ventilation (as above if separate)	
Inside ventilation rating (poor, moderate, good)	
Window in cooking area	
Outside fire/stove	
Months of year cooking outside	
Distance from cook area to device (lat, vert)	
Cooking Time	
Fuel switching during sampling?	

Person #	Gender	Age

G Filter Weighing

Filters were weighed prior to fieldwork in May and June of 2015, post fieldwork weighing took place in September and October of the same year. Filters of either type were examined for damage or signs of contamination post-field work; any filter with signs of damage or contamination were not weighed post fieldwork.

Filter weighing technique was as follows.

1. Prior to filter weighing the ? microbalance was calibrated according to laboratory standards, using two different standard weights. This scale is accurate to 0.001mg or 1µg.
2. Each filter was handled using stainless steel tweezers only.
3. Each filter was passed through a de-ionizing device, a ?, for 10 seconds, then placed on the scale balance.
4. The scale balance chamber was sealed and the scaled was allowed to settle for 15 seconds. The scale readout at this time was taken and recorded on a laptop computer.
5. The scale was then opened, the filter removed and passed through the de-ionizer for 10 seconds before being returned to the scale for the next measurement. The scale was allowed to re-zero itself during this time.
6. This process was repeated until three measurements were taken within 0.005 mg of each other. The pre- and post-sampling weight assigned to each filter was the average of the three measurements taken.

7. If a weight outside this range was observed then the process was restarted on the next measurement.

H Filter Absorbance Measurements

Light absorbance measurements for all filters, HI and UPAS, were made after filter weighing was complete. Light absorbance is a good proxy measurement of combustion by-products, standard gravimetric analysis does not discriminate the source of the particles captured by a filter.

All absorbance measurements were made using a Diffusion Systems Model 43 smoke-stain reflectometer using that instrument's standard operating instructions.

Absorbance was calculated using the following formula:

Where

- a = absorbance
- A = area of the stain on the filter
- V = volume sampled (m^3)
- R_F = average reflectance of the field blank filters
- R_S = reflectance of the sample filter as a percentage of R_0, where R_0 is the clean control filter (set to 100.0)

Absorbance measurement technique was as follows:

1. The smoke-stain reflectometer was allowed to warm up for at least 10 minutes prior to calibration and use.
2. The reflectometer was first zeroed according to instructions.
3. A blank filter of either type, HI and UPAS, was selected and calibrated according to instructions.

4. After blank calibration five filters were measured, then the reflectometer was re-set using the selected blank.
5. The sample head of the reflectometer was always kept on the dark grey standard when not in use, this helped to prevent drift between measurements.
6. Each sample was placed on the white standard plate, then the sample head was placed on the first of the five locations specified in the reflectometer instructions and allowed to rest for 15 seconds, then a reading was taken and recorded on a spreadsheet.
7. The sample head was placed on the dark grey standard for 15 seconds, then the next measurement was made immediately.
8. The previous two steps were repeated until five measurements of the sample were made, at the center, top, right, bottom, and left edges of the sample.
9. Care was taken not to include the outside edge of either type of filter where no material accumulated due to contact with the monitor internals during sampling, this area has a high reflectivity and would produce artificially high reflectivity measurements if included.

I Mass Concentration Calculations

Using Excel software, the $PM_{2.5}$ concentration for each successful HI and UPAS gravimetric sample were calculated by dividing the average mass gained by a filter by the volume of air passed through each HI and UPAS monitor and expressed in $\mu g/m^3$. HI sample volumes were calculated by multiplying run-times, in minutes, by the average of pre- and post-sample flow rates. UPAS sample volumes were calculated automatically by each UPAS monitor and extracted from the run log file associated with each household and personal sample.

J PURE-AIR Monitoring Field Sampling Protocol[1]

[1] The purpose of this document is to explain how to prepare, operate, and retrieve the UPAS monitor when collecting personal and household air pollution samples in the PURE AIR Study. The UPAS monitor is produced by Access Sensor Technologies, of Fort Collins Colorado. This protocol was initially developed by Aaron Birch, MSc candidate –School of Population and Public Health, The University of British Columbia, Canada.

Table of Contents

Table of Contents

1 Summary

This document describes use of the UPAS air monitor, and its accessories, for the PURE-AIR study. Specifically, this document will instruct you in how to prepare, deploy, and collect the UPAS monitor for both household and personal measurements.

Study coordinators will need to use the supplied equipment to collect the required number of 48-hour household and personal $PM_{2.5}$ exposure measurements. Coordinators and staff will need to:

- Pre-fieldwork:
    a. Contact selected PURE households and participants and arrange a time when sampling can take place
    b. Set up a clean and secure work area with reliable electricity
    c. Unpack supplied equipment
    d. Arrange internet access for project smartphones
- UPAS Preparation:
    a. Recharge each UPAS
    b. Gather monitors, filter cartridges and paperwork for each household monitored
    c. Gather the required support equipment
- UPAS deployment:
    a. Acquire consent
    b. Prepare paperwork
    c. Load UPAS monitors with filter cartridges
    d. Place household UPAS monitors in each home's indoor cooking area
    e. Equip participants with personal UPAS monitors
    f. Program and activate each UPAS monitor using a smartphone
- UPAS collection:
    a. Collect all UPAS monitors and support equipment
    b. Make basic observations of each PURE home and administer a short questionnaire
- Post collection:
    a. Unload used filter cartridges from the monitors
    b. Complete paperwork
    c. Upload sample records to a PURE AIR smartphone
    d. Clean, reload and recharge the monitors
- Post-Fieldwork
    a. Repack all monitors and support equipment for shipping to the next study site
    b. Pack all samples and paperwork separately for return to PURE AIR project headquarters

In every PURE household selected for this project 1 UPAS monitor will be placed on a stand in the cooking area. In 1 out of every 5 selected PURE household personal exposure measurements will be taken, ideally from a male and female household member.

PURE AIR project coordinators will instruct local coordinators on which households and persons to recruit for sampling.

1 Introduction

Please read through this entire document before unpacking and using the equipment provided. Short videos have been made for some sections. These videos can be found on the microSD cards for the smartphones, (look in the *PURE AIR videos* file), and online at YouTube.com.

1.1 Household Air Pollution

Household air pollution (HAP) is one of the biggest threats to the health of people all over the world. One billion people around the world are exposed to HAP through use of poor quality fuels for cooking and heating

Figure 8: The Ultrasonic Personal Aerosol Sampler (UPAS)

1.2 The PURE-AIR Project

The goal of the PURE AIR project is to better understand the health risks from air pollution. Specifically, in PURE AIR measurements of air pollution in the homes and personal breathing spaces of male and female PURE participants will be used to estimate health risks related to HAP exposure.

1.3 The UPAS Device:

The Ultrasonic Personal Aerosol Sampler (UPAS) measures indoor and individual air quality.

The UPAS monitor samples air pollution by passing a measured amount of air through a special filter contained in a cartridge. The filters are delicate and fragile and should **never be taken out of the cartridge.**

The UPAS needs to be **recharged after every use for at least 10 hours**.

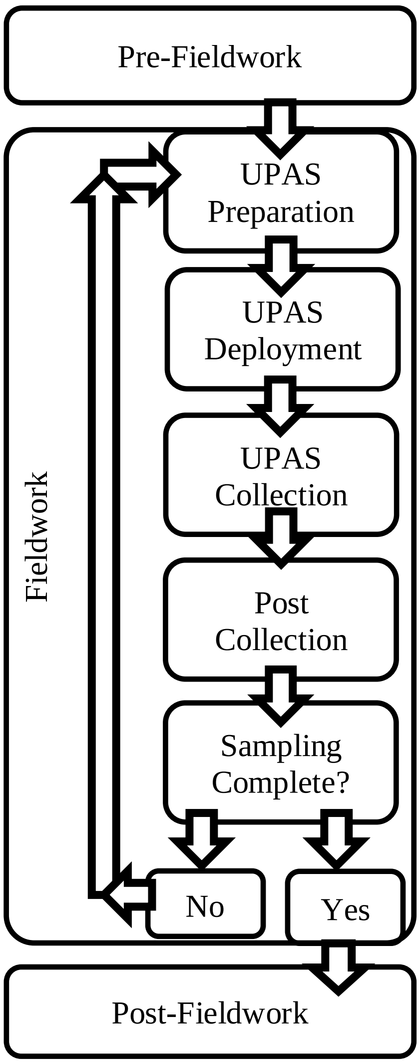
The monitor keeps a record of how much air passes through the cartridge, this file is called a *run log*. **This information is very important**, and it is critical to match this information to the cartridge in the device.

A special smartphone app controls the UPAS. This app assigns a unique file name for each measurement taken with the UPAS, this is called a *sample number*. The app also controls when the UPAS starts a 48-hour household or personal HAP measurement. The app also collects uploads files from the UPAS to the smartphone, and then automatically transmits that information back to PURE AIR headquarters via the internet.

2 Overview

This section has a short video. [Please click here to view](#).

There are several steps in collecting measurements of HAP with the UPAS. The diagram below shows an outline of the order of these steps. These steps are divided into several sections: pre-fieldwork, UPAS preparation, deployment, collection, post-collection work and post-sampling work (Figure 2).



Pre-Fieldwork steps describe what to do before collecting samples from selected PURE households and participants.

Preparation steps describe what needs to be done every time before sampling in the field.

UPAS Deployment steps describe what to do when deploying the UPAS devices for household and personal measurements.

UPAS Collection steps describe what to do when retrieving the UPAS monitors

Post Collection steps describe what to do after the UPAS monitors have been retrieved.

If all the required household and personal measurements have been collected, then proceed to the Final Steps; otherwise return to the Preparation.

Post-fieldwork steps describe what to do after collecting all the required household and personal measurements.

Figure 9: Sequence of steps in fieldwork

3 Pre-Fieldwork

In each PURE study community, PURE AIR project management will provide local coordinators with a list of PURE households and persons to recruit for participation. The list will contain extra households and persons in case some households or persons cannot participate.

PURE AIR project management will select households to match the overall characteristics of the community based on PURE data.

All selected PURE households will have 1 UPAS placed in the cooking area for 48-hours. In 1 out of every 5 households the UPAS will be used for 48-hour personal measurements, ideally in households with both male and female participants.

If one or two participants in a home selected for personal measurement cannot, or will not, participate the household and remaining personal measurements should still be taken. The missing personal measurement, and a new household measurement, will have to be taken from a list of backup households.

Household and the personal monitoring must be done at the same time.

Each site coordinator will need to determine how many household and personal samples will be collected on a given day and what time of day field teams will arrive at each home.

3.1 Planning the Sample Collection Schedule

PURE AIR project coordinators will supply a list of homes and persons to recruit for household and personal measurements. It will be the responsibility of the local coordinator to schedule when the selected homes and persons are measured. When planning a measurement collection schedule please consider that:

- Household measurements will run for 48 hours to capture **two** mornings and **two** evenings cooking events.
- For personal measurements, select a time to be at a household when **at least** one, but ideally both, male or female PURE participants are present.
- **Do not** leave a UPAS at a home for a selected participant to put on later. All personal measurements **must** be started by a field staff member.
- UPAS monitors can be collected any time after the 48-hour measurement period has ended. The UPAS devices will stop on their own.
- It will take **10 hours** to recharge and reload a UPAS monitor between 48-hour deployments. **You will not be able to re-use a UPAS the same day it is collected.**
- At least 1 of the 3 supplied Moto G smartphones is required to program and start each UPAS monitor.
    - It will not be possible to deploy in more than three different locations simultaneously.

3.2 Work Area

The local coordinator or the field team members will need to set aside some space with a table, workbench or desk where they can keep the UPAS monitors, the filter cartridges, and all other equipment.

This area should have sufficient electrical power and be large enough to recharge all the supplied UPAS devices at the same time.

The work area should be secure, as clean and as free of dust as possible and protected from excessive moisture. The work space should be in a non-smoking area, and no candles or incense should be used in the work area. If available, an air-conditioned room is ideal, but not essential.

3.3 Equipment

After setting up a work area you can unpack the equipment.

3.3.1 Field Kit Contents

A field kit contains all of the necessary equipment, and is shipped in three containers:

PURE AIR C1: Filter cartridges and microSD cards
PURE AIR C2: UPAS monitors and monitor stands
PURE AIR C3: Monitor stands, smartphones, USB chargers

If the receiving field team finds missing or damaged items they should contact their coordinator immediately. The coordinator will work with PURE AIR administrators to arrange resupply.

3.3.2 PURE AIR C1 Contents:

- Packaged filter cartridges **x100 DO NOT OPEN until you are about to use.**
- Tape
- Travel blank cartridge packages **DO NOT USE OR OPEN**
- Smartphone microSD cards **x3**
- UPAS microSD cards **x22**

Figure 12: Smartphone microSD card

Figure 11: UPAS microSD card

Figure 10: Filter cartridge in sealed package.

3.3.3 PURE AIR C2, C3 Contents:

- UPAS personal exposure monitor **x22**

Figure 13: UPAS monitor: There are two version, one has the serial number on the front, the other on the back. Both operate identically.

- 7-port USB charger **x4**

Figure 14: 7-Port USB Charger

- Anker micro-USB cables **x28**

Figure 15: USB to micro-USB Cable

- Tape measure **x3**
- Clip boards **x3**

- UPAS monitor personal harness **x6**
- UPAS monitor armbands **x6**
- Surge protector power bar **x1**

Figure 16: Power-bar

- Motorola Moto G smartphone **x3**

Figure 17: Moto-G Smartphone

- Pipe cleaners **x1 pack**
- UPAS monitor stands **x11**

Figure 18: UPAS sampling stand post (top) and base (bottom).

3.3.4 Storing and Managing the Filter cartridges

The filters for the UPASs have all been pre-weighed and loaded into cartridges. The cartridges are labeled and placed into special storage bags to keep them safe and clean during transport. **It is very important to keep these cartridges in good condition**. Please follow these guidelines:

- **Do not open the filter cartridges!**
- Leave the cartridges in the shipping container before and after use. Leave the shipping container closed as much as possible.
- Remove only as many cartridges as needed.
- **Wash and dry your hands before working with the filter cartridges**. Only touch the filter cartridge around the outside edge (Figures 12).

Figure 19: UPAS filter cartridge bottom (left) and top (right)

3.3.5 Travel blanks for the UPAS

Travel blanks are included in the supply of filter cartridges. These blanks will be specially labeled to set them apart from the regular filter cartridges.

Travel blanks are included to help determine if filters change weight from shipping. You do not need to use these cartridges. They will be clearly labeled and should remain in the travel case where they are packed.

3.4 Install MicroSD cards in PURE AIR smartphones

This section has a short video. [Please click here to view](#).

Before the smartphones can be used you need to install a microSD card in each smartphone. The microSD cards for the smartphones are found in the container with the filter cartridges. There are two bags, one bag contains microSD cards for the project smartphones and the other contains microSD cards for the UPAS. All the microSD cards in a bag are the same, but the smartphones and UPAS use different microSD cards from one another.

To install a microSD card in a smartphone, follow these steps (See Figure 10):

1. Open packet containing microSD cards for the smartphones and remove one card.
2. Open the rear of the phone by prying it open using a tab near the micro-USB port on the bottom of the phone.

3. Insert the microSD card into the microSD slot on the back of the phone near the camera lens.
4. Replace the back of the phone and press thoroughly all around the edges.

The microSD cards are pre-set to work in the project phones and should work automatically. **If** you insert a microSD card into the phone and you see a new icon at the top of the screen, then follow these steps:

1. Select the microSD icon at the top of the screen.
2. Select setup from the menu.
3. Select use as **portable storage**, and then select **Next**.
4. Select **Move later**, and then select **Next**.
5. Select **Done**.

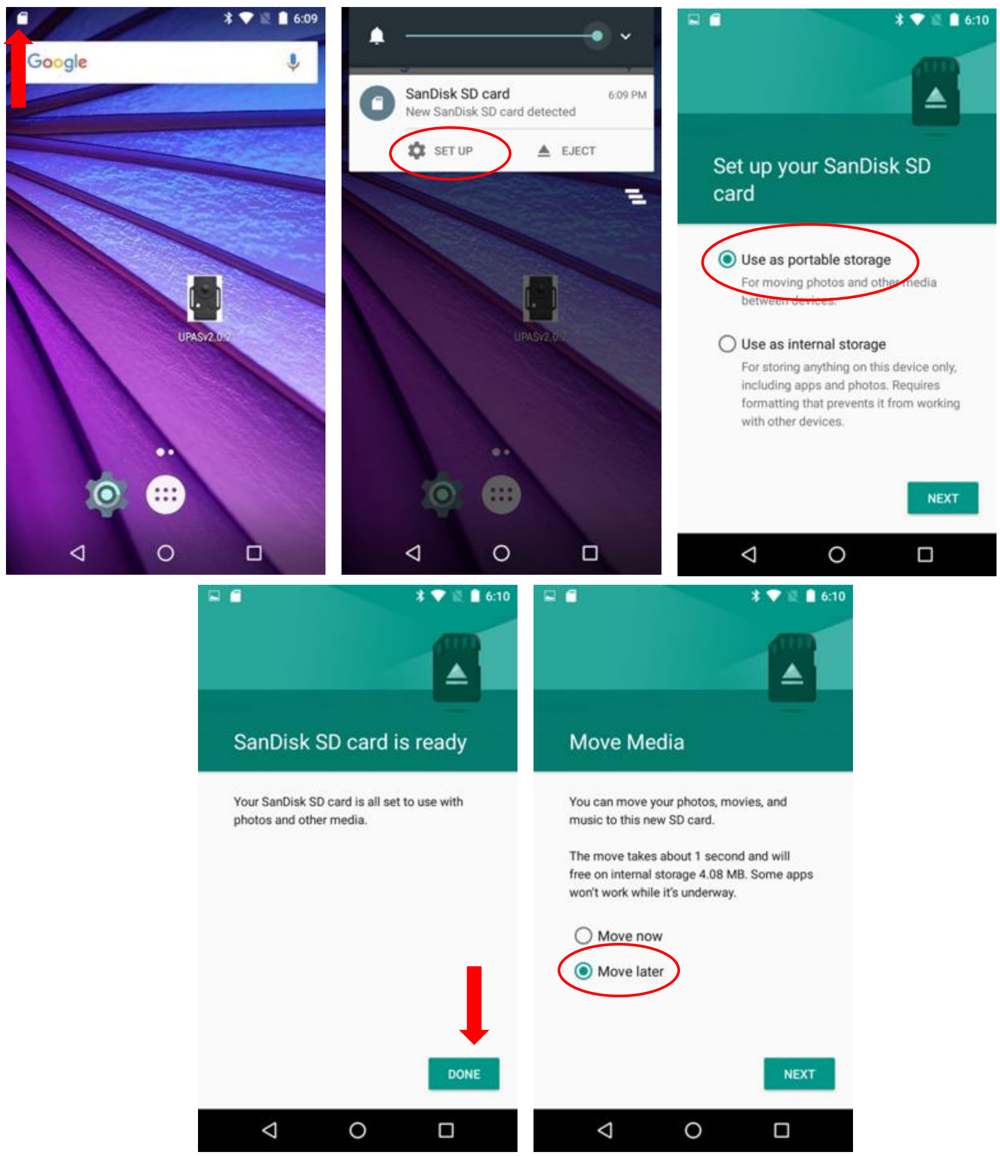


Figure 20: Clockwise from top left: Select the microSD icon, select setup, select Use as portable storage, select Move later, select Done.

3.5 Install MicroSD cards in UPAS

This section has a short video. Please click here to view.

Before the UPAS can be used you need to install a microSD card in each UPAS. The microSD cards for the UPAS are found in a labeled bag in the container with the filter cartridges.

To install a microSD card in a UPAS, follow these steps:

1. Open packet containing microSD cards for the UPAS and remove one card.
2. Inset the microSD card into a small slot on the bottom of the UPAS near the metal ring.
    a. Make sure the gold metal tabs on the microSD card are facing the back of the UPAS.
    b. **Gently** push the card in with your fingers until you feel it **click** into place. It will push back slightly and then stop.
    c. You may need to use a thin metal edge to push the card in all the way.

Figure 21: Insert microSD card into bottom of UPAS near metal ring.

3.6 Internet Access for PURE AIR smartphones

This section has a short video. Please click here to view.

The smartphones included with the rest of the equipment are needed to program and start the UPAS when collecting household and personal HAP measurements, and to retrieve the record of each measurement from the UPAS afterwards. If the smartphones can be connected to a Wi-Fi network the smartphones will also automatically upload these records to a PURE AIR project server.

To connect the supplied smartphones to your Wi-Fi network you will need to know the name of the network and its password.

You will need to repeat the connection steps for each of the 3 smartphones supplied. To connect a smartphone to your follow these steps (Figure 10):

1. Select settings on the main screen
2. Select Wi-Fi
3. Select the network you want to join (in Figure 10 this is technivorm)
4. Enter the network’s password
5. Select connect
6. After a moment, the phone will connect to the network

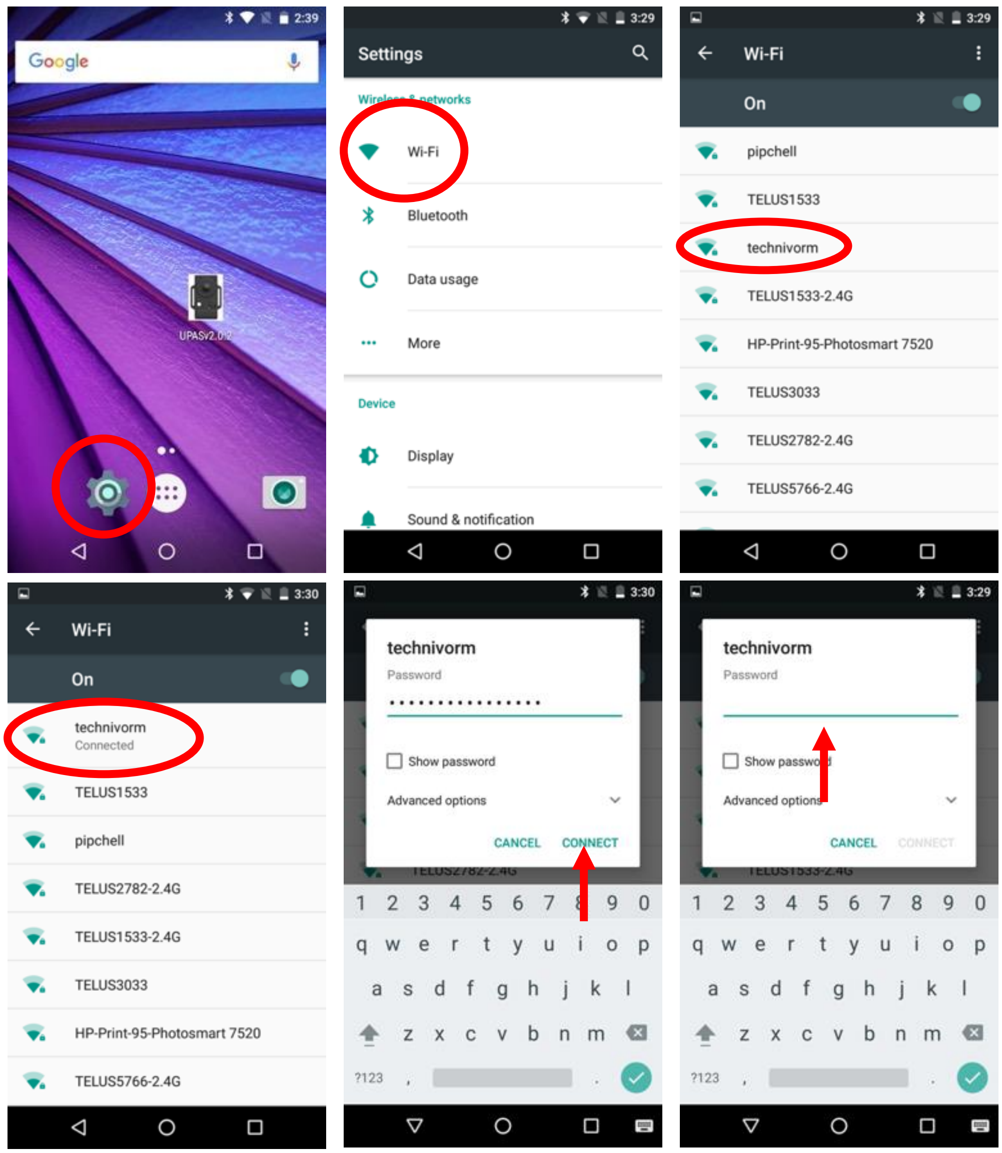


Figure 22: Clockwise from top left: Select settings, Select Wi-Fi, Select the network you want to join, Enter the password for the network, Network should show Connected

If these steps don't work contact your network's administrator. If you do not have a Wi-Fi network, or you are not able to connect the smartphones to it you can still collect the required samples.

4 UPAS Preparation

You will need to repeat the steps in this section as well as the *UPAS Deployment*, *UPAS Collection* and *Post Collection* sections for every UPAS monitor set you use in the field.

4.1 Charging the UPAS

This section has a short video. Please click here to view.

Before the UPAS can be used in the field they need to be charged. Every time the device is charged it should be charged for **at least 10 hours**; the monitors can be left connected to the charger, they will not overcharge.

The UPAS **must be charged every time** before they are deployed. Make sure to plug the USB chargers into the supplied surge-protectors/power bars, this will help make sure all the equipment works properly.

To charge the device follow these steps:

1. Connect the supplied power bar to your electrical supply. You may need to purchase a plug adaptor.
2. Connect the supplied USB multi-port chargers to the power bar.
3. Connect the supplied USB to micro-USB cables to the multi-port chargers. Use **only the supplied cables** to connect the UPAS to the multi-port charger. **Do not use another type or brand of cable**.
4. Connect the UPAS to the micro-USB end of the supplied cables (Figure 13).
5. Turn the UPAS on after connecting it. You should see the light on the front start to blink. When the UPAS is fully charged, the light will blink **blue 4 times** and **pink 1 time**.

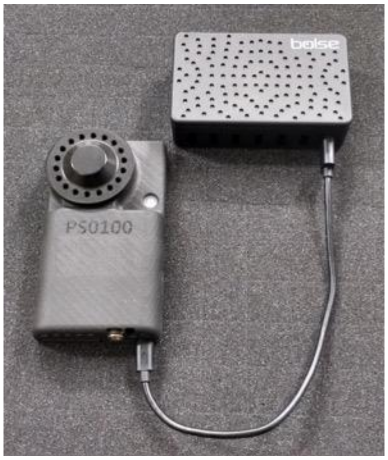


Figure 23: UPAS and charger. The micro-USB port is located on the bottom of the UPAS.

Only use UPAS monitors that show they are fully charged

While the UPASs are charging, it is a good idea to check on them periodically. To check the charge level for a UPAS:

- Unplug the UPAS from the charger.
- Turn the UPAS off (press and hold the button on the front of the device for five (5) seconds).
- Plug it into a charger.
- Turn the UPAS back on (press and hold the button on the front of the device for 5 seconds). The button light should turn green then blink **blue 4 times** then **pink 1 time**. If you do not see the pink light blink the UPAS is not fully charged. The blinking light pattern will repeat until the UPAS is turned off or unplugged from the charger. If the device is unplugged from the charger the light on the front will turn red briefly and then turn pink constantly to show it is ready to connect to a phone.

If you find that a UPAS is **not** charging, follow these steps:

- Take it off the charger.
- Turn it on.
- Then turn it off.
- Plug it into the charger again.
- Turn it on again.
- Check it again.

Note: The UPAS monitor will **not communicate** with a smartphone while the UPAS is charging. It is not possible to program a UPAS or upload information from a UPAS to a smartphone while that UPAS is charging.

4.1.1 Gather Equipment and Pack for Fieldwork

Field staff will need to collect and pack all the equipment they will need for fieldwork. You will need to bring:

- UPAS monitors:
  - **1** UPAS for every location with **only** household monitoring.
  - **3** UPAS for every location with household **and** personal monitoring.
- Filter cartridges packages: **1** for every UPAS monitor. **DO NOT** open the packages until you have received consent to monitor household and individual participants.
- Monitor stands. **1** for every household you will visit, remember that there are two parts to each monitor.
- UPAS monitor harnesses. **2** for every household with personal monitoring.
- PURE AIR project smartphones. At least 1 for every team working by themselves.
- Clip boards or something to write on.
- Pens to write with. **Do not fill out CRFs in pencil**.

5 UPAS Deployment

This section covers placing the UPAS in the home and on a participant. This section, along with the *Pre-Deployment* and *Collection* sections, need to be repeated for every household and personal measurement collected. Figure 17 outlines the sequence of actions to take when placing UPAS monitors in a home and when equipping participants with UPAS monitors for personal exposure monitoring.

5.1 Obtain Consent

Before either household or personal monitoring can take place, you **must** obtain consent from the PURE participants in that household.

5.2 UPAS Deployment for Household Monitoring

After you have acquired consent from the participants you need to gather all the equipment you will need for this location. If possible set the equipment on a clean table or similar surface, otherwise use a clipboard or tray.

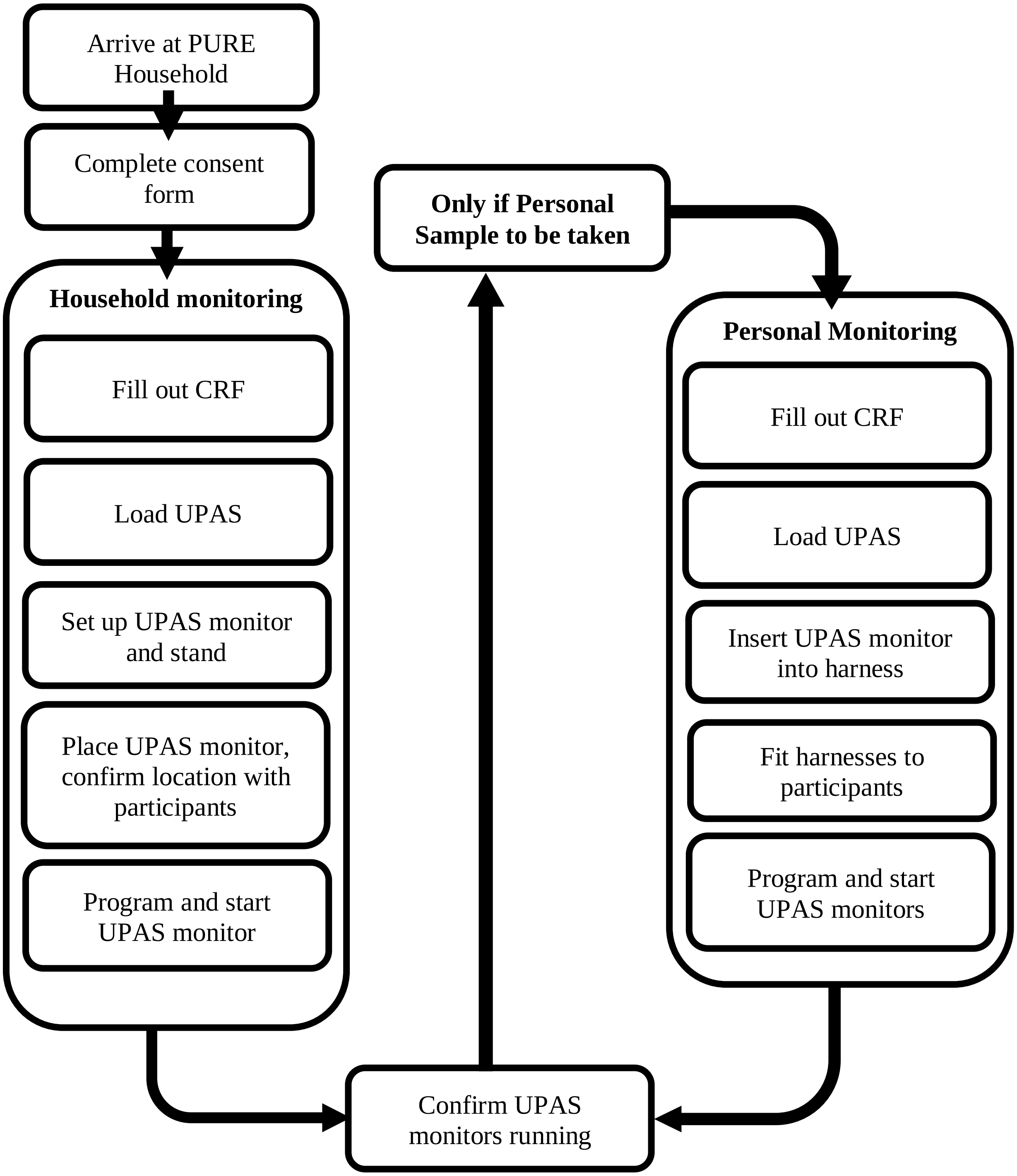


Figure 24: Order of steps when placing monitors in a home and when equipping participants with a UPAS monitor.

5.3 Preparing CRFs

This section has a short video. [Please click here to view](#).

After you have acquired consent from the participants a CRF must be prepared for that household. Personal samples will be recorded on the same CRF as household samples.

To prepare a CRF for a household sample follow these steps:

1. Take 1 UPAS monitor and 1 filter cartridge package and read their numbers. Do not open the filter cartridge package now.
2. Under Household Sample ID on page 1 of Household Air Monitoring Questionnaire enter (Figure 18):
   - PURE household ID:
     - Center #
     - Community #
     - Household #
     - Member # (This is **always zero (0)** for household samples).
       - You will need to re-enter these numbers at the top of page 2 of the questionnaire.
   - UPAS (Air Monitor) #
   - Filter cartridge #
   - Sample start date: write the date the sample will be taken.

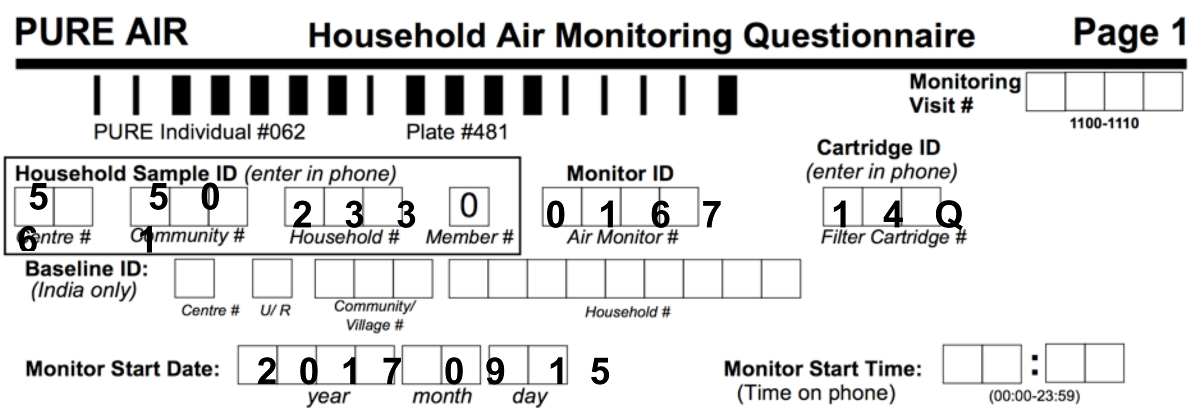
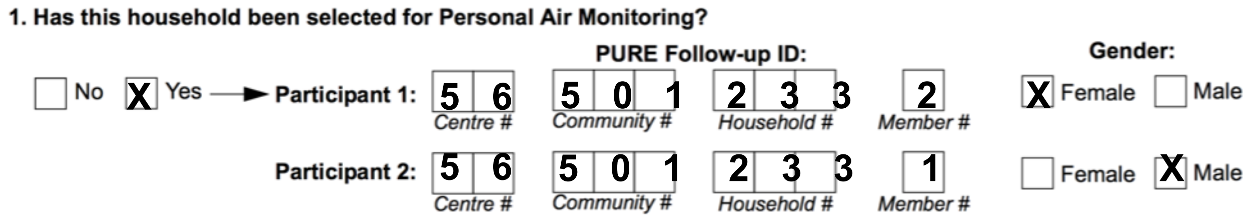

PURE AIR Household Air Monitoring Questionnaire Page 1
Monitoring Visit # 1100-1110
PURE Individual #062 Plate #481
Household Sample ID (enter in phone): 5 6 Centre # | 5 1 0 Community # | 2 3 3 Household # | 0 Member #
Monitor ID: 0 1 6 7 Air Monitor #
Cartridge ID (enter in phone): 1 4 Q Filter Cartridge #
Baseline ID: (India only) Centre # | U/R | Community/ Village # | Household #
Monitor Start Date: 2 0 1 7 year 0 9 month 1 5 day
Monitor Start Time: (Time on phone) : (00:00-23:59)

Figure 25: Household information section of the CRF.

3. Only centers in India will use the Baseline ID line for more data entry. Indian coordinators will supply this information to staff.
4. Indicate if the household you will be working with has been selected for Personal Air Monitoring by selecting No or Yes for question #1 (Figure 19).
   - If the household has **not** been selected for personal monitoring, select **No** and go to section 6.4

- **If** the household has been selected for personal air monitoring, select **Yes** and enter the PURE ID # for both participants who will be wearing the UPAS for the 48-hour sample period.



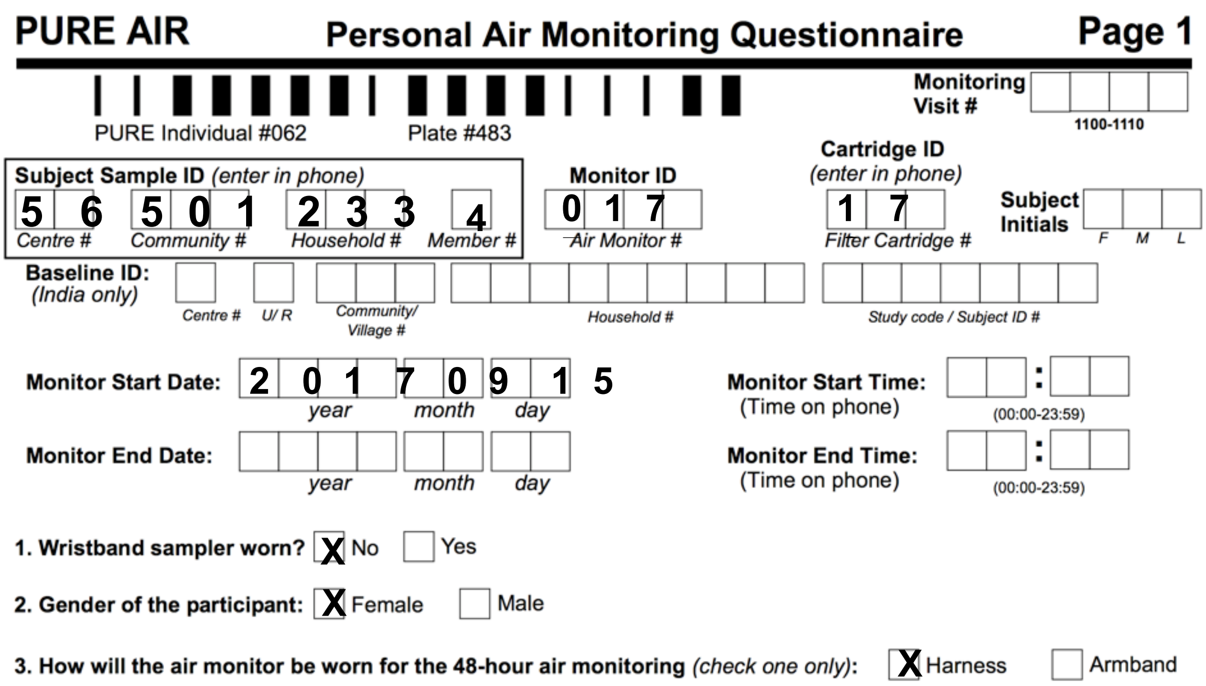
1. Has this household been selected for Personal Air Monitoring?

☐ No ☒ Yes → **Participant 1:** PURE Follow-up ID: 5 6 (Centre #) 5 0 1 (Community #) 2 3 3 (Household #) 2 (Member #) Gender: ☒ Female ☐ Male

Participant 2: 5 6 (Centre #) 5 0 1 (Community #) 2 3 3 (Household #) 1 (Member #) ☐ Female ☒ Male

Figure 26: Personal Air Monitoring information on page 1 of the Household Air Monitoring CRF

5. Collect 2 more UPAS and 2 more filter cartridge packages. Do steps 6 to 9 in this section with 1 participant and 1 UPAS and 1 filter cartridge package, then repeat with the other participant.
6. On Page 1 of the Personal Air Monitoring Questionnaire enter information for Participant 1. This includes (Figure 20):
   - PURE Subject ID:
     - Center #
     - Community #
     - Household #
   - UPAS #
   - Filter cartridge #
   - Monitor start date



PURE AIR **Personal Air Monitoring Questionnaire** **Page 1**

PURE Individual #062 Plate #483

Monitoring Visit # 1100-1110

Subject Sample ID *(enter in phone)*: 5 6 (Centre #) 5 0 1 (Community #) 2 3 3 (Household #) 4 (Member #)

Monitor ID: 0 1 7 (Air Monitor #)

Cartridge ID *(enter in phone)*: 1 7 (Filter Cartridge #)

Subject Initials F M L

Baseline ID: *(India only)* Centre # U/ R Community/ Village # Household # Study code / Subject ID #

Monitor Start Date: 2 0 1 7 (year) 0 9 (month) 1 5 (day)

Monitor Start Time: (Time on phone) __ : __ (00:00-23:59)

Monitor End Date: year month day

Monitor End Time: (Time on phone) __ : __ (00:00-23:59)

1. Wristband sampler worn? ☒ No ☐ Yes

2. Gender of the participant: ☒ Female ☐ Male

3. How will the air monitor be worn for the 48-hour air monitoring *(check one only)*: ☒ Harness ☐ Armband

Figure 27: Female information section of the CRF, Male section is the same.

7. If the participant will be wearing a special wristband enter yes for question #1
8. Enter the gender of the participant for question #2
9. Enter how the participant will be wearing the monitor, either in the harness or in the armband holder
10. Repeat step 6 for Participant 2.

Once these steps are completed, you need to load the filter cartridge into the UPAS.

5.4 Wristband samplers:

Some centers will use special wristbands, but **only** during personal air monitoring. If you are using these wristbands see section 6.10 for how to deploy them.

At this point, no more information can be entered in this part of the CRF. Do not fill out any other sections until the UPAS monitor is in place and working correctly.

5.5 Load filter cartridge into UPAS

This section has a short video. Please click here to view.

Once the CRF has been started the UPAS must be **loaded with a new unused filter cartridge for every 48-hour sample**.

1. **Wash and dry your hands thoroughly**.
2. Collect 1 unused filter cartridge package for every UPAS.
3. Remove the black screw-on intake cap from the front of the UPAS monitor. To do this, hold the black plastic body of the device in one hand and unscrew the black cap with the other hand turning counter clockwise (to the left) (Figure 21). The ring should unscrew without much effort.
4. Remove the filter cartridge from its package by opening the silver plastic bag (Figure 22).

Figure 28: Unscrew intake cap by twisting counter clockwise

a. Cut open the cartridge package at the top above the seal. The dotted blue line in Figure 22 indicates where to cut. **Do not throw the filter packaging away.** The filter cartridge **must** be returned to its packaging after use.

Figure 29: Filter cartridge in sealed package with number facing out.

5. Each filter cartridge has a number on the back of the cartridge. Also, each UPAS monitor has a number on it, on the front of the device. You need to write these numbers on the CRF in the correct place. **This is very important.**
   a. For **household samples,** you need to write the filter cartridge and UPAS numbers in the ***Household Information*** section of the CRF.
   b. For the **first** PURE participant, you need to write the filter cartridge number, the monitor number, and the gender of the participant on page 1 of the Personal Air Monitoring Questionnaire CRF.
   c. For the **second** PURE participant, you need to write the filter cartridge number, the monitor number, and the gender of the participant, (which should be the **opposite** of the first participant), on page 1 of the Personal Air Monitoring Questionnaire CRF.
6. Use the clean fingers and reach into the package and carefully remove the filter cartridge.
7. The cartridge fits in the front of the UPAS with the black top of the cartridge facing up. The cartridge should drop into the cup in the front of the UPAS (Figure 23).

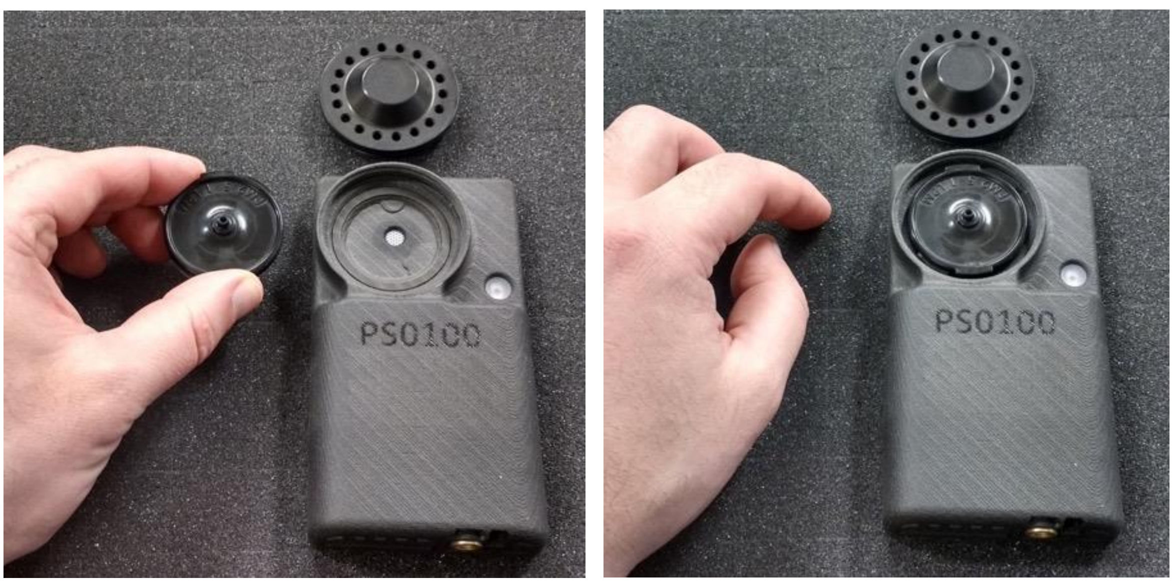


Figure 30: Insert the filter cartridge into the cup on the front of the UPAS.

8. Replace the screw-on cap. It does not take much force to screw the cap on, only use your fingertips. **Do not use tools to do this!**
9. Collect all the empty filter cartridge packages and keep them. Make sure you know which UPAS and CRFs are for which PURE household.

5.6 Set up UPAS Monitor and Stand

There is a short video for this section. Please click here to view.

To collect a household measurement, connect the UPAS to the supplied sampling stand and place that stand in the household's cooking area.

- The stand is shipped in two parts, a base and a post (Figure 24):

Figure 31: Base (bottom) and post (top) of monitor stand

- To unfold the base, hold the longest and shortest legs and twist. When unfolded the base looks like this:
- The silver tip at the bottom of the post plugs into the base and is held by tightening the thumb screw:

Figure 32: Insert the post into the base of the monitor stand and tighten the thumb screw

To connect the UPAS monitor to the stand, remove the silver stud from the top of the monitor stand, screw it into the base of the UPAS, then fit the stud back into the monitor stand. DO NOT use tools to tighten them together (Figure 26).

Figure 33: Remove the silver mounting stud from the monitor stand, screw it into the base of the UPAS, then fit the stud back into the monitor stand.

5.7 Selecting a Location for the UPAS Monitor in the Kitchen Area

There is a short video for this section. Please click here to view.

The UPAS monitor and stand should be placed in the kitchen area as close to **one meter (1m)** from the primary cooking stove as possible **without interfering with the normal activities** in the kitchen. Talk to the person doing the cooking and make sure that wherever you put the monitor it will not interfere with their activities.

2. Household air monitor distance from stove: [1.] meters

3. Household air monitor distance off floor: [.] meters

Figure 34: Questions 2. and 3. on the CRF. Enter distances to the nearest 0.1 meters

When you have placed the UPAS monitor and stand in a good location measure the distance from the primary cookstove to the monitor and write this distance, to the nearest 0.1 meters, in the **Household Air Monitoring Questionnaire, question #2: Household air monitor distance from stove** section of the CRF (Figure 27).

Additional points:

- **Do not** put the UPAS monitor and stand outside.
  - If there will be no indoor cooking in the 48-hour sample period **do not** sample in this household.
- Try to keep the monitor at least 50cm away from a door or window if you can while keeping it one meter away from the main cookstove.

- If you cannot place the UPAS monitor **and** stand in the kitchen in a good way try to put the UPAS by itself on a shelf or flat surface as close to one meter away from the main cookstove and one meter above the floor as possible. Measure the distance, to the nearest 0.1 meter, from the monitor to the stove and from the monitor to the floor and write them in **question #3: Household air monitor distance off floor**, on page 1 of the Household Air Monitoring Questionnaire.

5.8 Activating UPAS for Household and Personal Samples

5.8.1 Household sample number

There is a short video for this section. Please click here to view.

Once field staff have found a good place for the UPAS monitor in the kitchen area of the home they will need to program the UPAS using the supplied smartphone and the UPAS app. To do this each UPAS must be programmed with a unique number representing the household being monitored.

For **household measurements** follow these steps:
The **household** sample number is exactly 9 characters long; it is a combination of the following numbers:

a. The first two (1,2) character are the PURE center ID number
b. The next three characters (3, 4, 5) are the PURE community ID number.
c. The next three characters (6, 7, 8) are the PURE household ID number.
d. The next character (9) is the member number, for households this is **always zero** (0).

Make sure these numbers are recorded in the correct order.

Household sample example (Figure 28):

- Given PURE center = 56, PURE community = 501, PURE household = 233, PURE member # = 0
- Sample number = **565012330**
- This number will be entered in the smartphone app, which controls the UPAS monitor (Section 6.5.5). **It is vital that this number be entered correctly into the smartphone app when programming and starting the UPAS monitor.**

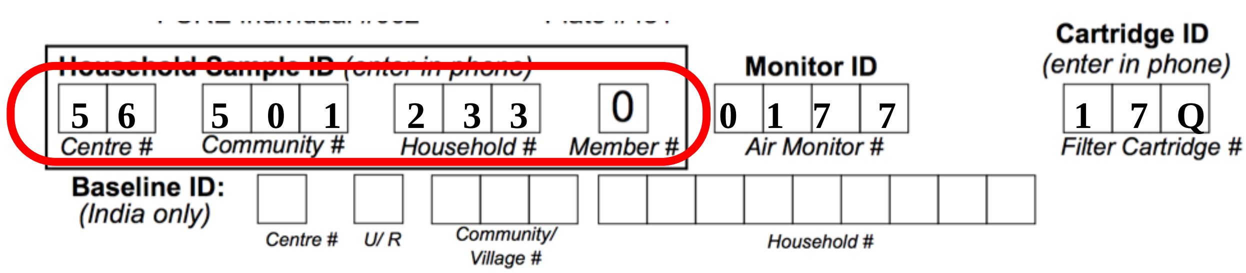


Figure 35: Household information section of the CRF. Household sample number in red rectangle. Do not use any numbers from the Baseline ID when programming the UPAS.

5.8.2 Personal sample number

This section has a short video. [Please click here to view](#).

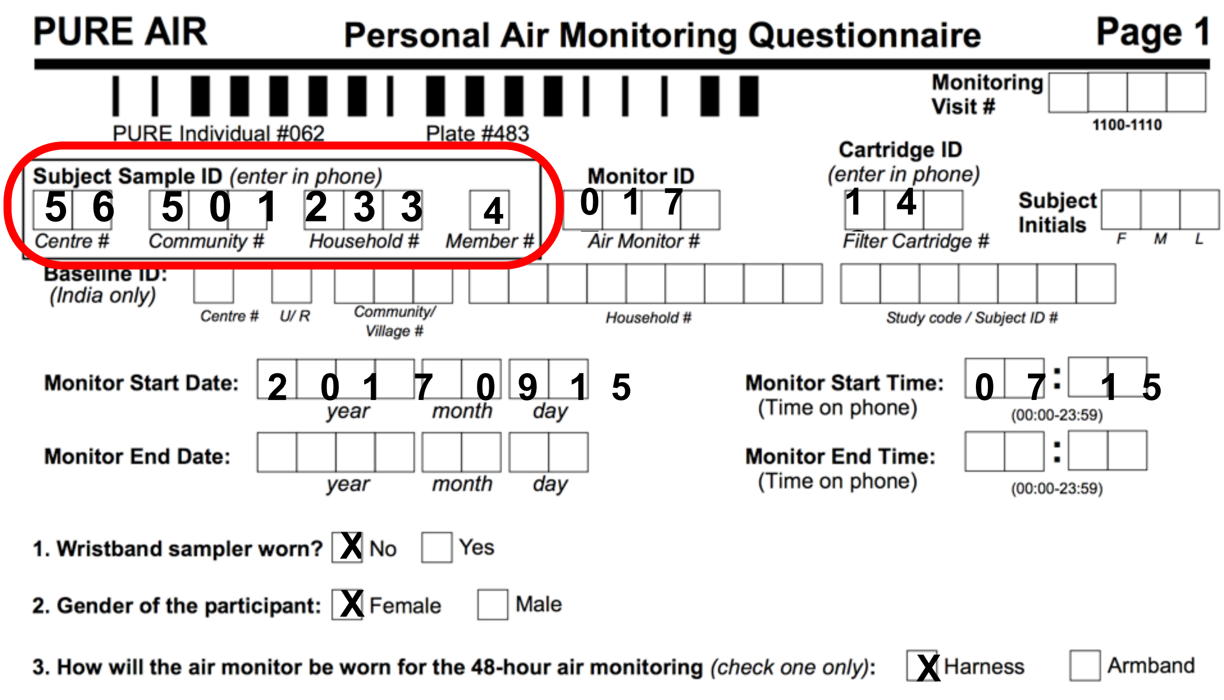
For every household selected for personal measurements **2** more sample numbers need to be made, one for each participant. These numbers are made in the same way as the household sample number **except** the PURE member ID # is **not** zero.

For **personal measurements** follow these steps (Figure 29):

1. The sample number is exactly 13 characters long; it is a combination of the following numbers:
   a. The first two (1,2) character are the PURE center ID number
   b. The next three characters (3, 4, 5) are the PURE community ID number.
   c. The next three characters (6, 7, 8) are the PURE household ID number.
   d. The next character (9) is the PURE member number.

   Make sure these numbers are recorded in the correct order.

   Household sample example:
   - Given PURE center = 56, PURE community = 501, PURE household = 233, PURE member = 4
   - Sample number = 565012334
   - This number will be entered in the smartphone app, which controls the UPAS monitor (Section 6.5.5). **It is vital that this number be entered correctly into the smartphone app when programming and starting the UPAS monitor.**


PURE AIR Personal Air Monitoring Questionnaire Page 1

PURE Individual #062 Plate #483

Monitoring Visit # 1100-1110

Subject Sample ID *(enter in phone)*: 5 6 | 5 0 1 | 2 3 3 | 4
Centre # *Community #* *Household #* *Member #*

Monitor ID: 0 1 7 *Air Monitor #*

Cartridge ID *(enter in phone)*: 1 4 *Filter Cartridge #*

Subject Initials *F M L*

Baseline ID: *(India only)* *Centre #* *U/ R* *Community/ Village #* *Household #* *Study code / Subject ID #*

Monitor Start Date: 2 0 1 7 0 9 1 5 *year* *month* *day*

Monitor Start Time: (Time on phone) 0 7 : 1 5 (00:00-23:59)

Monitor End Date: *year* *month* *day*

Monitor End Time: (Time on phone) : (00:00-23:59)

1. Wristband sampler worn? X No ☐ Yes

2. Gender of the participant: X Female ☐ Male

3. How will the air monitor be worn for the 48-hour air monitoring *(check one only)*: X Harness ☐ Armband

Figure 36: Female subject ID on page 1 of the Personal Air Monitoring Questionnaire section of the CRF. Sample number highlighted in red rectangle. The Male information looks the same except for member number and gender of the participant. ***Do not*** *use any numbers from the Baseline ID when programming the UPAS.*

5.8.3 Programming and Starting the UPAS

There is a short video for this section. [Please click here to view](#).

The next step is to program the UPAS. When the UPAS device you are working with is in place and ready to begin the 48-hour measurement, follow these steps:

1. Turn on the UPAS by pressing and holding the white button for five seconds. When the monitor is on the button will turn green, then briefly red, then purple.
2. Turn on the phone and open the UPAS app (Figure 30).
3. When the app starts, it will show the main screen, but it will not be connected to the monitor. To connect to the monitor, press the three-dot symbol at the top right of the screen. Then select *Connect to an Air Sampler* (Figure 31). Then select the serial number of the UPAS monitor you need to connect to. This number is on the front of the UPAS (Figure 3).
    a. If the monitor you are trying to connect to does not appear in the app see the trouble shooting section at the end of the protocol.
    b. Remember that you cannot connect to a UPAS if it is charging.

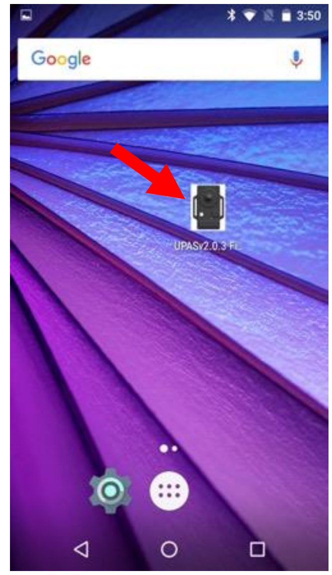


Figure 37: Tap the UPASV2.0.2 icon to start the UPAS app.

4. The app will go back to the main screen, wait a few seconds for the app to connect to the monitor. When the app connects to the monitor the connection status at the top of the screen will show the monitor number.

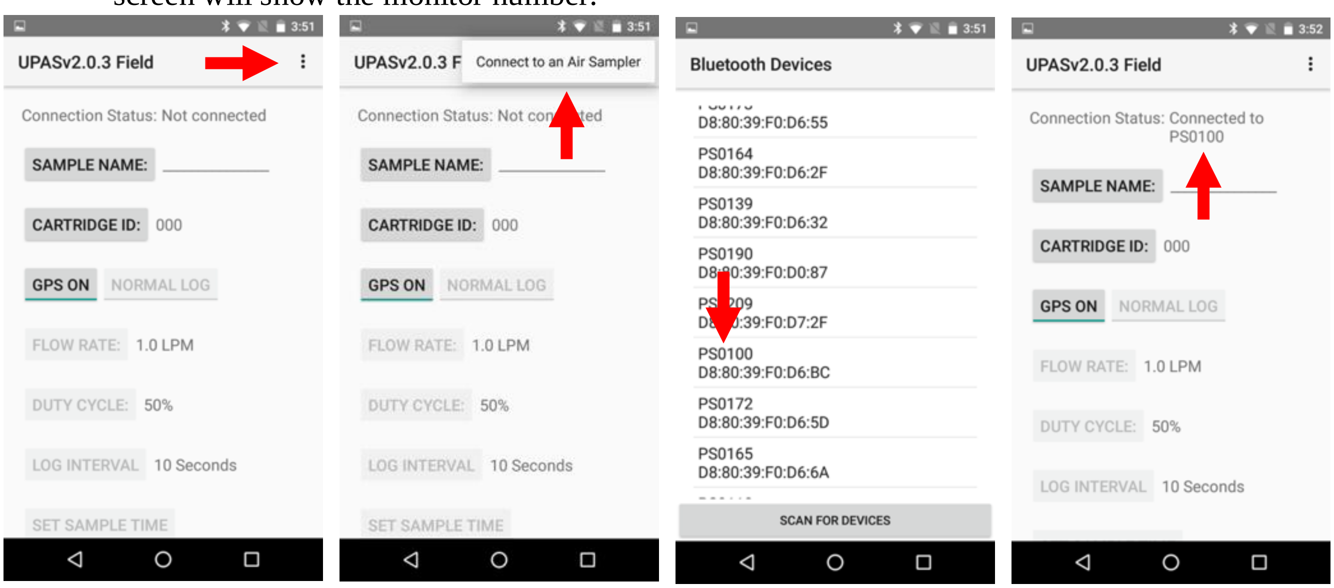


Figure 38: Left: Tap the three dots at the top left of the screen, Left-Right: Then select "Connect to an Air Sampler, Center-Right: Then select the serial number of the monitor you want to program (note that you will see different device ID numbers), Right: You will see the connection status change to connected.

5. Enter the sample name by selecting the *Sample Name* button, then enter the following numbers as **one single number** (Figure 32):
    a. PURE center #
    b. PURE community #
    c. PURE household #
    d. PURE member # (**always zero** for household samples).

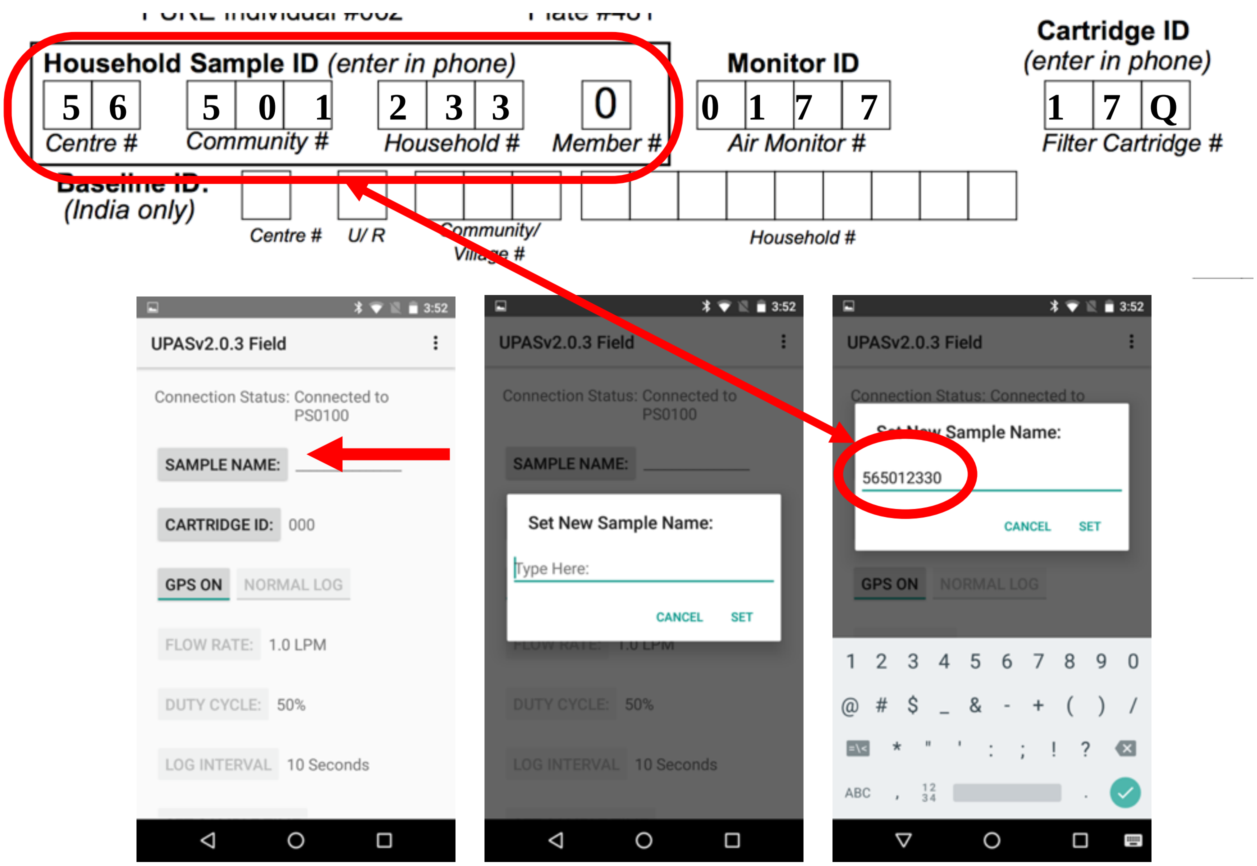


*Figure 39: Left: To program the sample name select "Sample Name", Center: tap on the "Type Here" field to use the keyboard, Right: Enter the sample filename **exactly** as it is written on the CRF.*

6. Enter the cartridge ID (Figure 33):
    a. Select cartridge ID
    b. Enter the cartridge ID number from the CRF.
    c. Select Set

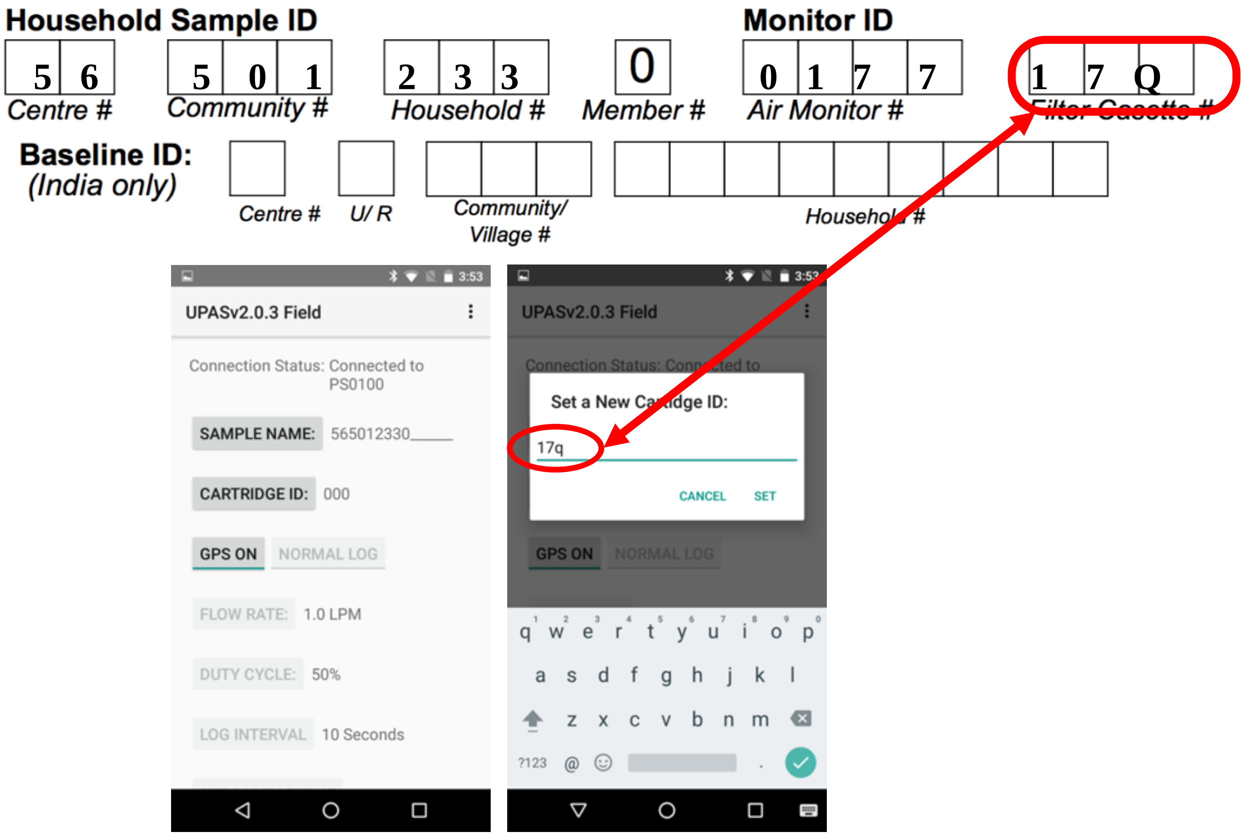


Figure 40: Left: Select Cartridge ID, Right: enter cartridge ID from CRF.

7. Start the UPAS. Once the UPAS has been programmed is can be set to run (Figure 34):
    a. Select the *Start* button.

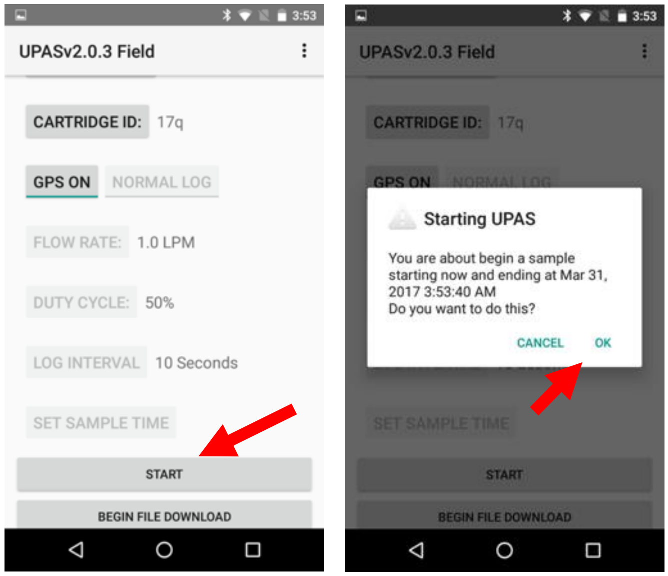


Figure 41: Once the UPAS monitor is programmed it can be triggered by selecting the start button (lower left) and then, if the start and stop times are correct, select OK.

    b. A warning sign will appear asking if the sample start and stop times are correct, you cannot alter the sample length, select **OK**. The light on the front of the UPAS will blink orange unless the GPS is off in which case it will blink blue (Only turn the GPS off if the participant does not agree to GPS monitoring in the consent process). (See Figure 31).
8. If the button on the front of the device does not turn on, or is red and stays red, follow these steps:
    a. Turn the device off by pressing on the button on the front of the UPAS monitor for 5 seconds. The light should go out and the button should turn white
    b. Start again at step #3 in this section (6.5.5)

9. Occasionally the Bluetooth pairing between the UPAS monitor and a smartphone may not work correctly.
    a. In some cases, when you attempt to connect the smartphone to a UPAS monitor the phone will ask you to pair the UPAS to your phone (Figure 35).
    b. If you see a notification icon or hear a warning sound, swipe down from the top of the screen and touch the notification.
    c. The phone will ask if you want to pair with a UPAS. You do not need to enter a code, just select PAIR.
    d. The phone will pair with the UPAS.

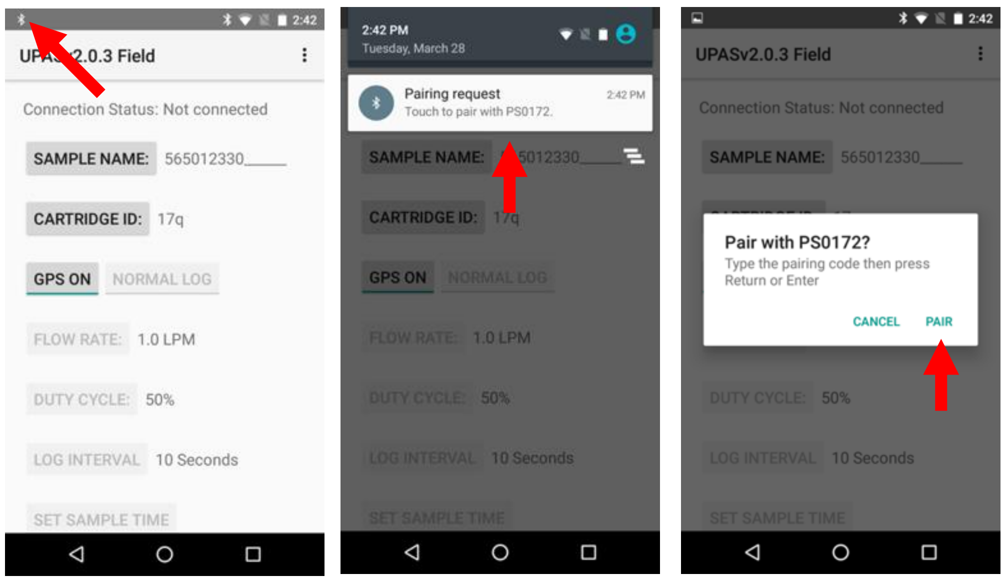


Figure 42: Occasionally when you try to select a UPAS to connect to an icon will appear at the top of the screen (left), swipe down and touch the notification (center), then select PAIR, (right), you do not need to enter a code.

5.8.4 Enter Information into CRF
Once field staff have placed the household UPAS monitor they need to enter more information into the CRF. Not all parts of the CRF can be completed at this time.

The following parts of the CRF can be filled out at this point:
- Monitor Start Date
- Monitor Start Time
- Question 2. Air monitor distance from stove
- Question 3. Air monitor distance from floor
- Question 4. Cooking location and ventilation features in the indoor cooking area **and/or** months per year spent cooking outside
- Question 5. Primary fuel used for cooking?
- Question 6. Primary fuel use history

All other parts of the CRF will be completed after the 48-hour measurement.

5.8.5 Confirm that the UPAS Monitor is Working
Field staff should make sure the UPAS monitor is running properly. To do so, follow these steps:

a. When the UPAS monitor starts to run the light on the front will turn from purple to green or red
b. After a few seconds, the red light will turn green.
c. When the UPAS starts running it will make a faint noise, you may need to listen closely to hear it.
    a. The UPAS will stop and start at regular intervals.
d. The light may change from green to red or green to yellow for short periods of time (a few seconds). This is fine.
e. If the light turns red and stays red for more than a few minutes there is a problem.
    i. Turn the device off by pressing the button for five seconds
    ii. Start again at step #1, in section 3.6.5
b. If steps from #3 to #8 in section 3.6.5 have been repeated and the light on the front of the device turns red and stays red, there is a problem with the device. Field staff must cancel this household sample and any personal samples taking place in the same home. Field staff must contact their coordinator immediately. Stop using this UPAS, label it as broken, and return it to its shipping container.

5.9 UPAS Deployment for Personal Monitoring
In each PURE community **20% (1 in 5)** of households selected for HAP measurements will also have the 1 male and 1 female PURE participants take part in personal measurements. This requires wearing the sampler for 48-hours, except when bathing or sleeping. If you go to a household to do personal monitoring and one of the PURE subjects cannot or will not participate you should still do household monitoring and you should take the remaining personal measurement. You will need to select a new household for personal monitoring where you can take a new household measurement and a personal measurement of the gender of the participant missed in this household, or come back to this household and try a household and personal

measurement again. **Remember**; **all** personal measurements **must** be taken simultaneously with a household measurement.

One of the participants, male or female, should be the person in the home who will be doing the cooking during the 48-hour sample period.

Before loading and programming the UPAS device consider the following:

1. Participants will wear the UPAS monitor for 48-hours, except when they are sleeping or bathing. You must have confirmation from the male and female participants that they are willing to participate for the **full** 48-hours.
2. Also confirm that the participant will be available when you return to collect the UPAS. If the participant will not be at home at the end of the 48-hour sample, or will be unavailable for any other reason, **do not** collect a personal sample from this participant.
    a. The UPAS must be worn for 48 hours and placed near the participant when bathing or sleeping. But it is important to tell the participant that they are free to stop wearing the UPAS if it leads to discomfort or inconvenience. If the participant stops wearing the UPAS during sampling they should try to remember the approximate time when they stopped wearing the UPAS.
    b. If a participant stops wearing the UPAS during sampling staff must ask the participant the approximate time when they stopped wearing the UPAS. Staff should collect the monitor and handle it in the same way they would all other samples. Please notify your coordinator that this personal measurement was stopped prematurely by the participant.
3. To avoid confusion field staff should finish working with one participant before working with the other. Personal samples do not need to start at exactly the same time, but they must both last 48-hours.

5.9.1 Filling out the CRF for Personal Measurements

See section 6.3 for how to enter information into the Male and Female PURE participant sections of the CRF. This is the only information that can be entered into the CRF at this time.

5.9.2 Loading the UPAS monitor

UPAS monitors for personal measurements are loaded in exactly the same way as they are for household measurements. See section 6.5.

5.9.3 Fitting the UPAS Monitor Harness to Participants

There is a short video for this section.
Please click here to view.

In order to collect a good personal air measurement, it is necessary for the participant to wear a special harness which holds the UPAS on the participant's body over the collar-bone between their shoulders and their neck (Figures 37 and 38). By placing the monitor on this part of the body the monitor will be sampling the same air as the participant is breathing and allow the participants to freely use their hands.

In order for the monitor to work it is very important that the harness be properly fitted to the participant. The harness is designed to be adjustable, so it should be able to fit people of very different sizes and shapes.

Figure 44: UPAS monitor and harness. Front view. Note position of UPAS over the collar bone.

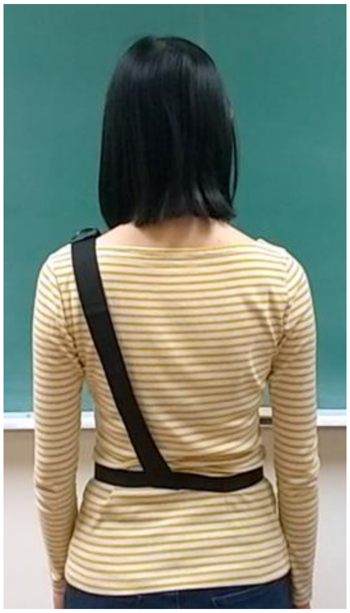


Figure 43: UPAS harness. Back view. Note the joint between the horizontal and vertical straps is over the spine.

To fit the UPAS and harness to a participant follow these steps:

1. Insert the UPAS into the harness
2. Pass the thick strap over the participant's left shoulder.
3. Fasten the horizontal strap around the participant's waist.
4. Adjust the position of the UPAS so it sits on top of the participant's collar bone.

Please watch the video for this section, it is found on the microSD card installed in the project phones and is in the PURE AIR videos file.

When fitting the UPAS harness to participants please keep the following points in mind:

- Make sure the front of the UPAS device does not get covered or blocked by clothing or other items like jewelry or small children during the personal sampling period.
- Ask participants to remove the harness and monitor when they sleep or bathe. Also, ask them to put the harness and monitor within reach of their bed, and at about the same height above the ground as their head when they are sleeping.
- The UPAS monitor will work in the rain; it is not necessary to cover it when the subject wears the device in the rain.
- The UPAS must always be worn outside clothing – if the participant wears a jacket after they start wearing the harness they must take the harness off and then wear it over the jacket.

5.9.4 Fitting the UPAS monitor armband to participants

As an alternative to wearing the special harness, participants may also choose to wear a special armband to carry the UPAS monitor for the 48-hour sample period. This armband fits to either the left or right arm, as the participant prefers.

To fit the UPAS and armband to a participant follow these steps:

1. Insert the UPAS into the armband
2. Slide the armband over the hand and lower arm until the armband sits just below the shoulder. One strap should fit above the bicep muscle, the other strap should sit below the bicep muscle.
3. Adjust the straps until they are comfortable for the participant, but are tight enough for the armband to remain in place.

When fitting the UPAS armband to participants please keep the following points in mind:

- Make sure the front of the UPAS device does not get covered or blocked by clothing or other items like jewelry or small children during the personal sampling period.
- Ask participants to remove the armband and monitor when they sleep or bathe. Also, ask them to put the armband and monitor within reach of their bed, and at about the same height above the ground as their head when they are sleeping.
- The UPAS monitor will work in the rain; it is not necessary to cover it when the subject wears the device in the rain.
- The UPAS must always be worn outside clothing – if the participant wears a jacket after they start wearing the harness they must take the armband off and then wear it over the jacket.

5.9.5 Programing the UPAS for Personal Measurements, Starting the UPAS Monitor

Once field staff have fitted the male and female participants with a harness and UPAS they will need to program it and start it. The device is programmed and turned on in **exactly** the same way as the UPAS being used for household samples (See section 6.2.4). The process is also exactly the same for both male and female subjects.

DO NOT confuse the information from one participant with the information from the other. Complete the work for one participant before starting to work with the other. It is not a problem if male female personal measurements do not start at exactly the same time. It is important that the start times for both participants are correctly recorded, and that both participants are sampled for the entire 48-hours required.

5.9.6 Confirming the UPAS Device is Working for Personal Measurements

Once they have been programmed and triggered the UPAS devices need to wait a few minutes before they start working. Check to make sure the personal monitors are working in the same way that household monitors were checked (Section 6.5.7).

5.10 Wristband Sampler Deployment

Some centers will also apply wristband samplers during personal air monitoring. These are passive samplers that absorb gas phase chemicals in the air. If you are deploying the wristband check yes. To deploy a wristband, you will:

- Remove wristband from bag and give to participant to put on either one of their wrists. The band can be worn at all times (even during bathing and while sleeping) during the 48-hr measurement.
- **Do not throw the wristband bag away.** The wristband **must** be returned to its packaging after use. Important, close the bag with the plastic clasp (you will need this after sampling is complete).
- Print the Subject Sample ID # (center#, Community#, Household#, Member#) on the bag (clearly) and the monitor start-time.

6 UPAS Collection

This section covers how to retrieve the UPAS devices when the 48-hour household or personal samples are done. When field staff retrieve the UPAS devices they will need to make a few observations about conditions in the homes where the devices were deployed. Staff will also need to finish entering information into the CRFs for each household.

6.1 Collecting the Household Measurement UPAS Monitor and Stand

When staff return to the home where they had previously deployed the UPAS device for household measurements they will need to collect the UPAS monitor and the stand the device was mounted on.

Staff should check to see if the device and stand fell over and were damaged during the 48-hour sample period. If they were, **do not** blame the participants; participants are **not** responsible for damaged or malfunctioning equipment. Please make a note of any damage and notify the local coordinator.

If you arrive at the sampled household ahead of time and the device is still running, please wait and let the device complete the 48-hour sample. If staff need to collect the device ahead of time they will need to turn off the device before removing it from the household or the participant.

To turn off the UPAS before the automatic stop time, press and hold the button on the front of the device for 5 seconds.

6.2 Collecting the Personal Measurement UPAS Monitors and Harnesses

Field staff will need to collect the UPAS monitors and harnesses when they return to households participating in personal measurements.

Staff should ask the subjects if they had any problems with the monitors or the harnesses. Staff should record any problems noted by the subjects and inform their coordinator.

After collection, staff should remove the monitors from their harnesses. Harnesses should be inspected for damage and cleaned if necessary. If a harness has been damaged **do not** blame the participant; participants are not responsible for damaged or malfunctioning equipment.

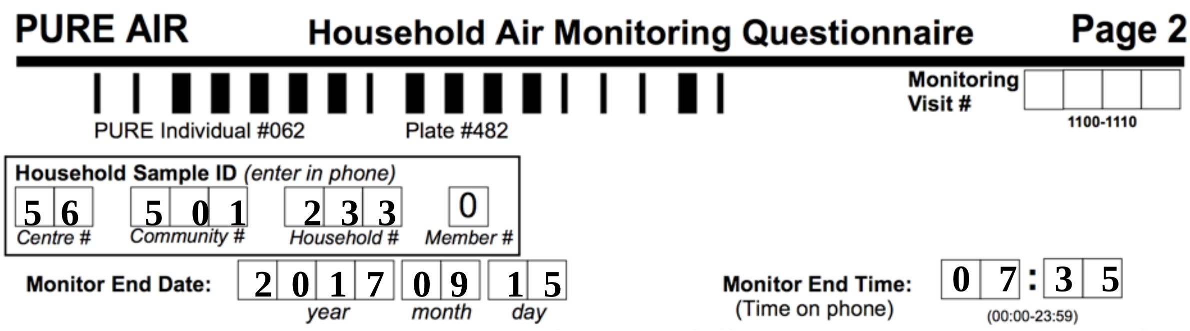
If staff arrive at the sampled household ahead of time and the device is still running, please wait and let the device complete its sampling. If, for some reason, staff need to collect the device ahead of time and cannot wait they will need to turn off the device. To turn off the UPAS press and hold the button on the front of the device for five seconds. Staff must record the collection time even when a sample has been halted early.

6.3 Entering Household and Personal Information into CRF

When the UPAS used for household and personal measurements are collected you can enter the remaining information into the CRFs.

If **only household** monitoring took place interview the household's residents and answer questions 5 to 9 on pages 1 and 2 of the **Household Air Monitoring Questionnaire**.

Note: On page 2 of the Household Air Monitoring Questionnaire; enter the **date and time** when **you** collected the UPAS. Do not enter the programmed stop time and date.


PURE AIR Household Air Monitoring Questionnaire Page 2

PURE Individual #062 Plate #482

Monitoring Visit # 1100-1110

Household Sample ID *(enter in phone)*: 56 (Centre #) 501 (Community #) 233 (Household #) 0 (Member #)

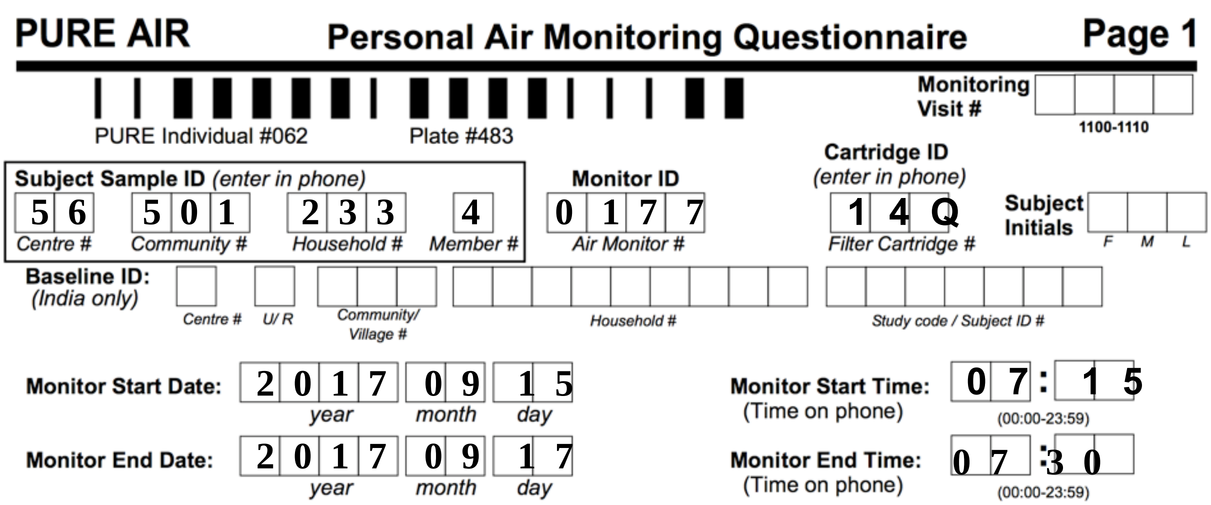
Monitor End Date: 2017 (year) 09 (month) 15 (day)

Monitor End Time: 07:35 (Time on phone) (00:00-23:59)

*Figure 45: Enter the date and time when **you** collect the UPAS from household monitoring. Do not enter the programmed stop date and time.*

If **personal monitoring** took place interview each participant and answer questions 3 to 11, (questions 9, 10 and 11 are for China **only**) on pages 1, 2 and 3 of the **Personal Air Monitoring Questionnaire**. You must do this for **both** participants.

Note: On page 1 of the Personal Air Monitoring Questionnaire enter the date and time when **you** collect the UPAS from personal monitoring. **Do not** enter the programmed stop date and time.


PURE AIR Personal Air Monitoring Questionnaire Page 1

PURE Individual #062 Plate #483

Monitoring Visit # 1100-1110

Subject Sample ID *(enter in phone)*: 56 (Centre #) 501 (Community #) 233 (Household #) 4 (Member #)

Monitor ID: 0177 (Air Monitor #)

Cartridge ID *(enter in phone)*: 14Q (Filter Cartridge #)

Subject Initials: F M L

Baseline ID: *(India only)* Centre # U/R Community/Village # Household # Study code / Subject ID #

Monitor Start Date: 2017 (year) 09 (month) 15 (day)

Monitor Start Time: 07:15 (Time on phone) (00:00-23:59)

Monitor End Date: 2017 (year) 09 (month) 17 (day)

Monitor End Time: 07:30 (Time on phone) (00:00-23:59)

Figure 46: Enter the date and time when you collect the UPAS from personal monitoring. Do not enter the programmed stop date and time.

7 Post UPAS collection

7.1.1 Unloading the Used Filter Cartridges

There is a short video for this section. **Please click here to view**.

After the UPAS monitors have been collected and staff have returned to the work area the used filter cartridges need to be unloaded and returned to their packages.

IT IS VERY IMPORTANT to keep the information or filter cartridge from 1 UPAS separate from other UPAS monitors:

- Sort the devices and CRFs by household. Place each UPAS monitor on top of its CRF. Then find the filter cartridge packages for the deployed devices, place each package with the matching device. Keep these items together (Figure 40).
- Completely process 1 device, CRF and filter cartridge package at a time. **Do not** try to process all of the collected devices at the same time.

Figure 47: Gather UPAS, CRF and filter cartridge bag for each household sampled.

Once the collected devices and the CRFs have been sorted, the used filter cartridges need to be removed from each UPAS monitors and returned to their original packages (Figure 41):

1. Wash and dry your hands thoroughly.
2. Unscrew the black intake cap from the front of the UPAS device. **Do not** use tools.
3. Remove the filter cartridge from the monitor. Only hold the filter cartridge by the edges.
4. Return the filter cartridge to its original package. **Do not open the filter cartridge**.

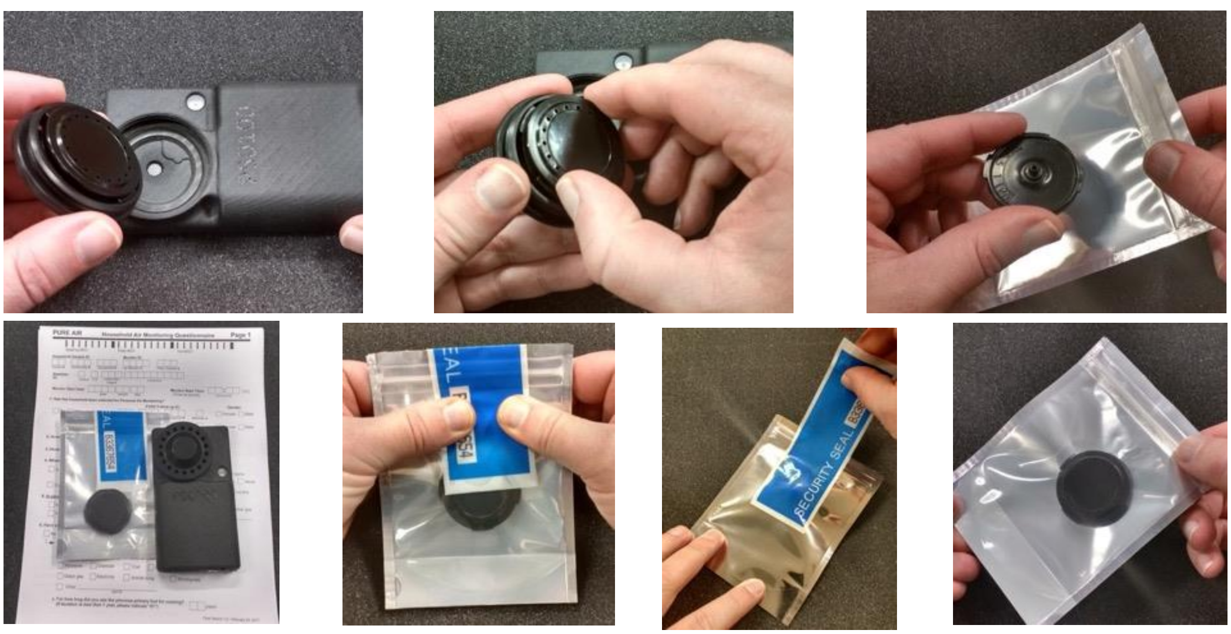


Figure 48: Clockwise from top left: Unscrew the intake cap, the filter cartridge may stick, press sideways to release, put the filter cap back in its bag, use a piece of tamper proof tape to seal the bag, keep everything together until the work is finished.

5. Take a section of tape from the roll provided and seal the package.
6. Seal the package by closing the opening seal and then wrapping the sealing tag across the opening.
7. Place the monitor and filter cartridge package back on the CRF for that device.
8. Repeat steps 1 to 7 for every device collected.
9. When all the filter cartridges have been removed from their UPAS monitors keep the monitor, the filter cartridge package and the CRF together.

7.1.2 Retrieving Run Logs from UPAS Devices

This section has a short video. Please click here to view.

After the used filter cartridge has been removed from the UPAS monitor, the data from the device needs to be retrieved. To do this follow these steps:

1. Take 1 smartphone and select every UPAS monitor that smartphone was used with. Keep the UPAS monitor, CRF, and filter cartridge package together.
2. Work with one monitor at a time
3. Turn the UPAS monitor on.
    a. If it has run out of power, connect the UPAS monitor to the charger. It may be necessary to wait up to half an hour for the monitor to build up enough charge to turn on again.
4. Turn the Moto-G smartphone on and open the UPAS app.
5. Connect the phone to the monitor, do this the same way the phone was connected to the monitor when programming the UPAS monitor at the start of sampling (Section 6.2.4).
6. At the bottom of the main screen tap the *Begin File Download* button and wait. Figure 42)
    a. The light on the front of the monitor will turn from blue to orange while the file transfers. When the transfer is completed the light will turn blue again. This may take **5 to 10** minutes per file. You cannot transfer more than one file at a time.
7. Repeat steps 3 and 4 above for every UPAS monitor deployed with one smartphone.
8. Repeat steps 1 to 7 for every smartphone.

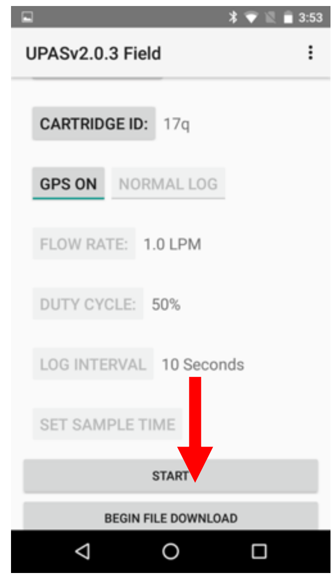


Figure 49: Select the "Begin File Download" button at the bottom of the screen.

7.1.3 Upload UPAS Files to PURE AIR Server

This section has a short video. Please click here to view.

Note:

- This step will only work if you have a working internet connection and you have been able to connect the PURE AIR project smartphones to your Wi-Fi network.
- If you do not have a working internet connection, or you do not have working Wi-Fi, skip this step and go to section 8.1.4.

- If you have temporarily lost your internet connection or your Wi-Fi network you can skip this step until your internet or Wi-Fi return.

After all run logs have been uploaded to their controlling phones those run logs can be uploaded to the PURE AIR project server computer.

To upload run logs from a PURE AIR project smartphone, follow these steps:

1. Go to the phone's second screen and open the AndFTP app
2. Select the PURE AIR folder icon
3. After a moment, the AndFTP app will connect to the PURE AIR server and you will see a screen with many files listed. Select the circular sync icon at the top right of the screen.

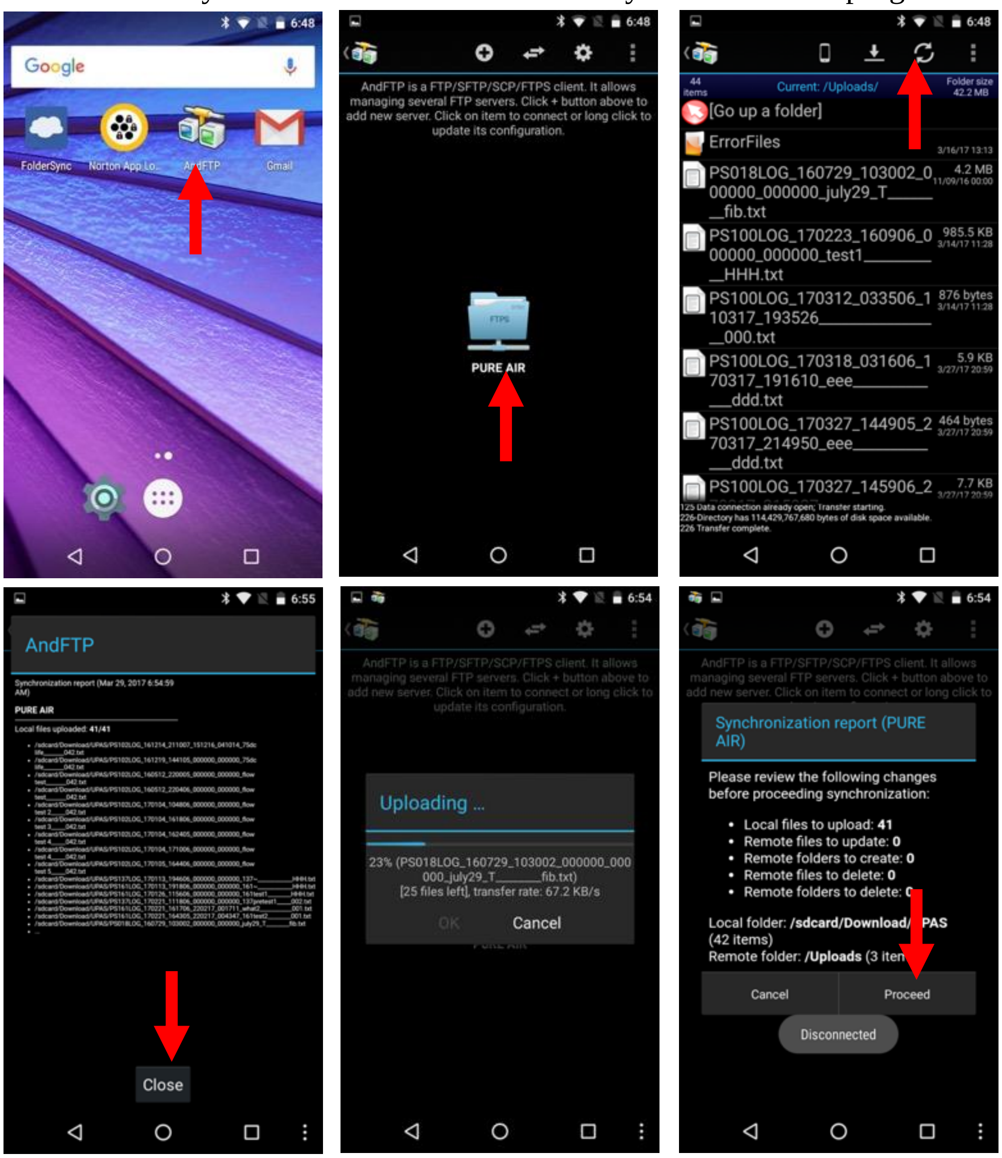


Figure 50: Clockwise from top left: Select the AndFTP app, select the PURE AIR icon, select the round sync icon on the top right, select Proceed, select Close.

4. You will see a Synchronization report pop up, select Proceed.
   a. Do not worry if you see the word Disconnected here.

5. You may see the app uploading files to the server. This can happen very fast.
6. When the app is done uploading you will see a synchronization report, select Close.
7. Exit the app.

7.1.4 Clean the UPAS Monitor

Staff must clean each collected UPAS monitor once the filter cartridges have been unloaded and the run logs downloaded. The UPAS monitors should be inspected every time they are used. If you see any amount of dust on the inside of the intake cap, or on the filter cartridge you should clean the entire UPAS.

To do this follow these steps:

- Use a Kim wipe to wipe around the inside of the UPAS monitor filter cartridge socket.
- Use the rest of the Kim wipe to clean the intake ring and the rest of the UPAS monitor.
- Use a flat tool to lever the inner cyclone away from the rest of the intake cap (Figure 44)
- Clean the inside of the cyclone and the intake cap

Figure 51: Clockwise from top left - Use a flat tool to separate the cyclone from the intake cap, the cyclone and the intake cap apart, clean the inside of the cyclone, re-assemble the cyclone and intake cap by pressing them together.

- When the cyclone and the intake cap have, all been cleaned then re-assemble the intake cap by pressing the two parts together with your fingers firmly. **Do not use tools or too much force**.
- Repeat for all monitors using a fresh Kim wipe for each monitor.

7.1.5 Recharging the UPAS Monitors

Once the collected monitors have been cleaned the monitors need to be recharged. To recharge the monitors, connect each one to the supplied charger using the supplied USB cables. Do this in the same way as described in section 5.1

7.1.6 Packing Used Filter cartridges and Completed CRFs

Once the collected monitors have begun recharging staff, place all of the re-sealed filter cartridge packages into the large Ziploc bags for used filter cartridges; these are marked with a piece of tamper proof tape. Return the completed CRFs to your coordinator.

8 Post-Fieldwork

This section will cover what needs to be done once all the required samples have been collected.

8.1 Removing microSD cards from phones and UPAS

When all required samples have been collected you need to remove the microSD cards from both the UPAS and the project smartphones.

8.1.1 Removing microSD cards from project smartphones

To remove the microSD cards from the project smartphones, reverse the steps in section 4.4. Place the microSD cards back in the package they came in and place that package back in the filter cartridge packing container.

8.1.2 Removing microSD cards from UPAS

To remove the microSD cards from the UPAS, reverse the steps in section 4.5. Place the microSD cards back in the package they came in and place that package back in the filter cartridge packing container.

8.2 Packing equipment for shipping

8.2.1 Pack filter cartridges and microSD cards

When fieldwork is complete, all used filter cartridges should be packaged in the Ziploc bags marked with tamper-proof tape, you should be able to fit 50 cartridges to a bag. All microSD cards should be returned to the plastic boxes they came in. **DO NOT** pack filter cartridges or microSD cards with the UPAS monitors, monitor stands and other equipment.

The following photos show one way to pack this container efficiently (Figure 45).

Container C1 (Filter cartridges, microSD cards)

Figure 52: Clockwise from top left: 4 bags of used cartridges, lay 1 bag flat and to one side, add envelope with microSD cards to back and one bag vertically on the side, lay two more bags horizontally and add roll of tamper-proof tape.

8.2.2 Pack UPAS devices and accessories

When fieldwork is complete, all UPAS monitors, monitor stands, chargers, harnesses, and other items in the two large cases. **DO NOT** pack any of these items with the filter cartridges or microSD cards in container #1.

The following photos show how to pack these containers efficiently. **Note**: the UPAS monitors must be packed in container C2 **exactly** as shown.

Container C2 (UPASs)

Figure 53: Packing sequence for case #1. Pack UPAS on lower level in slots, tape measures in larger cut-out, insert plastic divider, monitor stands, monitor stand bases and power bar, clip boards on top.

Container C3 (Monitor stands, phones, harnesses)

Figure 54: Bottom layer of monitor stands, monitor stand bases, and USB chargers, layer of foam and plastic divider, contents of smaller containers (USB cables, monitor stand parts, project smartphones), top layer of small containers and UPAS harnesses.

K PURE AIR project smartphone setup guide

The purpose of this document is to explain how to set up a PURE AIR project smartphone. This document also collects all the needed passwords and IDs.

1 Basic Information:

1.1 The phone:

The PURE AIR project, under Drs. Brauer (UBC) and Hystad (OSU), uses Motorola Moto-G (3^{rd} generation) smartphones. These phones are unlocked (not tied to any carrier) and are compatible with GSM, CDMA, HSPA, and LTE radio networks (the phones should work with any carrier around the world).

Anyone interested in the technical specifications of the phones should simply Google "Motorola Moto G 3^{rd} generation" or go to http://www.gsmarena.com/motorola_moto_g_(3rd_gen)-7247.php

1.1.1 The OS:

These phones come with Android V6.0 (Marshmallow) and a suite of pre-installed Motorola apps. **Do not update the OS on project phones**, unless specifically instructed by the PURE AIR coordinator.

1.1.2 The security:

The phones are not locked out of the box. Once a phone has been properly set up it will have several layers of security.

1.2 Setting up the phone

1.2.1 Phone ID

Each Motorola Moto G phone used by the PURE AIR project should have been assigned a name when it was first registered with the project. This name may be recorded on a small sticker inside the phone's rear cover. Before setting up the phone open the rear cover of the phone and look for a name, it should be something like Moto01, Moto02, etc… If you cannot see the phone name look for the phone's serial #, this is also on the inside of the back panel. Each serial # is preface by TA: and should start with ZY…

You will also need a PURE AIR FTP account name and password to correctly set up the phone. Give the phone name and/or serial # to the PURE AIR coordinator and they will give you an account name and password for the phone to use when it connects to the PURE AIR FTP server.

1.2.2 Initial setup and Google sign in:

If a phone needs to be reset after an improper configuration or testing, then the phone needs to be reset. In the **Setting Menu** select the **Backup and reset** option, then select **Factory data reset**, then select **Reset phone**, then enter the phone's **PIN** number (if it has one), then select **Erase**

Everything. This will return the phone to its factory settings. Once this is done follow the steps below to properly configure the phone.

When configuring a new phone or a reset one the first thing you will see after turning the phone on is a **Welcome** screen with a language select option, select **English (Canada)** from the dropdown menu.

Next, select the name of the local Wi-Fi network you will be using, then enter that network's password. Then select **Accept** and **Continue**.

Because of the security setting the PURE AIR project phones use, one project phone can't be used to set up another. On the **Got another device** screen select **No thanks** and touch **Next**.

Now sign into the Google account for the PURE AIR project. In the **Add your account** screen enter this email address:

Pureair.upas@gmail.com

On the next screen enter this password:

3411#$!!

Then select accept.

De-select all the options on the Google services screen (make sure all the boxes are not checked). Select **Next**.

You may see a Get Google Now screen. If you do, scroll to the bottom of the screen and select **Skip**.

You may see a screen that says "You're all set!" and has a What's next section. If you do select **Maybe Later**.

Or you may see a screen that asks you to **Add another email**, if so select **Not now**.

To make sure the setup of the phone works properly, **do not** restore the phone from a backup. On the **Get your apps & data** screen select **Set up as new device** from the **Restore this device** drop down menu. Select **Next**.

It is very important that the phone have a **PIN** number. On the next screen select the **Protect this device** option. Then select PIN. Then enter **7873**. **This is very important**. **Do not** enter a different PIN number unless the PURE AIR coordinator explicitly tells you to. Re-enter **7873**.

On the next screen select the **Don't show notifications at all**. Select **Next**.

On the **Get Google Now** screen select the **Skip** option. Select **Next**.

You should now be done the device setup. You will see a home screen with a notification to make sure the phone's back is on tightly. Select **Got It**.

Now you need to install three other apps to set up the phone properly. Install these apps in following order. **Do not** install additional apps without authorization from the PURE AIR coordinator. PURE AIR project phones only need a few additional apps installed.

1.3 The MicroSD card

Each project phone needs to be equipped with a MicroSD card to expand the phone's storage.

To add the card, open the back of the phone by peeling the back panel off. On the top left of the back of the phone, near the camera, there is a slot marked microSD. Insert the microSD card into this slot with the gold contact points facing down. You need to press firmly to get the card to insert properly. DO NOT use a tool to do this.

When the card has been inserted the phone will recognize it. You will see a small notification icon at the top of the main screen, select this icon and then select **Set Up.**

The phone will ask you how to use the microSD card, select **Use as a portable storage**, then select **Next**, then select **Done.**

1.4 The additional apps:

The phones come with a suite of Google and Motorola apps pre-installed. These apps are not removable. Do not bother trying to remove them. Do not jail-break the phone in order to remove the stock apps.

1.4.1 UPAS app:

This app is used to program and control the UPAS monitors. This is the most important app to install on the project phones.

Installation:

To install this app, you need to download the. apk file from the pureair.upas@gmail.com account. Open the folder icon on the home screen labeled Google and drag the **Gmail** icon onto the main screen. Look for, or search, for an email labeled from "**Aaron Birch**" with **UPAS apk** in the subject line. Download the attachment by tapping on the attachment, then touch the **download icon**. (The phone will probably ask you to allow Gmail permission to access files and folders on the phone, select **Allow** and continue). Go back to the home screen, select the app launcher (the round white icon with six dots) and select **downloads**. Then select the **UPAS app**. The phone will show an **install blocked** alert, select **settings** and scroll down and select the **Unknown sources** option, select **OK**. Go back to **downloads** and select the app again and select **install**. Then select **Accept**. Then select **Open**. Then select **Allow**. Then select **OK**. Then select **Allow**. At this point the UPAS app should be running. Return to the home screen.

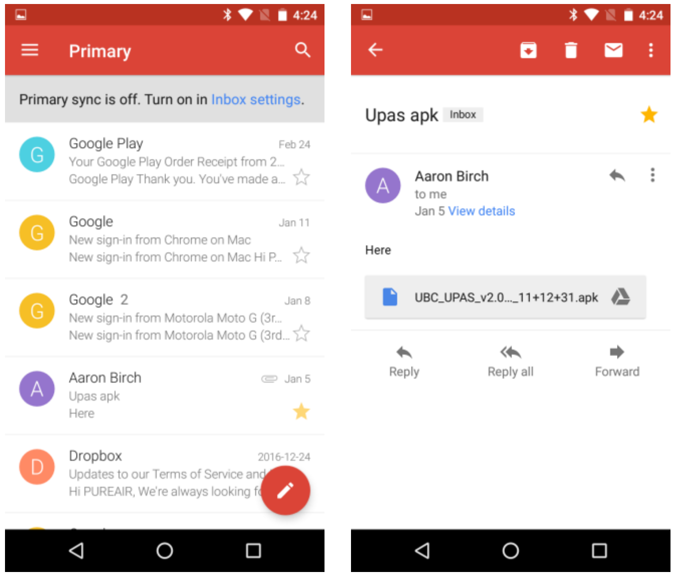


Figure 55: The Gmail screens that show where the UPAS apk is.

Setup:
The UPAS app doesn't need to be configured by itself. It does need to pair the phone to the UPAS monitors it will be controlling. This pairing procedure is covered in the UPAS protocol.

1.4.2 AndFTP app:
This is an FTP client capable of syncing files from the phone to the PURE AIR FTP server at UBC.

Installation:
There are two components to this app. The first is a **free base version** with limited functions and ads. The second component is the **pro-version** key which unlocks all the app's features and removes the ads.

To install the first component, open the **Google Play** store and select the **My apps & games** option from the menu at the top left of the main store screen. (This requires that the phone is signed into the pureair.upas@gmail.com account). Select **All** (next to the **Installed** option), scroll down until you see the **AndFTP (your FTP client)** app, this should be the **Free** app. Select this app and select **Install**, then select **Accept**. Once the app has installed backup one screen and select the **AndFTPPro** app, then select **Install**, then select **Accept**. Return to the home screen and select the **AndFTP** icon.

Setup:
When you open the app for the first time you will see a tip window, select the **Disable Tips** option, then select **Close**.

To create a connection from the phone to the PURE AIR FTP server select the round white plus icon at the top left of the main screen. Then enter the following into their respective fields:

Under General (one of three field options at the top of the screen)
Hostname: pa.soeh.ubc.ca
Type: FTPS (Explicit FTP over TLS/SSL)
Username: enter the name the PURE AIR coordinator gave you **exactly** (case sensitive)
Password: enter the password the PURE AIR coordinator gave you **exactly** (case sensitive)
Local dir: select the **Internal** icon, then **Downloads**, then touch and hold the folder icon for **UPAS** until a check mark appears over the folder icon, then select **OK**
Remote dir: (If the phone doesn't have internet when you select this it won't work). Select **Browse**, when the phone connects to the server you will see a folder for **Uploads**, touch and hold on the folder icon until a check mark appears over the folder icon, select **OK**.
Resume: Select **Enable resume support**.

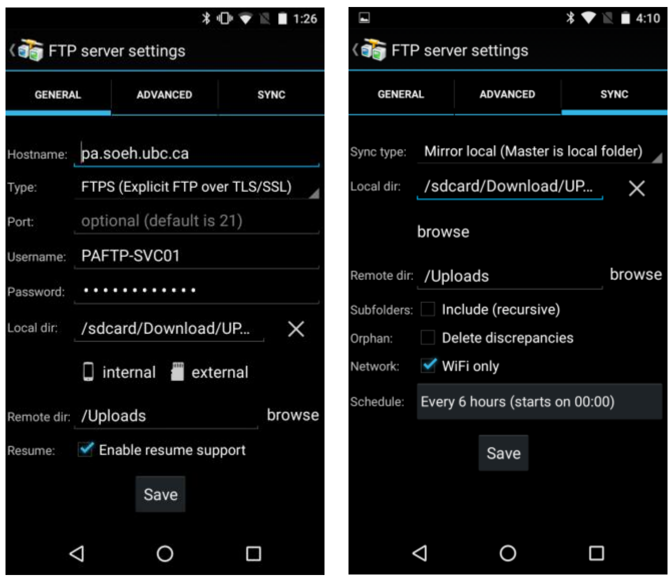


Figure 56: The general and sync screens in the AndFTP app after they have been properly setup.

Under Sync:
Sync Type: Select **Mirror local** (Master is local folder)
Local dir: Select the **Downloads/UPAS** folder the same way you did in the General screen
Remote dir: Select the **Uploads** folder the same way you did in the General screen
Network: Select WiFi only (unless the PURE AIR coordinator tells you not to)
Schedule: Select Every 6 hours (unless the PURE AIR coordinator tells you not to)

Select **Save** at the bottom of the screen. Then enter the name for the FTP connection as **PURE AIR**. Select **OK**. Return to the home screen.

1.5 UI configuration:

You will need to re-arrange the app icons on the phone's main screen. On the primary screen the only icon should be for the UPAS app. On the quick access field (the four app slots next the app launcher icon (the white circle with six dots)) the only the Settings icon should be there (drag this out of the app launcher). On the second screen there should only be icons for AndFTP, AppLock, and Gmail.

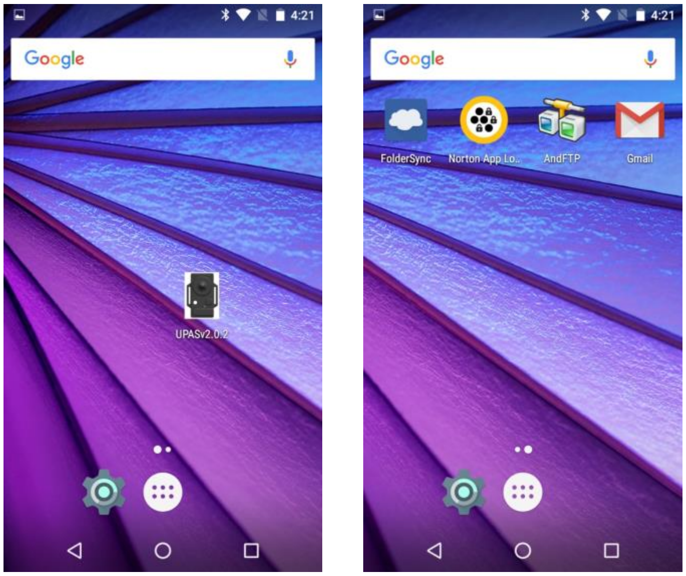


Figure 57: This is what the main screen (left) and the second screen (right) should look like.