ORIGINAL ARTICLE

Ecological study on solid fuel use and pneumonia in young children: A worldwide association

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ABSTRACT

Background and objective: Pneumonia constitutes one of the major causes of worldwide mortality in young children. Poverty has been traditionally assigned as the underlying factor accounting for these trends. However, the independent role of solid fuel use yielding biomass pollution on pneumonia rates among young children has not been extensively examined.

Methods: Independent socio-economic variables, and the percentage of solid fuel use, tobacco consumption, improved water access source and sanitation facilities were extracted for each country from the available public databases. Multivariate regression analyses were performed to assess potential associations between these recognized risk factors and country pneumonia incidence in young children <5 years of age.

Results: Multivariate linear regression analyses yielded two models that accounted for approximately 87% of the variance, and included solid fuel use, tobacco consumption, sanitation access, measles immunization, life expectancy, access to electricity and the Human Development Index (HDI) as being independently associated with the number of annual pneumonia cases per child <5 years of age.

Conclusion: In this ecological study, current country rates of pneumonia among young children are independently associated with the use of solid fuels. We postulate that interventions aimed at reducing indoor solid fuel biomass pollution through implementation of efficient stoves will translate into meaningful decreases in child mortality and morbidity.

Key words: biomass pollution, children, pneumonia, poverty, solid fuels.

SUMMARY AT A GLANCE

Solid fuels and associated biomass pollution have been implicated in an expanded array of adverse health effects. We performed a worldwide ecological assessment and identified that in addition to poverty and other economic indicators, solid fuels independently contribute to the prevalence of acute pneumonia in young children.

INTRODUCTION

The mortality for acute respiratory infections in children is 30-fold higher in developing countries than in Canada or USA, with annual work days or school days lost to acute lower respiratory infections (ALRIs) being sixfold greater than for those lost to heart attacks in the adult population. Indeed, ALRIs cause more lost life-years than any other disease, since they affect children most severely.

Of the 5 million annual deaths among children reported around the globe, diarrhoeal diseases have long been considered as the foremost cause in developing countries. However, acute respiratory infections are in fact the leading cause of death in the paediatric age range,4,6 with indoor air pollution, crowding and other factors associated with poverty playing major roles in the prevalence of ALRI.4

The first scientific study on the potential damage of atmospheric pollution was reported in 1930.5 Hundreds of people presented with laryngeal irritation, retrosternal pain, coughing fits and ‘dyspnoic breathing characterized by paroxysms and slowed expiration, such as asthma’, with 60 incident deaths.5 There are other subsequent descriptions, such as the 1952 epidemic in London, with approximately 4000 excess deaths occurring, primarily assigned to bronchitis and pneumonia, among other causes.6,7 In 1931, the report on the effect
of air pollution on health published by the Committee on Public Health Relations of the New York Academy of Medicine mentioned ‘the nuisance of smoke is present wherever fuel, rubbish, and gasoline are burned’, along with the observation that humans spend more than 90% of their time indoors. In developed countries, tobacco is the main contributor to indoor pollution. However, in developing countries, the solid fuels used for cooking are the prevailing source of indoor pollution and globally household air pollution is the third highest global risk factor for burden of disease, while it remains the first in South Asia. A recent assessment on the impact of house air pollution on health further reinforces the importance of such factors in global health.

In a systematic review on the use of unprocessed solid fuels and pneumonia risk in children aged <5 years, Dherani et al. found an overall pooled OR of 1.78. Furthermore, countries with the highest rates of pneumonia in young children appear to be those with the highest percentage of solid fuel use in the home. Here, we examined using an ecological study approach whether an independent association at the global level emerges between solid fuel use patterns and the incidence of pneumonia in young children (<5 years of age) even after accounting for other known factors such as poverty.

**METHODS**

This ecological study evaluated potential associations between socio-economic variables and pneumonia incidence in children younger than 5 years of age using risk factors that have been historically reported in the literature as being either directly or indirectly associated with a higher incidence of disease, morbidity or mortality rates (Fig. 1). The selection of pneumonia in young children as the outcome of interest was predicated on existing knowledge indicating that respiratory infections play a key role in the overall mortality in this age group.

From an operational standpoint, we classified the variables into five categories: indoor pollutants (solid fuel use and tobacco usage), sanitation and water access, economics (per capita income and poverty index), education (girls net enrollment ratio in primary education) and quality of life (measles immunization, life expectancy, electricity access and Human Development Index (HDI)). More comprehensive definitions for each of these factors are provided in Appendix S3 (Supplementary Information).

Data analysis was performed using commercially available statistical software (StataCorp. Stata Statistical Software: Release 14. 2015. College Station, TX: StataCorp LP). We performed an initial exploratory analysis which assessed for significant bivariate correlations between each one of the variables and pneumonia annual case rates in young children (see Table 1). Multivariate regression analyses were then conducted on the data set, while also examining for normality of residuals, independence of errors, homoscedasticity (Breusch–Pagan/Cook–Weisberg Test), multicollinearity (variance inflation factors (VIFs)) and model specification (Ramsey RESET test and Tukey’s one-degree-of-freedom test). The linearity assumption was tested via the augmented partial residual plot. We also reported standardized beta coefficients, which tell us how many SDs the outcome variable will change as a result of one SD change in the independent variable thus allowing for in-model ‘importance’ comparisons. To evaluate each variable for non-linear components, we used the

**Figure 1** Flow diagram of database search and analyses.
STATA module curve fit, as developed by Wei,\(^2\) which produces regression-based curve estimation statistics for more than 35 different models. Imputation was carried out based on regional means. For quartile analysis, we applied the Mann–Whitney’s test of medians.

### RESULTS

The initial exploratory analyses of the data examining potential associations between various country-based socio-economic variables and pneumonia rates in young children are summarized in Table 1. The values per country data set for every variable used and the World Health Organization (WHO) region are presented in Appendix S1 (Supplementary Information) and Figure 2. There was a very strong association (>0.8) between episodes of pneumonia in children-year with solid fuel use, sanitation access, electricity access, life expectancy and HDI. A strong correlation (0.6–0.8) was also identified for water access, per capita income and measles immunization, while there was only a moderate (0.4–0.6) correlation with tobacco-use prevalence and girl education. Full bivariate correlations for all items are presented in Appendix S2 (Supplementary Information). As every association was statistically significant at the 0.05 level, we proceeded to evaluate the mixed effects of these variables in the context of the

| Variable                                      | Correlation | \(P\)  | \(n\)  |
|-----------------------------------------------|-------------|-------|-------|
| Prevalence of solid fuel use                  | 0.8607      | <0.0001 | 191   |
| Prevalence of tobacco use                     | −0.5231     | <0.0001 | 187   |
| Access to water (%)                           | −0.7469     | <0.0001 | 191   |
| Access to sanitation (%)                      | −0.8678     | <0.0001 | 191   |
| Per capita income                             | −0.6125     | <0.0001 | 191   |
| Primary education enrolment                   | −0.594      | <0.0001 | 191   |
| Children measles immunization (%)             | −0.633      | <0.0001 | 191   |
| Life expectancy                               | −0.8039     | <0.0001 | 191   |
| Electricity access (%)                        | −0.8282     | <0.0001 | 191   |
| Human Development Index (HDI)                 | −0.8912     | <0.0001 | 191   |
| Poverty (%)                                   | 0.6312      | <0.0001 | 103   |

Figure 2 World frequency maps illustrating country pneumonia rates in young children (A; Reproduced from Rudan et al.,\(^{21}\) (CC BY IGO 3.0)) and solid fuel use (B; Reproduced from ChartsBin.com,\(^{22}\) with permission).
outcome variable, that is, pneumonia in children <5 years of age.

We observed a positive relationship between solid fuel use and pneumonia episodes per child-year in every country (Fig. 3A). We further categorized the solid fuel use by quartiles (Fig. 3B), and found significant differences across such quartiles for episodes of pneumonia per child-year ($P < 0.05$) except for the first and the second quartiles ($P = 0.1708$). Thus, children living in countries with the highest solid fuel use exhibit a sevenfold increase in the frequency of pneumonia episodes per year than children living in countries with the lowest solid fuel use (see also Fig. S1 (Supplementary Information) for regional patterns) of the relationship between solid fuel use and pneumonia rates.

Two multivariate models were constructed. Both models (Models A and B; Table 2) show a significant relationship between solid fuel use and pneumonia cases per year. Since HDI measures education, income and life expectancy, we ran Model A with each of these components included individually, while in Model B, HDI was used as the composite measure. When insufficient data for poverty analysis occurred ($n = 103$), income per capita was used as a proxy variable. Model A shows that both income and the interaction with solid fuel use have no significant correlations with pneumonia in children ($P = 0.852$ and $0.404$, respectively). Model B also shows no significant interaction between HDI and solid fuel use ($P = 0.318$). Even in a basic model which includes only solid fuel use, income per capita and the interaction between them as independent variables against pneumonia episodes per child-year, only solid fuel use emerged as statistically significant ($P < 0.05$). Indeed, higher HDI were associated with reduced pneumonia rates, but HDI was not associated with solid fuels use (Table 2, Model B). Similarly, there were no associations between pneumonia rates and girl education or water access. Measles immunization, access to electricity, tobacco-use prevalence and sanitation access were all significantly associated with pneumonia rates in children <5 years of age (Table 2). Although a moderate correlation emerged between per capita income and episodes of pneumonia per child-year (Table 1), this association did not persist in the multivariate regression model (Table 2, Model A). However, life expectancy showed a significant association with pneumonia rates, which persisted in the multivariate regression model (Tables 1,2 (Model A)).

Based on beta coefficients, both Models A and B showed that solid fuel use was ranked highest in the relative contribution to the model (Table 2). In Model B, HDI was ranked highest over all other significant variables, with solid fuel use being a close second. Both Models A and B showed similar correlation coefficients ($R^2$ of 0.874 and 0.868, respectively), and the overall contribution of solid fuel use for each of the models was also similar (Table 2).

**DISCUSSION**

This ecological study shows that there is a worldwide association between reported national rates of pneumonia in children <5 years of age with corresponding national prevalence of solid fuel use. Previous reports on pneumonia rates in developing nations were associated with low socio-economic status, and were a strong contributor to morbidity and mortality in children.\textsuperscript{15,24} The current ecological approach however suggests that per capita income per se is not correlated with pneumonia rates or with solid fuel use. Indeed, using a multivariate model that accounts for >87% of the variance in pneumonia rates, we found that for every one SD increase in the use of solid fuels, a 0.3 SD increase in the rates of pneumonia in children <5 years of age would be anticipated.

This study was not intended to provide an in-depth discussion of the relationship between solid fuel use and pneumonia rates within each country and region, but rather represents an attempt to demonstrate the basic empirical relationship between these two variables across countries through the use of ecological methods. Our ecological study has some limitations: First, because the relationship between solid fuel use and pneumonia was examined cross-sectionally, we cannot conclude that solid fuel use reductions will lead to parallel reductions in child pneumonia rates. This hypothesis should however be...
prospectively tested through interventional campaigns aimed at reducing the burden of solid fuel use. Second, because this study was ecological in nature, no inferences can be drawn about a specific type of solid fuel use and the odds of pneumonia. Third, malnutrition and low weight at birth were not included in these analyses due to insufficient availability of data.

We found no evidence for an association between solid fuel use and per capita income. However, even though economic development has been accompanied by a characteristic energy transition from one major fuel source to another,25 economic development per se does not necessarily translate into individual prosperity and income equality. Thus, per capita income is therefore not informative on a country’s spending habits including how citizens are achieving their energy needs.26 In this setting, other factors may also be operational. For example, Park and Shin found that by increasing primary schooling along with improvements in law and order, financial development becomes more effective in reducing inequality.27 Notably, no evidence for a significant correlation between per capita economic growth and increased life expectancy has consistently emerged.28 Notwithstanding, global efforts to fight poor sanitary conditions in the least developed countries can be highly effective, but may not necessarily account for a causal association between unfavourable health conditions and poverty.29

The HDI is a statistical tool used to measure a country’s overall achievement in its social and economic dimensions. It is more than simply a poverty measure, and represents a summary measure of average achievement in three key dimensions of human development: a long and healthy life, being knowledgeable and having a decent standard of living measured by per capita income. The HDI is the geometric mean of normalized indices for each of the three dimensions, but does not reflect on inequalities, poverty, human security or empowerment.30,31 Interestingly, both tobacco use and HDI were inversely correlated with the corresponding national rate of pneumonia. Evidence for significant associations
between HDI and tobacco consumption have been previously identified which may account for the similar directionality of these two risk factors. 

In contrast, the direct correlation between solid fuel use and pneumonia was not surprising, particularly considering that countries with higher HDI are also less likely to use solid fuel stoves. Similarly, tobacco consumption is associated with more frequent respiratory illnesses among children, who are related to second-hand exposures. However, solid fuel users are unlikely to be tobacco consumers as they do not have sufficient resources enabling the purchase and consumption of tobacco-related products. Historically, high levels of national income should foster early adoption and the spread of smoking because more people can afford tobacco.

Solid fuel use was strongly and linearly associated with pneumonia rates in children <5 years of age. Further separation of nations by solid fuel use prevalence quartiles revealed a sevenfold increase in the rates of pneumonia between the lowest and highest solid fuel use quartiles. Such a relationship was not found for smoking, whereby only when rates of smoking exceeded 40%, an increase in pneumonia cases in children becomes apparent. However, previous work has indicated that the number of cigarettes that the mother smoked per day increased the risk of pneumonia in their children.

Solid fuels are not only the cheapest but are also the most polluting. Cooking with these fuels using traditional stoves will generate a considerable amount of particulate matter and gases, usually leading to a higher intra-domiciliary pollution levels. Traditional biomass stoves are also highly inefficient, using only 10–15% of the fuels energy. The usual air concentration of particulate matter produced by traditional biomass stoves is >1000 times higher than found in urban settings. In autopsies of children who died from non-respiratory causes and were living in houses that had traditional biomass fuel stoves, an increased number of alveolar macrophages (AMs) along with anthracotic pigments in the alveoli and in the septum emerged. The increased susceptibility to respiratory infections associated with solid fuel use has been attributed to reduced mucociliary and macrophage clearance of pathogens. Persistent inflammation will lead to degenerative structural changes in the lung parenchyma, along with decreases in the collectins, Surfactant protein A (SP-A) and Surfactant protein D (SP-D), which contribute to agglutination and growth inhibition of infectious microbes, enhance phagocytosis in macrophages, interact with Toll-like receptors (TLRs) and TLR-associated molecules and modulate functions of neutrophil-derived innate immune molecules. Exposure to particulate matter is also related to epigenetic changes affecting the expression of SP-A, altering its functions and thus contribute to infectious susceptibility. In parallel, disruption of nasal mucociliary clearance (NMC) occurs, leading to accumulation of respiratory secretions, impaired pulmonary function, reduced lung defences and increased risk for infection. NMC time is significantly prolonged in biomass fuel users and facilitates the entry of inhaled pathogens. Furthermore, evidence showing PM2.5-mediated suppression of AM phagocytosis and decrease of natural killer cells in the lung provides an additional mechanism to increased susceptibility to pulmonary bacterial infections.

Ezzati et al. have shown that increased exposure to indoor particulates increases the frequency of ALRI, the risk being highest for exposures around 1000–2000 μg/m³. Risk of pneumonia in young children is increased by exposure to unprocessed solid fuels with ORs as high as 40.65 being reported. Randomizing participants in a study to use of a chimney wood stove or a traditional three-stone fire reduced exposures by 50%, and physician-diagnosed pneumonia by 30%, similar to previous estimates.

The impact of reductions in solid fuel use as a preventive measure of ALRI for children <5 years of age needs to be critically tested. Between 1980 and 2010, the proportion of households relying mainly on solid fuels for cooking decreased from 62% to 41%, but the actual number of persons exposed to solid fuels has remained stable at around 2.8 billion globally during the last three decades, due to concurrent population growth. In many parts of the world, it may be impossible to replace solid fuels for cooking, but aiming at decreasing >90% of exposure, and thus potentially reducing pneumonia risk, is potentially achievable through design and implementation of less polluting solid fuel stoves.

Considering that pneumonia is the leading cause of death among children, any interventions that effectively reduce this huge global burden would be highly desirable. Current findings suggest that programmes aimed at reducing solid fuel use may provide the desired feasibility in the context of pneumonia mortality among young children. However, the purpose of this study was to see if solid fuel domiciliary use would emerge as an independent risk factor for pneumonia in young children, and the findings of this ecological study are supportive of such relationship. In summary, country rates of pneumonia among young children are independently associated with the percentage of the country population using solid fuels. Prospective interventions aimed at reducing indoor solid fuel biomass pollution through implementation of efficient stoves are likely to translate in important decreases in child mortality and morbidity.

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Supplementary Information
Additional supplementary information can be accessed via the
html version of this article at the publisher’s website.

Appendix S1 Data used for analysis.
Appendix S2 Correlation matrix.
Appendix S3 Variable definitions.

Figure S1 Country groupings for the global assessment of dis-
ease burden. Country members of every WHO group are pre-
sented in Appendix S1 (Supplementary Information). (A) Very
low child mortality, very low adult mortality; (B) Low child, low
adult mortality; (C) Low child, high adult mortality; (D) High
child, high adult mortality; (E) High child, very high adult
mortality.