The effect of enhanced stove design on 'real life' exposure to $PM_{2.5}$ and CO in rural dwellings in Salambu, Nepal

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ABSTRACT

About 3 billion people worldwide, and more than 90% in developing countries, are at risk of developing respiratory and cardiovascular diseases and cancer, due to exposure to household air pollution attributable to the combustion of solid biomass fuels. In Nepal, various types of fuel are used, such as wood, animal dung, and agricultural residues, as a primary source of energy for domestic cooking and heating.

This study examined real-time exposures to particulate matter ($PM_{2.5}$) and carbon monoxide (CO) attributable to cooking in households in a rural environment in the village of Salambu, Nepal, for two daily cooking sessions (morning and evening). The real-time cooking exposure was monitored in houses containing one of two different cook-stove designs. The stoves were either a traditional cook stove (TCS) or an improved cook stove (ICS). The TCS is a simple single pot three stone open fire stove without a chimney, whereas the ICS is designed for improved efficiency and reduced emissions having two pots and a chimney. Kitchen $PM_{2.5}$and CO concentrations were recorded at 10 seconds interval for actual cooking periods and one-minute intervals for periods of around 24 hours under real life conditions.

The real-time mean averages, μ, and standard deviations, σ, of $PM_{2.5}$ and CO concentrations during cooking periods were μ=943.8ug/m^3 (σ=426.5ug/m^3) (13 households) and μ=13.5ppm (σ=5.2ppm) (13 households) respectively, in households using an TCS, and μ=334.6ug/m^3 (σ=228.6ug/m^3) (13 households) and μ=6.5ppm (σ=4.8ppm) (13 households) respectively in the households using an ICS. We conclude that the real-time concentrations of both $PM_{2.5}$and CO are comparatively lower in the households using an ICS than the households using a TCS. However, average $PM_{2.5}$ concentrations still exceed the WHO indoor air quality thresholds for $PM_{2.5}$ and national air quality guidelines. Furthermore, average 24-hour kitchen $PM_{2.5}$ and CO concentrations also exceed the WHO indoor air quality thresholds. Therefore, a significant proportion of the local population of this region remain likely to be at risk of developing diseases related to increased levels of air pollutants irrespective of their ownership of an ICS, although use of the ICS resulted in lower overall exposures and hence the absolute risk may be lower for those using an ICS. Additional measures to reduce exposures are required.

KEYWORDS

Biomass fuel, household air pollution, real time emission exposure, traditional cook stove, improved cook stove

1 INTRODUCTION

Long term exposure to particulate matter (PM) is associated with increased risk of mortality and morbidity (WHO, 2005). Ambient particulate matter exposure has been estimated to be responsible for 4.2 million deaths and 103.1 million disability-adjusted life-years (DALYs), representing 7.6% of total global deaths and 4.2% of global DALYs in 2015 (Cohen, 2017). The major source of particle mass with aerodynamic diameter less than 2.5 µm ($PM_{2.5}$) exposures, particularly in low and middle income countries is the combustion of solid biomass fuels for domestic energy needs (IEA, 2016).

Traditional biomass fuels like fuel-wood, agricultural residue and animal waste have been a primary source of residential energy for cooking and heating in low and middle income countries for many years. In 2014 biomass energy shared 14% of total final energy consumption world-wide, out of which 10.4% had been used for household cooking and heating (REN21, 2016). Approximately half of the world's population, and more than 90% of households in rural parts of developing countries, primarily use solid biomass fuels for daily cooking and heating purposes (Bonjour, et al., 2013). In Nepal, according to WECS, energy from traditional biomass (mainly fuel wood, agricultural residue and dried animal dung) remains the predominant contributor of country's total energy consumption in last nine years supplying 86.9 % in 2000/01 and 87.1% in 2008/09 (WECS, 2010).

Around the world for domestic cooking and household heating, traditional biomass fuels are often combusted indoors in a traditional stove or open fire (Smith, 2006) resulting in incomplete combustion. The incomplete combustion can generate higher concentrations of particulate matter, carbon monoxide (CO) and other health damaging pollutants (Naeher, et al., 2007). Two recent studies conducted in two different district of Nepal have found a daily indoor $PM_{2.5}$ concentration of 1376 µg/m^3 (Chen, et al., 2016) and a 48 hour average $PM_{2.5}$ concentration of 417.6 µg/m^3 (Barington, et al., 2017) in households using biomass fuel in Sarlahi and Janakpur respectively.

It is well understood that reduction in household air pollutants is likely to bring health benefits to all individuals who are dependent on biomass for cooking and heating. Replacement of traditional cook stoves with a more efficient improved cook stove has been found to be an effective solution to reduce indoor air pollution. The *plancha mejorada* cook stove in Guatemala (Albalak, 2001), the *pastari* in Mexico (Cynthia, 2008) , the *justa* stove in Honduras (Clark, 2010) , *three pot* *metallic cook stove* and *2 pot mud cook stove* (Thapa & Shrestha, 2013) in Nepal are some of the developments made around the world in design and dissemination of improved cook stoves to try and reduce emissions. However, most of the work performed to date has measured mean exposures at a fixed point in a room, rather than measuring an individual's exposures using a personal monitoring system.

A number of efforts have been made by Nepali government, NGOs and academic institution to improve the indoor air environment by disseminating improve cook stoves in rural settings in Nepal. Kathmandu University in close collaboration with Dhulikhel hospital had designed and successfully disseminated an improved cook stove (2 pot mud cook stove with chimney) in every household in the rural village of Salambu. The potential effect on real time personal exposure reduction after installation of improved stoves has yet to be monitored. In this paper we monitored personal real-time exposure to $PM_{2.5}$ and CO in households using traditional and improved cook stoves to quantify the effect of stove design on individual exposures and overall emissions.

2 METHODS

2.1 Study area and setting

The field work to monitor real time individual exposure to $PM_{2.5}$ and CO during cooking periods and 24 hour average $PM_{2.5}$ and CO concentrations was conducted in households in Salambu of MajhiFeda VDC, located in Kavrepalanchok district of central development region. MajhiFeda VDC has 624 households with a total population of 2669 (CentralBureauofStatistics, 2012). The emissions from two stove designs was monitored for morning and evening cooking period in 13 households in Salambu. About 99% of households in Salambu use biomass fuel for cooking and heating and most of the households have both traditional cook stoves (TCS) (figure 1 A) and improved cook stoves (ICS) (figure 1 B). Mixed fuel wood along with some agricultural residue, especially used to ignite the fire, is used with Pinus roxburghii (Salla) being the most common fuel wood in use.

2.2 Study Stoves

The real time personal exposure to $PM_{2.5}$ and CO during morning and evening cooking was compared between two stove designs, i) the TCS (figure 1 A) and ii) the ICS (figure 1 B). The TCS is simply an open fire where a cooking pot is normally adjusted in the centre of a triangular configuration of three stones. It has the advantage that fuel can be fed in from all directions which improves cooking speed but at the same time consumes more fuel wood.

The ICS on the other hand, is a fuel efficient two pot mud type stove which was disseminated by KU and installed by a trained local manufacturer. With the chimney attached to the stove design, most of the smoke coming from combustion is vented out of the kitchen area.

(A) (B)

Figure 1 Study stoves. (A) Traditional cook stove (TCS), locally made open fire stove adjusted with three stones. (B) Improved cook stove (ICS), two pot mud stove with chimney, manufactured by a trained local manufacturer.

2.3 Measurements and instruments

2.3.1 Indoor Air Pollution (IAP) meter

The real time personal exposures to $PM_{2.5}$ and CO and 24 hour average $PM_{2.5}$ and CO in the household were monitored using the IAP meter 5000 series (Aprovecho Research center, USA).

Testing Protocol

Real time pollutant concentrations were measured at 10 seconds interval over each cooking period from the moment the fire started till the fire extinguished. The IAP meter was turned on having set in 10 seconds mode and left in a clean environment for at least 10 minutes for background adjustment before it was worn by the subject (cook). Throughout the cooking period from the start of the fire, the wearer had the meter on her back with the adjustable tube attached to the meter box. The tube was adjusted over the left shoulder of the wearer with its inlet positioned on top of her shoulder (figure 2).The data stored in the SD card was downloaded to the computer after the completion of each test and processed through the software provided which was written for Microsoft excel.

A preliminary survey had shown that ≥ 75% households have both ICS and TCS. The study was therefore conducted in 13 randomly selected households where both ICS and TCS were present and in good working condition. The household owners were requested to cook their food using ICS in one day and using TCS on another day and real time pollutant exposures measured. The mean exposure level was calculated and compared for significant differences.

The 24 hour average concentrations were measured at 60 seconds interval over the 24 hour period in 6 randomly selected households from the 13 households, where 3 houses each were tested for ICS and for TCS. The same IAP meter was used and placed on the kitchen wall at approximately 1.5 m above the ground and 1 m from the stove (Fuyuen, 2017) for approximately 24 hours. The household owners were asked to use only ICS or TCS, depending on which stove design was selected for each particular house. It was found that in each household within 24 hours, the stove was used for two periods only, usually for morning cooking and for evening cooking. The mean emission concentration was calculated and compared for any significant difference.

(A)

(B)

Figure 2 Exposure monitoring by using IAP meter. (A) Exposure monitoring with ICS and (B) Exposure monitoring with TCS.

2.4 Data Analysis

Data were analysed using GraphPad Prism software (Version 6, GraphPad Software Inc.). The mean of the arithmetic means of indoor emissions of $PM_{2.5}$ and CO from ICS and TCS were obtained and compared for any significant difference using the t-test.

3 RESULTS

3.1 Time series Pollutant concentrations

Figure 3A and 3B shows an example of real time personalised $PM_{2.5}$ and CO concentrations monitored in the same house for morning cooking with ICS and TCS. The concentration of both $PM_{2.5}$ and CO increased markedly throughout the cooking period with the peak concentrations measured particularly at the start and at the end of cooking. The range of pollutant concentrations, peak concentration and average concentration was different for the two stove designs. The pattern of emissions for both morning and evening cooking for the respective stove designs were similar for all 13 cooking tests performed in different households. The peak $PM_{2.5}$ concentration with ICS in overall 13 tests was ranged from 1078 μg/m^3 to 9337 μg/m^3, whereas with TCS, it ranged from 2115 μg/m^3 to 11399 μg/m^3. Similarly the peak CO concentration ranged from 4.9 ppm to 40.3 ppm with ICS and 14.5 ppm to 88.8 ppm with TCS in overall 13 tests. The average concentration of $PM_{2.5}$ and CO emission with ICS ranged from 109 μg/m^3 to 869 μg/m^3 and 1.1 ppm to 10.8 ppm respectively whereas it ranged from 426 μg/m^3 to 1778 μg/m^3 and 8.1 ppm to 26.8 ppm respectively with TCS.

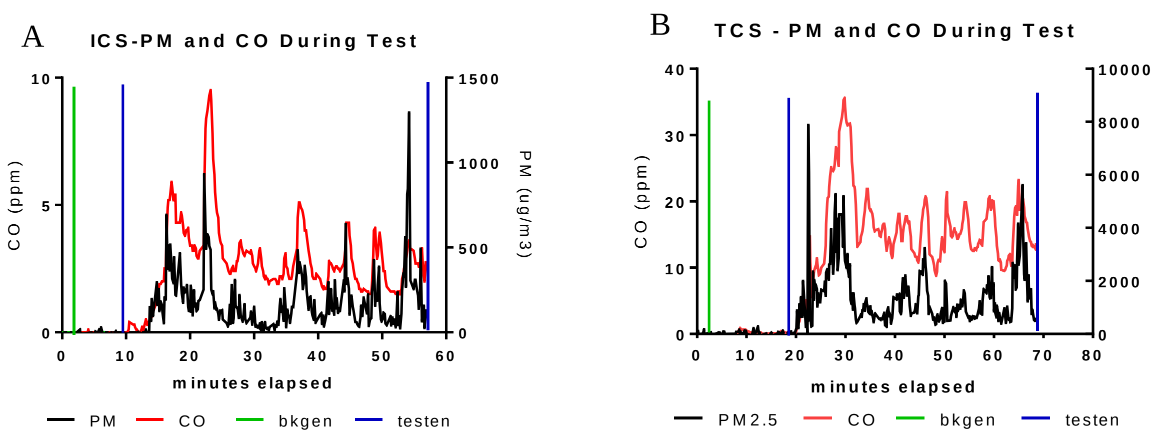

Figure 3 Real time $PM_{2.5}$ and CO measurement: The graph represents a time series emission exposure profile with the (A) ICS and (B) TCS conducted on a same house under identical conditions for morning cooking. Similar graphs were obtained for all other tests. bkgen indicates the start of the period for assessing background levels, and testen the cooking period.

3.2 $PM_{2.5}$ and CO concentrations

The real time exposures to $PM_{2.5}$ and CO were found to be reduced by 65% and 50% respectively in the households when the ICS was used compared with using the TCS. The real-time mean averages (SD) of $PM_{2.5}$ concentrations during cooking periods in the households using ICS and

TCS were 334.6 μg/m^3 (228.6 μg/m^3) and 943.8 μg/m^3 (426.5 μg/m^3) respectively. Similarly, real time CO concentrations in the household using ICS and TCS were 6.5 ppm (4.8 ppm) and 13.5 ppm (5.2 ppm) respectively. The real time emission monitoring was carried out for the two stove designs in each house for 13 houses under the same working condition and using same fuel and compared for significance level by paired t test. The reduction in exposure level was statistically significant ($p<0.001$).

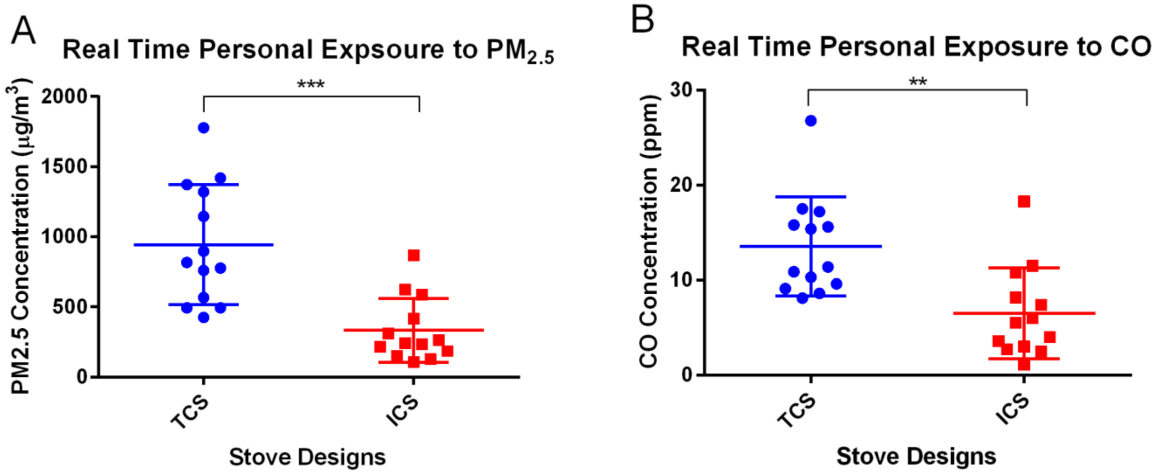

Figure 4 Comparison of real time pollutant exposure during cooking (A) $PM_{2.5}$ and (B) CO in a rural setting from two stove designs. The exposure to pollutants from two stove designs were measured in 13 households and the data represents the mean and standard deviation. ***=$p<0.001$ and **=$p< 0.01$.TCS=Traditional Cook Stove, ICS = Improved Cook Stove.

24 hour average $PM_{2.5}$ and CO concentration in the household using ICS and TCS were also monitored. The mean 24 hour average $PM_{2.5}$ and CO concentrations were significantly lower in the households when using ICS compared to TCS (figure 5). The $PM_{2.5}$ and CO concentrations were found to be reduced from mean (SD) 2820 μg/m^3 (1657 μg/m^3) to 375 μg/m^3 (173 μg/m^3) and 16.3 ppm (4.65 ppm) to 9.4 ppm (3.37 ppm) respectively. The number of households tested for both stove designs was 3 and the reduction was statistically significant ($p<0.05$).

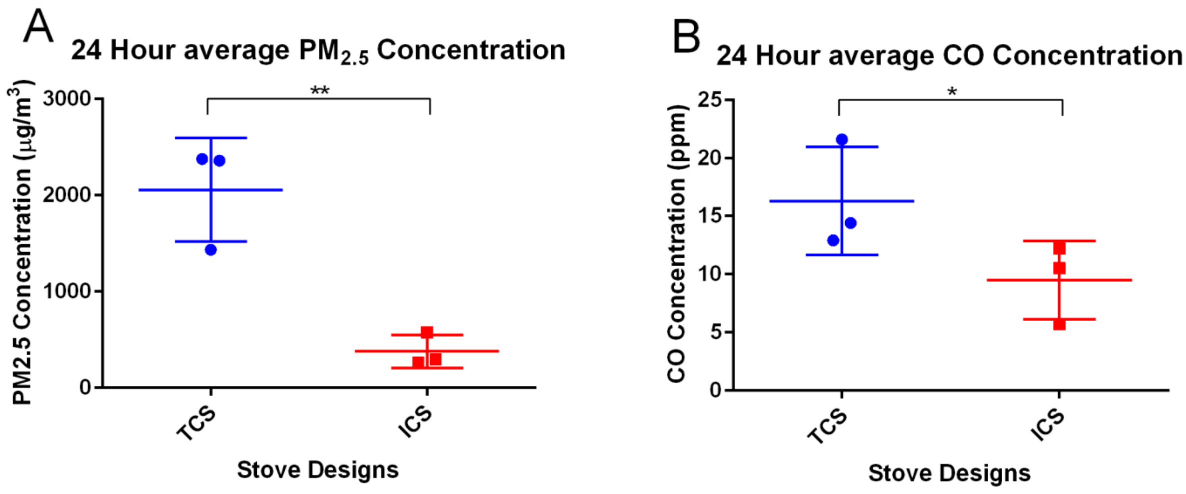

Figure 5 Mean 24-hour average concentration (A) $PM_{2.5}$ and (B) CO in the household using ICS and TCS. Mean average 24 hour concentration of $PM_{2.5}$ and CO in the household using ICS and TCS were measured (3 household for each stove designs). In each test the stove was used two times within 24 hour each for morning and evening cooking.**=$p<0.01$ and *=$p<0.05$. TCS=Traditional cook stove, ICS= Improved cook stove.

Real time exposures to $PM_{2.5}$ and CO were measured in two cooking period, morning cooking and evening cooking in each household for both stove designs. No significant difference in real time pollutant exposure was noted for both stove designs for morning and evening cooking (data not shown).

4 DISCUSSION

The findings from this study show that improved cook stove can significantly reduce the pollutant exposure levels in the household using biomass fuels, though the exposure level still exceed the WHO indoor air quality thresholds. Studies examining personal exposures to pollutants from biomass combustion in a real time cooking period are limited. However, several studies monitoring particulate matter emissions using traditional and improved cook stoves have identified significant reductions in mean PM concentrations of between 39% and 73% with use of improved cook stoves.

We found that daily average $PM_{2.5}$ concentration in homes using TCS is more than 20 times higher than the national indoor 24 hour standards set at 120 μg/m^3 (Nepal, 2009) and more than 100 fold higher than WHO ambient 24 hour average standards set at 25 μg/m^3 (WHO, 2005).Though only a few studies have been done in Nepal, the findings of this study are similar to comparative studies performed in other countries.

In this study, we also measured personal $PM_{2.5}$ and CO exposure for the actual cooking period with TCS and ICS in the same house in the same environment. The fuel used for all tests was the same and moisture content was in a range of 9 to 13%. We saw large reductions in personal exposure with ICS use. However, more studies need to be carried out to see the effects of housing size, position of stove in the kitchen, ventilation and other variables on emissions levels.

Although we found a significant reduction in emissions with ICS, the concentrations seen still exceed national and WHO indoor air quality thresholds, and hence a significant proportion of the local population of this region remain likely to be at risk of developing disease related to increased levels of sir pollutants irrespective of their ownership of an ICS. More health impact studies on reduction of indoor air pollutant exposure after installation of ICS should be carried out, especially given that some of the previous studies have reported no significant health effects of controlling indoor pollutant exposure (Smith, et al., 2011; Guarnieri, et al., 2015; Heinzerling, et al., 2016).

5 CONCLUSIONS

In summary, we have demonstrated that efforts to reduce indoor air pollution through the installation of ICS have been successful. However, the reduced levels of air pollutants seen with ICS use still exceed national and WHO indoor air quality thresholds and hence additional work is required to identify ways to further reduce personal exposures to indoor air pollution.

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