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Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal

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Abstract

Air purifiers (APs) and home sealing are interventions used to help protect U.S. diplomats against particle pollution in the home when working in polluted cities. We investigated the effect of these interventions on home indoor and personal $PM_{2.5}$ exposure in Kathmandu, Nepal. Twenty-one participants underwent repeated 48 hour personal monitoring before and after intervention. We analyzed these measurements by microenvironment. Indoor-outdoor ratios (I/O) using the home indoor $PM_{2.5}$ values were calculated in order to assess the air filtration capacity at home in light of increasing outdoor $PM_{2.5}$ post-intervention. To quantify the effect of intervention on home indoor $PM_{2.5}$, we conducted a meta-analysis of the results of dwelling-by-dwelling regression of indoor-on-outdoor (I/O) $PM_{2.5}$ concentrations. On average, adding high-capacity APs and home sealing led to a 15% decrease in $PM_{2.5}$ measured at home, excluding cooking periods, with a mean (standard deviation) of 7.5 (6.4) μg m^{-3} pre- to 6.4 (8.1) μg m^{-3} post-intervention despite a 57% increase in outdoor $PM_{2.5}$, from 43.8 (30.8) μg m^{-3} pre- to 68.9 (40.7) μg m^{-3} post-intervention. Overall mean personal exposure fell by 36% from 15.2 (10.6) μg m^{-3} to 9.8 (8.7) μg m^{-3}. I/O ratios decreased as outdoor $PM_{2.5}$ strata increased; when outdoor $PM_{2.5} < 25$ μg m^{-3} the I/O decreased from 0.38 pre- to 0.12 post-intervention and when outdoor $PM_{2.5}$ was 101–200 μg m^{-3} the I/O decreased from 0.12 pre- to 0.07 post-intervention. The mean regression slope of indoor-on-outdoor $PM_{2.5}$ decreased from 0.13 (95% CI 0.09, 0.17) in pre-intervention dwellings to 0.07 (0.04, 0.10) post-intervention. I/O ratios showed a weak negative (not statistically significant) inverse association with air changes per hour at home. In the high pollution environment of Kathmandu, APs with home sealing provide substantial protection against ambient $PM_{2.5}$ in the home environment, including during periods when outdoor $PM_{2.5}$ concentration was above 100 μg m^{-3}.

1. Introduction

United States (U.S.) diplomats live in numerous locations across the globe during their career, some of which may have high levels of outdoor air pollution. Given the well-established evidence of the harmful health effects of exposure to particulate matter $\leqslant$2.5 μm aerodynamic diameter ($PM_{2.5}$) and other air pollutants (Cohen *et al* 2017), (Cromar *et al* 2021) (Wellenius *et al* 2012), various mitigation measures are deployed to attempt to limit their exposure to polluted air. Those measures typically include the filtration of air in embassy offices and increasingly also the use of air purifiers (APs) and the sealing of the home to reduce the penetration of polluted outdoor air to the home environment. These measures directed at reducing home-indoor concentrations of $PM_{2.5}$ are important because of the proportion of the day typically spent in the home environment: the Human Activity Pattern Survey, for example, found that on average Americans spend 87% of their day indoors including 69% inside the home (Klepeis *et al* 2001).

In this paper, we report a study of the impact of APs and home sealing on particle air pollution exposure of diplomats in Kathmandu, Nepal, a city which, in 2019, had an ambient (outdoor) $PM_{2.5}$ annual mean (standard deviation (SD)) of 45.4 (15.6) μg m^{-3}, a value nine times higher than the World Health Organization(WHO) annual mean guideline of 5 μg m^{-3} outdoors (United States Environmental Protection Agency 2020), (World Health Organization 2021). In this city, most U.S. diplomats and their families live in traditional-style dwellings constructed of cement with wooden accents, which tend to have a fairly high air permeability (are 'leaky', especially around windows and doors), and so are affected by the ingress of polluted air from the outdoor environment.

In the autumn of 2019, U.S. diplomat families were offered high-capacity APs to improve the filtration of air in the home and many also chose to implement additional measures such as weather-stripping and caulking to reduce the leakiness of windows, doors and other apertures of the dwelling fabric. We conducted repeated personal air pollution monitoring by diplomats who work at the U.S. Embassy and diplomats' adult family members who do not work at the Embassy to assess the effect of such measures on $PM_{2.5}$ at home and 24 hour personal $PM_{2.5}$ exposure.

2. Materials and methods

2.1. Study participants

The study was of 30 Americans affiliated with the U.S. Embassy in Kathmandu, however, results are reported only for the 21 Americans that added APs to their home (figure A1). Work status among the 21 participants include 11 US diplomats who worked at the Embassy and ten adult family members of diplomats (two worked part-time at the Embassy and eight did not work at the Embassy). They included five married couples where only one of the couple worked at the Embassy. Participants were recruited by email sent to all U.S. diplomats working at the Embassy and their family members encouraging, but not requiring, participation. A survey was administered at the end of each monitoring session that included questions about APs use by room of the home, home sealing efforts, and method(s) of transportation used during the monitoring session.

2.2. Home air pollution mitigation

The homes occupied by participants, mostly traditional in style, were not insulated, the windows had either an aluminum/metal or a wooden frame and most were considered to be poorly sealed against the outdoor air. A photograph of a home similar to that occupied by study participants is included in figure A2. The heating, ventilation and air conditioning systems in participants' homes included several electrically powered, wall mounted mini-split unit air conditioners with heat pumps and many homes had cooking fans in the kitchen and ventilation fans in the bathrooms. Study participants had access to electric oil-filled space heaters to use at home if needed.

Beginning in November 2019, all U.S. Embassy diplomats in Kathmandu, including the study participants who enrolled this study, were offered additional supply of high capacity APs (Blueair 605 APs, with a clean air delivery rate (CADR) of 500 feet^3 hour^{-1}, converted to 14.2 m^3 hr^{-1}) (Blueair 2022b) and various measures to seal their home against the ingress of outdoor air including the use of caulking, draught-stripping and plastic sheeting on doors and windows. Twenty participants received two high capacity APs while one participant received one high capacity AP. The intervention examined in this study is the addition of high capacity APs.

Before this intervention, study participants had an average of 7 (range: 2–10) low-capacity APs (Blueair 203 APs with CADR of 180 feet^3 hour^{-1}, converted to 5.1 m^3 hr^{-1} on average) (Blueair 2022a) used to varying degrees (table 1). In order to consider the impact of the varied number of APs in use and the CADR for each house, home air purifier capacity (HAPC) (m hour^{-1}) was quantified by using the total of the CADR (m^3 hour^{-1}) for each AP in use in each home divided by the surface area of the home (m^2).

Pre-intervention the total HAPC per hour in participants' homes ranged from 1.6 to 5.9. All of the study participants kept the low-capacity APs in their home after adding the high-capacity APs instead of replacing them. Information about the frequency of APs use and intensity setting (high, medium or low) used both pre- and post-intervention are summarized on table 1.

2.3. Monitoring of personal exposure

Study participants underwent two to three cycles of 48-hour personal monitoring for $PM_{2.5}$ between September 2019 and March 2020. Periods of monitoring before the introduction of the high-capacity APs and home sealing are referred to as 'pre-intervention' period, and those conducted after installation/home sealing as 'post-intervention' period. In total, 21 participants underwent personal monitoring in both pre-intervention and post-intervention periods, and the main results presented below are based on this group of 21 with paired measurement periods. Nine further study participants had monitoring from either the pre-intervention or the post-intervention period but not both.

Table 1. Characteristics of the 21 participants with paired personal monitoring data for the pre- and post-intervention periods.

Characteristic	Pre-Intervention	Post-Intervention
Gender *n (%)*		
Female	13 (62%)	
Male	8 (38%)	
Age group *n (%)*		
30–39	3 (14%)	
40–49	9 (43%)	
50–59	6 (29%)	
60–69	3 (14%)	
Worked at US Embassy *n (%)*		
Full time	11 (52%)	
Part time	2 (10%)	
Did not work at the Embassy[a]	8 (38%)	
Home size *(m[b])*		
mean (min-max)	266.3 (131.3–360.7)	
Main mode of transportation[b] *n (%)*		
Personal car	14 (67%)	13 (62%)
Walk or run	11 (52%)	9 (43%)
Bicycle	2 (10%)	2 (10%)
Taxi	0 (0%)	2 (10%)
Did not answer	2 (10%)	3 (14%)
Number of air purifiers (APs) at home[c] *mean (min-max)*		
Low capacity Aps	6.8 (2–10)	6.8 (2–10)
High capacity Aps	0	1.9 (1–2)
Total home air purifier capacity (HAPC)[d] per hour *(m/hour), mean (SD)*	3.2 (1.2)	5.4 (1.9)
Efforts to seal the home *n (%)*		
Sealed, total	4 (19%)	11 (52%)
Sealed windows with tape and plastic	2 (9%)	3 (14%)
Sealed windows with tape	1 (5%)	3 (14%)
Sealed windows with caulk	0	2 (10%)
Sealed windows, backdoor with tape	0	1 (5%)
Sealing details unspecified	1 (5%)	2 (10%)
Not sealed	17 (81%)	10 (48%)
Always use APs in rooms at home *n (%)*		
Living Room	18 (86%)	21 (100%)
Bedroom	19 (90%)	20 (95%)
Kitchen	7 (33%)	12 (57%)
Setting used on APs *n (%)*		
Highest	13 (61%)	12 (57%)
Middle	4 (19%)	3 (14%)
Lowest	0	1 (5%)
Combination of Highest and Middle settings	2 (10%)	3 (14%)
Not answered	2 (10%)	2 (10%)
Leaky windows and doors in home *n (%)*		
Yes	15 (71%)	15 (71%)
No	0	0
Not answered	6 (29%)	6 (29%)

[a] Family members of diplomats that do not work at the Embassy.

[b] Participants could choose more than one mode of transportation. Pre-intervention 7 participants listed both walking and personal car. Post-intervention 5 participants listed walking and personal car and 1 participant listed taxi and personal car.

[c] Low capacity air purifiers (APs) have a clean air delivery rate (CADR) of 5.1 m^3/hour and high capacity APs have a CADR of 14.2 m^3/hour.

[d] Total home air purifier capacity (HAPC) (meters/hour) is the sum of the home air purifiers' clean air deliver rate (CADR) in cubic meters (m^3) per hour divided by the surface area of the home (m^2).

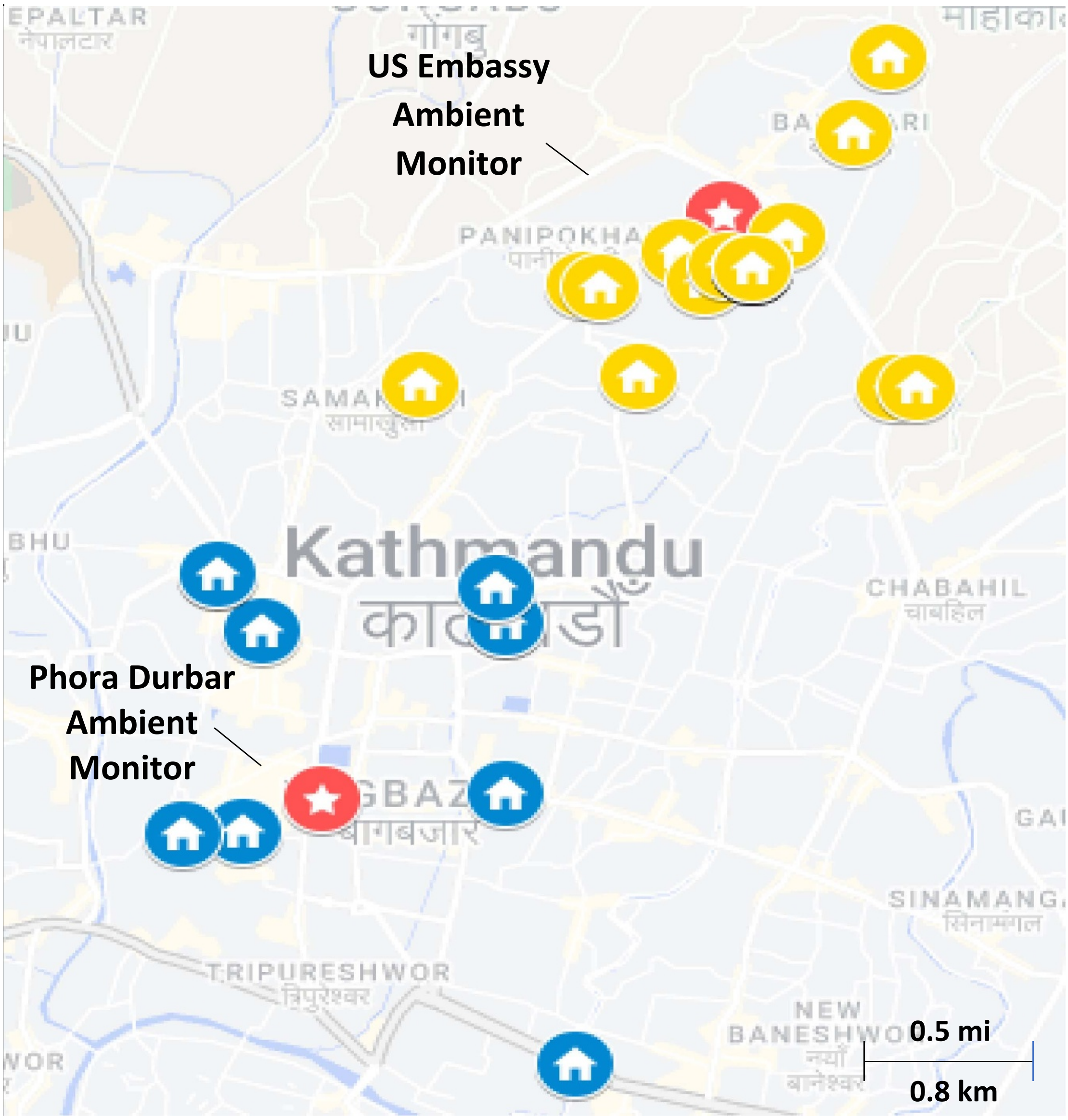

Figure 1. Map of ambient monitoring stations at the US Embassy and Phora Durbar Complex and homes of 21 study participants. Red markers indicate the fixed site ambient monitors located at the US Embassy and at the Phora Durbar Recreational Complex. Yellow icons are for the homes of the 13 participants that live closer to the ambient monitor located at the US Embassy. Blue icons are for the homes of the 8 participants that live closer to the ambient monitor located at the Phora Durbar Recreational Complex.

Participants wore an Applied Particle Technology (*APT) Minima* optical personal exposure monitor (figure A3) with a sampling interval of 1 min and sampling volume to 0.1 l air minute^{-1} (Applied Particle Technology 2020), (Li *et al* 2020). Participants wore the personal monitor in a custom made crossbody carrying case with openings in the fabric for the personal monitor's air collection outlet and charging port. Participants typically wore the crossbody carrying case with the personal monitor at waist level. No additional sampling tubing was needed for this personal monitor. The *APT Minima* records $PM_{2.5}$, temperature and humidity for each sampling interval. Each participant recorded time-activity patterns for the periods of monitoring using a standardized diary. They were asked to record time and location of activities such as home cooking, commuting and other outdoor movements. They also completed a questionnaire about efforts to seal the home against the outdoor air, AP use and sources of air pollution inside the home during each monitoring session.

Ambient (outdoor) $PM_{2.5}$ was measured at two U.S. Embassy fixed site outdoor air quality monitoring stations (BAM-1020, MetOne beta attenuation monitors, (BAMs)) located at the Embassy grounds at Maharajhung Road in Chakrapath and the Phora Durbar Recreation Center in the Thamel neighborhood (figure 1). All homes were within 1.8 miles (2.9 kilometers) of an outdoor fixed-site air quality monitor. The Thamel area has heavy road traffic while the U.S. Embassy is located in an area of relatively low population density and vehicular traffic. $PM_{2.5}$ data from the outdoor monitor located closer to each participant's home was used in the analysis. The monitoring equipment is maintained and calibrated by U.S. Embassy staff in conjunction with the standard operating procedures of the U.S. Environmental Protection Agency (EPA) for $PM_{2.5}$ monitoring. $PM_{2.5}$ concentrations are reported as hourly averages of 15-minute sampling and are publicly available at the Air Now website (US Environmental Protection Agency 2015).

An APT Maxima stationary air quality monitor was located next to the U.S. Embassy's BAM in Phora Durbar, to track the sensor calibration for local ambient aerosols. The Maxima has the same monitoring technology as the *Minima* used for personal monitoring but is surrounded with a durable, weather resistant exterior case. Comparison of APT Maxima in Phora Durbar with the BAM data showed a regression slope of 0.98, R-value of 0.9429. Independent of this study, a sensor performance evaluation conducted by South Coast Air Quality Management District which demonstrated a high level of agreement ($R^2 = 0.86$–0.91) when the APT Minima was run side-by-side with federal equivalent method instruments (South Coast Air Quality Monitoring District 2020).

2.4. Data analysis

The microenvironments occupied by each participant throughout the period of monitoring were determined using data from the time-activity diary in combination with inspection of the $PM_{2.5}$ trace and the temperature recorded by the personal monitor and outdoor temperature in an attempt to help improve the timing of the transition between environments. Six categories of microenvironment-activity were used in the study: (a) home (indoors, excluding cooking), (b) cooking at home, (c) inside the U.S. Embassy, (d) inside other indoor environments, including restaurants, hotels and shops, (e) travel by car and (f) outdoors. Participants did not reliably record periods of home cooking, so we labelled a period as a cooking period when the participant was in their home environment at a meal-time (7–9 am for breakfast, 12–2 pm for lunch, 5–8 pm for evening meal) and there was a sharp rise in $PM_{2.5}$ concentrations (see, for example, figure 3). Meteorological data including the daily ambient temperature and rainfall were examined and values were compared during pre- and post-intervention.

The database of personal exposure monitoring measurements recorded in this study was updated to include the corresponding hourly mean of the fixed-site ambient $PM_{2.5}$ monitor closest to each study participants' home for each personal monitoring datapoint recorded. This allowed for a comparison of the personal $PM_{2.5}$ to ambient $PM_{2.5}$ concentrations reflecting the direct timing of each personal monitoring session. Pre- and post-intervention mean (SD) and median (IQR) values for each microenvironment were calculated and the differences in means were tested using the Kruskal-Wallace test.

The contribution of each microenvironment to cumulative personal exposure (hours $\times$ μg m^{-3}) was computed as the product of number of hours within each microenvironment and the corresponding measured $PM_{2.5}$ concentration. The home indoor/outdoor (I/O) ratios of $PM_{2.5}$ concentrations were derived by dwelling-specific regression of the hourly mean personal monitoring $PM_{2.5}$ when the participant was at home (excluding periods of cooking) on the corresponding hourly outdoor $PM_{2.5}$ at the closer fixed monitoring site. The slopes of these regression analyses reflect the dwelling-specific I/O ratio of $PM_{2.5}$ concentrations allowing for differences in outdoor $PM_{2.5}$ concentrations at the time of personal measurement at home. Dwelling-specific I/O ratios of $PM_{2.5}$ concentration were weighted by the number of observations to derive these I/O ratios, with results for study participants (or dwellings) having larger weights if they spent more hours at home during the pre- or post- intervention monitoring period.

Separate regression slopes and y-intercepts of indoor-on-outdoor $PM_{2.5}$ were obtained for pre- and post-intervention periods. Meta-regression of the dwelling-specific regression slopes and y-intercepts was subsequently performed to obtain summary measures before and after intervention. We also analyzed the general relationship between the I/O slopes and the capacity of the APs.

Sensitivity analyses of the I/O ratios included: (a) restricting analysis to times when the outdoor temperature was less than 18 °C (64.4 °F) (to attempt to remove the effect of window opening on warmer days), (b) restricting the analysis to the include monitoring sessions from the 18 participants with at least 8 h of personal monitoring conducted in the home per 48 h monitoring session both pre- and post-intervention, (c) restricting analysis to include only the monitoring sessions with high and/or middle AP settings, and (d) using data from all 30 study participants even if there was no paired data for both the pre- and post-intervention periods.

All analyses were carried out in Stata version 17.0 (StataCorp 2021). The study was approved by the U.S. Department of State's Human Subjects Protection Committee and by the London School of Hygiene and Tropical Medicine's Research Ethics Committee.

3. Results

3.1. Characteristics of study participants

The primary analyses presented in the Tables and Figures below are based on the 21 participants that had paired measurements for both pre-intervention and post-intervention periods (table 1). Results for nine

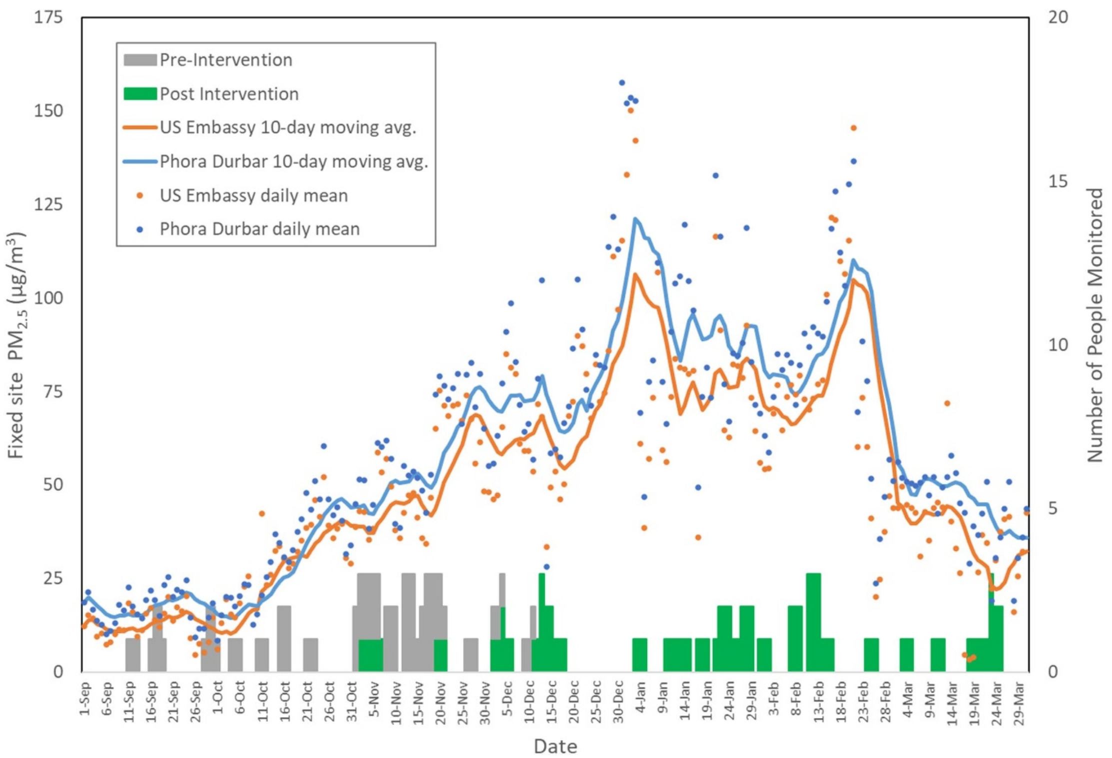

Figure 2. Monitoring data for ambient $PM_{2.5}$ at the US Embassy and the Phora Durbar Recreational Complex, Kathmandu, September 2019 to March 2020. Measurements at the US Embassy fixed-site monitoring station are shown by orange dots (daily mean) and line (10-day moving average), those at Phora Durbar fixed-site monitoring station in blue dots and line; the vertical bars indicate the number of people with personal monitoring (grey for pre-intervention and green for post-intervention).

participants without paired measurements are included in one of the sensitivity analyses of the intervention effect in figure A5.

Among the 21 with paired measurements, 11 (52%) worked full-time at the U.S. Embassy, two (10%) worked part-time at the Embassy, and eight (38%) were family members of diplomats who lived in a dwelling designated for a diplomatic family but did not work at the Embassy. None were smokers nor did they live with anyone who smoked. Dwellings varied greatly in size from 131.3 m^2 to 360.7 m^2. Seven (33%) participants improved the home sealing during the study including one that sealed their windows using plastic sheeting and weatherproofing tape, two that sealed their windows with weatherproofing tape, two that sealed their windows with caulk, one that sealed their windows and backdoor with weatherproofing tape and one that did not specify how they improved their home seal (table 1). Adding high capacity APs helped to increase the HAPC per hour in homes from mean (SD) of 3.2 (1.2) pre-intervention to 5.4 (1.9) post-intervention (table 1).

3.2. Ambient air quality and meteorological conditions

The hourly ambient $PM_{2.5}$ mean (SD) recorded at the closest fixed-site monitor increased from 45.3 (23.9) $\mu g\ m^{-3}$ pre- to 62.5 (32.1) $\mu g\ m^{-3}$ post-intervention (figure 2). The mean (SD) daily temperature and daily rainfall decreased from 15.8 (3.9)°C and 4.8 (9.7) mm pre- to 12.0 (4.5) °C and 3.4 (6.2) mm post-intervention. The mean (SD) daily windspeed increased from 3.0 (0.4) km $hour^{-1}$ pre- to 3.4 (0.7) km $hour^{-1}$ post-intervention.

3.3. Reported change in behaviors and experience

In addition to the greater clean air delivery capacity, the reported *use* of APs in the living room, bedroom and kitchen increased following the intervention (table 1). During each personal monitoring session, participants were asked if they had leaky (draughty) windows and doorways at home. Even though seven participants improved the sealing of their home against outdoor air, the same number of people (15) reported having a leaky home pre- and post-intervention (six of the 21 participants did not answer this question).

3.4. Personal exposure by microenvironment

Table 2 shows summary statistics of personal monitoring $PM_{2.5}$by micro-environment, the corresponding concentrations of ambient $PM_{2.5}$, and time spent in each microenvironment before and after the

Table 2. Summary of $PM_{2.5}$ exposure by microenvironment, confined to 21 participants with both pre- and post-intervention measures.

Pre-Intervention, 21 monitoring sessions								
	Microenvironment							
	Home—Indoors[a]	Home—Cooking	Indoor Other	Embassy	Commute by Car	Outdoors	Missing	Overall
$PM_{2.5}$ Mean (SD), μg/m[c]	7.5 (6.4)	42.9 (36.0)	43.4 (61.6)	0.6 (0.6)	22.5 (11.0)	44.4 (27.0)	n/a	15.2 (10.6)
$PM_{2.5}$ Median (IQR), μg/m[c]	5.4 (3.4, 10.8)	29.5 (22.2, 38.7)	28.5 (11.3, 48.5)	0.8 (0, 1.0)	21.8 (14.5, 30.2)	39.7 (28.9, 47.3)	n/a	5.1 (1.3, 17.6)
Fixed-Site Ambient[b] $PM_{2.5}$ mean (SD), μg/m[c]	41.8 (22.3)	57.8 (27.6)	38.9 (19.7)	54.2 (23.7)	41.4 (21.9)	45.8 (26.4)	42.7 (21.6)	43.8 (30.8)
# Participants in this Microenvironment	21	13	19	11	16	21	19	21
% Time in Location	44%	2%	10%	12%	4%	5%	23%	100%
Time in Microenvironment[c], hrs	439.2 h	23.7 h	100.6 h	116.3 h	41.1 h	45.7 h	241.4 h	1008.0 h
Cumulative exposure (CE), μg/m[c]* hrs	3223.9	953.9	4355.2	86.8	911.3	1875.9	n/a	11 407.1
CE per participant, μg/m[c]* hrs	153.5	73.4	229.2	10.6	57.0	89.3	n/a	522.8
Personal/Ambient Ratio[d]	0.18	0.74	1.12	0.01	0.54	0.97	n/a	0.32
Post-Intervention, 21 monitoring sessions								
	Home—Indoors[a]	Home—Cooking	Indoor Other	Embassy	Commute by Car	Outdoors	Missing	Overall
$PM_{2.5}$ Mean (SD), μg/m[c]	6.4 (8.1)	58.5 (18.4)	38.3 (38.8)	0.2 (0.4)	23.3 (16.5)	38.0 (23.7)	n/a	9.8 (8.7)
$PM_{2.5}$ Median (IQR), μg/m[c]	3.9 (1.4, 9.0)	50.3 (43.3, 75.5)	27.8 (17.7, 47.4)	0.0 (0.0,0.0)	21.4 (14.0, 26.8)	31.7 (19.7, 56.1)	n/a	2.6 (1.1, 12.0)
Fixed-Site Ambient[b] $PM_{2.5}$ Mean (SD), μg/m[c]	64.3 (26.4)	85.9 (57.1)	61.9 (38.3)	48.2 (20.8)	69.0 (32.7)	58.1 (30.9)	67.3 (36.1)	68.9 (40.7)
# Participants in this Microenvironment	21	5	14	17	18	19	11	21
% Time in Location	61%	1%	8%	11%	3%	3%	13%	100%
Time in Microenvironment[c], hrs	613.8 h	7.6 h	77.8 h	110.1 h	30.4 h	33.2 h	135.1	1008.0 h
Cumulative exposure, μg/m[c]* hrs	3191.2	387.4	2021.6	5.8	737.5	1149.7	n/a	8100.9
CE per participant, μg/m[c]* hrs	152.0	18.4	96.3	0.3	35.1	54.7	n/a	367.7
Personal/Ambient Ratio[d]	0.10	0.68	0.62	<0.01	0.34	0.65	n/a	0.16

[a] Home—indoors category does not include periods of cooking which are separated and included under the heading 'home—cooking'.
[b] Ambient (outdoor) data derived from the fixed-site monitor that was closest to each participant's home, either the US Embassy Kathmandu or Phora Durbar monitor.
[c] Time in microenvironment is the total number of hours for all participants in this location during personal monitoring.
[d] Personal/Ambient ratio is the $PM_{2.5}$ mean divided by the fixed-site ambient $PM_{2.5}$ mean, calculated according to each microenvironment and collectively the pre- and post-intervention monitoring periods.

intervention. The $PM_{2.5}$ mean (SD) at home, excluding periods of cooking, decreased from 7.5 (6.4) $\mu g\ m^{-3}$ pre- to 6.4 (8.1) $\mu g\ m^{-3}$ post-intervention ($p = 0.26$, Kruskal–Wallis) while the corresponding ambient $PM_{2.5}$ recorded at the closest fixed-site monitor while participants were at home increased from 41.8 (22.3) $\mu g\ m^{-3}$ pre- to 64.3 (26.4) $\mu g\ m^{-3}$ post-intervention ($p = 0.01$, Kruskal–Wallis). The ratio of the mean personal $PM_{2.5}$ at home (indoor) compared to the fixed-site ambient (outdoor) $PM_{2.5}$ was cut nearly in half from pre- (0.18) to post-intervention (0.10). The overall, time-averaged personal exposure to $PM_{2.5}$ across all

Table 3. Home indoor mean $PM_{2.5}$ concentration by strata of fixed-site outdoor $PM_{2.5}$ and the indoor/outdoor ratio among 21 participants with paired pre- and post-intervention personal monitoring. Analysis completed first using home excluding cooking periods and second with home including cooking periods.

Home Excluding Cooking Periods						
	Outdoor $PM_{2.5}$					
Pre-Intervention	*<25 μg/m³*	*26–50 μg/m³*	*51–75 μg/m³*	*76–100 μg/m³*	*101–200 μg/m³*	*>200 μg/m³*
Indoor (Home), mean (μg/m³)	6.0	5.8	9.7	8.7	13.2	—
Outdoors, mean	15.9	38.9	61.3	84.4	105.7	—
Duration, hrs	127.1	177.2	81.1	37.2	6.2	—
Indoor/Outdoor Ratio	0.38	0.15	0.16	0.10	0.12	
Post-Intervention	*<25 μg/m³*	*26–50 μg/m³*	*51–75 μg/m³*	*76–100 μg/m³*	*101–200 μg/m³*	*>200 μg/m³*
Indoor (Home), mean (μg/m³)	2.0	5.4	6.1	6.7	8.3	5.6
Outdoors, mean (μg/m³)	16.5	41.0	62.1	84.4	123.6	242.3
Duration, hrs	75.7	165.7	163.4	97.4	88.3	4.4
Indoor/Outdoor Ratio	0.12	0.13	0.10	0.08	0.07	0.02
Home Including Cooking Periods						
	Outdoor $PM_{2.5}$					
Pre-Intervention	*<25 μg/m³*	*26–50 μg/m³*	*51–75 μg/m³*	*76–100 μg/m³*	*101–200 μg/m³*	*>200 μg/m³*
Indoor (Home & Cooking), mean (μg/m³)	6.1	6.6	15.1	26.4	18.4	—
Outdoors, mean (μg/m³)	16.0	39.0	60.8	84.7	105.8	—
Duration, hrs	128.4	191.5	90.4	44.6	8.8	—
Indoor/Outdoor Ratio	0.38	0.17	0.25	0.31	0.17	
Post-Intervention	<25 μ g/m³	26–50 μg/m³	51–75 μg/m³	76–100 μg/m³	101–200 μg/m³	>200 μg/m³
Indoor (Home & Cooking), mean (μg/m³)	2.5	5.6	7.0	9.2	8.3	5.6
Outdoors, mean (μg/m³)	16.6	41.2	62.6	84.8	122.6	242.3
Duration, hrs	75.9	166.3	175.3	105.2	95.0	4.4
Indoor/Outdoor Ratio	0.15	0.14	0.11	0.11	0.07	0.02

micro-environments decreased from 15.2 (10.6) $\mu g\ m^{-3}$ pre- to 9.8 (8.7) $\mu g\ m^{-3}$ post-intervention ($p = 0.19$, Kruskal–Wallis), and the ratio of the mean personal $PM_{2.5}$ to the corresponding fixed-site ambient $PM_{2.5}$ concentration decreased from 0.32 pre-intervention to 0.16 post-intervention.

To examine the impact of the intervention on $PM_{2.5}$ concentrations inside the home *including spikes generated during cooking periods*, we analyzed the combined data for home and home-cooking micro-environments, which showed that the mean (SD) $PM_{2.5}$ measured at home *including* periods of cooking was 9.1 (6.9) $\mu g\ m^{-3}$ pre-intervention and 6.8 (8.8) $\mu g\ m^{-3}$ post-intervention ($p = 0.45$, Kruskal–Wallis). The ratio of the personal $PM_{2.5}$ at home including cooking periods to fixed-site ambient $PM_{2.5}$ was reduced by 48% from 0.21 pre-intervention to 0.11 post-intervention.

Participants spent 61% of their recorded time at home post-intervention compared with 44% pre-intervention (results for home environment including cooking periods at home, table 2). Participants spent 3% of their recorded time outdoors post-intervention compared with 5% pre-intervention. Three participants shifted from walking to work pre-intervention to commuting to work by car or taxi during post-intervention monitoring sessions.

Results by stratum of outdoor $PM_{2.5}$ concentrations confirm the pattern of lower ratios of indoor to outdoor $PM_{2.5}$ after intervention both for analyses based on data that excludes periods of cooking and based on data that includes periods of cooking (table 3). In each of the outdoor $PM_{2.5}$ strata examined, the post-intervention I/O ratio was less than the pre-intervention ratio, with the largest pre-post differences in ratio observed in the strata with the lowest outdoor concentration of $PM_{2.5}$ ($\leqslant 25\ \mu g\ m^{-3}$). Home $PM_{2.5}$ mean values and I/O ratios were often higher when cooking periods were included in the analysis compared to the analysis excluding cooking periods. For example, when ambient $PM_{2.5} < 25\ \mu g\ m^{-3}$, the pre-intervention I/O ratio was 0.38 both when excluding home cooking periods and when including home cooking periods, whereas the corresponding post-intervention I/O ratios were 0.12 and 0.15.

Data showing personal monitoring data for both pre- and post-intervention periods are shown in figure 3 for one participant whose intervention included both additional APs and home sealing. The periods

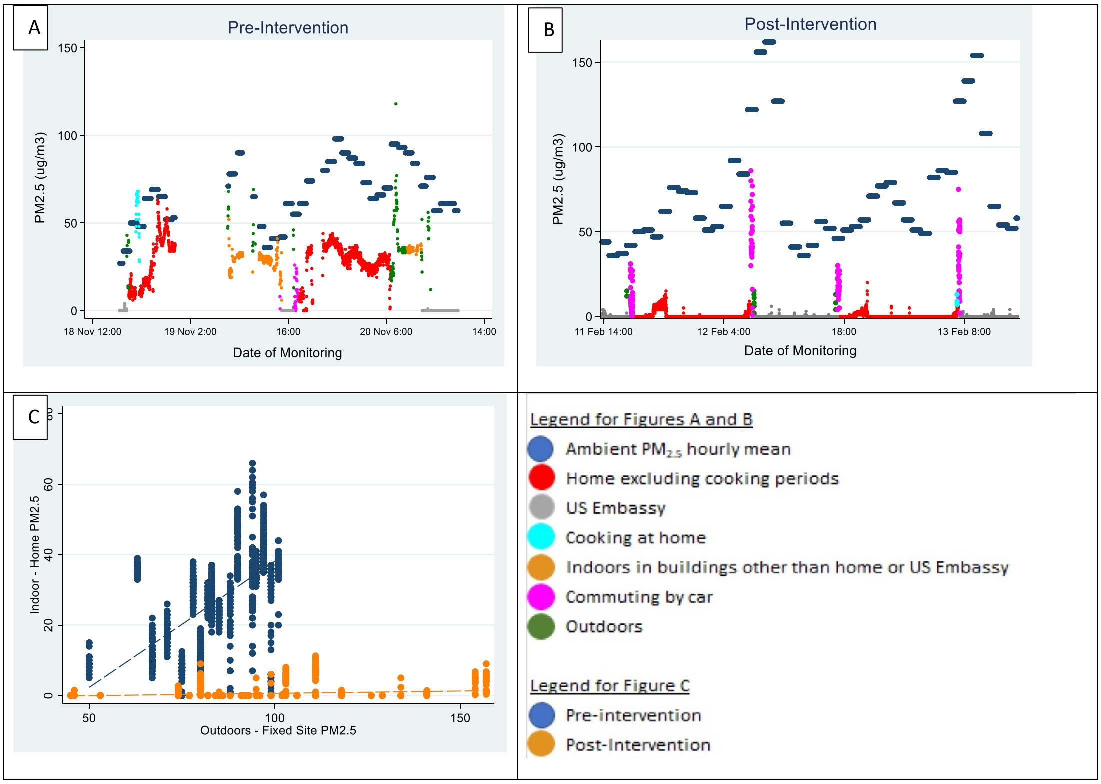

Figure 3. Personal exposure profile for a selected participant and time activity pattern before [A] and after [B] adding two additional room air cleaners and sealing windows and door ways at home for a study participant. Figures A and B include ambient hourly average $PM_{2.5}$ recorded at the US Embassy (navy bars), home indoors excluding cooking periods (red), cooking at home (light blue), indoors in buildings other than home and the US Embassy (orange), commuting by car (magenta), US Embassy (gray), and outdoors (green). [C] Indoor except cooking (I) $PM_{2.5}$ recorded at home compared to corresponding outdoor (O) $PM_{2.5}$ recorded by fixed site ambient monitor for pre-intervention represented in navy and post-intervention represented in orange. The slope of the I/O ratio in each session is represented by a corresponding colored long-dash line.

in the indoor environment excluding cooking are shown as the red trace in 3(A) and (B), and those during home cooking as light blue. Regression of the home (indoor) $PM_{2.5}$ measurements on the corresponding outdoor fixed-monitored $PM_{2.5}$ concentrations, excluding periods of cooking, are shown in figure 3(C) separately for the pre- and post-intervention monitoring periods. For this participant, there was a substantial reduction in the regression slope post-intervention.

3.5. Regression of indoor-on-outdoor $PM_{2.5}$

The results of the (dwelling-specific) indoor-on-outdoor regression slope for all 21 participants with paired pre-post data are shown as a Forest plot in figure 4. Meta-analysis of these regression slopes indicates a summary indoor/outdoor ratio of 0.13 (95% CI 0.09, 0.17) pre-intervention and 0.07 (95% CI 0.04, 0.10) post-intervention (figure 4). The corresponding meta-analytical result of the y-intercepts of these dwelling-by-dwelling regressions was 0.09 (−0.77, 0.94) in the pre-intervention period and 0.69 (95% CI −0.78, 2.16) in the post-intervention period (figure A4). These y-intercepts indicate the theoretical indoor concentrations of $PM_{2.5}$ when outdoor $PM_{2.5}$ is zero.

The relationship between indoor/outdoor ratios and the capacity of the APs to clean the air in each participant's dwelling is shown in figure 5. The regression slope of the indoor/outdoor ratios against AP capacity per m^2 floor area was −0.03 (95% CI −0.14, 0.20), indicating a weakly negative (and not statistically significant) relationship.

3.6. Sensitivity analyses

Sensitivity analyses of the dwelling-by-dwelling regression of indoor-on-outdoor $PM_{2.5}$ gave the following results: (a) restricting analysis to times when the outdoor temperature was < 18 °C (64.4 °F) gave a summary slope (95% CI) of 0.13 (0.09, 0.17) pre-intervention and 0.04 (0.02–0.05) post-intervention; (b) restricting analysis to the 18 participants with at least eight hours of personal monitoring at home both pre- and post-intervention gave a summary slope of 0.13 (0.09, 0.17) pre-intervention and 0.07 (0.04, 0.11) post-intervention; (c) restricting analysis to monitoring sessions with high and/or middle AP settings reported gave a summary slope (95% CI) of 0.11 (0.07, 0.15) pre-intervention and 0.04 (0.02–0.06)

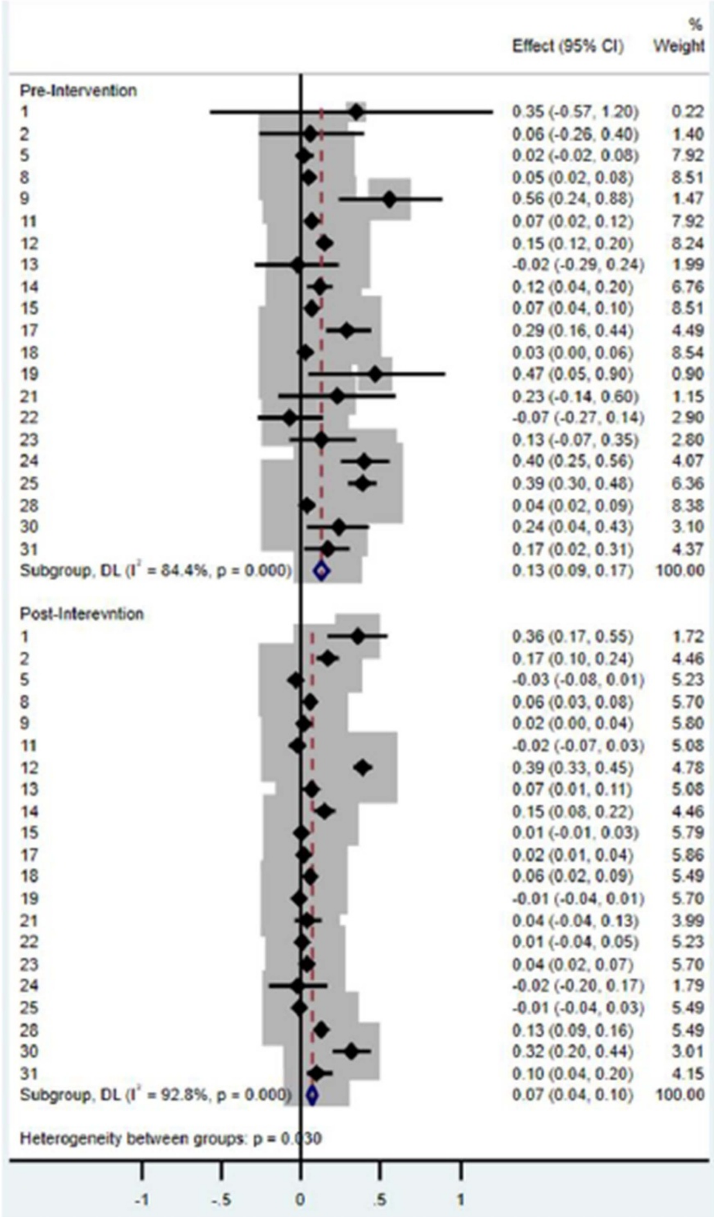

Figure 4. Meta-analysis of the dwelling-specific slopes of the indoor-on-outdoor $PM_{2.5}$ ratio pre- and post-intervention, n = 21.

post-intervention; (d) using data from all participants, including those with unpaired data from pre- or post-intervention periods gave a summary slope of 0.14 (0.10, 0.18) pre-intervention and 0.08 (0.06, 0.11) post-intervention (figure A5). These results therefore broadly support the findings of the main analyses based on the 21 participants with paired monitoring data.

4. Discussion

This study provides rare evidence about the combined effect of the use of high capacity APs and improving dwelling air tightness to limit personal exposure to fine particle pollution in a setting of poorly sealed traditional dwellings and high outdoor $PM_{2.5}$ concentrations. The results suggest that such combined measures achieved a considerable reduction in the indoor/outdoor ratio of $PM_{2.5}$ concentrations—to a very low post-intervention ratio of around 0.07. This indicates a very high degree of protection in the home environment against exposure to $PM_{2.5}$ derived from polluted outdoor air.

A strength of our study was that it was based on simultaneous measurement of indoor and outdoor $PM_{2.5}$ concentrations and the dwelling-by-dwelling derivation of a regression slope for the indoor/outdoor ratio of $PM_{2.5}$. Thus, even though mean outdoor concentrations of $PM_{2.5}$ were different in the

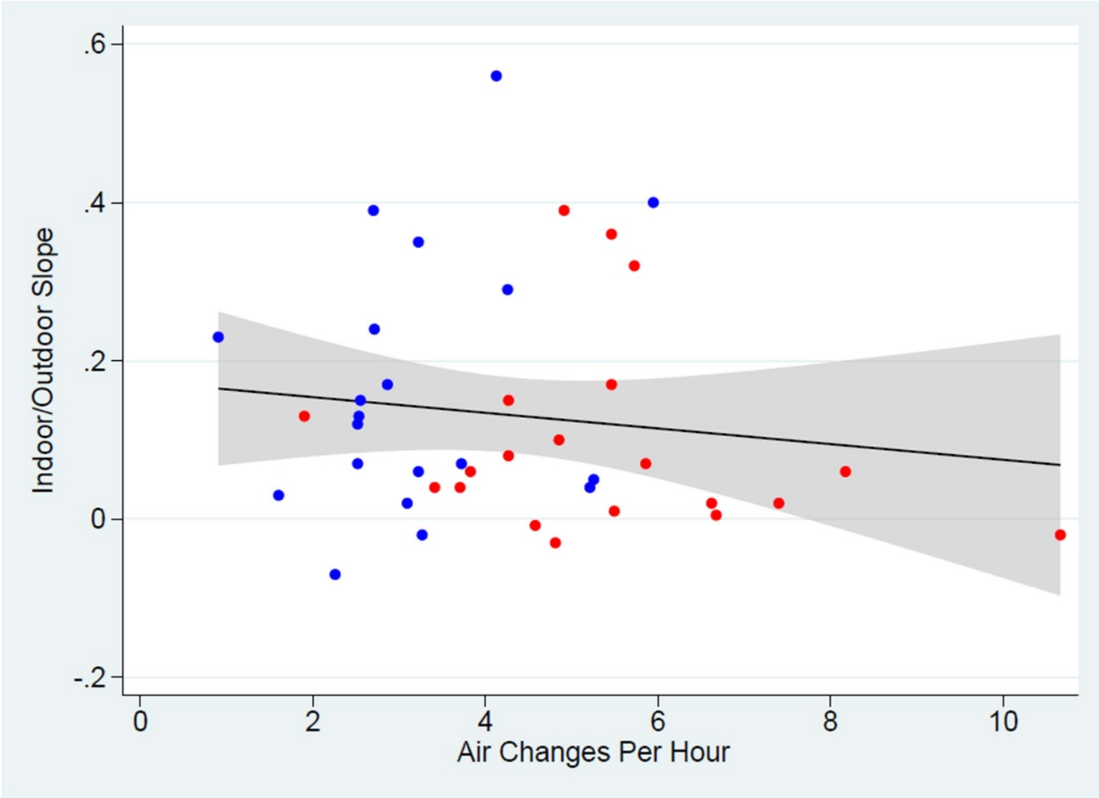

Figure 5. The slope of the regression of indoor-on-outdoor (I/O) $PM_{2.5}$ using home (indoor) $PM_{2.5}$ and corresponding fixed-site ambient (outdoor) $PM_{2.5}$ versus the air changes per hour (ACH) at home among the participants that added air purifiers excluding one participant where home size was not available, $n = 20$. Indoor values are when participants were at home excluding cooking periods. Blue represents measurements before adding high capacity air purifiers (pre-intervention), red represents measurements after adding air purifiers (post-intervention).

pre-intervention and post-intervention periods of monitoring, we believe the regression analyses made a reasonable correction. It would have been better still to have had measurements at similar outdoor concentrations during the pre- and post-intervention periods, but we were limited by the circumstance of the 'natural experiment', with the decision of the Embassy to provide additional home APs in the late autumn of 2019 at a time when outdoor concentrations of $PM_{2.5}$ typically increase (because of increased combustion of fuels in winter). We cannot exclude the possibility that the slightly colder weather of most of the post-intervention period may have had some impact in encouraging householders to keep windows and doors tightly closed, but our sensitivity analysis confined to times when the outdoor temperature was <18 °C (64.4 °F) gave a broadly similar result to our headline finding.

One concern was that the sealing of the home might result in higher indoor concentrations of $PM_{2.5}$ derived from indoor sources, notably cooking, despite the increase in home AP capacity. Moreover, the results used in the main analysis for the I/O ratios deliberately excluded $PM_{2.5}$ data for periods of cooking. During periods of home cooking, concentrations of indoor $PM_{2.5}$ were in fact higher post-intervention than pre-intervention. This might reflect the fact that post-intervention homes were more air-tight, and even with high capacity APs, the clearance of particle pollution generated by cooking was slower, although differences in the outdoor level again complicate interpretation. The net effect of intervention on personal exposure (non-cooking and cooking periods combined) in the home environment appears rather less impressive than the reductions in I/O ratios might suggest. But it should be noted that it is only for these ratios that our analyses fully adjust for the effect of differences in outdoor $PM_{2.5}$ concentrations during the periods of monitoring. It is pertinent that the mean concentration of $PM_{2.5}$ was higher post-intervention during cooking periods at home and commuting by car while remaining microenvironments saw higher $PM_{2.5}$ concentrations pre-intervention. Overall, personal exposure was lower in the post-intervention period despite higher outdoor concentrations. Interpreting the reasoning for the post-intervention increase in $PM_{2.5}$ while outdoors is complex. Participants decreased the amount of time they spent outdoors post-intervention which is expected given that the post-intervention monitoring occurred during the winter (December to March) when the weather was colder and the hours of daylight were shorter than during pre-intervention monitoring (September to November). Fewer participants commuted by foot to work (with close proximity to traffic-related pollution sources) and exercised outdoors at the Phora Durbar Recreational Complex post-intervention than during the pre-intervention period.

Previous studies demonstrated that APs can appreciably reduce the concentration of indoor $PM_{2.5}$ in settings affected by wood smoke. Wheeler *et al* used one high capacity AP in dwellings with smoke generated by burning wood and found a 52% reduction in $PM_{2.5}$ measured at home compared to using a sham filter (Wheeler *et al* 2014). Kajbafzadeh *et al* conducted an intervention study using two APs (one in the living room and one in the bedroom) in dwellings with indoor woodsmoke that were in close proximity to roadway traffic and found a 40% reduction in $PM_{2.5}$ measured at home when APs were used (Kajbafzadeh *et al* 2015). McNamara *et al* examined the impact of using two APs at home (one in the living room and one in the bedroom) among children with asthma and found that indoor $PM_{2.5}$ was reduced by 66% when APs were used (McNamara *et al* 2017). In a small study in seven dwellings in an area with active wildfires, Xiang *et al* found a 48% to 78% reduction in home $PM_{2.5}$ when using one high efficiency particulate air (HEPA) filter per dwelling (Xiang *et al* 2021). Two studies using APs in dwellings in high traffic areas provide further evidence of the use of APs in dwellings with high ambient air pollution levels. Cox *et al* reported the indoor/outdoor ratio decreased by 0.6 after placing one AP in the bedroom (Cox *et al* 2018). A study conducted in United States' public housing dwellings in a highly trafficked area found that particle counts decreased by 21% to 68% in 15 apartments where high efficiency wall mounted APs were used (Padro-Martinez *et al* 2015).

Three intervention studies in China lend further support to the capacity for APs to reduce indoor $PM_{2.5}$ in locations with high outdoor $PM_{2.5}$. In a study of indoor air quality in a variety of buildings in Beijing, Deng *et al* found that using an AP reduced the I/O ratio by 0.35–0.55 (Deng *et al* 2017). Chen *et al* reported a 57% decrease in indoor $PM_{2.5}$ in Shanghai university dormitory rooms when one AP was added (R. Chen *et al* 2015). In a study of children with asthma in Shanghai, indoor $PM_{2.5}$ was reduced by 80% when one AP was used in the bedroom (Barkjohn *et al* 2021). Two studies conducted in Denmark reported 46% to 63% reduction in indoor $PM_{2.5}$ levels after adding two APs in the dwelling (Brauner *et al* 2008, Karottki *et al* 2013). A long-term study in southern California in two communities with high ambient $PM_{2.5}$ reported a 48% decrease in indoor $PM_{2.5}$ following the use of a high efficiency AP (Bennett *et al* 2022). In a controlled laboratory study, Spilak *et al* found that APs reduced $PM_{2.5}$ by 52% with an I/O of 0.35 after 30 min of use (Spilak *et al* 2016).

There are appreciably fewer studies regarding efforts to improve dwelling airtightness and impact of these efforts on indoor air quality. Yang *et al* examined adding low-cost efforts to improve the airtightness of a school in South Korea and found that sealing windows with film and adding padding to window closures helped to reduce air leakage by 37% and indoor fine dust by 22% (Yang *et al* 2022). In a study of more than 200 homes in Colorado, weather stripping and sealing air handling ductwork were indicated as the two most effective measures to reduce the ingress of ambient air (Shrestha *et al* 2019). Current evidence from these studies was based on a single mitigation intervention, either APs or home sealing. Here we provide evidence about the combined effect of the use of high capacity APs and increased home seal in a setting of typically poorly-sealed dwellings and seasonally very high outdoor concentrations.

We identified only one other study of the combined effect of enhanced home air filtration using APs and improved air tightness to reduce indoor $PM_{2.5}$. In a study of four apartment buildings in China with varying levels of air filtration and air tightness, Wang *et al* found that the building with the highest level of filtration and air tightness had the lowest indoor $PM_{2.5}$ (26.0 ± 1.6 $\mu g\ m^{-3}$) and lowest mean I/O ratio (0.19 ± 0.06) (Wang *et al* 2016). Wang's results, although based on just four dwellings, are consistent with the findings of our study. Our estimate of the post-intervention indoor/outdoor ratio was smaller than that of the Wang study, which may reflect the fact that the APs were high capacity (able to filter 14.2 m^3 per hour).

A key strength of our study is that it included more participants/dwellings than many previous studies. The relatively large group of participants meant that we had sufficient monitoring data to be able to implement a dwelling-by-dwelling regression analysis of the indoor-outdoor ratios of $PM_{2.5}$ in the pre- and post-intervention periods, which should have provided robust adjustment for differences in the outdoor $PM_{2.5}$ concentrations during the periods of monitoring. However, it is less easy to make similar adjustments for the spikes of indoor $PM_{2.5}$ concentrations associated with periods of cooking, so our evidence is therefore less clear on the net effect of the intervention on overall home exposure to $PM_{2.5}$ in the context of the large differences in outdoor concentrations. But, overall, the study demonstrated the impact of increasing the air purification capacity, measured by the HAPC per hour, on the $PM_{2.5}$ concentration at home and overall personal exposure even while the outdoor $PM_{2.5}$ concentration increased dramatically during the post-intervention monitoring period.

Several limitations were identified for this study. The original plan for this study was to collect one year of data with study participants wearing personal monitors four times in a calendar year or roughly once every three months. Due to COVID-19 related social distancing measures and other related policies, many study participants moved back to the United States or began teleworking from their home in Kathmandu. Study subjects had a high socio-economic status and access to high quality housing and APs and their results may not be generalizable to the population in Kathmandu but may be relevant to other diplomats, expatriates and other persons who have access to high quality housing and APs for use at home. Participants were not asked to explicitly indicate when cooking started and ended at home. Global positioning system (GPS) latitude and longitude data would have helped with the precision of microenvironment assignments, beyond what was detailed in the time activity log. GPS data collection was planned for this study but there were difficulties with data collection via cellular phone technology in Kathmandu. Home tightness was not directly measured through blower door testing or other methods to quantify improvements in home seal tightness made after the addition of tape, caulk and plastic sheeting to windows and doors. Chen *et al* defined the infiltration factor as the 'equilibrium fraction of ambient particles that penetrates indoors and remains suspended' and the penetration factor as the 'fraction of particles in the infiltration air that passes though the building shell' (Chen and Zhao 2011). The infiltration and penetration factor are figures that would be helpful to better understand the association between indoor and outdoor $PM_{2.5}$ levels as the indoor $PM_{2.5}$ can vary due to indoor sources of $PM_{2.5}$ including cooking, vacuuming, using a wood fireplace and other combustion-related activities in the home. This study focused on the general tendency by dwelling-specific I/O slopes from multiple observations. Further improvement of measurements including the infiltration and/or penetration factors should be considered when developing future personal monitoring studies. A final limitation of the study is that indoor carbon dioxide (CO_2) was not monitored in personal residences during the study. Dwellings with a tight seal may have low level of air changes per hour and, as a result, have high CO_2 levels when people are at home and APs will not remove this excess CO_2. The CO_2 level is important to consider when improving the home tightness and CO_2 measurements in future studies could contribute to the actual air change rate per hour estimations.

The intervention described in this study included the use of high capacity APs in each dwelling. Each AP is able to clean more than twice the area of the prior APs used in Embassy dwellings. The high capacity APs are expensive, more than $500 U.S. each at the time this article was written, and the cost is likely a barrier for adoption in many homes in Nepal. APs with a high CADR are especially helpful for the homes occupied by U.S. diplomats which are typically older and with reported leaky gaps in windows and doorways that allow for the influx of outdoor $PM_{2.5}$ into the homes. Study participants were highly educated and informed about the importance of using APs in dwellings, which may mean their use of APs was better than might be assumed for a typical Nepali resident. The total of the home AP capacity per hour of all APs in participants' homes increased by 69% from 3.2 pre- to 5.4 post-intervention and findings from the study represent what could be achieved when people have access to a very high level of air purification at home. Unfortunately, most people living in highly polluted cities do not have access to as many APs as the study participants. The use of low-cost efforts such as adding caulk or weatherproofing tape to windows and unused exterior doors to improve home tightness to reduce the ingress of outdoor air pollution is something that should be considered when costs are a barrier to purchasing APs. Concern should be taken if home participants cook over an open flame or use a wood or coal stove to heat the home, efforts to improve the home tightness may not be appropriate.

Although the cost of high capacity APs may be a barrier to widespread uptake and use of this technology, options for improving home air filtration and improving home air-tightness should be considered in order to reduce $PM_{2.5}$ in dwellings.

5. Conclusions

Personal monitoring in Kathmandu revealed that adding high capacity APs and improving the seal of the home to the ingress of outdoor air helped to reduce the indoor $PM_{2.5}$ level at home, even at outdoor $PM_{2.5}$ levels more than 10 times the WHO's maximum daily mean level of 15 ug m^{-3}. I/O ratios decreased post-intervention during the winter when outdoor $PM_{2.5}$ was high. These findings confirm that in locations with high outdoor $PM_{2.5}$, it is possible to achieve low home $PM_{2.5}$ levels and very low indoor/outdoor ratios in homes that utilize high capacity APs and enhanced air tightness.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

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Appendix

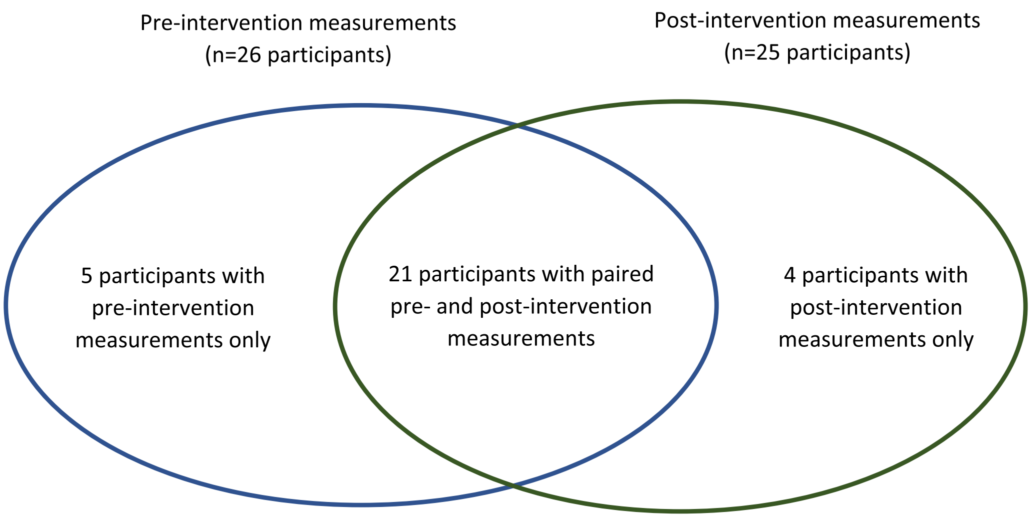

Figure A1. Summary of participants with personal monitoring recording periods.

Figure A2. Home in Kathmandu that is similar to the style, size and construction of study participants' homes.

Figure A3. The APT Minima personal air sampler. The monitor is 7.6 cm x 7 cm x 3.2 cm (*L* x *W* x *H*) and weights 138.9 g.

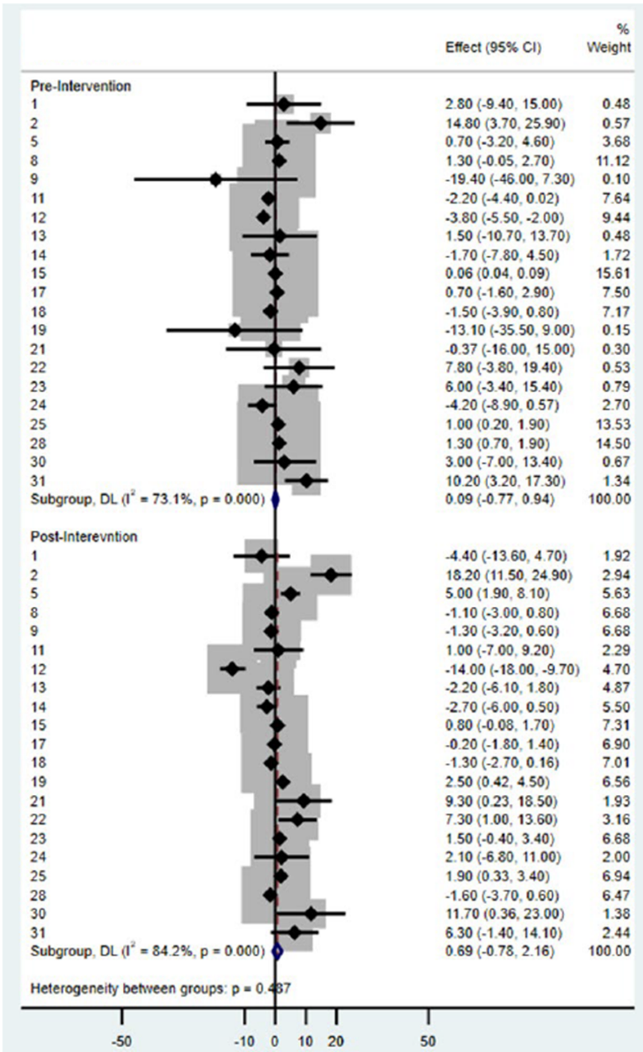

Figure A4. Meta-analysis of the dwelling specific y-intercepts of the indoor/outdoor (I/O) $PM_{2.5}$ ratio pre- and post-intervention, $n = 21$.

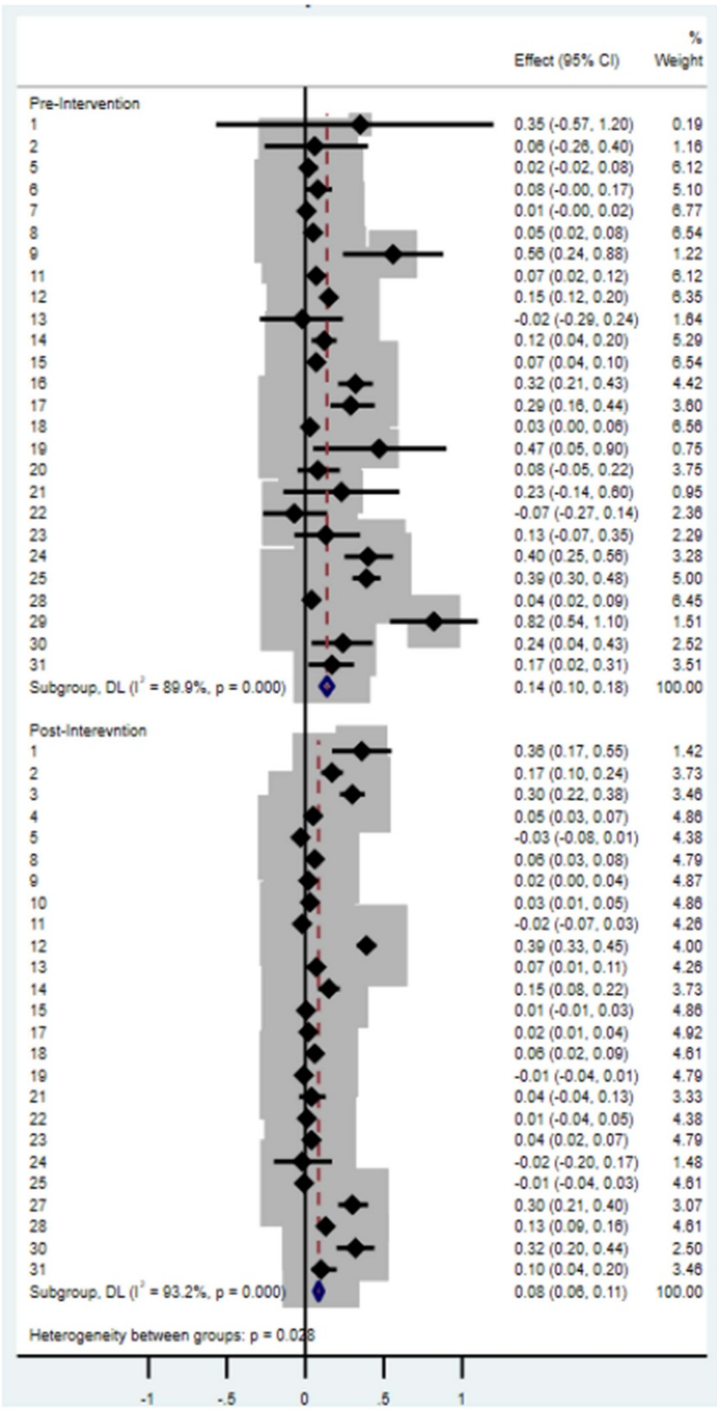

Figure A5. Meta-analysis of the dwelling-specific slopes of the indoor/outdoor (I/O) $PM_{2.5}$ ratio for all study participants, including those with unpaired data from pre- or post-intervention periods.

Table A1. Summary of $PM_{2.5}$ exposure by microenvironment, includes 30 participants with all pre- and post-intervention measures.

Pre-Intervention (31 monitoring sessions)								
	Home—Indoors[a]	Home—Cooking	Indoor Other	Embassy	Commute by Car	Outdoors	Missing	Overall
$PM_{2.5}$ Mean (SD)	7.7 (7.0)	43.9 (33.9)	38.3 (53.6)	0.4 (0.5)	22.9 (11.6)	42.8 (24.6)	n/a	26.4 (32.5)
Ambient $PM_{2.5}$ Mean	44.8 (27.7)	58.3 (36.8)	37.6 (17.6)	55.6 (25.3)	39.9 (19.5)	46.0 (26.0)	43.9 (24.9)	45.7 (26.0)
# Participants in this ME	31	19	26	18	24	30	28	n/a
% Time in Location	49%	2%	9%	12%	3%	4%	21%	100%
Time in Microenvironment (hrs)	727.0 h	26.7 h	127.9 h	174.7 h	50.7 h	63.4 h	331.0 h	1488.0 h
Cumulative exposure	5229.3	1095.6	4395.5	99.9	1221.9	2563.4	n/a	15566.1
Cum. Exposure per person	178.4	35.3	141.7	3.2	39.4	83.1	n/a	488.4
Personal/Ambient Ratio	0.17	0.75	1.02	0.01	0.57	0.93	n/a	0.58
Post-Intervention (33 monitoring sessions)								
	Home—Indoors[a]	Home—Cooking	Indoor Other	*Embassy*	Commute by Car	Outdoors	Missing	Overall
Mean (SD)	8.4 (10.1)	45.5 (19.8)	38.9 (36.5)	0.2 (0.5)	23.3 (14.8)	46.3 (31.2)	n/a	24.9 (28.0)
Ambient $PM_{2.5}$ Mean	70.3 (26.8)	58.3 (47.2)	61.4 (32.6)	51.4 (23.5)	69.4 (31.4)	61.5 (32.5)	77.5 (41.5)	66.9 (33.6)
# Participants in this ME	33	15	23	26	27	28	17	n/a
% Time in Location	63%	2%	9%	9%	3%	4%	11%	100%
Time in Microenvironment (hrs)	997.0 h	29.5 h	135.3 h	138.7 h	49.6 h	57.5 h	179.7 h	1584.0 h
Cumulative exposure	7616.0	1492.3	4476.0	16.1	1334.2	2590.2	n/a	17524.8
Cum. Exposure per person	219.9	45.7	133.4	0.5	35.8	83.6	n/a	518.8
Personal/Ambient Ratio	0.12	0.78	0.63	<0.01	0.34	0.75	n/a	0.37

[a] Home—indoors category does not include periods of cooking which are separated and included under the heading 'home—cooking'.
[b] Ambient data derived from the data reported from the fixed site monitor (US Embassy or Phora Durbar) that was closest to each participants' home during personal monitoring.

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