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Integrated Evaluation of Smoke Exposure, Health Impacts and User Satisfaction of an Improved
Cookstove Intervention

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Abstract

Globally, household biomass and coal usage is the most widespread source of indoor air pollution. Traditional biomass burning typically occurs over open-fire cookstoves without chimneys. The public health impact of the high levels of pollutants emitted by these traditional cookstoves is large. It is estimated that indoor air pollution from solid fuels contributes to over 1.6 million premature deaths per year and represents almost 4% of the global burden of disease, disproportionately affecting women and children. To date, no standard questionnaire exists to evaluate respiratory health related to improved cookstove intervention, and few studies evaluating the health effects of indoor air pollution have conducted spirometry or blood pressure measurements in their assessment. Moreover, studies that have evaluated the associations between improved lung function and blood pressure, and cookstove interventions have yielded inconsistent results. Research has shown that improved biomass cookstoves with ventilation systems significantly reduce exposure to indoor air pollution. However, experience in community development has shown that improved technology does not guarantee usage. Through an iterative process, this research sought to design a stove that met both technical criteria of efficiency and emissions and was well accepted by users. The study also evaluated the pulmonary and cardiovascular health effects of an improved cookstove technology on indigenous women living in rural Bolivia.

Based on random home visits and post-intervention questionnaire responses, over 90% of users adopted the improved cookstove technology. Reductions of approximately 80% were seen for 24-hour mean CO and PM levels, as well as mean cooking and peak PM levels one year post-intervention. Yanayo stove implementation resulted in significantly improved (lower) St.

George's Repiratory Quality of Life (SGRQ) Total scores as well as Activity and Impact scores. Overall differences in pre- and post-intervention SGRQ Symptoms scores were not statistically significant. However, a number of individual question scores in this category were significantly lower in women post-implementation of the Yanayo stove. Mean improvements of FEV₁ from 1.95 L (\pm 0.6) to 2.15 L (\pm 0.7), $p < 0.005$ were seen post-intervention. Improvements in FVC and FEV₁/FVC were also seen, but these changes were not significant. Mean systolic blood pressure (SBP) decreased from 114.5 mm Hg (\pm 13) to 109.0 mm Hg (\pm 9), ($p = 0.014$). Decreases in diastolic blood pressure (DBP) were also seen, but these changes were not significant. Decreases in SBP were correlated with 24-hour, mean kitchen PM levels ($\mu\text{g}/\text{m}^3$) ($R = 0.587$, $p = 0.035$). Somewhat stronger correlations were found between reductions in cooking PM concentrations ($\mu\text{g}/\text{m}^3$) and reductions in both SBP ($R = 0.662$, $p = 0.014$) and DBP ($R = 0.658$, $p = 0.014$). This is the first study to observe significant improvements in lung function post implementation of an improved cookstove and the first to find associations between decreases in both 24-hour mean and mean cooking PM levels and decreases in SBP following an improved cookstove intervention.

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List of Abbreviations

ARI	acute respiratory infection
ATS	American Thoracic Society
BP	blood pressure
cm	centimeter
CO	carbon monoxide
COPD	chronic obstructive pulmonary disease
DBP	diastolic blood pressure
EWB-UWS	Engineers Without Borders – University of Washington
FEV ₁	forced expiratory volume in one second
FVC	forced vital capacity
HRQoL	health-related quality of life
kg	kilograms
K-S	Kologmogorov-Smirnov
L	liter
LPG	liquid petroleum gas
M	meter
mm Hg	millimeters mercury
µg/m ³	micrograms per cubic meter
PM	particulate matter
PM _{2.5}	particulate matter less than 2.5 micrometers in diameter
ppm	parts per million
SBP	systolic blood pressure

SD	standard deviation
SGRQ	St. George's Respiratory Questionnaire
TTB	time-to-boil
TWA	Time-weighted-average
UCB	University of California-Berkeley
WBT	water boiling test
WHHs	Women head-of-households
WHO	World Health Organization

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CHAPTER 1

INTRODUCTION

1.1 Motivation and Specific Aims

Globally, household solid fuel usage is the most widespread source of indoor air pollution. Worldwide, almost 3 billion people rely on biomass fuels (wood, crop residues, dung, and charcoal) and coal for their primary domestic energy needs [1, 2]. In many developing countries, biomass accounts for almost one-half of domestic energy and as much as 95% in some lower income countries [1, 3]. Biomass fuels, which are typically burned in open-pit fires or inefficient cookstoves without appropriate ventilation, emit significant amounts of pollutants and known health hazards including particulate matter (PM), carbon monoxide (CO), nitrogen dioxide, formaldehyde, and polycyclic organic matter, including carcinogens such as benzo[a]pyrene [4, 5]. This contributes to levels of exposure in developing countries more than 10 – 20 times greater than World Health Organization (WHO) guidelines [6-8].

The public health impact of the high levels of pollutants emitted by these primitive cookstoves is large. Women and young children, who spend hours a day indoors near the source, are disproportionately affected. Indoor air pollution from combustion of household biomass fuels in developing countries is linked to significant health effects including acute respiratory infections, chronic obstructive pulmonary disease, asthma, otitis media, low birth-weight, cataracts, lung cancer, and tuberculosis [9-12]. It is estimated that global mortality due to indoor air pollution from solid fuels contributes to 1.6 million premature deaths per year and represents

almost 4% of the global burden of disease disproportionately affecting women and children [10, 13].

To date, no standard questionnaire exists to evaluate respiratory health related to improved cookstove intervention. The St. George's Respiratory Questionnaire (SGRQ) is a well-established tool for quantifying health status in chronic pulmonary diseases and has been shown to correlate well with symptoms and disability due to disease [14]. It encompasses a broad range of respiratory symptoms including both asthma and chronic obstructive pulmonary disease (COPD) and has previously been used to measure health-related quality of life (HRQoL) for industrial diseases such as pneumoconiosis [15]. This study represents the first use of the SGRQ in improved cookstove interventions where pre-implementation indoor air pollution is several orders of magnitude higher than what is normally experienced in developed countries. While most questionnaires on respiratory health such as the commonly used Medical Research Council Questionnaire (MRCQ) focus on identifying symptoms only, the SGRQ measures the overall HRQoL [14]. The SGRQ allows researchers to determine the impact of disease on a subject's daily life and represents a valuable evaluation tool to assess the benefits of improved cookstove interventions.

It has been reported that the use of biomass fuels, including wood, have been associated with lung function impairment [16, 17]. However, few studies evaluating the health effects of indoor air pollution have conducted spirometry measurements in their assessment [17-26], and fewer still have conducted intervention studies involving high elevation populations [25, 26]. Moreover, studies that have evaluated the associations between improved lung function and cookstove interventions have yielded inconsistent results [17, 18, 22, 23, 25, 26] or have been

unable to demonstrate improvements in lung function from improved cookstoves [17, 18, 25, 26].

Fine particulates and secondhand tobacco smoke are associated with cardiovascular morbidity and mortality [27-32] including increased risk of myocardial infarction and stroke [33-35]. PM-induced increases in blood pressure (BP) have been one of the mechanisms proposed for these cardiovascular effects [36]. Several observational studies [37-48] and controlled human exposures [49-51] suggest that ambient air pollution could raise blood pressure; however, other observational studies have not replicated these findings [52-57]. However, the World Health Organization (WHO) Comparative Risk assessment attributes only respiratory diseases to the household use of solid fuels; cardiovascular outcomes were not attributed to solid fuel use [58].

Research has shown that improved biomass cookstoves with ventilation systems significantly reduce exposure to indoor air pollution [59-61]. However, experience in community development has shown that improved technology does not guarantee usage. Throughout the world improved stoves sit idle, as households are reluctant to adopt technology that it is difficult to install or maintain, less convenient, or offers fewer options than traditional methods [62]. Technical advances in cookstoves are crucial for the developing world for economic, environmental and health reasons. Overuse of biomass fuels depletes resources, both financial and physical, degrades local environments, and creates indoor air pollution problems that have wide-ranging, deleterious health effects.

As part of a student chapter of Engineers Without Borders (EWB-UWS) at the University of Washington, improved wood-burning, cookstoves with ventilation, herein called the ‘Yanayo’ cookstove, were installed in several small, rural Bolivian communities from 2007-2010. Through

an iterative process, this research sought to design a stove that met both technical criteria of efficiency and emissions and was well accepted by users. Women heads-of-household (WHH) subjects were evaluated pre-and post-intervention to assess the association between the Yanayo cookstoves and their health status. My two hypotheses are as follows:

1. An efficient stove can be designed that meets user needs and preferences as well as technical criteria of efficiency and emissions. Participant input in establishing stove design criteria, an education program and consistent follow-up improves stove adoption rates compared to other intervention studies.
2. Use of an improved cookstove results in significant improvements in pulmonary and cardiovascular health measures in women head-of-households in rural, Quechua-speaking villages in Bolivia.

The **goal** of this project was to design a cookstove that satisfied user needs while improving quality of life, including pulmonary and cardiovascular health.

To address this goal, the following specific aims were set:

Specific Aim 1:

Optimize the existing Yanayo cookstove design to maximize user satisfaction without compromising fuel efficiency or indoor exposure levels

One aim of this research was to maximize user satisfaction of the Yanayo cookstove while still delivering a stove that significantly reduces woodsmoke exposure and boils as quickly as the open-pit cookstoves currently used throughout the region. Experience in community development has shown that improved technology does not guarantee usage. Households are

reluctant to adopt technology that it is difficult to install or maintain, less convenient, or offers fewer options than traditional methods. Through an iterative process using water-boiling tests on design modifications and user surveys and observations, this research sought to create the most efficient, least polluting stove possible that still was accepted by the users. This testing was performed within the communities so that factors which affect the use or non-use of the design could be quickly identified. This general method may lead to new stove design and implementation techniques while ensuring long-term user acceptance.

Specific Aim 2:

Assess the functionality of the Yanayo cookstove by performing pre- and one year post-intervention indoor air quality and exposure testing

In this study, passive diffusion carbon monoxide (CO) tubes and UCB particle monitors, a light-scattering tool used to measure particulate matter < 2.5 microns in diameter (PM_{2.5}), were used. CO tubes have been used as a tracer for assessing exposures to PM in similar settings [63]. They are easy to use and economical and serve as a good proxy for traditional PM filter sampling. The UCB particle monitor is a low-cost particle monitor, developed by the University of California-Berkeley, for measurement of micrometer and sub-micrometer aerosols [64].

Specific Aim 3:

Evaluate the effects of cookstove intervention on the health of women head-of-households

To support the exposure measurements, traditional pre- and post-intervention health evaluations of the community were performed concurrently. These evaluations consist of

spirometry measurements to assess lung function and blood pressure measurements. Finally, a health-related quality of life (HRQoL) questionnaire was administered to qualitatively assess the health impacts associated with woodsmoke exposure in the community. This research sought to assess whether successful cookstove interventions that high adoption rates can lead to significant improvements in health-related quality of life and pulmonary and cardiovascular health.

1.2 Background

1.2.1 Yanayo Cookstove

The Yanayo cookstove, designed by me and other members of EWB-UWS, was built with recognized engineering principles based on the Rocket Stove fundamentals developed by Dr. Larry Winiarski [65, 66]. In addition, it was a very user-driven design. Maximum usability was ensured by studying the cooking practices in the region where implementation would take place and through feedback from community members. After several redesigns, the final stove design was a compromise of engineering efficiency and usability. The stove could be the greatest and most efficient stove in the world, however if the community refused or decided not to use the stove, the stove would have an efficiency of 0%. The two design requirements that were never compromised were: 1) minimizing smoke released in the home; and, 2) providing a stove that boils equally as fast as the traditional cookstoves. If the stove requires the use of more time, there is less of an incentive to adopt the new stoves. Figure 1.1, below is a drawing of the final stove design. More details on the design principles and stove specifications can be found in Appendix A.

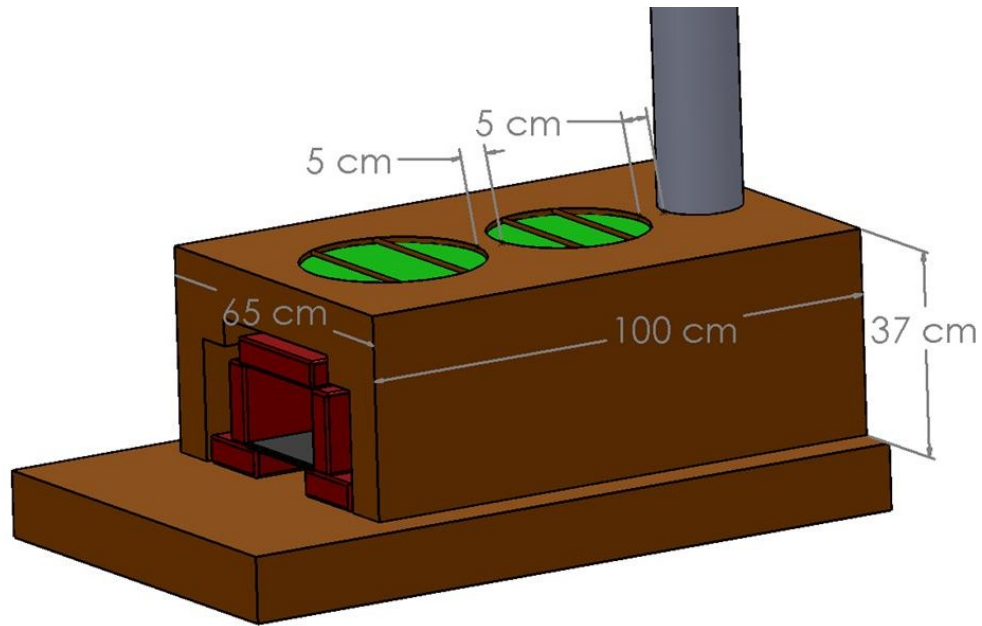


Figure 1.1. Final Yanayo cookstove design

1.2.2 Exposure Sampling

1.2.2a Carbon monoxide passive diffusion sampling correlated to PM

To date, numerous studies have assessed personal CO exposure and kitchen levels of CO due to burning of biomass fuels from open-pit cookstoves [39, 59, 67-70]. Naeher et al. (2001) demonstrated that CO is a good proxy for PM_{2.5} as an indicator for pollutant risks from fuelwood combustion. Because CO passive diffusion sampling tubes are economical and easy to use, they are a good surrogate for the more cumbersome, expensive PM sampling pumps that are commonly utilized in such settings.

1.2.2b UCB Particulate matter monitor used as a tool to measure indoor air quality in developing countries.

Recently the University of California Berkeley developed and calibrated a small, inexpensive, datalogging particle monitor called the UCB monitor [64, 71, 72]. This particle monitor was designed principally to measure indoor air pollution in developing countries for measurements of PM_{2.5} at a reasonable price. This method provides several advantages to the more cumbersome, labor-intensive, and relatively expensive methods commonly used to measure PM_{2.5} such as pumps, filters and size selective devices.

1.2.3 Health Testing Techniques

1.2.3a Health related quality of life questionnaire St. George's Respiratory Questionnaire

The St. George's Respiratory Questionnaire is a well-established method to quantify health status in chronic pulmonary diseases and has been shown to correlate well with symptoms and disability due to disease [14]. It encompasses a broad range of respiratory diseases including both asthma and COPD and has previously been used to measure health-related quality of life (HRQoL) for industrial diseases such as pneumoconiosis [15]. This study represents the first use of the SGRQ in improved cookstove interventions where indoor air pollution is several orders of magnitude higher than what is normally experienced in developed countries. While most questionnaires on respiratory health, such as the commonly used Medical Research Council Questionnaire focus only identifying symptoms, the SGRQ measures the overall HRQoL [14]. The SGRQ allows researchers to determine the impact of disease on a subject's daily life and is a valuable evaluation tool to assess the benefits of improved cookstove interventions. To date, no

standard questionnaire exists to evaluate respiratory health related to improved cookstove intervention.

1.2.3b Lung function: Spirometry testing

Indoor air pollution from biofuels has long been associated with increased respiratory diseases, especially acute lower respiratory infections in children and chronic obstructive pulmonary disease in adults [2, 8, 9, 73-75]. Although numerous studies have evaluated the associations between improved lung function and cookstove interventions, results have been inconsistent [17, 18, 22, 23, 25, 26]. In a small randomized cross-sectional study, Rinne et al. evaluated lung function in women and children using both liquid petroleum gas and biomass fuels in a high altitude region in Ecuador [18]. Their study of women with a mean age of 45 found no difference in lung function between LPG users and biomass users. They did, however, find higher than expected lung function values, as did Romieu and colleagues who studied the respiratory status of young women in Mexico [25]. Although Romieu and colleagues did not see any increase in lung function post-intervention; they did observe significantly less FEV₁ decline among the improved cookstove users than among the open fire users after one year. The lack of improvement in lung function may reflect low usage of the improved cookstove, as only 50% of the women in the intervention group reported using the improved cookstove, and many continued to use both types of stoves, compared to our study which had a greater than 90% compliance rate. Smith-Siversten et al. studied young Guatemalan women in a randomized intervention trial to evaluate the respiratory health effects of introducing an improved stove called the plancha. Their results indicated that the plancha had no statistically significant effects on lung function within the 18-month follow-up period. Finally, Regalado et al. conducted a cross-sectional survey of women in a high-elevation, rural village near Mexico City. The authors

found no significant differences in FEV₁ or FVC in biomass users compared to LPG users, but did see a significantly lower FEV₁/FVC ratio in women cooking with wood stoves compared to those cooking with gas stoves.

1.2.3c. Cardiovascular effects: blood pressure testing

Elevated blood pressure (BP) increases risks of cardiovascular morbidity and mortality. While results have been inconsistent, several observational studies have shown positive associations between air pollutants and BP [42, 48, 76]. Few studies, however, have evaluated the cardiovascular effects of chronic exposure to indoor biomass burning. Baumgartner et al. (2011) studied the effects of biomass burning on blood pressure in adult women in rural China. The authors observed positive associations between personal PM_{2.5} exposure and post-exposure measurements of systolic blood pressure (SBP) and diastolic blood pressure (DBP). This relationship was most apparent among women > 50 years of age where a 1-log- $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} exposure was associated with 4.1 mm Hg higher SBP and 1.8 mm Hg higher DBP. Clark et al. conducted a baseline evaluation of 124 women using traditional cookstoves in Guatemala. Although their results were not statistically significant, a 1.78 mm Hg increase in systolic blood pressure was associated with an increase in 48-hour average indoor CO concentrations of 24 ppm. This relationship was stronger among obese patients in whom an 8.51 mm Hg increase in SBP per 24 ppm increase in 48-hour average CO concentrations was observed. McCracken and colleagues, the only study to evaluate the differences in users with traditional cookstoves compared to those using improved cookstoves, found, in their between-group comparison study, that use of improved cookstoves was associated with 3.7 mm Hg lower SBP ($p = 0.10$) and 3.0 mm Hg lower DBP ($p = 0.02$) relative to a traditional open-fire control group.

1.2.4 Stove optimization tests

1.2.4a Efficiency tests (water boiling test)

The water boiling test (WBT) is a rough model of the cooking process that is intended to understand how well energy is transferred from the fuel to the cooking pot for a particular stove [77]. It is a standardized, replicable test that can be used on almost any stove throughout the world that measures the stove's performance at high and low power outputs.

1.2.4b Stove Questionnaire

The stove questionnaire evaluates the user's needs and desires. The questionnaire is used to help the designer modify the stove to best suit the user's needs. It is essential that the user likes and understands how to use the stove. Without user input, a great, thermally efficient stove could be designed, but may not be used. In designing a stove, this is the most important factor.

1.3 Dissertation Framework

The following chapters are a culmination of several years of research I conducted in Tuquiza, Bolivia. Chapter 2 entitled, "Assessing User Satisfaction and Adoption Rates" evaluates the key issues that cause a user to adopt (or not adopt) an improved cookstove technology. The chapter details the iterative process I took to ensure high adoption rates. Results of Water Boiling Tests and questionnaires will be presented.

Chapters three, four, and five are stand-alone journal articles submitted for publication or in the final stages of preparation. Chapter three, entitled "The association between improved stove implementation and respiratory health-related quality of life in a small intervention study

in Bolivia” uses the St. George’s Respiratory Questionnaire to evaluate improvements in respiratory-related quality of life. Chapter four, entitled “FEV₁ changes in Indigenous Bolivian Women Head-of-Households Associated with an Improved Cookstove Intervention” presents findings on the changes in FEV₁ in WHHs associated with implementation of the Yanayo Cookstove. Chapter five, entitled “Systolic Blood Pressure Changes in Indigenous Bolivian Women Associated with an Improved Cookstove Intervention” presents findings on the association between reductions in particulate matter due to implementation of the Yanayo cookstove and changes in systolic blood pressure.

Finally, Chapter six is a summary of this work and highlights my findings. This chapter discusses the strengths and weaknesses of my study. A section within Chapter 6 is also devoted to suggested future research.

CHAPTER 2

INTEGRATED EVALUATION OF USER SATISFACTION AND STOVE USAGE

2.1 Introduction

Nearly half of the world's population relies on solid fuels, such as biomass, coal or dung, for their cooking needs [78]. Indoor air pollution emitted by burning solid fuels within the home has deleterious health effects which disproportionately affect women and children [58]. In addition to adverse health effects, negative social impacts can also be associated with using traditional biomass stoves. For example, inefficient cookstoves require more time to gather fuel which can divert time from other activities. Burning of biomass in inefficient cookstoves increases ambient air pollution [79] and also damages the environment. Unsustainable harvesting of wood degrades local forests [80] and the byproducts of incomplete combustion affect the climate by emitting black carbon [81] and other pollutants, such as methane and carbon monoxide [82] into the atmosphere.

Despite evidence that improved cookstoves can affect human health and the environment, efforts to promote these technologies have been hindered by difficulties surrounding their dissemination and implementation. Experience in community development has shown that improved technology does not guarantee usage. Households are reluctant to adopt technology that it is difficult to install or maintain, less convenient, or offers fewer options than traditional methods. Currently, there is a small body of evidence suggesting that potential consumers do not invest in or maintain environmental health technologies (including improved cookstoves)

because they do not understand the potential benefits of the modification. Moreover, in many cases, consumers are unwilling or unable to finance such technologies [83]. One study suggests that implementation and dissemination challenges may be due to ineffective financing, poor distribution channels, or insufficient social marketing [84]. More generally, challenges associated with adopting improved cookstoves may be because the design is unsuitable for local customs. A simple example would be providing an improved cookstove to rural Guatemala that did not have a griddle, which is used to cook tortillas, a staple of their diet. [85].

With the recent formation of the Global Alliance for Clean Cookstoves, which aims to have 100 million homes adopt clean cookstoves by 2020 [86], more studies showing practice-based evidence of adoption is needed to realize these goals [87, 88]. In an attempt to ensure satisfaction with and usage of the stove, this research used an iterative process involving user-guided modifications to the original Yanayo cookstove, water-boiling tests, user surveys, observations, education, and random house visits. This testing was performed within the communities so that factors which affect the use or non-use of the design could be quickly identified. The general method described here will hopefully lead to new stove design and implementation practices that ensure long-term user acceptance.

2.2 Methods

This study was conducted in the communities of Yanayo Grande and Tuquiza, Bolivia from July 2009 to October 2009 and from July 2010 to November 2010. These neighboring villages lie in the sub-Andean valley region of Bolivia in the northern region of the department of Potosí. The altitude of these villages range from 2,800 m to 3,350 m. Inhabitants of Yanayo Grande and Tuquiza are of Quechua-descent, and share the same general socioeconomic status and education level. All of the inhabitants use the same fuel source and use open-pit fires cookstoves to prepare their meals. Additionally, residents utilize similar cooking practices and prepare similar foods.

This research was conducted in two stages.

2.2.1 Stage 1:

In 2007, the University of Washington chapter of Engineers Without Borders (EWB-UWS) implemented an improved cookstove design, called the Yanayo cookstove, in 22 households in the village of Yanayo Grande. The cookstove, constructed by members of EWB-UWS, was based on the principles of the Rocket Stove fundamentals developed by Dr. Larry Winiarski [65, 66]. In 2008, EWB-UWS returned to Yanayo Grande to monitor and evaluate the use and acceptance of the Yanayo stove and to undertake another improved cookstove implementation project within the region. Based on observations and questionnaires given to the users, it was apparent that the intervention had not been highly successful, as there was only a 45% adoption rate. According to questionnaire results, the users' main complaints were the stove was too tall, the entry of the combustion chamber was too small for large pieces of wood, the

soot emitted from the cookstove during lighting blackened the walls and the ceiling, and the back pot took too long to boil.

Prior to the initiation of health studies, a research technician and an additional expert stove builder were recruited to work closely with EWB-UWS on all aspects of stove implementation, follow-up and design testing. Both the technician and the stove builder were from a neighboring village, spoke both Quechua and Spanish, and each owned and operated an improved cookstove. Both team members were trusted and well-liked within the region and had extensive experience working with EWB-UWS.

Working with the cookstove technician, we redesigned the cookstove using an iterative process to meet the needs of the community members. The aim of this research was to maximize user satisfaction with the Yanayo cookstove while also minimizing woodsmoke exposure and maximizing fuel efficiency. To optimize the stove performance, a combination of stove efficiency testing and user input was needed. Modifications were made on the stove and then tested using a stove efficiency test called the water boiling test (WBT) (described below). If the modified stove performed better than the current Yanayo stove, the stove was evaluated for its 'usability'. To assess the usability, a questionnaire was given. Observations of the users cooking with the stove were also incorporated into the design process. This process was conducted for three years, until finally a 'best design' was chosen. Subsequent health and exposure studies only involved the final Yanayo cookstove design.

After a final design was chosen, the Yanayo cookstove was implemented in the community of Tuquiza. Three repeated WBTs were then completed on three traditional stoves and twelve Yanayo stoves. The WBT is a series of three sub-tests which are performed in

immediate succession. To ensure consistency, the research technician was in charge of lighting the stove and keeping the fire stoked and lit. She was accompanied by two researchers at all times. One researcher was in charge of recording the data and the other was in charge of weighing the wood and water as well as keeping track of time and water temperature. The testing procedures are described below:

Cold start

The first test is called the “cold start time-to-boil” test. For this test, the stove must be “cold”. To be considered cold, a stove cannot have been used in the previous 24 hours and the firebox must be at room temperature. Before starting the test, approximately four kilograms (kg) of dried wood (defined as wood that has been drying for two weeks) is weighed to the gram. The recommended amount of water is 5 liters but this was modified to 3 liters to minimize use of precious firewood in the region. The water is weighed and its temperature is taken. The stove is lit and the time-to-boil is monitored with a stop watch and a wall clock. After one pot of water begins to boil, the temperature in the second pot is noted. Both pots are weighed to find the change in water weight. The remaining wood is then immediately weighed. The charcoal present in the firebox is removed from the firebox and then weighed. All of these data are input into a spreadsheet available from the Household Energy and Health Program, Shell Corporation, which calculates stove efficiency [77].

Warm start

The “warm start time-to-boil” test is performed immediately after the cold start test. The test is performed in the exact same matter as the cold start test except the charcoal is not weighed after removal.

Simmer test

The simmer test, performed immediately after the warm start test, is performed just below boiling to determine the amount of fuel required to simmer three liters of water for 45 minutes. This test simulates the long cooking periods required to cook hominy, a local staple.

2.2.2 Stage 2:

The second stage of this research assessed the factors that influence the use and acceptance of the Yanayo cookstove.

Before the improved cookstove intervention, a stove-related questionnaire was given to all participants. This questionnaire focused on features a stove must possess in order to satisfy user needs. During implementation, each user was required to work with the expert stove builder in constructing her new stove. This was to ensure that the women could fix their stoves if problems were to arise. Directly after implementation, educational sessions on the health impacts of the improved cookstove and stove workshops were given in the community by the technician and another local leader. Both the WHHs and their spouses and other stove users living in the household were required to attend. These workshops were culturally appropriate (i.e. they were given to the technician and leader, and then they made modifications based on understanding-level and cultural appropriateness). The community leader showed pictures of healthy lungs and unhealthy lungs. They discussed the impacts of cooking in high levels of indoor air pollution for an entire lifetime and discussed the impacts that an improved cookstove could have on the health of their children. These workshops were given in both Spanish and Quechua. There was a long question-and-answer session held at the end of each workshop.

After the workshops, the technician visited each household to ensure their stove was working properly. If the stove was not working properly, she would fix the stove and return a second time. The technician also instructed the user to properly light and maintain the cookstove. She would stay with the user until she was competent in using her new stove. During the year following the intervention, the research technician made between four to six random visits to each household to monitor whether the stove was being used and to check for any problems the stove might be having. She recorded all data and observations. In the rare event that the stove wasn't functioning properly, the technician would work with the user to fix her stove.

One year after intervention, a final visit was made to each household at which time another questionnaire was given to the user. This questionnaire focused on user satisfaction levels. The questionnaire is shown below in Table 2.1.

Table 2.1 Post-intervention questionnaire regarding user satisfaction of the Yanayo cookstove

	Question	Response
1	What factors influence stove usage the most (please circle)?	Time-to-boil Smoke emitted Backdraft Amount of wood used Difficulty in starting a fire Difficulty in using the stove Other reason?
2	Does your new stove use more wood or less wood than your old stove?	More Less
3	Does your new stove boil faster or slower than your old stove?	Faster Slower
4	Do your pots boil at the same time? If yes, which pot boils faster?	Front Back
5	Do you have more or less smoke in your new kitchen compared to your old kitchen?	More Less Same
6	Do you experience backdraft?	Yes Sometimes Only when windy Never
7	How would you rate your new stove compared to your old stove	Better Same Worse

	Question	Response
8	List any complaints you have regarding your stove	
9	How satisfied are you with your new stove?	Highly satisfied Moderately satisfied Unsatisfied
10	Has your new cookstove provided any other benefits?	
11	Do you have a problem with the stove that you would like us to fix?	

Statistical analysis on the stove efficiency testing was conducted using non-paired t-tests.

2.3 Results

2.3.1 Final Design

To address users' complaints, alterations to the exterior of the cookstove, firebox, internal channels, pot placements, and chimney were all made. First the stove was lowered by 10 cm and the firebox was enlarged. Then based on results published by Boy and colleagues demonstrating the benefits of an angled firebox, it was angled 12 degrees (Figure 2.2) [89]. This allows more direct fire to hit the second pot causing it to boil faster. Results indicate that by angling the firebox the second pot boils approximately twelve minutes faster and the first pot boils two minutes slower. Figure 2.1 below is a drawing of the final stove design. More details on the design principles and stove specifications can be found in Appendix A.

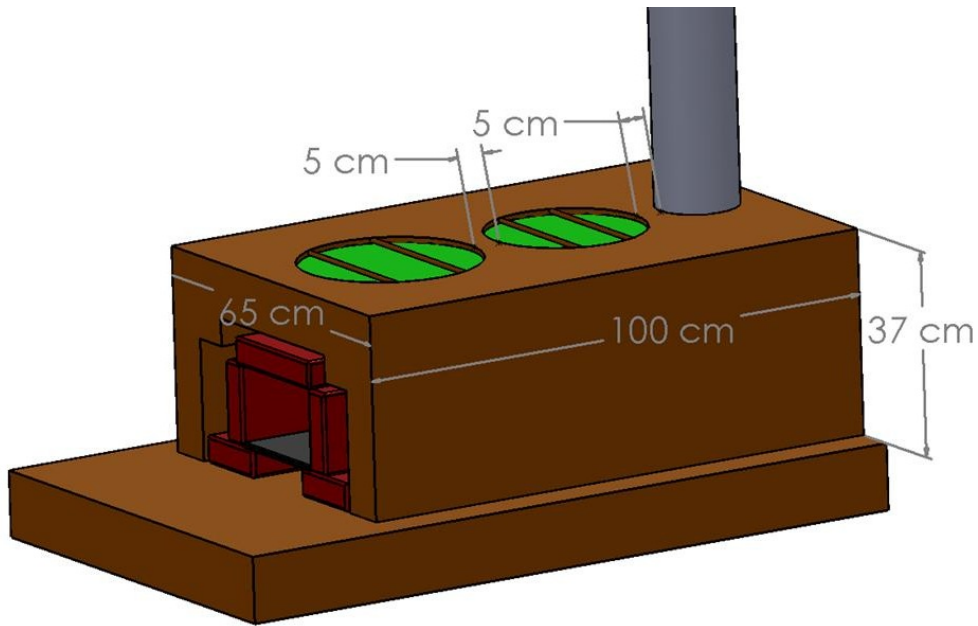


Figure 2.1. Final Yanayo cookstove design

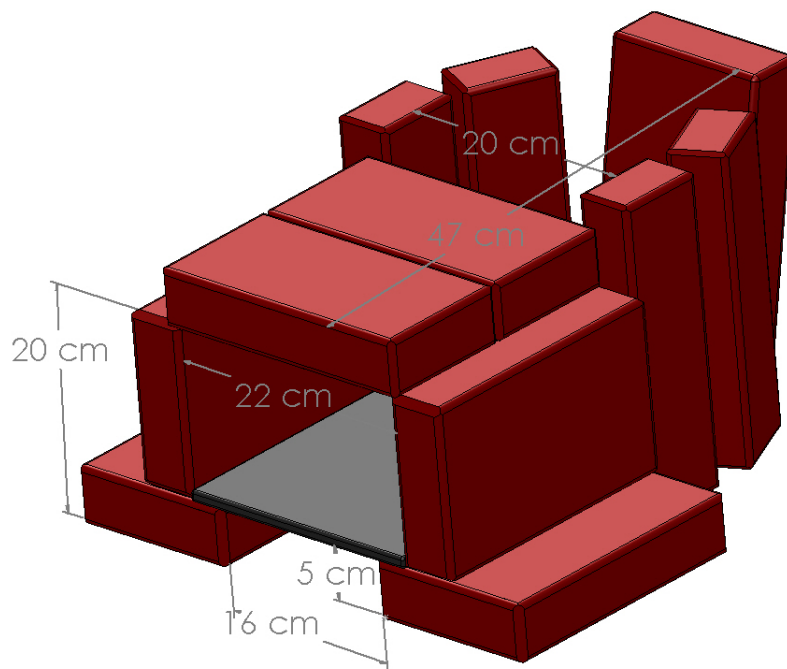


Figure 2.2. Yanayo cookstove firebox pitched with 12 degree angle at back of box

The third issue, backdraft, only occurs in some homes (approximately 25 percent of homes note the occasional occurrence of backdraft). Because the region is topographical

complex, many homes experience high winds while others are largely sheltered. Homes located in windier areas were more likely to report backdraft. Several chimney designs were tested, and the final design consisted of an enlarged, conical-shaped cap (Figure 2.3). This design was chosen because it was economical and stove builders could construct this with minimal tools and time. Other options were considered which more adequately prevented backdraft, but they were deemed infeasible due to their cost and construction difficulty.

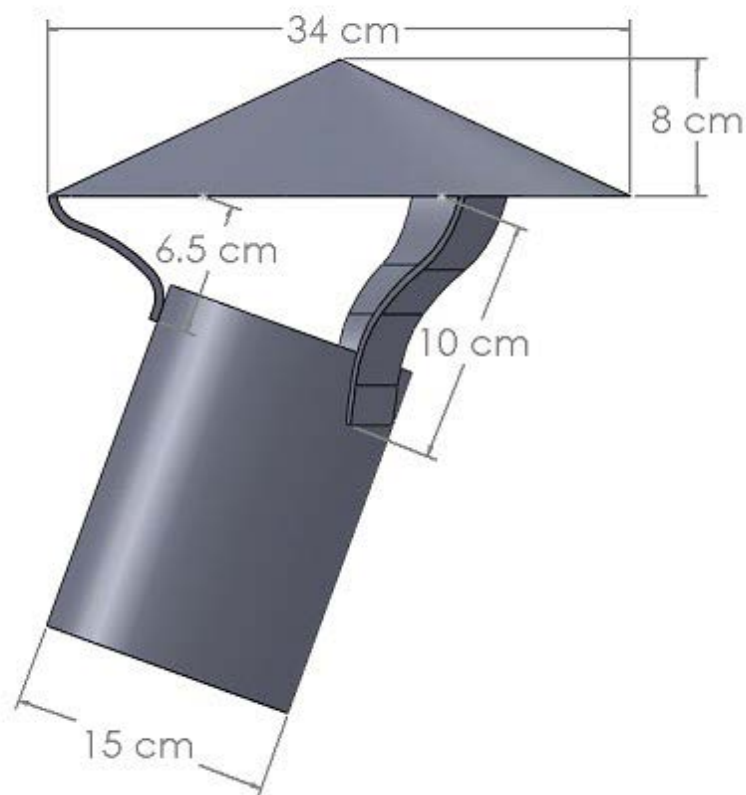


Figure 2.3. Yanayo cookstove chimney design

Lastly, a metal mold (30 cm long x 13 cm wide x 10 cm high mold) was constructed to eliminate variability in the stove channel among the stoves. Before the technician shaped the channel that passed underneath the pots, she placed a mold in the cookstove. When the stove was

dry she removed the mold. The mold was designed such that minimal smoke could escape from spaces between the pot and stove top when lighting the stove.

2.3.2 Stove efficiency and time-to-boil (TTB) testing

Results indicate the Yanayo stove performed equally as well or better than the traditional stove during the water boiling tests. For the cold start there was no statistically significant difference between the two stoves; however, for the warm start the time-to-boil of the improved stove was 12 percent faster. As the stove takes at least 24 hours to cool down, a warm start is more indicative of the conditions at which the women will use the stove (the women cook twice daily for two to three hours each cooking period with approximately six to ten hours between each use). These data can be seen in Table 2.2.

Table 1.2. Time-to-boil of traditional vs. Yanayo cookstove

Test	Traditional Stove TTB*	Improved Stove TTB†	p-value
Cold Start	21.1 min	21.0 min	0.5
Warm Start	19.1 min	16.8 min	0.08
Thermal Efficiency	10.8%	9.0%	0.2

*Three tests were performed on three separate traditional cookstoves for an n of 9

†Three tests were performed on 12 separate Yanayo cookstoves for an n of 36

Although there was no statistical significance between the thermal efficiency of the traditional stove and the Yanayo stove, data suggest that the traditional stoves are more efficient than the Yanayo cookstoves. Original Yanayo stoves, before modifications were made in 2009, performed more efficiently than traditional cookstoves (14.7 % vs. 10.8%; $p = 0.1$); however, the women were not satisfied with their design. The design was subsequently changed to satisfy the user needs and ultimately reduced the efficiency of the stove. Although the modifications resulted in a stove that is less efficient than the original design, users report much higher

satisfaction levels with the new Yanayo stove design (the design used in the Tuquiza intervention).

2.3.3 User satisfaction and adoption rates

Using a questionnaire designed to evaluate user satisfaction and user perception of stove performance, interviews were given to users pre- and one year post-intervention (see Table 2.1). Based on interviewee responses, a ‘good stove’ was quick to boil and did not emit a significant amount of smoke. Women also wanted a stove that was easy to light and operate. Although it was expected that women would prefer a stove that used less wood, 70% of women did not mention this as an issue. This could be due to the fact that the men traditionally collect the wood or because the women collect wood while pasturing animals and therefore it does not require extra time.

Using Tuquiza pre- and post-intervention data, on average users reported spending the same amount of time collecting wood before and after intervention. Users reported spending 9.42 (\pm 6.4) hours weekly collecting wood before intervention and 9.41 (\pm 6.6) hours after intervention. These numbers are very similar, which could be due to the fact that people from this region measure wood by the armload, blanket (used as a carrying device), or a donkey load.

When asked how satisfied users were with the new Yanayo stove, 95% report being moderately or highly satisfied. Only one user reported being unsatisfied with the stove. Backdraft was the biggest complaint reported by users (25%). This has been a persistent problem with these stoves; however, the chimney was re-designed before the 2010 intervention (and retrofitted for all Tuquiza users), after which fewer users complained of backdraft. Other users

complained of blackening of the walls and ceiling from the smoke that is emitted during lighting (20%). Two users also noted that their pots did not boil at the same time (10%).

Table 2.3. User satisfaction and compliance data

Usage rate (# of WHHs)*	# of People
Always	16
Most of the time	2
Sometimes	1
Never	1
Satisfaction level†	
Highly satisfied	16
Moderately satisfied	3
Unsatisfied	1

*as reported by technicians during random visits

†as reported during the final questionnaire

When asked what features the users liked best about their improved cookstoves, almost unanimously they stated that they had fewer problems with their eyes and had overall better respiratory health (these data can be found in chapter 3). Thirty percent of users stated that they had experienced fewer burns with the improved cookstoves over a one year period. Unexpectedly, women had found that by placing their mote (hominy) over the Yanayo cookstove during the night, they would wake up in the morning to find a finished product. This process usually takes six to eight hours and requires constant attention when prepared using a traditional cookstove, and takes constant tending of the fire. With the new cookstove not only do the women gain substantial hours for other activities by cooking their mote while they sleep, but this also saves considerable amounts of fuelwood.

2.4 Discussion

The results of this study show that the Yanayo cookstove boils as fast as the traditional cookstoves during cold starts and faster than the traditional cookstoves during warm starts.

Ninety-five percent of women report being moderately or highly satisfied with their improved cookstoves, and only one subject reported being unsatisfied with her cookstove. Ninety percent of users were found to be using their stove at every visit, and two users (10%) were found to be using their stoves most of the time. Only one subject did not use her stove post intervention.

To ensure a high adoption rate of the Yanayo cookstove the author worked extensively with community members to design a cookstove that most suited user needs. Over a three year period, the original design was modified and tested until all user requirements were satisfactorily met: a cookstove that boils as fast as the traditional cookstoves, one that does not emit significant quantities of smoke, and one that is easy to use and light. Once the design was complete, the Yanayo cookstoves were implemented in the homes. In each home, the user was required to help with stove construction in order to ensure that she would be able to make minor repairs in the future. After the cookstoves were installed, extensive education was given to the community regarding the health impacts of the new design. Finally, several follow-up visits were made to the households to verify that the stoves were being used and to address any problems users encountered. To the author's knowledge, no other studies worked as intensively at including the users during the design phase of a project. Additionally, nowhere is it reported that an intervention program had an extensive educational and follow-up component.

A study done in Pakistan suggests that lack of motivation, awareness and institutional support are the main reasons adoption rates are hindered [90]. Another study argues that socioeconomic status and education are barriers to adopting an improved cookstove [85]. These studies, however, are not intervention studies and rely only on empirical evidence to make their conclusions.

This study suggests an education, training, and follow-up program can result in high adoption levels regardless of socioeconomic status, education level, or proximity to city, as suggest by other studies.

CHAPTER 3

EVALUATING THE ASSOCIATION BETWEEN IMPROVED STOVE IMPLEMENTATION AND RESPIRATORY HEALTH-RELATED QUALITY OF LIFE IN A SMALL INTERVENTION STUDY IN BOLIVIA

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3.1 Abstract

While the installation of improved cookstoves with chimneys reduces smoke and soot within the home, the effects on respiratory health-related quality of life have not previously been reported. The association between woodsmoke exposure and respiratory quality of life outcomes was evaluated in a small community in rural Bolivia using a pretest-posttest intervention study design. Indoor carbon monoxide levels from traditional stove use without a chimney and from use of improved cookstoves with chimneys (Yanayo stoves) were measured. The subject population of women heads-of-households from subsistence farming families was recruited based on use of indoor solid fuel for cooking and planned implementation of improved

cookstoves with chimneys designed by the University of Washington chapter of Engineers Without Borders. Women were interviewed in August and September 2009 (pre-intervention) and in a one year follow-up in September of 2010 (post-intervention). A final cohort of 20 women was analyzed for the study. Yanayo stove implementation resulted in lower indoor CO values and correlated positively with significantly improved (lower) SGRQ Total scores as well as Activity and Impact scores. Overall differences in pre- and post-intervention SGRQ Symptoms scores were not statistically significant. However, a number of individual question scores in this category were significantly lower in women post-implementation of the Yanayo stove. This study represents the first use of a standardized respiratory health-related quality of life assessment to determine the impact of reducing wood smoke through implementation of improved cookstoves with chimneys. We show a pronounced improvement in respiratory health-related quality of life effect and significant reduction of household CO levels following installation of improved cookstoves.

3.2 Introduction

Nearly 2.7 billion people rely on biomass fuels (wood, crop residues, dung, and charcoal) for their primary domestic energy needs [91-93]. In many developing countries, the burning of biomass accounts for almost one-half of domestic energy production and can reach as high as 95% in some lower income countries [6, 93-95]. In these countries, biomass fuels are typically burned in open pit fires or inefficient cookstoves without sufficient ventilation. This practice results in exposure to many known health hazards including particulate matter, carbon monoxide, nitrogen dioxide, formaldehyde, and polycyclic organic matter [96, 97]. This contributes to levels of exposure in developing countries that are more than 10 – 20 times greater than World

Health Organization (WHO) guidelines [98-100]. Studies have shown that indoor air pollution from household combustion of biomass fuels in developing countries is linked to acute respiratory infections, chronic obstructive pulmonary disease, asthma, and other health problems [101-104]. In 2004, global mortality due to indoor air pollution from solid fuels was estimated at nearly 2 million deaths per year [105].

To date, no standard questionnaire exists to evaluate respiratory health related to improved cookstove intervention. The St. George's Respiratory Questionnaire (SGRQ) is a well-established tool for quantifying health status in chronic pulmonary diseases and has been shown to correlate well with symptoms and disability due to disease [106]. It encompasses a broad range of respiratory symptoms including both asthma and chronic obstructive pulmonary disease (COPD) and has previously been used to measure health-related quality of life (HRQoL) for industrial diseases such as pneumoconiosis [15]. This study represents the first use of the SGRQ in improved cookstove interventions where pre-implementation indoor air pollution is magnitudes higher than what is normally experienced in developed countries. While most questionnaires on respiratory health such as the commonly used Medical Research Council Questionnaire (MRCQ) focus on identifying symptoms only, the SGRQ measures the overall HRQoL [106]. The SGRQ allows researchers to determine the impact of disease on a subject's daily life and represents a valuable evaluation tool to assess the benefits of improved cookstove interventions.

Reducing exposure to indoor air pollution is one of the main goals of improved biomass cookstove implementation projects. However, due to the difficulty of logistics and long duration of sampling periods, the usual particulate matter (PM) monitoring equipment (e.g. sampling pumps and PM sampling apparatuses) can be problematic and expensive in stove implementation

studies [17]. This study used CO concentrations as a marker for woodsmoke exposure. CO passive diffusion tubes have been shown to be a reliable proxy for particulate matter < 2.5 µm (PM_{2.5}) in prior woodsmoke studies [101, 107, 108]. In a recent review of woodsmoke exposure studies, 8-hour averages for CO ranged from 1.2 – 60 mg/m³ (1 – 49 ppm) [100]. National Ambient Air Quality Standards (NAAQS) set by the U.S. Environmental Protection Agency (EPA) require that 8-hour average CO concentrations of 10 mg/m³ not to be exceeded more than once per year [109].

3.3 Methods

3.3.1 Study Design

The study was conducted using a paired pretest and posttest assessment of health-related quality of life and carbon monoxide levels following installation of improved cookstoves.

This research was conducted in the sub-Andean Valley region of Bolivia (altitude range 2,900 – 3,300 m) in northern Potosí. In this region, most women cook indoors over open-pit fires for three to five hours per day without the benefit of a chimney. Their primary fuel sources are shrubs and some hardwood trees, depending on village elevation. The primary language and culture of the region is Quechua, although some individuals also speak Spanish. Communities range in size from eight to sixty households (25 to 250 inhabitants), and are governed by both a local magistrate and mayor who is responsible for all villages within the Acacio province (approximately 6,000 inhabitants) of northern Potosí.

The village of Tuquiza was selected for assessment based on the use of indoor solid fuel for cooking and planned implementation of improved cooking stoves with roofs and chimneys

designed by the University of Washington chapter of Engineers Without Borders (EWB-UWS). In September 2009, EWB-UWS installed improved cookstoves, described as the ‘Yanayo’ cookstoves herein. Details of community statistics are given in Table 3.1. The Yanayo cookstove is a modified rocket stove design with a metal chimney that exits through an adobe wall and extends above a metal roof.

Fifty improved cookstoves were implemented in Tuquiza in September 2009. Of those, 40 non-smoking women heads-of-households (WHHs) were eligible to participate in the study. Thirty-six women elected to join the study. During the months of August and September 2009, pre-implementation assessments of these women were performed via a face-to-face HRQoL interview using the St. George’s Respiratory Questionnaire (SGRQ). Additionally, CO levels were assessed in each household for two consecutive 24-hour periods prior to intervention. Between year one and year two, eleven women dropped out of the study due to illness, death, alcoholism, or re-location. In 2010, a one-year post-implementation follow up was performed for the remaining 25 women using the same SGRQ survey and CO level detection. Two women were excluded from the analysis due to use of outdoor gas stoves prior to implementation. Two more reported their baseline health as “very bad” during the post-implementation assessment due to intestinal worms or debilitating migraine headaches and were not included in the analysis. Another woman did not sufficiently complete the post-intervention interview questionnaire for analysis. In total, 20 subjects were analyzed in the paired pre- and post-intervention cohort.

The SGRQ is a well-established method to quantify health status in chronic pulmonary diseases and has been shown to correlate well with symptoms and disability due to disease. The SGRQ includes questions related to Symptoms (e.g., coughing, shortness of breath, chest pain, etc.), Activity (e.g., walking uphill, walking at a rapid pace) and Impact (e.g., disrupted sleep,

expectations of improvement in or control over respiratory-health) and weights each of these sections for a Total score. Scores range from 0 to 100 for each SGRQ category with higher scores indicating poorer respiratory HRQoL than lower scores. The SGRQ was validated in Peruvian Spanish through formal translation and back translation and linguistic validation was performed to obtain the final Peruvian version [110]. The interviews were verbally translated from the Peruvian Spanish version of the SGRQ into Quechua by a bi-lingual interpreter during the face-to-face interview, as Quechua is not a written language. Face-to-face and telephone interviewing for the SGRQ has previously been validated and care was taken to ensure that the same translation was used for each interview [111].

Prior to interviews, the SGRQ was pre-screened by the bi-lingual Quechua-Spanish interpreter for culturally appropriate content. During the pre-screening, three questions were found to contain culturally inappropriate wording. Of these three questions, one multipart question was modified to exclude the term “stairs” as nearly all buildings in the villages were single story dwellings and ladders were used to reach the upper floor of those buildings with a second story. Additionally, the phrase describing swimming was excluded from the list of activities in a second question as swimming is not an activity performed in this region. Finally, the term “wheeze” does not have a direct translation in Quechua and was instead described as a “whistling in the chest or back of the throat” during the interviews.

Gastec brand CO passive diffusion tubes were placed in the women’s households both pre- and post-intervention for two consecutive, roughly 24-hour periods. The cookstoves are always located in a corner of the kitchen near a wall. Tubes were placed on the wall nearest to where each woman sits, level with her head and adjacent to her position during cooking periods, such that the CO levels were most indicative of the exposure levels of the women. Because

women are different sizes and use different cooking techniques (i.e., some sit on stools and others sit on the ground), the placement was varied for each individual household. On average, the CO tubes were placed 57 cm from the floor and 36 cm away from the stove.

The time of placement and collection were recorded. From these data, time-weighted-average values were calculated to find CO in parts per million (PPM) using the midpoint where the color stain begins to fade and the end of the color stain. The CO passive diffusion tubes were read blind and recorded onsite by two or more research associates, immediately following the sampling period.

During the testing days, women were asked to use the stove as they would on a customary day, using the same type of fuel source, cooking the same type of food, and cooking for a typical amount of time. The number of times that the stoves were used was recorded upon collection of the CO passive diffusion tubes.

The independent variables in this study were the implementation status of the Yanayo cook stove and the household CO levels. The dependent variable in the study was the resulting SGRQ scores (Symptoms, Activity, Impact, and Total). These outcomes were compared pre-versus post-stove intervention. SGRQ scores were also examined as a function of subject age. All 20 women in the cohort report using their improved cookstoves as their sole cooking device following the 2009 intervention.

Questionnaire results were analyzed with the SGRQ Analysis package for Microsoft Excel [106]. All datasets were examined using the Kolomogorov-Smirnov (K-S) test to ensure normal distribution prior to performing parametric tests. Pre- and post-intervention outcomes were compared using paired t-tests, and Spearman rank correlation tests were used to determine

relationships of SGRQ outcomes to exposures (CO concentrations, Age) using XLSTAT (Addinssoft).

3.4 Results

We examined CO levels in the home and interviewed female heads of households, both prior to receiving a Yanayo stove and in a one year follow up after implementation of the cookstoves, to determine the women's respiratory quality of life and CO levels in the home. Table 3.1 summarizes these results in addition to the ages of the women.

Table 3.1. Tuquiza Community Statistics*, Health Status, and CO

	Pre-Intervention		Post-Intervention	
	Mean (SD)	Range	Mean (SD)	Range
Mean Age (years)	47.2 (15.9)	23 to 77	48.2 (15.9)	24 to 78
SGRQ Scores (0-100)**				
Total	58.2 (13.3)	26.2 to 75.0	35.3 (22.9)	0.0 to 68.4
Symptoms	51.8 (23.4)	9.4 to 90.8	42.4 (26.8)	0.0 to 81.5
Activity	68.4 (20.4)	17.8 to 100.0	40.7 (28.7)	0.0 to 88.2
Impact	54.3 (14.3)	19.6 to 73.6	29.9 (20.8)	0.0 to 61.2
Household CO level (PPM)	10.8 (4.4)	3.2 to 17.9	2.3 (1.6)	0.2 to 6.5

*All 20 participants were non-smoking female heads-of-households of subsistence farming families interviewed during August and September of 2009 (pre-intervention) and again in September of 2010 (post-intervention).

**Lower SGRQ scores and Household CO levels are considered preferable to higher ones.

3.4.1 SGRQ Scores

Figure 3.1 shows within-subject changes in SGRQ pre and one year post-intervention. Table 3.2 summarizes the changes in SGRQ results obtained by subtracting each woman's post-intervention score from her pre-intervention score in each category. Improvement in subjects' HRQoL is associated with a decrease in the Scores from pre- to post-intervention while a

worsening of HQRoL is associated with an increase in scores. Women using Yanayo stoves with chimneys had significantly improved (lower) SGRQ Scores than the pre-implementation scores of these same women using traditional cookstoves without chimneys. These variables were found to have a normal distribution according to the K-S test. Overall, 85% (17/20) of the women in the study had improved Total SGRQ Scores.

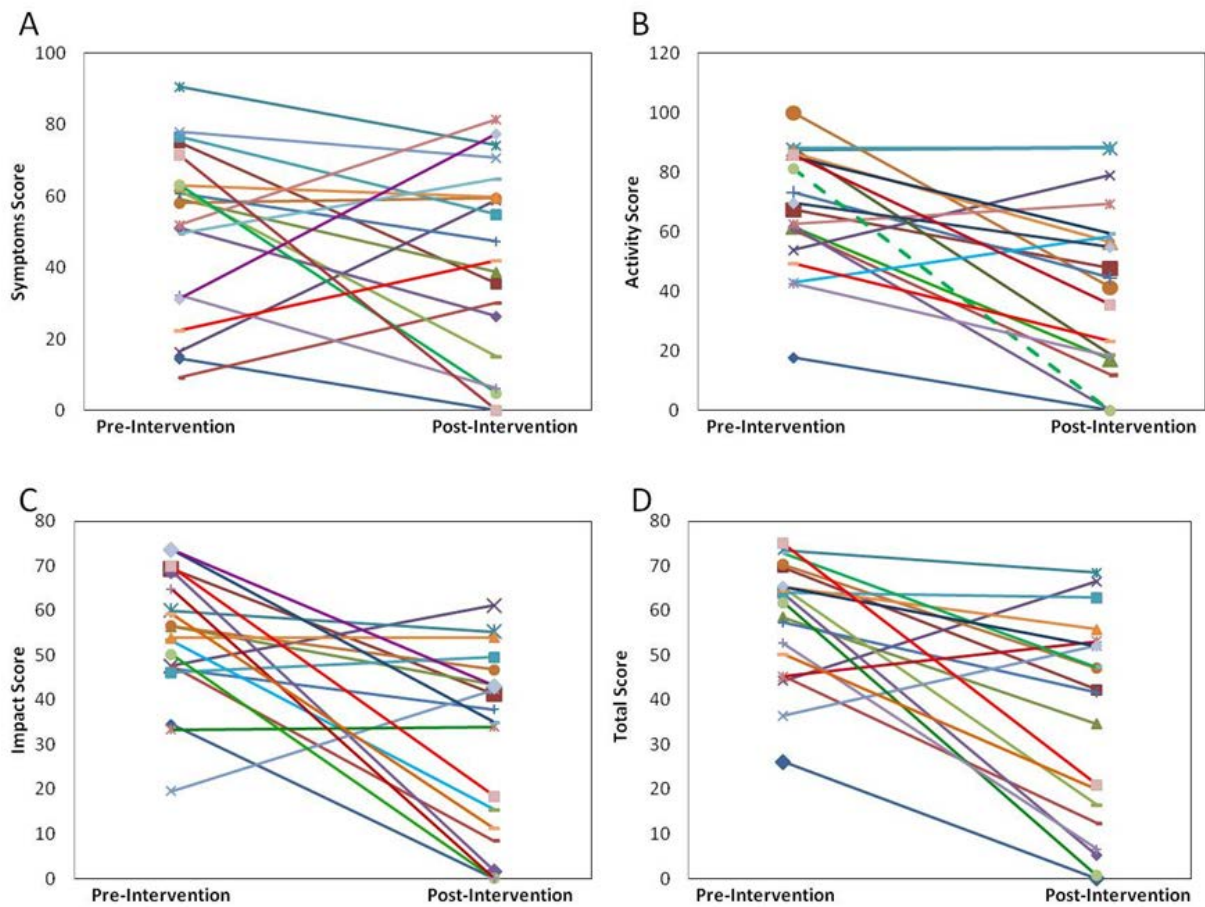


Figure 3.1. Within-subject SGRQ Symptoms (A), Activity (B), Impact (C), and Total scores

Note: The dashed line in Activities score represents the outlier removed for statistical analysis in the text.

Symbols are the same for each woman in across sub-figures.

Table 3.2. Change in SGRQ Scores*

	Mean Change (p value)	Range of Δ SGRQ Score
Δ SGRQ Score		
Δ Total	-22.8 (0.0004)	-61.1 to 22.2
Δ Symptoms	-9.2 (0.2)	-71.5 to 46.1
Δ Activity	-27.2 (0.0004)	-67.3 to 22.7
Δ Impact	-24.3 (0.0003)	-71.5 to 46.1

*Post-intervention score minus pre-intervention score

A further breakdown of questions contributing to the Symptoms score shows that attacks of wheezing, and severity and length of attacks of chest trouble were all significantly reduced post-implementation of the Yanayo stoves ($p < 0.03$, 0.02 , and 0.001 respectively). There was no statistical difference in frequency of coughing or shortness of breath. However, frequency of productive coughs (bringing up phlegm) was lower post-intervention ($p < 0.06$). The number of days without chest trouble was higher post-intervention, as well ($p < 0.07$).

3.4.2 Household CO

Pre- and post-intervention CO concentrations in Tuquiza confirmed the reduction of CO in all homes following implementation of Yanayo stoves. Following intervention, CO concentrations in households decreased, on average, to 20% of the pre-implementation levels ($p < 0.0001$). These variables followed a normal distribution according to the K-S test.

3.4.3 Comparison of Individual Exposure Data Correlation with SGRQ Scores

Changes in SGRQ scores are plotted versus changes in CO from pre- to post-intervention in Figure 3.2. The Spearman rank coefficients and p values are also reported on each figure. We expected that a reduction in CO following stove implementation would result in a reduction in SGRQ scores (improved quality of life), resulting in a positive correlation between these two metrics. Although this expected relationship was observed for the SGRQ Activity, Impact, and

Total scores, there is a suggestion, albeit weak, of the opposite relationship for the SGRQ Symptoms score.

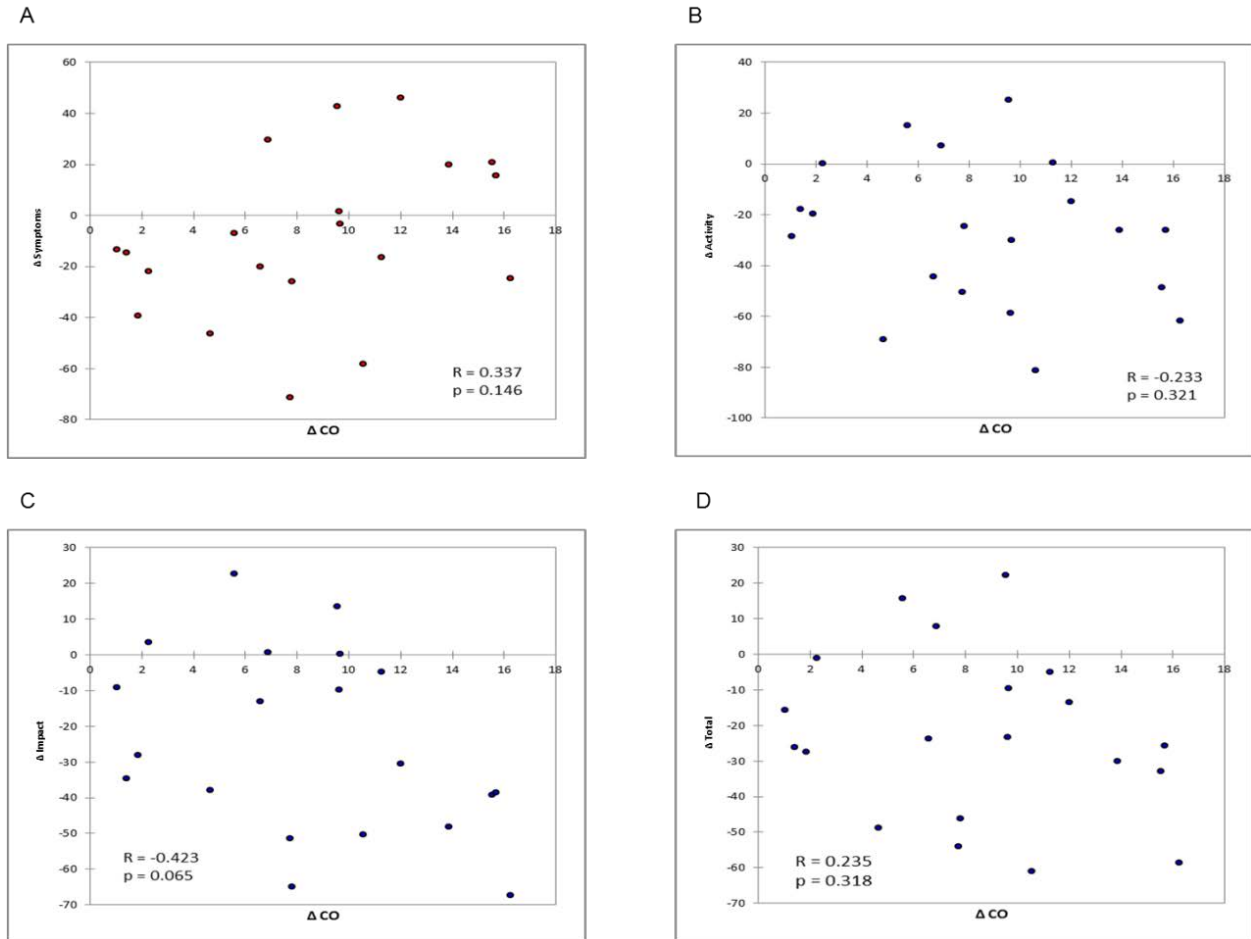


Figure 3.2. Changes in Symptoms (A), Activity (B), Impact (C) and Total Scores (D) versus changes in kitchen carbon monoxide (CO) concentrations (ppm).

Note: Spearman Rank Coefficients (R) and p values are also shown.

As seen in Figure 3.3., a slightly negative correlation was observed between subject age and change in Activities scores, with older individuals reporting a larger improvement in their activity level post intervention compared to younger women (Spearman $R = -0.219$, $p = 0.35$). Removing the extreme outlying data point from the analysis, the only point that is greater than two standard deviations outside of the mean score, the correlation strengthens (Spearman $R = -0.408$, $p = 0.08$). Excluding the outlier, the mean change in Activity Score for women less than

40 years was $-9.7 (\pm 21)$, while the mean change for women older than 40 was $-35.9 (\pm 24)$. There was no observed correlation between changes in Symptoms, Impact or Total scores and subject age.

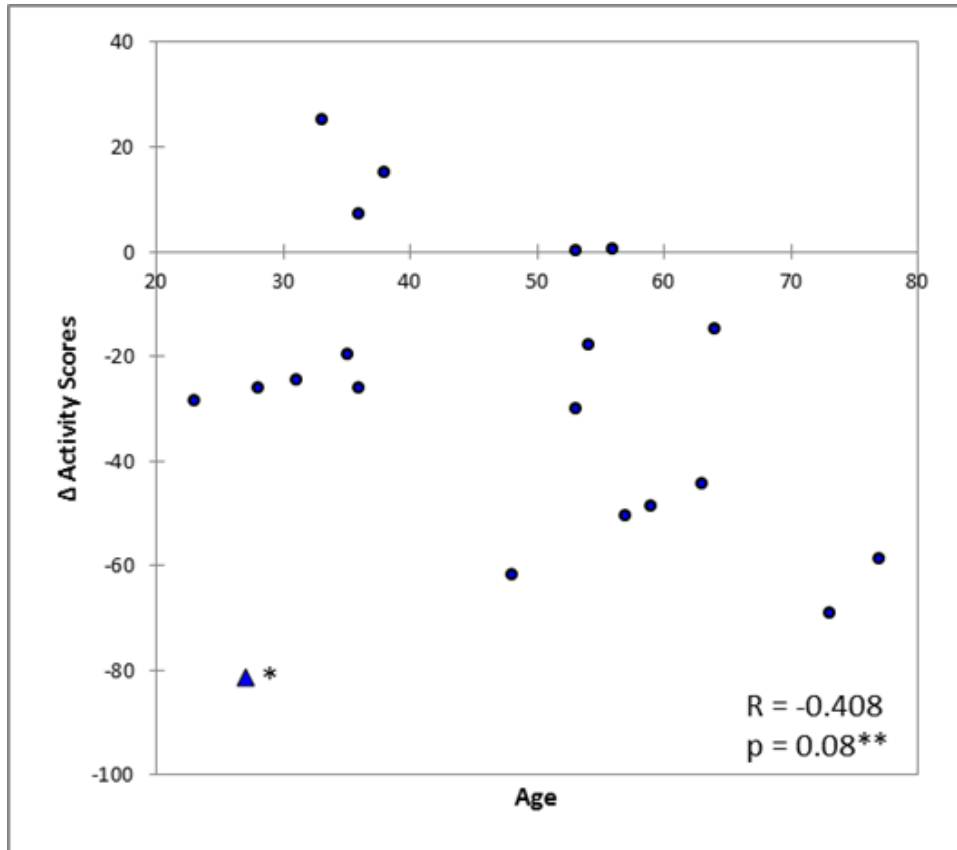


Figure 3.3. Changes in Activity Scores versus age
 *Outlier point: defined as greater than two standard deviations away from the mean for women under the age of forty.
 **Spearman R and p values omitting the outlier point.

3.5 Discussion

The CO data in this study agree with results from other studies. In a review evaluating the health effects of woodsmoke exposure, Naeher *et al.* reported average daily CO values ranging from $1.2 - 60 \text{ mg/m}^3$ (approximately $0.97 - 48.6 \text{ ppm}$) [104]. These values are consistent with

the CO values from our study which range from 1.01 PPM (post- intervention) to 10.16 ppm (pre-intervention).

Pre- and post-intervention CO data illustrate a decrease in CO exposure due to implementation of the Yanayo stoves. Potentially, survey responses to questionnaires and interviews such as the SGRQ could be biased by a subjects desire to receive a stove or other further assistance. Participation in this study, however, was not required for obtaining a Yanayo stove, making this bias unlikely.

In this study CO is a limited snapshot of indoor air quality, indicative of an overall improvement in indoor air quality rather than a precise chronic exposure metric. Taken together with survey results on woodstove use, our CO measurements support the hypothesis that stove implementation is associated with significant improvements in indoor air quality, as has also been seen in other studies [101, 111, 112].

We found an association between woodstove implementation and improved HRQoL as measured by SGRQ Activity, Impact, and Total scores. However, decreases in SGRQ Total scores post-stove intervention are only partially described by concurrent decreases in CO in the households. Measurement of CO levels was affected by placement in the home. Passive diffusion CO tubes were placed at the locations where women planned to be seated while cooking to ensure accurate measurement of CO levels. Other factors can influence the relationship between personal exposure and our stationary CO measurement, including outdoor wind direction, backdraft from chimneys, and changed seating positions, CO levels in the rest of the room, and a woman's time away from the cookstove.

At the time of the follow-up post-intervention surveys, Yanayo stoves with chimneys had been used by the women for one year. Excluding the most extreme data point, prior to intervention, women older than 45 had average Activity scores that were 17 points greater than women younger than 40 (there are no women in the study from ages 40 – 45), meaning their activity levels were much lower than younger women. After intervention, a greater effect was seen on older women, who then reported having activity levels almost equal to those of younger women. While a lower activity level is expected for older people, overall these results suggest that a dramatic improvement in air quality, as seen in this study, may be significant for the activity levels of older women.

A previous study by Ferrer *et al.*, has reported mean Symptom, Activity, Impact, and Total scores in healthy populations (with no lung disease) of women at 7.8, 14.8, 4.3, and 8.2 respectively [113]. The women sampled in the study were from a cross-section of ages, educations, and socioeconomic statuses status in Spain. A study of pneumoconiosis (due to inhalation of small dust particles from coal) in men in Hong Kong resulted in SGRQ scores for Symptoms, Activity, Impact, and Total scores of 38.0 (\pm 19.3), 44.5 (\pm 21.9), 34.2 (\pm 17.9) and 39.4 (\pm 17.4), respectively.[15] Both of these populations had significantly lower SGRQ scores than the Tuquiza women prior to Yanayo stove intervention. The population with pneumoconiosis had SGRQ scores most similar to those women with improved cookstoves post-intervention. It is likely that, in addition to disease presence, the differences in population and environment play a role in these variations. The villages in the present study are located between 2,900 to 3,300 meters above sea level, resulting in much less available oxygen than the locations where the other studies were performed. While this may potentially exacerbate symptoms of

chronic respiratory disease, published studies of patients living at high altitudes are lacking [114].

In the present study, women's SGRQ Total scores improved significantly after installation of the improved cookstoves with chimneys. According to the authors of the SGRQ, clinically significant improvements in health status of COPD patients are associated with a four point decrease in SGRQ Total scores [106]. While no clinical diagnosis of disease has been made in the present study, Total scores declined significantly by more than 22 points, a clear indication of better HRQoL for women after implementation of improved cookstoves and chimneys.

This study had a relatively small number of subjects. While differences in Symptoms scores were seen following Yanayo stoves and chimneys, no statistical difference was apparent. Based on the magnitude of the outcome effect that we observed, this study was underpowered for Symptoms scores but not for the other scores.

As the SGRQ was originally designed as a self-test for patients, it is possible that some bias could have been introduced by the interview method and translation into Quechua. However, as almost none of the women could read Spanish, and Quechua was not traditionally a written language, no alternative self-test method was available. The use of interviewing has previously been validated in both telephone and face-to-face interviews for the SGRQ [111].

3.5.1 Summary

In this study we report the first use of a respiratory HRQoL assessment to determine the impact of reducing indoor air pollution through implementation of cooking stoves with chimneys. Women cooking on new Yanayo stoves had significantly better respiratory health-

related quality of life than prior to implementation when these same women were cooking on traditional stoves. However, the post-implementation HRQoL was still much worse than that of healthy populations, and is instead, similar to populations suffering from pneumoconiosis due to inhalation of coal dust. Implementation of Yanayo stoves reduced air pollution exposures as measured by CO levels and produced a concurrent improvement in SGRQ scores. Our results suggest that indoor air pollution from poorly vented stoves leads to detrimental long-term effects on women's respiratory health-related quality of life which can be ameliorated by improving stove technology and ventilation.

Indoor air pollution from primitive household cooking is the leading environment cause of death in the world [115]. As organizations expand their efforts to improve global health and indoor air quality, further research on the impact of improved cookstoves is necessary to ensure that both indoor air quality and health-related quality of life are improved by these efforts. Because of its focus on HRQoL aspects beyond Symptoms, the SGRQ presents a valuable evaluation tool to assess the benefits of improved cookstove interventions.

CHAPTER 4

FEV₁ CHANGES IN INDIGENOUS BOLIVIAN WOMEN HEAD-OF-HOUSEHOLDS PRE- AND POST-COOKSTOVE INTERVENTION

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4.1 Abstract

Almost half of the world's population relies on biomass fuels for their primary energy needs. Indoor air pollution from biomass burning is linked to significant health effects including chronic pulmonary disease. Few studies evaluating the health effects of indoor air pollution have conducted spirometry measurements in their assessment, and those studies have yielded inconsistent results. This study evaluated the lung function of 20 women head-of-households pre- and one year post-intervention in a small, indigenous community in rural Bolivia. The subject population was recruited based on use of indoor wood fuel for cooking and planned implementation of improved cookstoves with chimneys designed by the University of Washington chapter of Engineers Without Borders. Technicians made random visits throughout the year to evaluate user compliance. Lung function and kitchen CO measurements were taken

in August and September 2009 (pre-intervention) and in a one year follow-up in September and October of 2010 (post-intervention). Based on random home visits, a 90% adoption rate of the Yanayo cookstove was reported. Yanayo stove implementation resulted in mean reductions in kitchen CO levels from 10.6 ppm (\pm 4.3) to 2.3 ppm (\pm 1.6), $p < 0.0001$; and mean improvements of FEV₁ from 1.95 L (\pm 0.6) to 2.15 L (\pm 0.7), $p < 0.005$. Improvements in FVC and FEV₁/FVC were also seen, but these changes were not significant. This study represents the first study to see significant improvements in lung function post implementation of an improved cookstove.

4.2 Introduction

Globally, household solid fuel usage is the most widespread source of indoor air pollution. Worldwide, almost three billion people rely on biomass fuels (wood, crop residues, dung, and charcoal) and coal for their primary domestic energy needs [2, 116]. Biomass smoke contains hundreds of chemical compounds, including particulate matter, carbon monoxide and polycyclic aromatic hydrocarbons [117]. Many of these compounds are hazardous to human health [9, 118, 119]. Traditional biomass burning typically occurs over open-fire cookstoves consisting of simple designs such as a three stone configuration, a pit in the ground, a U-shaped hole in a block of clay, or a poorly functioning earth or metal stove. Most of these stoves, in which combustion is incomplete and emissions are high, produce very high levels of indoor air pollution [120]. These practices contribute to levels of fine particles and carbon monoxide well above WHO regulatory standards [8, 12, 60, 121, 122].

The public health impact of the high levels of pollutants emitted by these primitive cookstoves is large. Women and young children, who spend hours a day indoors near the source,

are disproportionately affected. The World Health Organization (WHO) ranks indoor air pollution from traditional household cookstoves as one of the leading environmental causes of death in the world [58, 88]. Indoor air pollution from biomass burning is linked to significant health effects including acute respiratory infections and chronic pulmonary disease [7, 8, 123-126].

It has been reported that the use of biomass fuels, including wood, have been associated with lung function impairment [16, 17]. However, few studies evaluating the health effects of indoor air pollution have conducted spirometry measurements in their assessment [17-26], and fewer still have conducted intervention studies involving high elevation populations [25, 26]. Moreover, studies that have evaluated the associations between improved lung function and cookstove interventions have yielded inconsistent results [17, 18, 22, 23, 25, 26] or have been unable to demonstrate improvements in lung function from improved cookstoves [17, 18, 25, 26].

It is likely that biomass fuel use in developing countries will remain stable or even increase in the near future, as few rural families can afford cleaner-burning fuels [25]. One approach to reducing the health burden from biomass cooking fuels in developing countries has been through the provision of improved wood-burning cookstoves in rural areas [127, 128]. Here we report the results of a small intervention study in the highlands of rural Bolivia aimed at assessing the respiratory health impacts of reducing indoor air pollution through the documented use of an improved wood-burning cookstove with ventilation called the Yanayo cookstove. To determine the health impact of biomass burning, we examined the effect of reducing woodsmoke exposure levels on level of lung function among non-smoking female head-of-households in the

Bolivian village of Tuquiza. We then assessed the correlation of change in lung function with change in respiratory symptoms and kitchen carbon monoxide levels.

4.3 Methods

This study was conducted in Tuquiza, Bolivia, a community of approximately 60 families, which lies in the sub-Andean valley region of Bolivia in the northern region of the department of Potosí. The altitude within the village ranges from 3,000 – 3,350 m. An initial general questionnaire was administered at baseline to obtain information about general health status, household characteristics, and socioeconomic status. All participants in this study lived in adobe houses with thatched roofs, are of Quechua descent, and were of the same economic status. Other eligibility requirements for this study included women head-of-households (WHHs) that cooked exclusively indoors over open-pit fires without ventilation, lived in the community permanently, did not smoke, and were in good health. Women spend three to eight hours per day cooking and their primary fuel source is hardwood trees and shrubs.

All participants received the improved cookstove intervention in September 2009. The intervention – implemented by the University of Washington chapter of Engineers Without Borders (EWB-UWS) – had been underway in several villages throughout the region since 2007. EWB-UWS policy required all recipients of the improved cookstove to construct a 3m x 4m adobe structure which would house the Yanayo stove. The intervention included an improved wood cookstove called the Yanayo cookstove with chimney and a metal roof. Upon receiving the improved cookstoves, two local technicians provided mandatory workshops on how to use the cookstove properly. One technician then visited each household and cooked with the WHH until the participant could use the stove properly. Following this stage of the project, two technicians

visited each household randomly throughout the year with the intention of addressing any problems or concerns the users were having with their improved cookstoves. At each visit, which occurred every three or four months, the technicians documented whether the stove had been recently used. Using a questionnaire and making observations such as evidence of another stove, pots and dishes near the improved cookstove, ashes in the firebox, and warmth of the firebox, the technicians were able to determine if the stoves were being used.

Household exposure measurements, spirometry readings, and respiratory symptom reporting were recorded in 20 WHHs prior to and one year after cookstove intervention during the dry season (September, 2009 and October, 2010 respectively). All community members who desired the cookstove intervention received one whether they participated in this study or not. Of the 63 families in the community, 47 participated in the intervention. Of these, 33 WHHs enrolled in the study, 13 dropped out in the second year of testing: three women were chronically ill and could not complete the study. Five women did not understand how to correctly use the spirometer even though the technician repeatedly demonstrated the proper method; two women died after year one of testing; three women decided they no longer wanted to participate in the study for personal reasons. While 20 women participated in the study in year two, three women were too intoxicated to perform acceptable measurements. Data from these three women are shown and then omitted from final analysis.

The respiratory questions in this research were taken from the Saint George's Respiratory Questionnaire (SGRQ). A detailed description of the methods and the results are found in Alexander et al., (2012). The questionnaire was pre-screened for culturally appropriate content and then translated from the Peruvian Spanish version into Quechua by an interpreter during the face-to-face interview. Because Quechua was not originally a written language, very few people

read Quechua; therefore, the questionnaire was verbally translated by a bi-lingual translator. During the pre-screening, it was found that participants had difficulty understanding one question. The term “wheeze” does not have a direct translation in Quechua and was, therefore, described as a “whistling in the chest or back of the throat”. The translator also demonstrated wheezing to explain the phrase.

Exposure measurements were taken in adobe kitchens detached from the house. No exposure measurements were taken within the houses themselves as they are only used for sleeping and are locked during the day. Gastec brand CO passive diffusion tubes were placed in the women’s kitchens both pre- and post-intervention for two consecutive, roughly 24-hour periods. Tubes were placed on the wall, level with the women’s heads during cooking, such that the CO levels were most indicative of the exposure levels of the women. Because women are different sizes and use different cooking techniques (i.e., some sit on stools while others sit on the ground), the placement was varied for each individual household. On average, the distance from the floor was 57 cm, and the distance away from the stove was 36 cm. The time of placement and collection were recorded, as were the number of times stoves were used. Time-weighted-average CO values were calculated. The CO passive diffusion tubes were read and recorded onsite by two or more research associates, immediately following the sampling period. To minimize errors associated with reading the CO tubes, all tubes were read blind by the same two readers immediately following the sampling period. To check that CO was acting as a surrogate for smoke, and to provide some additional exposure information for comparison with other studies, UCB particle monitors, developed by the University of California Berkeley to measure PM_{2.5} based on light scattering principles, were placed in a subset of kitchens for a 24-hour period [64, 71, 72].

Two local bilingual (Quechua and Spanish) field workers were recruited to perform spirometry measurements and read and translate the questionnaires. Spirometry was performed in accordance with the American Thoracic Society (ATS) guidelines using Micro DL portable spirometers [129]. Spirometric measurements included forced expiratory volume in 1 s (FEV₁) and forced vital capacity (FVC). Testing was performed in the morning after all other measurements had been completed (e.g., blood pressure, questionnaires, etc.), and each participant was required to perform the procedure a minimum of three consecutive times in a standing position without a nose clip. Weight, age, height, and waistline of each participant were recorded at the time of testing. Time, temperature, humidity, and atmospheric pressure were also recorded during testing. Air volume calibration checks, using a 3 L syringe, were performed daily. Data were deemed acceptable if two values of forced expiratory volume in one second (FEV₁) and forced expiratory vital capacity (FVC), respectively, did not differ by more than 10%. Data analysis was conducted on the largest FEV₁ and FVC of the two curves, respectively. The largest FEV₁ was used to calculate the FEV₁/FVC ratio for each subject. If a participant could not perform two consecutive measurements in four attempts, the team returned the next day to perform the testing again. If the participant could not perform the testing on the second day, her data were omitted from the analysis. Testing was conducted pre- and one year post-intervention.

For the duration of the study, all women reported exclusively using wood fuel for cooking and heating. No women reported being pregnant during pre or post-intervention testing. Their exposure to tobacco smoke was insignificant as it is not culturally acceptable for women to smoke, and men only occasionally smoke and then only while working away from the home. Similarly, occupational exposure to dust was deemed insignificant as women only work in the

fields during brief planting and harvesting periods. The community of Tuquiza did not have electricity during the one year evaluation period and households used small kerosene lamps or candles to light their houses in the evenings. This exposure was deemed relatively small and disregarded in the analysis.

Questionnaire results were analyzed with the SGRQ Analysis package for Microsoft Excel [106]. Individual symptom scores were then analyzed using paired-t tests. The Kolomogorov-Smirnov (K-S) test was used to assess normality of distributions prior to performing parametric tests. Pre- and post-intervention exposure and health outcomes were compared using paired t-tests, and Spearman rank correlation tests were used to determine relationships of symptoms and lung function to exposures (CO and nominal PM concentrations, age) using XLSTAT (Addinsoft).

4.4 Results

Personal information including kitchen exposure levels and baseline spirometry values are presented in Table 4.1.

Table 4.1. Baseline characteristics of recruitment group

Baseline Characteristics	Mean (SD)	Min - Max
Mean age, years	48 (16)	23 – 77
Weight, kg	52 (8)	33 – 65
Height, cm	146 (5)	138 – 156
Lung function at recruitment*		
FEV ₁ , L	1.98 (0.8)	0.34 – 3.25
FVC, L	2.60 (1.0)	0.39 – 4.50
FEV ₁ /FVC	0.78 (0.1)	0.54 – 0.97
Indoor air pollution at recruitment		
Mean kitchen PM, ($\mu\text{g}/\text{m}^3$) †	260.6 (244)	23 – 553
Mean kitchen CO, (ppm) ‡	10.6 (4)	3.3 – 17.5

*Includes lung function data for all 20 subjects.

†Includes data from 10 households; nominal values based on factory calibration.

‡Mean kitchen CO is the average of two consecutive days for all 20 subjects.

Throughout the year following implementation, the technicians randomly visited the homes to address any problems and evaluate usage rate. In addition to these random visits we evaluated satisfaction level and usage rate at the one year follow-up (Table 4.2). During this visit we saw a high level of compliance and satisfaction with the Yanayo stove, as over 90% of recipients reported being satisfied or highly satisfied with the Yanayo cookstove and all but one recipient reported using her improved cookstove. Our observations were consistent with what the WHHs reported in their questionnaire responses.

Table 4.2. Compliance Data

Usage rate (# of WHHs)*	# of People
Always	16
Most of the time	2
Sometimes	1
Never	1
Satisfaction level†	
Highly satisfied	16
Moderately satisfied	3
Unsatisfied	1

*As reported by the technicians during their random visits

† As reported during the final questionnaire

Personal Exposures

Using Gastec brand passive diffusion CO tubes, kitchen CO levels were measured over approximately 24-hour time intervals for two consecutive days and averaged. Mean kitchen pre-intervention CO levels were 10.6 ppm (± 4.3) and mean kitchen post-intervention CO levels were 2.3 ppm (± 1.6), a reduction of 77 percent (p -value < 0.0001). Figure 4.1 shows the within-subject CO levels pre-intervention and post-intervention. Using the Spearman Rank correlation test, a relatively strong correlation was found between kitchen CO and PM levels for the pooled pre- and post-intervention data sets ($R = 0.68$; $p < 0.004$; $n = 16$). These data can be seen in Figure 4.2.

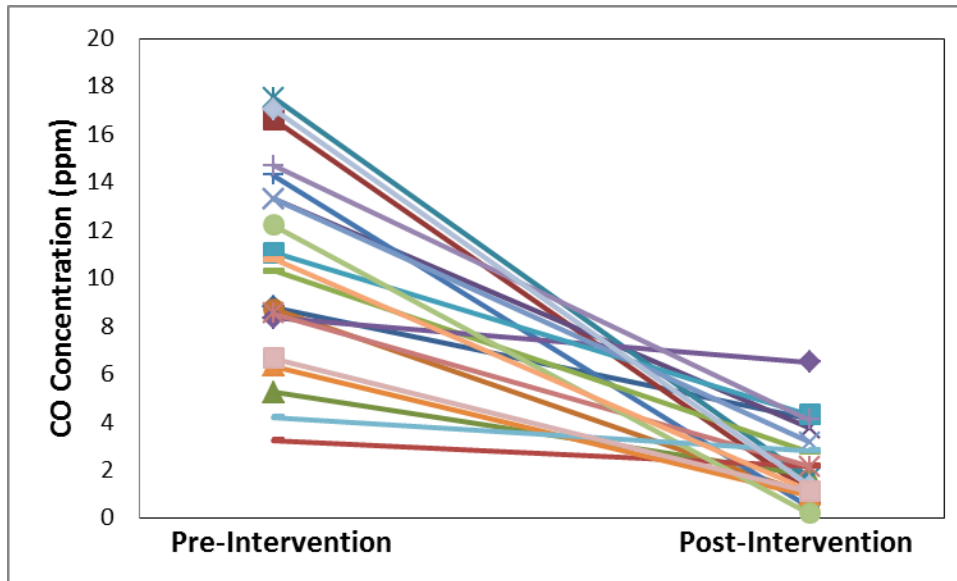


Figure 4.1. Pre- and post-intervention kitchen CO concentrations

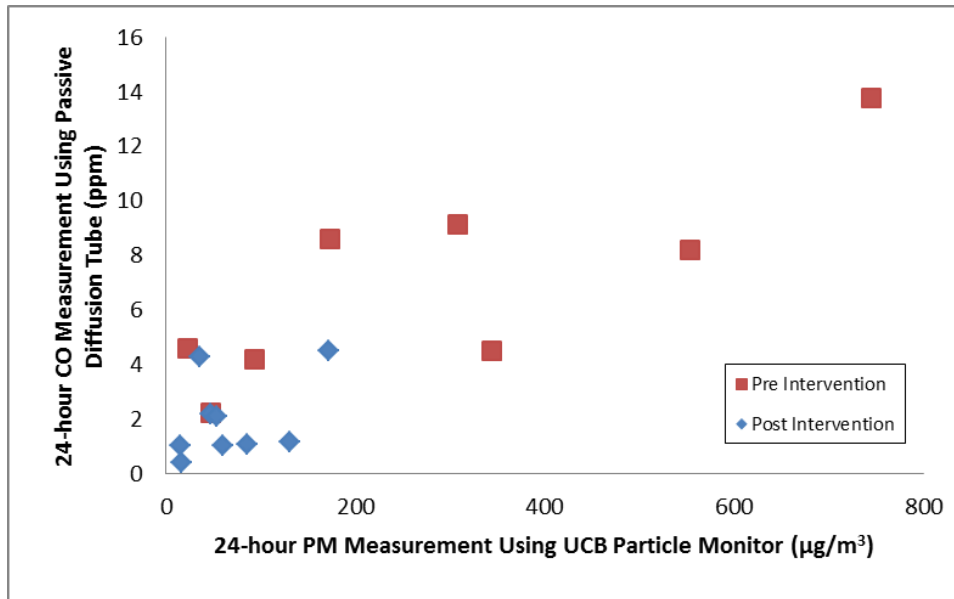


Figure 4.2. Correlation between mean kitchen CO and mean PM levels

Self-reported Respiratory Symptoms

In this paper we build on the work of Alexander et al. (2012) and attempt to correlate changes in self-reported respiratory symptoms with age, exposure and change in level of lung function (discussed below). Although no statistically significant correlations were found between respiratory symptoms and age, the data suggest younger women experienced a greater reduction in attacks of wheezing than older women ($R = 0.4$; $p < 0.18$). No correlations were found between changes in exposure and changes in respiratory symptoms.

Lung Function

Spirometry was completed on twenty subjects, pre- and post-intervention. Raw data for FEV₁, FVC, and FEV₁/FVC are shown in Appendix B. Of the twenty subjects, data from three subjects were omitted due to intoxication and severe illness at the time of the post-implementation evaluation. Mean FEV₁ value for the 17 subjects increased from 1.85 L (± 0.7)

to 2.11 L (± 0.7) ($p = 0.008$). Figure 4.3 shows the within-subject FEV₁ pre-intervention and post-intervention. One subject's FEV₁ value was two standard deviations below the mean value pre-intervention and drastically improved post-intervention. If this data point is removed, post-intervention FEV₁ values are still significantly higher than pre-intervention values ($p < 0.005$), with FEV₁ improving from 1.95 L (± 0.6) to 2.15 L (± 0.7). These 16 subjects were used in the rest of the data analysis. The FVC values for the 16 subjects improved from 2.53 (± 0.7) pre-intervention to 2.65 (± 0.7) post-intervention ($p = 0.2$). Although the difference between pre- and post-intervention FEV₁/FVC ratio was not significant, the mean post-intervention value was 0.01 higher with post-intervention ratios increasing from 0.79 (± 0.1) pre-intervention to 0.81 (± 0.1) ($p = 0.3$; $n = 16$) post-intervention.

Half of the women pre-intervention had FEV₁/FVC ratios below 80% with almost one-third having FEV₁/FVC ratios below 75%, and two women had FEV₁/FVC ratios below 60%. Post implementation of the Yanayo cookstove, one-third of the women had FEV₁/FVC ratios below 80% and less than one-fifth had FEV₁/FVC ratios under 75%, and no women had FEV₁/FVC ratios below 60%.

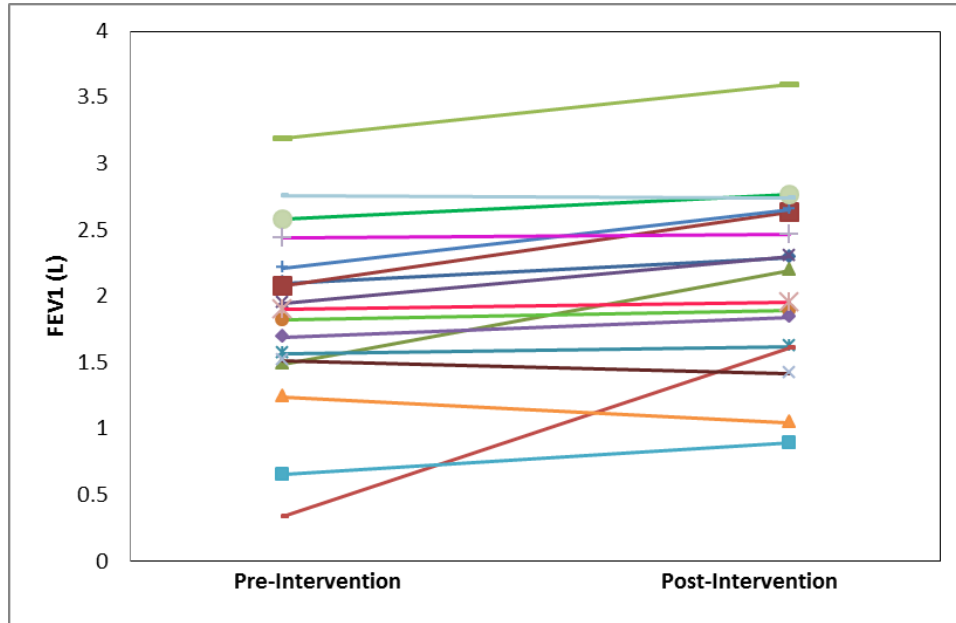


Figure 4.3. Within-subject change in FEV₁ values pre- and post-intervention

Trends, albeit weak, can be seen with change in FEV₁ with age (Figure 4.4). Using the Spearman Rank Test, we observed a marginally significant relationship between change in FEV₁ and age. Other data also suggest that the Yanayo cookstove has a greater impact on the respiratory health of younger women. Specifically, we observed a relationship, albeit not significant, between improvements in the number of days without chest trouble and age ($R = 0.4$, $p = .17$, $n = 13$). Similarly, improvements in FEV₁ were correlated with improvements in the number of days without chest trouble ($R = 0.61$, $p < 0.03$, $n = 13$), but were not correlated with other respiratory symptoms.

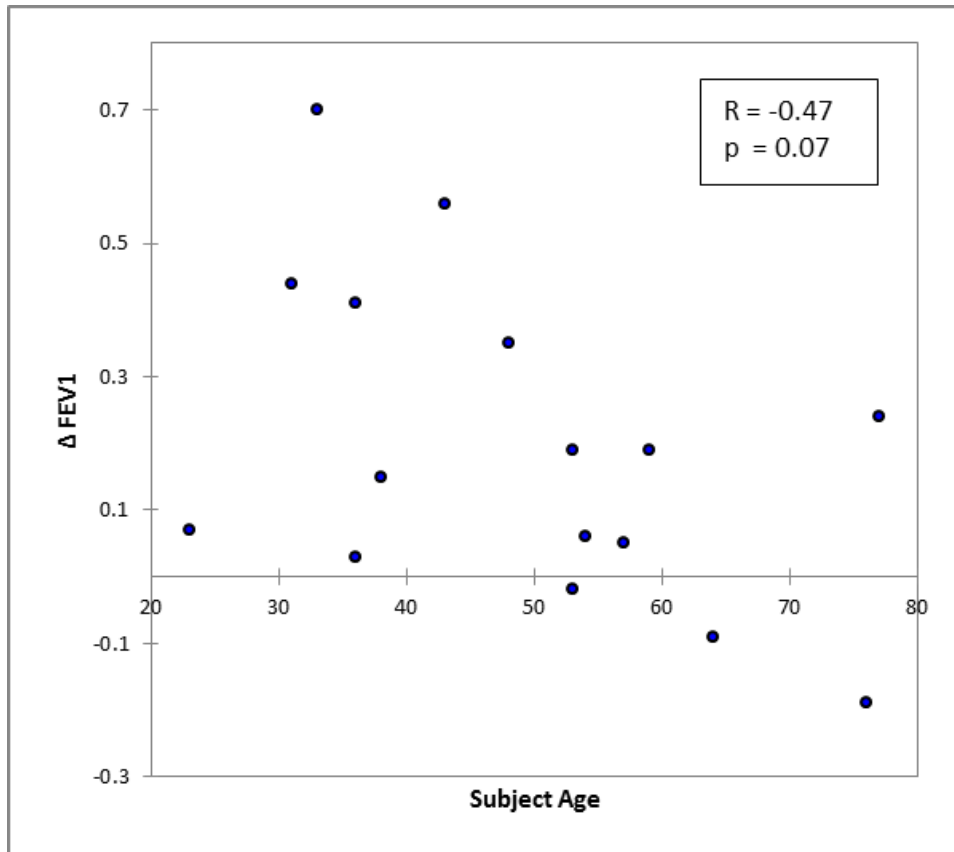


Figure 4.4. Change in FEV₁ with age

4.5 Discussion

Our study of the health effects of an improved cookstove intervention in rural Bolivia indicates that kitchen CO levels are correlated with kitchen PM levels and were therefore used to assess exposure in this study. Similar results were found by Naeher and colleagues (2001) in Guatemala who used PM pump and filter data to correlate CO and PM, a more exact method for measuring PM. Results indicate that households using the Yanayo stove had a mean reduction of kitchen CO levels of 80% and a mean increase in FEV₁ of 9.3%. FVC and FEV₁/FVC ratios also increased at the one year follow-up, but were not statistically significant. As Alexander and colleagues (2012) previously reported, the prevalence of self-reported respiratory symptoms in this population was reduced one year post- intervention. Improvements in FEV₁ were correlated

with improvements in the number of days without chest trouble, but were not correlated with other respiratory symptoms.

Several studies have evaluated household carbon monoxide levels before and after improved cookstove interventions [60, 130, 131]. While our results are consistent with baseline kitchen CO levels found in these studies, our data suggest greater reductions in kitchen CO levels post implementation of the Yanayo cookstoves. Other studies report reductions between 40 – 70% to post intervention levels between 8 ppm and 3 ppm [60, 130, 131]. In our study, mean kitchen CO levels were reduced 80% to a range of 0.2 to 6.5 ppm with a mean value of 2.0 ppm.

Living at high altitudes has been associated with higher than predicted lung function values [18, 23, 25, 26, 132, 133]. In a small randomized cross-sectional study, Rinne et al. evaluated lung function in women and children using both liquid petroleum gas and biomass fuels in a high altitude region in Ecuador [18]. Their study of women with a mean age of 45 found no difference in lung function between LPG users and biomass users. They did, however, find higher than expected lung function values, as did Romieu and colleagues who studied the respiratory status of young women in Mexico [25]. Although Romieu and colleagues did not see any increase in lung function post-intervention; they did observe significantly less FEV₁ decline among the improved cookstove users than among the open fire users after one year. The lack of improvement in lung function may reflect low usage of the improved cookstove, as only 50% of the women in the intervention group reported using the improved cookstove, and many continued to use both types of stoves, compared to our study which had a greater than 90% compliance rate. Smith-Siversten et al. studied young Guatemalan women in a randomized intervention trial to evaluate the respiratory health effects of introducing an improved stove called the plancha. Their results indicated that the plancha had no statistically significant effects

on lung function within the 18-month follow-up period. Finally, Regalado et al. conducted a cross-sectional survey of women in a high-elevation, rural village near Mexico City. The authors found no significant differences in FEV₁ or FVC in biomass users compared to LPG users, but did see a significantly lower FEV₁/FVC ratio in women cooking with wood stoves compared to those cooking with gas stoves.

Of all of these studies, ours is the only one that observed significant increases in FEV₁ post intervention, as well as suggested increases in FVC and FEV₁/FVC. Our data were compared to validated lung function references for healthy Mexican-American females [134] using the mean height (147 cm) and age (49 years) of the 16 subjects. The mean values for FEV₁ pre-intervention values were 12.6% lower than predicted values, while the mean post-intervention FEV₁ values were only 2.6% lower than the Mexican-American reference population. FVC pre-intervention was slightly lower than predicted (-3.4%); however, FVC values one year post implementation of the Yanayo cookstoves were equal to the reference population predicted values. While our baseline FEV₁ values were lower than those of other high-elevation studies, they were comparable to those of Regalado and colleagues who studied women of relatively the same age and same elevation. Both Romieu et al. and Smith-Sivertsen et al. studied a much younger population [25, 26]. The lower than expected values of our study may be the effect of the lifetime exposure to woodsmoke, which due to the mean age of the study population was, on average, much longer than those found in other studies. In our study, we saw a greater increase in lung function in younger women than in older women. This suggests that chronic exposure to woodsmoke might have a larger, longer-lasting effect on those with a longer lifetime exposure.

To our knowledge, no other studies provided consistent follow-up and training in stove use throughout the year using locally-trained technicians. These technicians, who visited the houses periodically, spent hours with each participant teaching them how to properly use the stove, reduce their fuel usage, and explain the health benefits of the improved cookstoves. The local technicians had good rapport with the community members and thus were most likely able to gain the confidence and trust of the WHHs, ensuring a high level of satisfaction and compliance. This high level of compliance may be why we saw a greater improvement in lung function than other studies such as Pine et al., who only saw a 50% use rate. Additionally, as noted above, our data suggest greater decreases in kitchen CO levels than other studies at the one year follow-up [135]. This considerable reduction in kitchen CO may have also played a factor in the improvements in lung function seen one year post-intervention.

Women reported improvements in some respiratory symptoms but not in others, which indicates that results were not skewed by false answers of improvement to please investigators. The measureable improvements in respiratory health seen in this study but not in other studies may be related to the higher level of use and satisfaction with the Yanayo stove. Local trainers were used to teach how to use the stove and to correct any problems that arose.

Another possible explanation for the increase in lung function is the result of a learning effect of both the subjects and the technicians, but other studies using the same methods did not see an improvement or even saw decreases in lung function which makes this unlikely [17, 18, 25, 26]. It is also possible that the technicians learned how to coach subjects on how to properly attempt the spirometry maneuvers over time. We have evidence, however, that this is not the case, as pre-intervention spirometry measurements were conducted by the same technicians in a nearby community, Piriquina, on 25 women head-of-households directly after finishing all of the

follow-up measurements in Tuquiza. The mean baseline FEV₁ and FVC values in Piriquina were 2.01 L (\pm 0.6) and 2.45 (\pm 0.6), respectively. These values are slightly higher than those found in Tuquiza pre-intervention; however, the women from Piriquina, on average are five years younger and three inches taller than those in Tuquiza; therefore, one would expect to see higher baseline lung function values. Moreover the baseline FEV₁ value in Piriquina is still 140 ml less than the mean post-intervention FEV₁ value in Tuquiza. These data can be seen in the online supplement.

While we did see significant decreases in exposure levels and significant improvements in lung function values, we did not see correlations between the two. There are several possible reasons for this. The first obvious reason is the small sample size. Secondly, it was noted that some women chose to use the new kitchens as bedrooms after receiving the Yanayo cookstove. Women stated that because of the reduction of smoke, they were now able to sleep in a warm room during the winter months. This also provided more sleeping room for larger families. While women do not light the stove at night, they do leave smoldering coal and ashes in the stove overnight in order to cook mote (hominy), one of their main food staples. Another possible reason for the lack of correlation between exposure and health effects is that the daily life of a woman is not captured in household exposure levels, especially in a single 24-hour measurement taken once a year. It is much less common for an older woman to go out with the livestock than younger women, as most have family members tending to their herds. Because of this, in general, older women reported spending more time in the kitchens than younger women. While a very good proxy for particulate matter and to evaluate the reduction in exposure due to the intervention, our mean measured household CO concentrations cannot fully reflect personal exposures to biomass smoke.

Finally, the proximity to other households may have confounded the results. In Tuquiza, houses vary in distance from each other. Households in the community which did not participate in the improved cookstove intervention continued to use traditional, smokier cookstoves at the one year follow-up, some of whom were cooking outside. Study participants living near these homes may have experienced higher than expected exposure levels that were not captured by the kitchen CO concentrations. While these observations were noted, the analysis showed no correlations between proximity of outside pollutant sources and changes in lung function. This is likely due to the small sample size.

In summary, data from this small paired pre – post intervention study suggest that improved coosktoves can improve respiratory health. Even though only twenty subjects were analyzed pre- and one year post-implementation of the Yanayo cookstove, results showed significant improvements in FEV₁ values. Our study had a larger decrease in household CO levels and higher usage of the improved stove than other studies which may have contributed to the ability to detect improved respiratory health. Improvements in respiratory health are not assured just by provision of a better stove; it also must be used most of the time.

CHAPTER 5

SYSTOLIC BLOOD PRESSURE CHANGES IN INDIGENOUS BOLIVIAN WOMEN ASSOCIATED WITH AN IMPROVED COOKSTOVE

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5.1 Abstract

The use of biomass fuels as a primary fuel source is widespread and is linked to significant health effects. Particulate matter-induced increases in blood pressure have been shown to be associated with cardiovascular effects including myocardial infarction and stroke. Few studies evaluating the health effects of indoor air pollution have conducted blood pressure measurements in their assessment. This study evaluated the effects of changes in particulate matter on blood pressure in 28 women head-of-households pre and one year post-intervention of an improved cookstove in a small, indigenous community in rural Bolivia. Blood pressure and kitchen particulate matter measurements were taken in August and September 2009 (pre-intervention) and in a one year follow-up in September and October of 2010 (post-intervention).

Mean systolic blood pressure (SBP) decreased from 114.5 mm Hg \pm 13 to 109.0 mm Hg \pm 9, ($p = 0.014$). Decreases in diastolic blood pressure (DBP) were also seen, but these changes were not significant. Decreases in SBP were correlated with 24-hour, mean kitchen PM levels ($\mu\text{g}/\text{m}^3$) ($R = 0.587$, $p = 0.035$). Somewhat stronger correlations were found between reductions in cooking PM concentrations ($\mu\text{g}/\text{m}^3$) and reductions in both SBP ($R = 0.662$, $p = 0.014$) and DBP ($R = 0.658$, $p = 0.014$). This study is the first to find associations between decreases in both 24-hour mean and mean cooking PM levels and decreases in SBP following an improved cookstove intervention.

5.2 Introduction

Approximately half of the world's population relies on solid fuels combustion for their primary domestic energy needs [1, 78, 136]. In many developing countries, the burning of biomass accounts for almost 50% of domestic energy production and can reach as high as 95% in some lower income countries [2-4]. In these countries, biomass fuels are typically burned in open pit fires or inefficient cookstoves without sufficient ventilation and can result in extremely high levels of indoor air pollution. Typical PM_{10} (particulate matter less than 10 micrometers in diameter) concentrations in homes burning biomass fuels ranges between 200 to 5000 $\mu\text{g}/\text{m}^3$ [2]. Studies have shown that indoor air pollution from household combustion of biomass fuels in developing countries is linked to acute respiratory infections [11, 12], chronic obstructive pulmonary disease [7-9] asthma, and other health problems [61, 75]. In 2004, global mortality due to indoor air pollution from solid fuels was estimated at 1.6 million deaths and 3.6% of the global burden of disease was attributed indoor air pollution from the burning of solid fuels [10]. However, the World Health Organization (WHO) Comparative Risk assessment attributes only

respiratory diseases to household use of solid fuels; cardiovascular outcomes were not attributed to solid fuel use [58].

The importance of blood pressure as a risk factor for cardiovascular disease is well documented [137]. In a collaborative study, Lewington and colleagues conducted a meta-analysis of individual data for one million adults in 61 prospective studies. In their findings, even a 2 mm Hg decline in the population mean systolic blood pressure (SBP) could result in about a 10% lower stroke mortality and about 7% lower mortality from ischemic heart disease or other vascular causes in middle age [138]. It is hypothesized that oxidative stress and systemic inflammation are plausible mechanisms for the effects of fine particles on cardiovascular health [34, 139].

Fine particulate matter and secondhand tobacco smoke are associated with cardiovascular morbidity and mortality [27, 28, 30, 31] including increased risk of myocardial infarction and stroke [33, 34] [35]. PM-induced increases in blood pressure have been shown to be associated with these cardiovascular effects [36]. Controlled human exposures have reported increases in blood pressure with concentrated ambient particles [49] and diesel exhaust [50]. A controlled facemask intervention study [51] also reported increased blood pressure associated with filterable PM. Several community observational studies [37-48] suggest that ambient air pollution could raise blood pressure; however, other studies have not replicated these findings [52-57].

Thus far, three studies have demonstrated that the use of improved biomass cookstoves is associated with lower BP [38, 39, 47]. All of these studies conducted between-group comparisons of improved cookstove users compared to those using traditional cookstoves. In

addition, McCracken and colleagues (2009) also evaluated the effects of a chimney stove intervention on BP, seeing changes consistent with their cross-sectional results.

In 2009, we began a study to evaluate the health effects of an improved cookstove intervention in rural Bolivia. We hypothesized that reductions in PM levels during cooking would be associated with reductions in BP. Here we report the relationship between PM concentrations and BP in women who participated in the intervention. In this study, there was a cookstove adoption rate of over 90%.

5.3 Methods

This study was conducted in the northern region of the department of Potosí, Bolivia in a community called Tuquiza. The community of approximately 60 families lies in the sub-Andean valley region of Bolivia. The altitude within the village ranges from 3,000 – 3,350 m, and all inhabitants are subsistence farmers, live in adobe houses with thatched roofs, and are of Quechua descent. Kitchens, which are detached from the house, are of the same type of structure. An initial general questionnaire was administered at baseline to obtain information about general health status, diet, household characteristics, and socioeconomic status. This same questionnaire was administered at the one-year post-intervention follow-up. Other eligibility requirements for this study included women head-of-households (WHHs) that cooked exclusively indoors over open-pit fires without ventilation, lived in the community permanently, did not smoke, and were in good health. Women spend three to eight hours per day cooking and their primary fuel source is hardwood trees and shrubs.

All participants participated in an improved cookstove intervention in September 2009, implemented by the University of Washington chapter of Engineers Without Borders (EWB-UWS). EWB-UWS policy required all recipients of the improved cookstove to construct a 3m x 4m adobe structure which would house the Yanayo stove. The intervention included an improved wood cookstove called the Yanayo cookstove with chimney and a metal roof.

For the duration of the study, all women reported exclusively using wood fuel for cooking and heating. No women reported being pregnant during pre- or post-intervention testing. Their exposure to tobacco smoke was insignificant as it is not culturally acceptable for women to smoke, and men only occasionally smoke and then only while working away from the home. Similarly, occupational exposure to dust was deemed insignificant as women only work in the fields during brief planting and harvesting periods. The community of Tuquiza did not have electricity during the evaluation period and households used small kerosene lamps or candles to light their houses in the evenings. This exposure was deemed relatively small and disregarded in the analysis.

Household exposure measurements and blood pressure measurements were recorded in 28 WHHs August/September 2009 prior to intervention and September/October 2010, one year after cookstove intervention. All community members who desired the cookstove intervention received one whether they participated in the study or not. Of the 63 families in the community, 47 participated in the intervention. Of these, 30 WHHs enrolled in the study, two women died after year one testing. The total number of subjects who participated in the study was 28.

UCB particle monitors were placed in a random subset of 15 women's kitchens both pre- and post-intervention for roughly 24-hour periods to measure particulate matter concentrations.

The UCB monitors, developed by the University of California Berkeley to measure (particulate matter < 2.5 microns) PM_{2.5}, are based on light scattering principles [64, 140]. The UCB particle monitors were placed on the wall, level with the women's heads during cooking, such that the PM levels were most indicative of the exposure levels of the women. Because women are different sizes and use different cooking techniques (i.e., some sit on stools while others sit on the ground), the placement was varied for each individual household. On average, the distance from the floor was 57 cm, and the distance away from the stove was 36 cm. The time of placement and collection were recorded, as were the number of times stoves were used. Hobo brand thermocouples were placed in the chimney of the improved cookstoves to verify cooking times. No exposure measurements were taken within the houses themselves as they are only used for sleeping and are locked during the day. All data presented are based on factory calibration using pine wood smoke and filter based samples of the light scattering signal with gravimetric mass. Post-processing of the data involved baseline adjustment to account for within-machine baseline shifts.

An Omron blood pressure monitor (Model HEM-705CP) was used to measure systolic and diastolic blood pressure and heart rate in the supported left arm of the seated subject after a 10-minute rest. Two repeat measures were taken within 10 minutes of continued rest. Blood pressure of each participant was taken both pre- and one year post-intervention. Blood pressure measurements were taken in the morning hours between 5:00 a.m. and 10:30 a.m. during or directly after cooking. The mean of the repeated measures was used in the final analysis

Two local bilingual (Quechua and Spanish) field workers were trained to take blood pressure measurements and read and translate the questionnaires. The first author was also

present during all testing. Neither field worker was experienced in using the Omron blood pressure monitor but was trained extensively before performing blood pressure measurements.

Normality of measured data was assessed using the Kolomogorov-Smirnov (K-S) test prior to performing parametric tests. Pre- and post-intervention outcomes were compared using paired t-tests, and Pearson correlation coefficients were used to assess the relationships between PM concentrations and blood pressure.

5.4 Results

We enrolled 30 women between the ages of 23 and 81. Of these, 28 completed the study. Subject information, kitchen PM concentration levels and baseline blood pressure levels are presented in Table 5.1.

Table 5.1. Baseline Characteristics

Baseline Characteristics	Mean (SD)	Range
Mean age, years (SD)	52 (18)	23 – 81
Weight, kg (SD)	52 (10)	30 – 70
Height, cm (SD)	147 (7)	133 – 160
BMI (SD)	23.0 (4)	16.7 – 30.7
Blood Pressure at recruitment		
SBP (SD)	114.5 (13)	97 - 141
DPB (SD)	71.2 (6)	64 – 89
Indoor air pollution at recruitment*		
Mean kitchen PM, ($\mu\text{g}/\text{m}^3$) (SD)	240 (210)	23 - 622
Mean cooking PM ($\mu\text{g}/\text{m}^3$) (SD)	780 (440)	87 – 1,652
Peak PM ($\mu\text{g}/\text{m}^3$) (SD)	21,100 (16,400)	1,457 – 63,783

*Includes data from 15 randomly selected homes

5.4.1 Personal Exposures

Using the UCB particle matter monitor, 24-hour mean kitchen PM levels, mean cooking PM levels, and peak PM levels were measured over approximately 24-hour time intervals in 15 randomly selected homes. Kitchen pre-intervention levels ranged from 23 $\mu\text{g}/\text{m}^3$ to 745 $\mu\text{g}/\text{m}^3$ [mean, 240 $\mu\text{g}/\text{m}^3 \pm 210$] and kitchen post-intervention levels ranged from 8 $\mu\text{g}/\text{m}^3$ to 171 $\mu\text{g}/\text{m}^3$ [mean, 48 $\mu\text{g}/\text{m}^3 \pm 41$], an 80 percent reduction ($p = 0.005$). Pre-intervention cooking PM levels ranged from 87 $\mu\text{g}/\text{m}^3$ to 1652 $\mu\text{g}/\text{m}^3$ [mean, 780 ± 440], while one-year, post-intervention cooking PM levels ranged from 39 $\mu\text{g}/\text{m}^3$ to 395 $\mu\text{g}/\text{m}^3$ [mean, 135 $\mu\text{g}/\text{m}^3 \pm 97$], an 83 percent reduction ($p < 0.0001$). Similarly, pre-intervention peak PM levels ranged from 1,457 $\mu\text{g}/\text{m}^3$ to 63,783 $\mu\text{g}/\text{m}^3$ [mean, 21,100 $\mu\text{g}/\text{m}^3 \pm 16,400$]; whereas, one-year, post-intervention peak PM levels ranged from 545 $\mu\text{g}/\text{m}^3$ to 18,710 $\mu\text{g}/\text{m}^3$ [mean, 3,500 $\mu\text{g}/\text{m}^3 \pm 4,600$], an 83% reduction ($p = 0.001$). These data can be seen in Figures 5.1, 5.2, and 5.3.

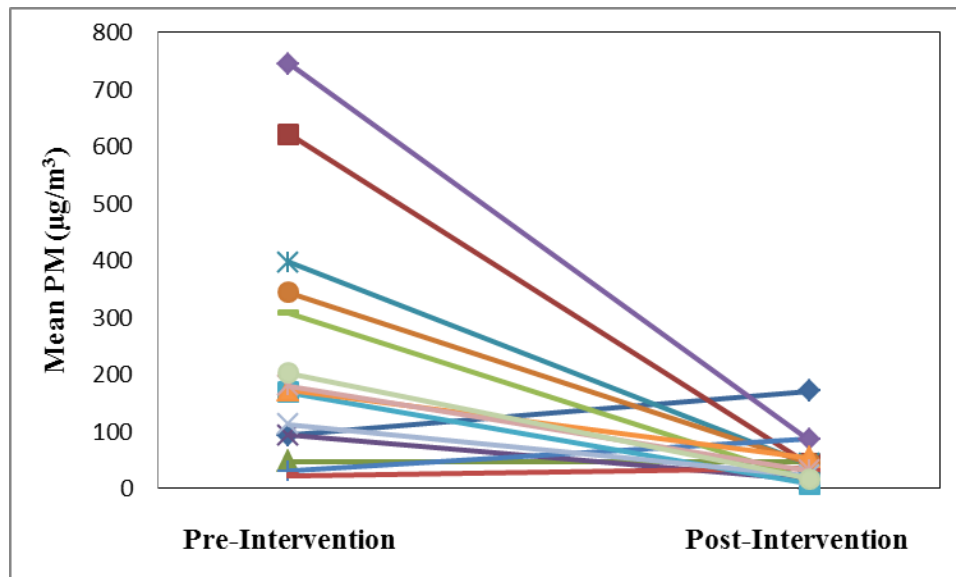


Figure 5.1. Pre- and post-intervention mean kitchen PM concentrations

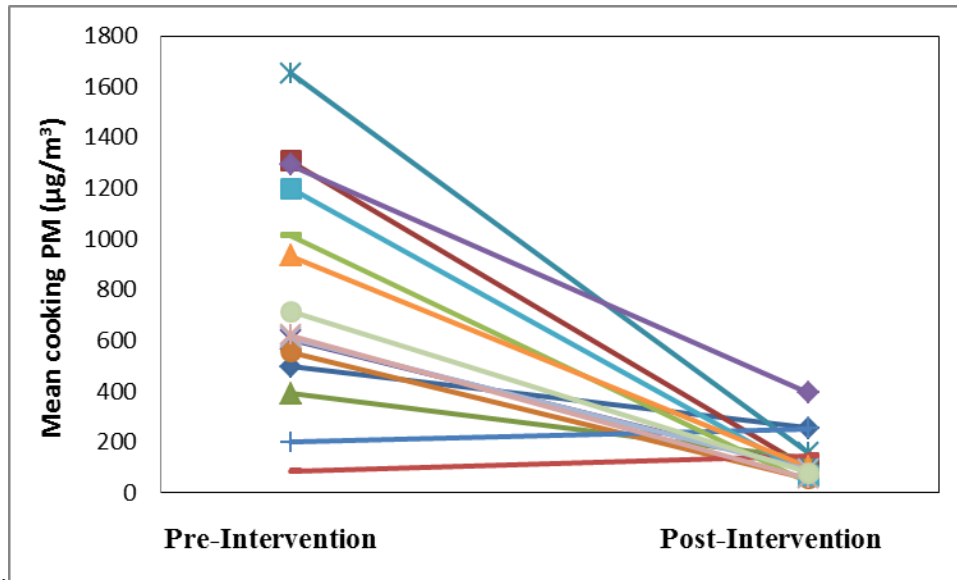


Figure 5.2. Pre- and post-intervention mean cooking PM concentrations

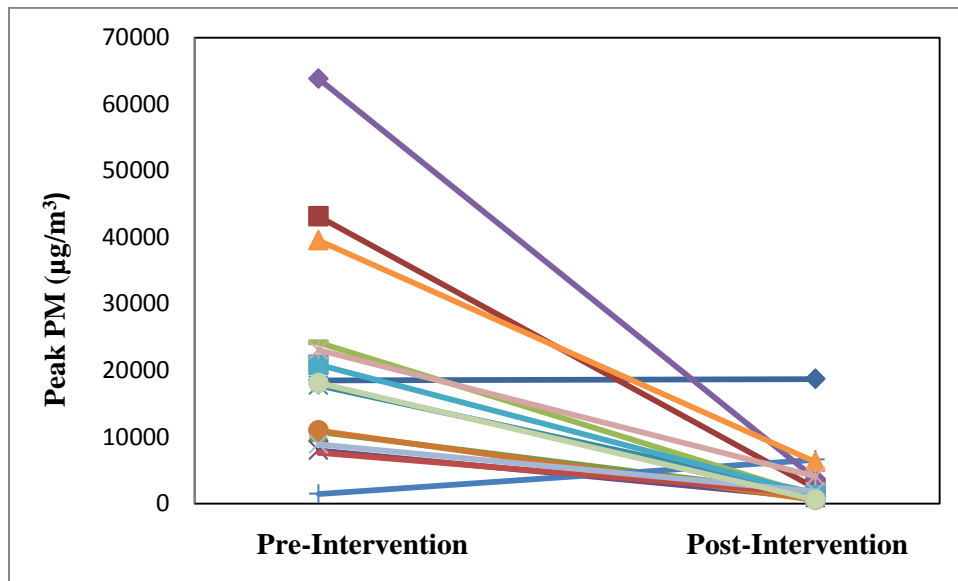


Figure 5.3. Pre- and post-intervention Peak PM concentrations

5.4.2 Blood Pressure

Blood pressure measurements were completed on 28 subjects, pre- and post-intervention.

Mean pre-intervention SBP was 114.5 mm Hg \pm 13 [range, 89.8 mm Hg to 142.0 mm Hg]. One-

year, mean post-intervention was significantly reduced to 109.0 mm Hg \pm 9 [range, 89.0 mm Hg to 134.0 mm Hg], a reduction of 4.8 percent ($p = 0.014$). Similarly mean DBP was reduced from 71.2 mm Hg \pm 6 [range, 62.8 mm Hg to 89.8 mm Hg] pre-intervention to 70.1 mm Hg \pm 8 one-year, post-intervention [range, 56 mm Hg to 88 mg Hg], although the change was not statistically significant (Table 5.2).

Table 5.2. Pre-and post-intervention blood pressure

	N	Pre- Intervention	Post- Intervention	p-value
SBP	28	114.5 \pm 13	109.0 \pm 9	0.01
DBP	28	71.2 \pm 6	70.1 \pm 8	0.5

We then split the subjects into two age groups: 23 – 50 years and > 50 years). We saw statistically significant decreases in SBP in women > 50 years of age ($n = 15$) one-year post-intervention, from 115.2 mm Hg \pm 14.6 to 108.2 mm Hg \pm 12.3 ($p = 0.048$). No significant decrease was seen in women < 50 years of age ($p = 0.165$, $n = 13$). Changes in BP in underweight and normal weight women compared to overweight and obese women were also examined. In the normal weight classes, SBP decreased by 5.9 mm Hg from 111.8 mm Hg \pm 13.8 to 105.9 mm Hg \pm 7.7 ($p = 0.087$, $n = 15$). In the overweight category SBP decreased from 117.7 mm Hg \pm 11.8 to 112.6 mm Hg \pm 12.1 ($p = 0.084$, $n = 13$).

5.4.3 PM – Blood Pressure Associations

Reductions in 24-hour, mean kitchen PM levels ($\mu\text{g}/\text{m}^3$) were correlated with reductions in SBP ($R = 0.587$, $p = 0.035$, $n = 13$). Somewhat stronger correlations were found between reductions in cooking PM concentrations ($\mu\text{g}/\text{m}^3$) and reductions in both SBP ($R = 0.662$, $p =$

0.014, n = 13) and DBP (R = 0.658, p = 0.014, n = 13). These results can be seen in figure 5.4a, 5.4b, and 5.4c.

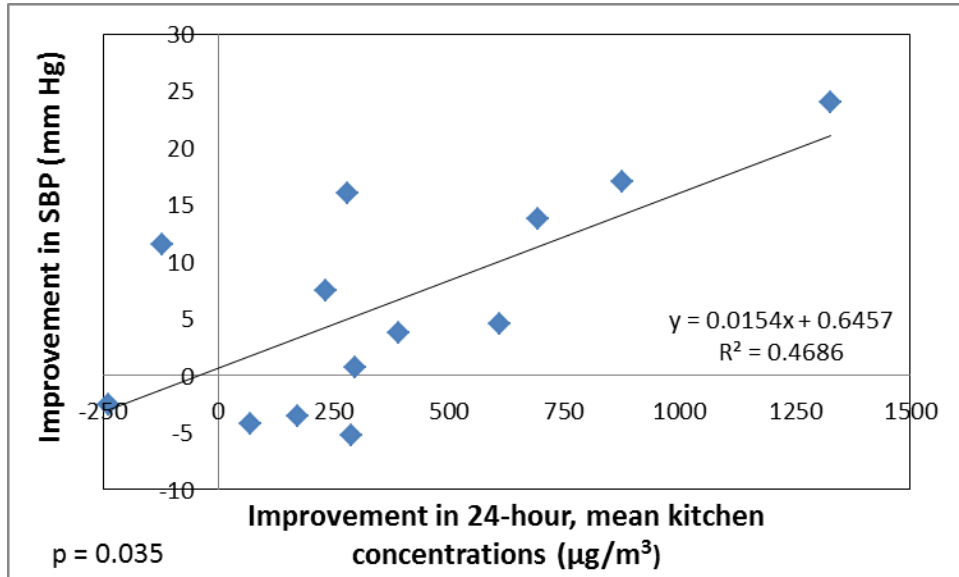


Figure 5.4a. Change in 24-hour, mean kitchen concentrations and change in systolic blood pressure

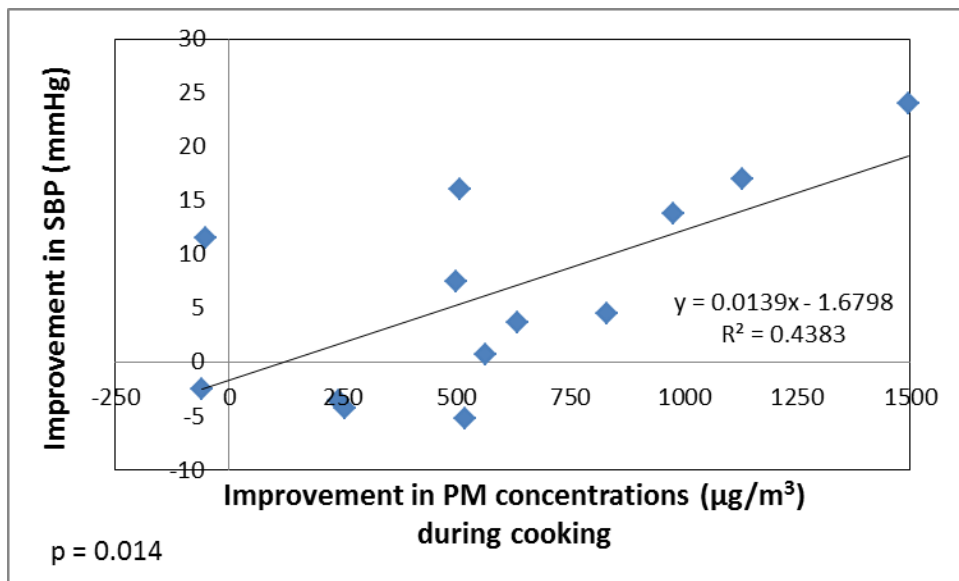


Figure 5.4b. Change in PM concentrations during cooking and change in systolic blood pressure

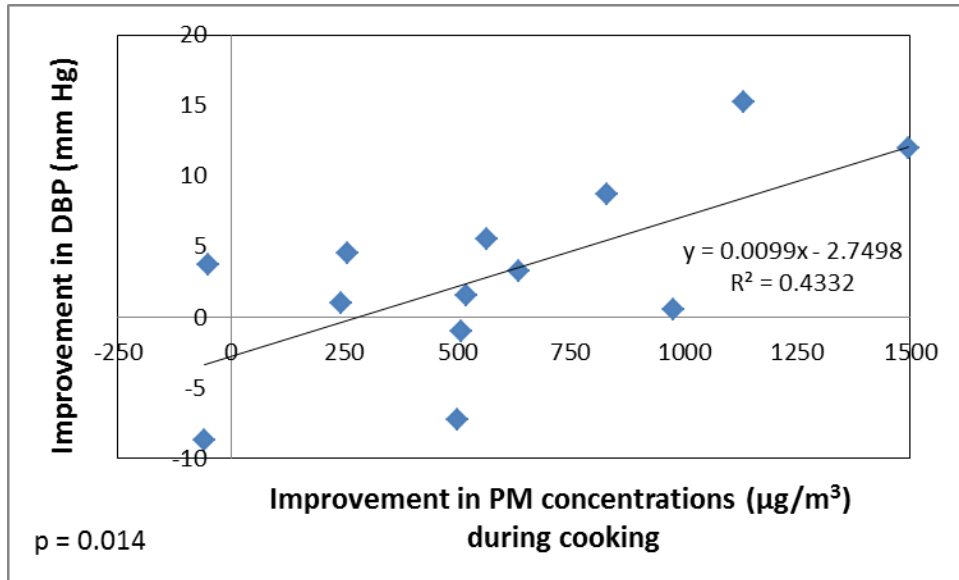


Figure 5.4c. Change in PM concentrations during cooking and change in diastolic blood pressure

5.5 Discussion

Our study of the health effects of an improved cookstove intervention in rural Bolivia indicates that households using the Yanayo stove had a mean reduction of kitchen PM levels of 80%, a mean reduction of kitchen PM levels during cooking of 83%, and a mean reduction in peak PM levels of 83%. SBP also decreased by 4.8% (114.5 mm Hg \pm 13 to 109.0 mm Hg \pm 9, $p = 0.014$) one-year post intervention with the improved cookstove. DBP was also reduced post implementation of the Yanayo cookstove, although the changes were not significant. Decreases in SBP were associated with decreases in 24-hour mean PM cooking levels ($R = 0.587$, $p = 0.035$, $n = 13$). Stronger correlations were found between reductions in cooking PM levels and improvements in both SBP ($R = 0.662$, $p = 0.014$, $n = 13$) and DBP ($R = 0.658$, $p = 0.014$, $n = 13$). This is the first such study to see statistically significant decreases in BP using an

intervention study design and to see significant changes in both SBP and DBP with changes in PM exposure due to intervention. By splitting the data into two age groups (23 – 50 years and > 50 years), we saw statistically significant decreases in women > 50 years ($p < 0.05$). The results were not significant for women 23 – 50 years ($p = 0.17$). We also evaluated the effect of the improved cookstove intervention on two weight classes: underweight or normal weight (BMI range, < 18.5 to 24.9) and overweight or obese (BMI range ≥ 25.0). In this case, we saw significant decreases in SBP post-intervention for both groups ($p = 0.087$ and $p = 0.084$, respectively).

Our results are consistent with previous epidemiologic studies on indoor biomass smoke and BP [38, 39, 47], which found that lower PM exposure was associated with lower BP. Baumgartner and colleagues studied the effects of biomass burning on blood pressure in adult women in rural China. The authors observed positive associations between personal $PM_{2.5}$ exposure and post-exposure measurements of SBP and DBP [38]. This relationship was most apparent among women > 50 years of age where 1-log- $\mu\text{g}/\text{m}^3$ increase in $PM_{2.5}$ exposure was associated with 4.1 mm Hg higher SBP and 1.8 mm Hg higher DBP. Clark et al. conducted a baseline evaluation of 124 women using traditional cookstoves in Guatemala [39]. Although their results were not statistically significant, a 1.78 mm Hg increase in systolic blood pressure was associated with an increase in 48-hour average indoor CO concentrations of 24 ppm. This relationship was stronger among obese patients who had an 8.51 mm Hg increase in systolic blood pressure per 24 ppm increase in 48-hour average CO concentrations. McCracken and colleagues, the only study to evaluate the differences in users with traditional cookstoves compared to those using improved cookstoves, found, in their between-group comparison study,

that use of improved cookstoves was associated with 3.7 mm Hg lower SBP ($p = 0.10$) and 3.0 mm Hg lower DBP ($p = 0.02$) relative to a traditional open-fire control group [47].

In two of these studies, the PM exposure levels were considerably lower than in our study [38, 47], and to the authors' knowledge, no studies have seen positive associations between changes in PM concentrations and changes in BP at the levels seen in our study during cooking periods.

An important strength of this study is its intervention design. Given the high adoption rate of the improved cookstove and the large decreases in exposure, only a small sample size was needed to see significant reductions in blood pressure. Although pre-intervention BP could have been unusually high for unknown reasons, this is unlikely, as similar baseline BP levels (SBP = 115.1 ± 12 ; DBP = 71.8 ± 8 , $n = 33$) were seen in a neighboring community of similar size, socioeconomic status, and culture.

While this work adds to the scientific body of evidence that decreases in BP associated with the installation of improved cookstoves are likely caused by reduction in air pollution exposure, the intervention may alter other factors that influence BP. The pre- and post-intervention comparisons rely on the assumption that BP would not have changed in the study population in the absence of an intervention. In a previous study on the same population, Alexander and colleagues (2012) reported an increase in activity level one year post-intervention of the improved cookstove. It is not clear what impact this had on the reductions in BP of the study population. Changes in diet can affect BP levels, but questionnaire data taken both pre and post-intervention suggest that diet did not change with the introduction of the Yanayo cookstove.

Lack of a control group of women followed over the same period of time, but with the cookstove intervention, is a limitation of the study. Due to the nature of Engineers Without Borders, the organization providing the improved cookstoves, all families within a community that wish to participate in a project must receive a cookstove. That the observed decreases in BP were not due to a temporal trend is supported by the correlation between reductions in PM (both 24-hour mean and mean cooking) and BP. Bias could also have been introduced because neither the participants nor the researchers were blinded, although this is not likely as an automatic blood pressure machine was used.

Summary and Implications

To the authors' knowledge, this is the first intervention study to see statistically significant associations between reductions in PM and reductions in BP due to introduction of an improved cookstove. Positive associations between changes in PM and changes in BP, both SBP and DBP, were seen over a large range in PM concentrations. This study adds to the body of evidence that cardiovascular disease may be a public health burden of indoor air pollution in developing countries and that improved cookstove interventions have significant cardiovascular health benefits.

CHAPTER 6

SUMMARY AND FINDINGS

6.1 Summary

This study was an integrated evaluation in rural Bolivia of user satisfaction, woodsmoke exposure, and health impacts of an improved cookstove design, the Yanayo cookstove. The first stage of the research was to design an improved cookstove that met the needs of community members. The Yanayo cookstove, designed by members of EWB-UWS, was a user-driven design. Maximum usability was ensured by studying the cooking practices in Yanayo, Bolivia and through feedback from community members. After several redesigns, the final stove design was a compromise of engineering efficiency and usability. The final Yanayo stove design was then used in an intervention study conducted in Tuquiza, Bolivia from July 2009 to October 2010.

The Yanayo cookstove was well-accepted among the recipients, with 95% reporting being moderately or highly satisfied with the new technology and 90% of users adopting the technology as their main cooking device. An extensive education and follow-up program were key features of this intervention study and probably contributed to the high rates of usage.

Both 24-hour PM and CO concentrations were measured in WHHs' kitchens pre-intervention and one-year post-intervention. Mean kitchen PM and CO concentrations both decreased by approximately 80% post-intervention. Mean kitchen PM concentrations decreased

on average from $236 \mu\text{g}/\text{m}^3 (\pm 210)$ to $48 \mu\text{g}/\text{m}^3 (\pm 41)$ ($p = 0.005$) and mean CO concentrations decreased from 10.6 ppm (± 4.3) to 2.3 ppm (± 1.6) ($p < 0.0001$). A correlation was found between mean CO concentrations and mean PM concentrations ($R^2 = 0.71$). Mean cooking PM concentrations and mean peak PM concentrations both decreased by 83% post-intervention. Cooking PM concentrations decreased from $779 \mu\text{g}/\text{m}^3 (\pm 440)$ to $135 \mu\text{g}/\text{m}^3 (\pm 97)$ ($p < 0.0001$). 1-minute peak PM concentrations decreased from $21,100 \mu\text{g}/\text{m}^3 (\pm 16,400)$ to $3,500 \mu\text{g}/\text{m}^3 (\pm 4,600)$ ($p = 0.001$).

To evaluate the overall health impact of the Yanayo cookstove intervention on WHH subjects, three metrics were used. 1) The St. George's Respiratory Questionnaire assesses self-reported impact of respiratory disease on a subject's daily life 2) spirometry, an important tool used for measuring lung function and 3) blood pressure, an indicator of cardiovascular health.

The SGRQ was used to assess the impacts of the improved cookstove on overall respiratory health of the WHHs. Results of the SGRQ show that women using Yanayo stoves with chimneys had significantly improved Activity ($p = 0.0004$), Impact ($p = 0.0003$), and Total SGRQ Scores ($p = 0.0004$) after the implementation of the Yanayo stove. . Although there was no significance change seen in total Symptoms scores post-intervention ($p = 0.2$), there were significant improvements in individual symptoms. A further breakdown of questions contributing to the Symptoms score shows that attacks of wheezing, and severity and length of attacks of chest trouble were all significantly reduced post-implementation of the Yanayo stoves ($p < 0.03$, 0.02 , and 0.001 respectively). There was no statistical difference in frequency of coughing or shortness of breath. However, frequency of productive coughs (bringing up phlegm) was lower post-intervention ($p < 0.06$). The number of days without chest trouble was higher post-intervention as well ($p < 0.07$). A positive correlation was observed between CO

concentrations and SGRQ Activity, Impact, and Total scores. There was no relationship between CO concentrations and the SGRQ Symptoms score.

Spirometry was performed on 20 WHHs pre- and one-year post-intervention. For the mean value pre-intervention and drastically improved post-intervention. Data from this subject were removed, leaving 16 subjects with acceptable data, the mean FEV₁ value for the 16 subjects increased from 1.85 L (\pm 0.6) to 2.16 L (\pm 0.7) ($p < 0.005$). The FVC values for the 16 subjects improved from 2.53 (\pm 0.7) pre-intervention to 2.65 (\pm 0.7) post-intervention ($p = 0.2$). The mean FEV₁/FVC ratio post-intervention value was 0.02 higher with post-intervention ratios increasing from 0.79 (\pm 0.1) pre-intervention to 0.81 (\pm 0.1) ($p = 0.3$) post-intervention.

We observed a marginally significant relationship between change in FEV₁ and age ($R = -0.47$, $p = 0.07$), with younger women experiencing greater improvements in FEV₁ post-implementation of the Yanayo cookstove. Other data also suggest that the Yanayo cookstove had a greater impact on the respiratory health of younger women. Specifically, we observed potential signs of improvements in the number of days without chest trouble and age ($R = 0.4$, $p = 0.17$, $n = 13$). Similarly, improvements in FEV₁ were correlated with improvements in the number of days without chest trouble ($R = 0.61$, $p < 0.03$, $n = 13$), but were not correlated with other respiratory symptoms.

Improvements in BP were also seen post-intervention with the Yanayo cookstove. Blood pressure measurements were completed on 28 subjects, pre- and post-intervention. Mean pre-intervention SBP was 114.5 mm Hg (\pm 13). One-year, mean post-intervention SBP was significantly reduced to 109.0 mm Hg (\pm 9), a reduction of 4.8 percent ($p = 0.014$). Similarly

mean DBP was reduced from 71.2 mm Hg (± 6) pre-intervention to 70.1 mm Hg (± 8) one-year, post-intervention, although the change was not statistically significant.

We saw statistically significant improvements in SBP in women > 50 years of age one-year post-intervention ($p = 0.048$), but not in women < 50 years of age ($p = 0.165$). There was no difference by weight.

A correlation was found between decreases in 24-hour, mean kitchen PM levels ($\mu\text{g}/\text{m}^3$) and decreases in SBP ($R = 0.587$, $p = 0.035$), one-year, post-intervention. Slightly stronger correlations were found between reductions in cooking PM concentrations ($\mu\text{g}/\text{m}^3$) and decreases in both SBP ($R = 0.662$, $p = 0.014$, $n = 13$) and DBP ($R = 0.658$, $p = 0.014$).

6.2 Conclusions

This study reported both better health outcomes compared to other interventions studies which may have been due to much higher than previously reported usage rates. The higher usage rates may have been due to the attention paid to individual user input, education and follow-up. Although no direct correlations can be made between these factors and compliance rates, this is the first study to report such high rates of adoption. In other studies, compliance rates were either not reported [26] or they reported low adoption rates [25]. While other studies reported economic status and education levels as factors that inhibit rates of adoption of improved cookstoves [85, 90], the results of this study demonstrate that while economic status may preclude some families from purchasing an improved cookstove, it does not necessarily affect compliance.

The SGRQ has been widely used to assess HRQoL; however, this study is the first use of a respiratory HRQoL assessment to determine the impact of reducing indoor air pollution via a cookstove implementation. Women cooking on new Yanayo stoves had significantly better respiratory health-related quality of life post-intervention. Implementation of Yanayo stoves reduced air pollution exposures as measured by CO levels and produced a concurrent improvement in SGRQ scores. These results suggest that indoor air pollution from poorly vented stoves leads to detrimental effects on women's respiratory health-related quality of life which can be ameliorated by improving stove technology and ventilation.

In addition to seeing improvements in SGRQ scores, this study is the only one that has observed significant increases in FEV₁ post intervention, as well as suggestive increases in FVC and FEV₁/FVC. These data were compared to validated lung function references for healthy Mexican-American females [134] using the mean height (147 cm) and age (49 years) of the 16 subjects. The mean values for FEV₁ pre-intervention values were 12.6% lower than predicted values, while the mean post-intervention FEV₁ values were only 2.6% lower than the Mexican-American reference population. FVC pre-intervention was slightly lower than predicted (-3.4%); however, FVC values one year post implementation of the Yanayo cookstoves were equal to the reference population predicted values. The lower than expected values of our study may be the result of lifetime exposure to woodsmoke, which due to the mean age of the study population was, on average, much longer than that in other studies [25, 26]. In our study, we saw a greater increase in lung function in younger women than in older women. This is consistent with the idea that chronic exposure to woodsmoke would have a greater, longer lasting detrimental effect on those with longer lifetime exposure.

Thus far, three studies have demonstrated that the use of improved biomass cookstoves is associated with lower BP [38, 39, 47]. All of these studies conducted between-group comparisons of improved cookstove users compared to those using traditional cookstoves. In addition, McCracken and colleagues also evaluated the effects of a chimney stove intervention on BP, seeing changes consistent with their cross-sectional results [47]. In two of these studies, the PM exposure levels were considerably lower than in our study [38, 107].

To the author's knowledge, this is the first intervention study to see statistically significant associations between reductions in PM and reductions in BP due to introduction of an improved cookstove. Positive associations between changes in PM and changes in BP, both SBP and DBP, were seen over a large range in PM concentrations. This study adds to the body of evidence that cardiovascular disease may be a public health burden of indoor air pollution in developing countries and that improved cookstove interventions have significant cardiovascular health benefits.

6.3 Strength and Weaknesses of Study Design

Two important strengths of this study are its intervention design and its high woodstove adoption rate. Given the high adoption rate of the Yanayo cookstove and the large decreases in exposure, only a small sample size was needed to see significant improvements in respiratory HRQoL and FEV₁ and significant reductions in SBP.

One unique aspect of this study was the continued interaction of locally trained technicians with the WHHs. To our knowledge, no other studies provided consistent follow-up and training throughout the year using locally-trained technicians. These technicians, who visited

the houses periodically, spent hours with each participant teaching them how to properly use the stove, reduce their fuel usage, and explain the health benefits of the improved cookstoves. The local technicians had good rapport with the community members and thus were most likely able to gain the confidence and trust of the WHHs, ensuring a high level of satisfaction and compliance. This high level of compliance may be why significant effects on respiratory HRQoL, FEV₁ and BP were seen.

Although a small sample size was sufficient to see significant changes in many health endpoints, SGRQ Symptoms scores were not significant. Based on the magnitude of the outcome effect that we observed, this study was underpowered for Symptoms scores but not for the other scores.

One weakness of this study design is that there was no control community to account for changes in lung function due to factors other than woodstove intervention. One possible bias which may account for the increase in lung function is the result of a learning effect of both the subjects and the technicians. However other studies using the same methods did not see an improvement or even saw decreases in lung function which makes this unlikely [17, 18, 25, 26, 135]. It is also possible that the technicians learned over time how to coach subjects on how to better perform the spirometry maneuvers. We have evidence, however, that this is not the case, as pre-intervention spirometry measurements were conducted by the same technicians in a nearby community, Piriquina, on 25 women head-of-households directly after finishing all of the follow-up measurements in Tuquiza. The mean baseline FEV₁ and FVC values Piriquina were 2.01 L (\pm 0.6) and 2.45 (\pm 0.6), respectively. These values are slightly higher than those found in Tuquiza pre-intervention; however, the women from Piriquina, on average are five years younger and three inches taller than those in Tuquiza; therefore, one would expect to see higher baseline

lung function values. Moreover the baseline FEV₁ value in Piriquina is still 140 ml less than the mean post-intervention FEV₁ value in Tuquiza.

Another weakness that could have been verified with a control community is that the pre-intervention BP could have been unusually high for unknown reasons, or that there was a temporal trend of reduction in BP. This is unlikely, as similar baseline BP levels (SBP = 115.1 (\pm 12); DBP = 71.8 (\pm 8), n = 33) were seen in Piriquina. Furthermore, an automated BP monitor was used, which minimizes the likelihood of any biases. The most important evidence that this did not occur was the strong correlation between changes in BP and PM. The between-subject variability in exposure acts as a control for other factors, given that this exposure variability for this many subjects is unlikely correlated with other factors affecting BP.

6.4 Suggested Future Research

To further validate the work of this study, an intervention study with a control community or a randomized control trial should be conducted. This would also account for biases that may have been present in this study. Although health impacts of the improved cookstove were seen, a larger sample size would give a study of this type more power.

Indoor air pollution from traditional household cooking is the leading environmental cause of death in the world [115]. As organizations expand their efforts to improve global health and indoor air quality, further research on the impact of improved cookstoves is necessary to ensure that both indoor air quality and health-related quality of life are improved by these efforts. Because of its focus on HRQoL aspects beyond Symptoms, the SGRQ presents a valuable evaluation tool to assess the benefits of improved cookstove interventions.

Associations were seen between both 24-hour mean PM concentrations and SBP and cooking PM concentrations and both SBP and DBP. This poses questions as to whether the affect is acute or chronic. To further investigate this topic, a study design in which repeated BP measurements are taken during cooking sessions is recommended. This would help to determine if the reductions in BP seen in the study are an acute response to large decreases in exposure to PM.

To evaluate the fuel efficiency of the Yanayo cookstove, the WBT was used. While this is a rough tool used to emulate a real cooking session, the controlled cooking test (CCT) would give a better indication of how the Yanayo stove compares to the traditional cookstoves.

Finally, to verify that education, training, and follow-up improve adoption rates, a study design in which a small subset of a cohort is chosen to receive extensive education, training, and follow-up. These results could then be compared to the larger cohort.

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APPENDICES

A. Appendix A: Final Cookstove Design

The foundation of the stove, and the reason for its high efficiency, is the 'Rocket elbow'. Below is an illustration of a Rocket elbow. The first component of the rocket elbow is the shelf that wood rests on while burning; this serves two purposes. The first is to help induce a draft through the stove. As the sticks burn on the shelf, the hot coals and ashes fall and rest on the bottom of the elbow. With no obstructions under the shelf, air is drawn and flows freely through the coals. Secondly, the air then becomes pre-heated before reaching the fire. Less energy is then wasted heating up the air, so the fire can burn hotter and waste less wood. A corollary benefit is that hotter fires burn cleaner, meaning that the shelf results in a cleaner burning, more efficient fire. The optimal location for the shelf is approximately 1/3 of the way up the opening of the firebox.

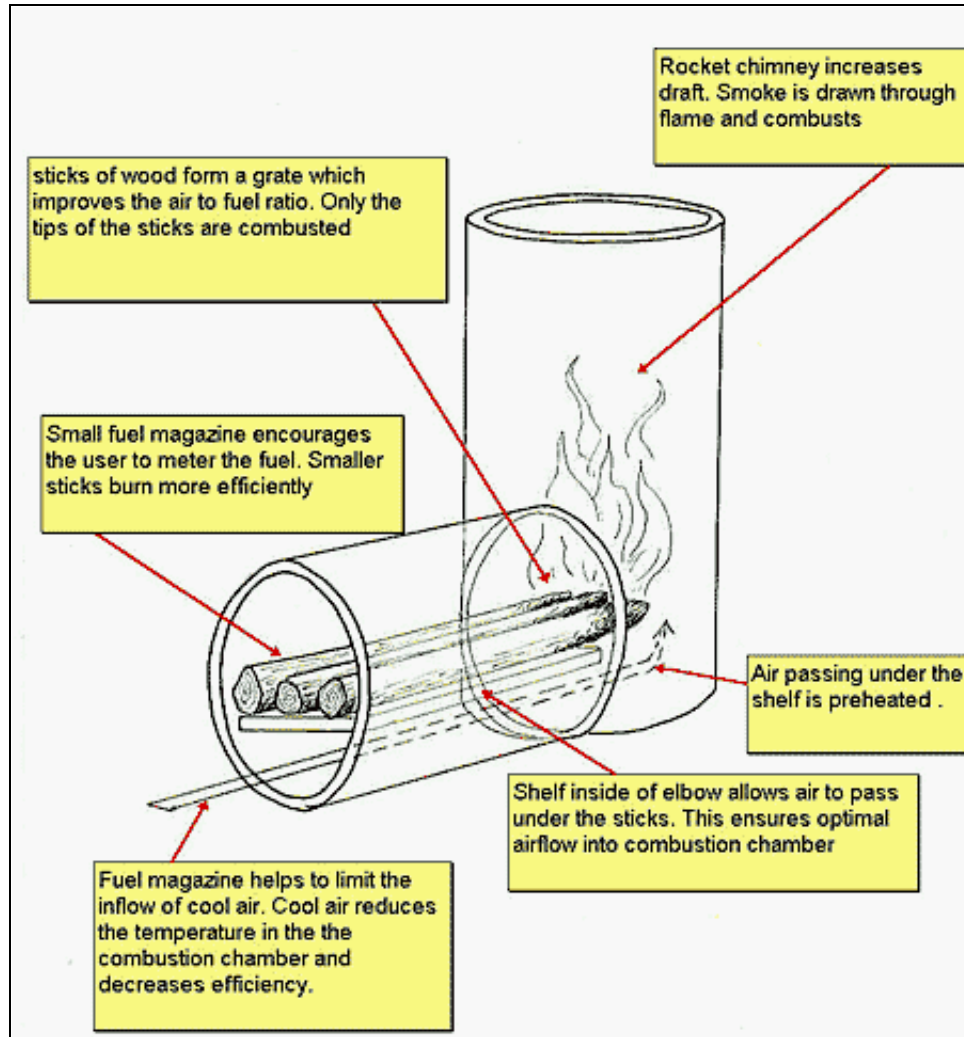


Figure A.1. Rocket Elbow

A.1. Stove Specifications

The Yanayo stove (Figure A.2) is constructed entirely of materials made in the community or purchased in the nearest city. The body of the stove is approximately 37 cm high × 65 cm wide × 100 cm long. The cooking surface on the stove top consists of two pot holes, with a larger hole in the front and with rebar crossbeam to support pots above the fire. The firebox, shown in Figure A.3, opens at the front of the stove. The mouth of the firebox is 16 cm wide at the base and 20 cm high. At a height of 5 cm, the mouth of the firebox widens to 22 cm. Here, a metal plate is placed to hold firewood off the bottom of the firebox to promote air flow

through the stove. The firebox is approximately 42 cm long at its base and 48 cm long at the top and is constructed of fire bricks purchased in the city of Cochabamba. The front 20 cm of the firebox is cubic, and behind this section the firebox opens into a vertical cylinder approximately 30 cm tall. The stove is insulated with porous, broken fire bricks, which surround the pot holes and the whole bricks that form the firebox. This insulating material helps keep the stove warm between uses, reducing fuel consumption.

The body of the stove is comprised of hand-made 22 cm × 10 cm × 8 cm adobe bricks. Each stove requires approximately 80 bricks. The stove also has six larger bricks, 40 cm x 20 cm x 15 cm, which are placed at the back of the stove to provide a stronger foundation.

The two pots holes are placed approximately 20 cm and 50 cm from the front of the stove, with the exact locations depending on the sizes of the pots anticipated to be used for cooking. The first pot is heated by direct fire, and the second by hot air that passes through the channels of adobe below it. These channels are approximately 13 cm wide by 6 cm high and provide space for airflow to the chimney, which chokes down to 10 cm wide by 6 cm high before it exits from the back of the stove.

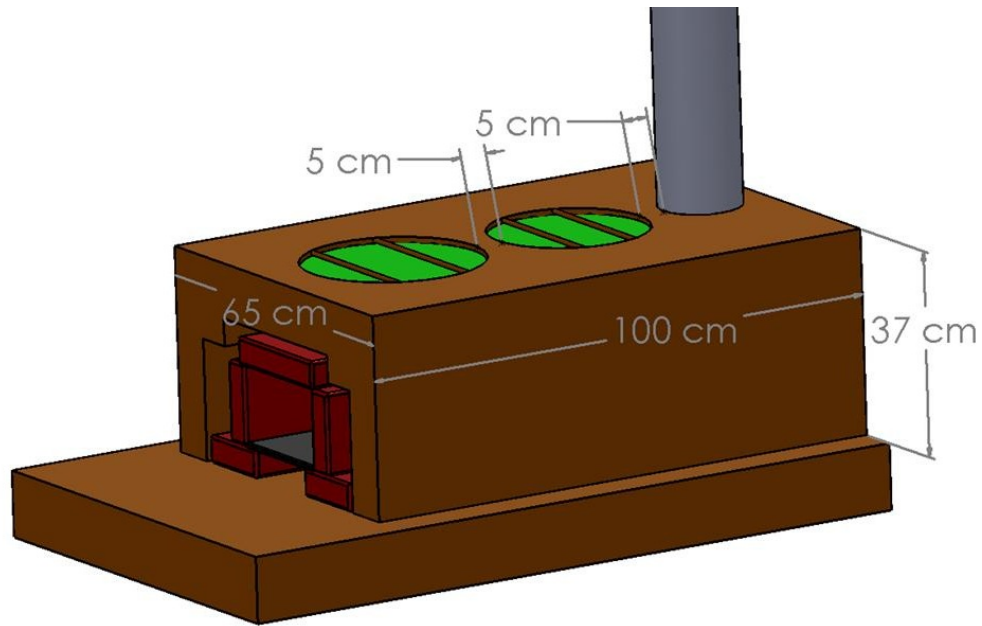


Figure A.2. Yanayo cookstove design

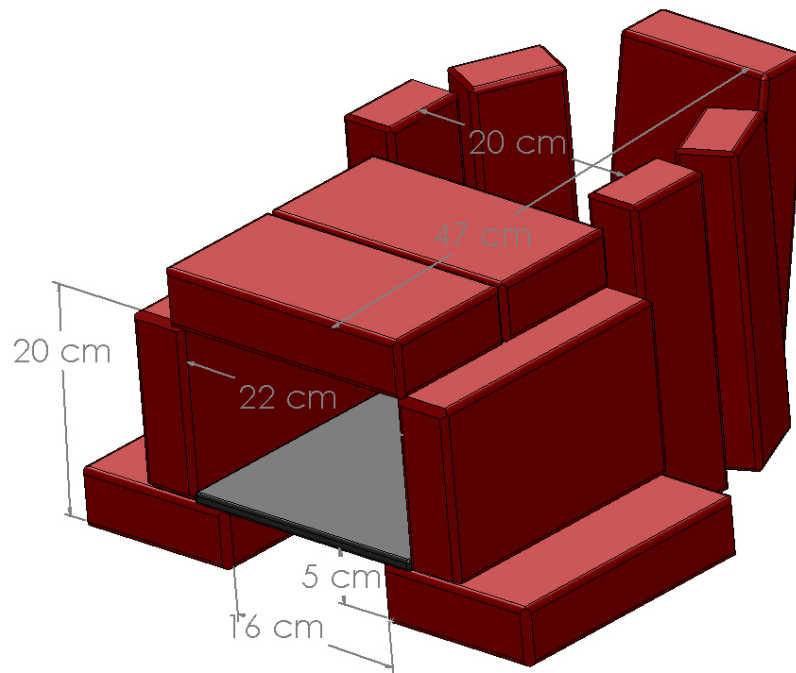


Figure A.3. Yanayo firebox design

The 15-cm-diameter sheet metal chimneys are produced by a metal technician in Cochabamba. The chimney exits vertically through the stove top and has a 45° elbow

approximately 1.5 m up, allowing it to pass through the adobe wall of the kitchen. The chimney extends out of the house and rises above the roofline. The top of the chimney is protected from wind and rain by a conical-shaped sheet metal cap that is manufactured on-site (Figure A.4).

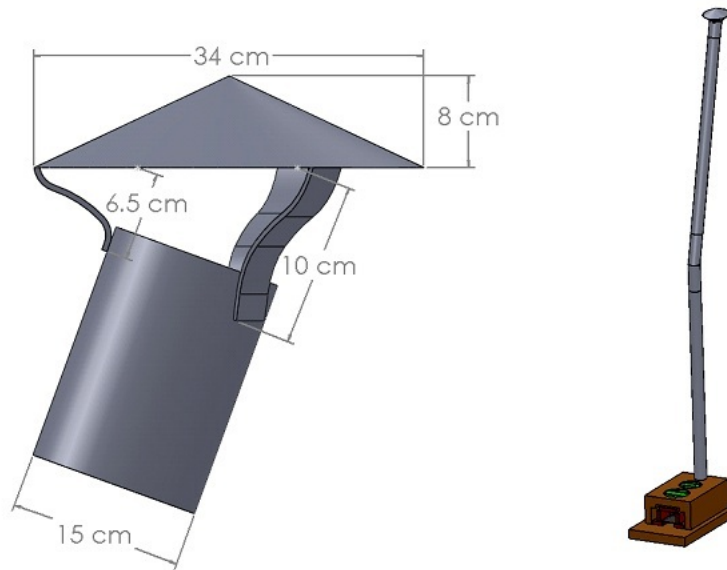


Figure A.4. Yanayo cookstove chimney cap and chimney design.
(Note: chimney is not to scale).

B. Appendix B: Lung Function Raw Data

Table B.1. Tuquiza pre- and one year post-intervention lung function data

Subject #	Pre-Intervention			Post-Intervention		
	FEV ₁	FVC	FEV ₁ /FVC	FEV ₁	FVC	FEV ₁ /FVC
1	1.69	2.47	0.68	1.11	2.28	0.49
	1.74	2.54	0.69	1.03	2.21	0.47
	1.93	2.53	0.76	1.33	2.31	0.58
2	1.72	2.12	0.81	2.17	2.41	0.90
	2.10	2.41	0.87	2.29	2.64	0.87
	1.99	2.33	0.85	2.27	2.61	0.87
3	2.05	2.32	0.88	2.64	3.13	0.84
	2.08	2.45	0.85	2.50	2.92	0.86
	1.49	1.78	0.84	2.38	2.78	0.86
4	1.47	2.23	0.66	2.18	2.64	0.83
	1.49	2.62	0.57	2.13	2.62	0.81
	2.11	2.62	0.81	2.19	2.65	0.83
5	2.20	2.71	0.81	2.23	2.64	0.84
	1.95	2.78	0.70	2.26	2.64	0.86
	1.95	2.43	0.80	2.30	2.83	0.81
6	1.57	2.21	0.71	1.33	1.63	0.82
	1.25	1.54	0.81	1.62	1.98	0.82
	1.50	2.19	0.68	1.55	1.85	0.84
7	3.25	3.96	0.82	1.35	3.54	0.38
	3.17	4.02	0.79	1.60	3.85	0.42
	2.96	4.04	0.73	1.50	3.75	0.40
8	1.65	2.99	0.55	1.63	2.43	0.67
	1.80	3.40	0.53	1.89	2.74	0.69
	1.82	3.40	0.54	1.35	2.88	0.47
9	2.21	3.01	0.73	2.47	2.99	0.83
	2.10	2.40	0.88	2.59	2.81	0.92
	2.58	2.73	0.95	2.65	2.90	0.91
10	0.34	0.39	0.87	1.54	2.81	0.55
	0.34	0.39	0.87	1.60	2.95	0.54
	0.34	0.39	0.87	1.61	3.00	0.54

Subject #	Pre-Intervention			Post-Intervention		
	FEV ₁	FVC	FEV ₁ /FVC	FEV ₁	FVC	FEV ₁ /FVC
11	3.09	3.55	0.87	3.60	4.09	0.88
	3.19	3.61	0.88	3.40	3.98	0.85
	3.16	3.62	0.87	3.42	4.03	0.85
12	1.69	1.99	0.85	1.84	2.67	0.69
	1.67	1.99	0.84	1.82	2.37	0.77
	1.21	1.85	0.65	1.65	2.52	0.65
13	0.66	0.68	0.97	0.88	1.21	0.73
	0.64	0.70	0.91	1.02	1.10	0.93
	0.13	0.13	1.00	0.90	0.96	0.94
14	0.88	1.26	0.70	1.01	1.47	0.69
	1.15	1.64	0.70	1.05	1.57	0.67
	1.24	1.71	0.73	1.05	1.58	0.66
15	1.51	1.90	0.79	1.42	1.88	0.76
	1.45	1.79	0.81	1.33	2.00	0.67
	1.46	1.87	0.78	1.40	1.82	0.77
16	2.86	4.21	0.68	1.11	2.28	0.49
	3.07	4.50	0.68	1.10	2.31	0.48
	3.13	4.31	0.73	1.08	2.28	0.47
17	1.82	2.19	0.83	1.88	2.45	0.77
	1.45	2.37	0.61	1.93	2.38	0.81
	1.90	2.41	0.79	1.96	2.61	0.75
18	2.56	3.00	0.85	2.70	3.40	0.79
	2.55	3.02	0.84	2.77	3.28	0.84
	2.58	3.00	0.86	2.75	3.28	0.84
19	2.43	3.04	0.80	2.28	2.83	0.81
	2.41	2.76	0.87	2.35	2.90	0.81
	2.44	2.78	0.88	2.47	2.83	0.87
20	0.53	3.03	0.17	2.66	3.15	0.84
	2.76	3.26	0.85	2.74	3.27	0.84
	2.22	3.20	0.69	2.63	3.11	0.85