Low-Cost Air Quality Monitoring Methods to Assess Compliance With Smoke-Free Regulations: A Multi-Center Study in Six Low- and Middle-Income Countries

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Abstract

Introduction: Many low- and middle-income countries (LMICs) have enacted legislation banning smoking in public places, yet enforcement remains challenging. The aim of this study was to assess the feasibility of using a validated low-cost methodology (the Dylos DC1700) to provide objective evidence of smoke-free (SF) law compliance in hospitality venues in urban LMIC settings, where outdoor air pollution levels are generally high.

Methods: Teams measured indoor fine particulate matter (PM₂.₅) concentrations and systematically observed smoking behavior and SF signage in a convenience sample of hospitality venues (bars, restaurants, cafes, and hotels) covered by existing SF legislation in Mexico, Pakistan, Indonesia, Chad, Bangladesh, and India. Outdoor air PM₂.₅ was also measured on each sampling day.

Results: Data were collected from 626 venues. Smoking was observed during almost one-third of visits with substantial differences between countries—from 5% in India to 72% in Chad. After excluding venues where other combustion sources were observed, secondhand smoke (SHS) derived PM₂.₅ was calculated by subtracting outdoor ambient PM₂.₅ concentrations from indoor measurements and was, on average, 34 μg/m³ in venues with observed smoking—compared to an average value of 0 μg/m³ in venues where smoking was not observed (P < .001). In over one-quarter of venues where smoking was observed the difference between indoor and outdoor PM₂.₅ concentrations exceeded 64 μg/m³.

Conclusions: This study suggests that low-cost air quality monitoring is a viable method for improving knowledge about environmental SHS and can provide indicative data on compliance with local and national SF legislation in hospitality venues in LMICs.

Implications: Air quality monitoring can provide objective scientific data on SHS and air quality levels in venues to assess the effectiveness of SF laws and identify required improvements. Equipment costs and high outdoor air pollution levels have hitherto limited application in LMICs.
This study tested the feasibility of using a validated low-cost methodology in hospitality venues in six LMIC urban settings and suggests this is a viable method for improving knowledge about SHS exposure and can provide indicative data on compliance with SF legislation.

Introduction

Protection From Exposure to Tobacco Smoke

Tobacco kills nearly 6 million people globally every year.4 The Framework Convention on Tobacco Control is a global treaty that sets out the measures that governments are required to take to address the causes and consequences of this epidemic, and to date 180 countries are Parties to the Convention. Article 8 of the Framework Convention on Tobacco Control obliges governments to take effective measures to protect their populations from exposure to tobacco smoke.2 There is no safe level of exposure to secondhand smoke (SHS)3 and consequently the Article 8 Guidelines recommend that Parties implement comprehensive indoor smoking bans within 5 years of the Treaty coming into force in their countries.4 Major progress has been made in that 84% of Parties have implemented smoke-free (SF) provisions and many countries have legislation requiring a complete ban on smoking in public places, yet enforcement remains a challenge in many countries, with few Parties yet achieving the maximum implementation score for Article 8.5 Efforts to strengthen enforcement will benefit from a clear understanding of the level of compliance in these countries.

Methods to Assess SF Compliance

There are two established methods for assessing compliance with SF law.6 One approach is to conduct a structured observational survey of smoking and related matter, for example, presence of smoking materials, smoke/smoking smell, and signage. This has been successfully employed across a range of countries and used to support policy strengthening efforts.7,8 Key benefits include low costs and being relatively straightforward to conduct, train data collectors, and analyze data. The other method is to use Air Quality Monitoring (AQM) equipment to objectively measure the level of particulate matter (PM) concentrations that derive from SHS (PM_{2.5}). The major advantage of this method is that it can provide policymakers and other stakeholders with objective scientific data on SHS and air quality levels in venues thereby to assess the effectiveness of SF laws and any need for improved implementation and enforcement of the law. Additionally, well-designed research to gather objective air quality data enables comparison with established health-based limits.9 Disadvantages previously identified were the high cost of the instruments required, high noise levels that were problematic for covert use for compliance checks in hospitality venues, and also the considerably greater training required to use the equipment and analyze data than the observational survey method.

Measurement of SHS-Derived PM

The most commonly used methods for assessing SHS concentrations in indoor environments, including in offices, homes, cars, and hospitality venues, have been measurement of airborne particulate matter of diameter (PM) or gas-phase nicotine.10-13 Nicotine measurement incurs substantial laboratory analysis costs and requires extensive sampling periods and so is a less accessible method than PM. Although PM in indoor air can derive from many sources including use of biomass fuel and wood for cooking and heating and outdoor air pollution through open windows, tobacco smoking is generally the most significant source inside buildings when smoking is permitted.14 This is particularly true of urban settings where electricity is the main source of power.15 Most particles produced from tobacco smoking are less than 1 μm in diameter and so PM_{2.5} (fine PM less than 2.5 μm) is the commonly used metric for measuring SHS. A number of studies have demonstrated that ambient fine PM is a risk factor for increased respiratory and cardiovascular morbidity and mortality16,17 leading WHO to develop PM outdoor and indoor air quality guidelines.9 PM_{2.5} and its use as a marker has therefore enabled the public health community to successfully communicate indoor SHS concentrations.9,10,18,19 Real-time measurement has been used extensively in occupational settings to better understand how exposure changes over time and reflects differences in behaviour.9,14-20

Until recently, the majority of AQM studies of SHS concentrations used the TSI Sidepak AM510 Personal Aerosol Monitor (TSI, Shoreview, MN).21,22 As indicated above, limitations include high noise levels and a purchase cost of $3500 USD (2014). Recent research has used the Dylos DC1700 (Dylos Inc, Riverside, CA), a low cost ($450 USD) photometric particle counting device, to assess SHS concentrations in home settings in Scotland23,24 and the United States,21 and measuring relatively low ambient PM_{2.5} concentrations in the United States.26 All these studies have been in high-income countries. At the time of writing, there have been no studies published on the use of this low-cost instrument in low- and middle-income countries (LMICs) or within hospitality venues. Many urban environments in LMICs have high levels of outdoor air pollution and it has traditionally been considered difficult to determine SHS-derived PM_{2.5} (SHS-PM_{2.5}) from these high background levels of PM_{2.5} from other sources, such as diesel exhaust particulate.

The recent availability of an innovative and low-cost methodology to gather such data has potential to add value alongside observational SF compliance studies to provide robust SHS exposure data for discussions with policy makers about the success or otherwise of existing SF legislation. The aims of this study were therefore to determine the feasibility of using the Dylos DC1700 to quantify SHS-PM_{2.5} in hospitality venues in LMIC settings and to use the data generated to assess compliance with SF legislation in cities from across six different LMICs.

Methods

A team of six LMIC-based tobacco control advisors working for the International Union Against Tuberculosis and Lung Disease (The Union) received a 2-day AQM training course. This included training in how to operate a Dylos DC1700 (one provided per collection team), download acquired data, and collecting data in hospitality venues using a protocol similar to that used in studies in high-income countries over the past decade.10 The Protocol included details on venue selection, visit duration, researcher safety, inside/outside air monitoring duration, logging data, assessment sheet instructions, and data transferring (downloading, anonymity of venues [file matching ID] and data storage security).
Site Selection

Measurements were carried out in urban settings in six countries: Mexico (Mexico City), Chad (N’Djamena), Bangladesh (Dhaka), India (Delhi), Indonesia (Bali—various urban centers) and Pakistan (Islamabad). A convenience sample of hospitality venues covered by SF legislation—including hotels, restaurants, bars and cafes was selected using existing local inventories and informants in each country. This study sought to gather as much observational as well as air quality data from each country within the project time period and with the resources available. As such, a sample size was not generated. Approximately 100 venues were identified in each country and 4 to 8 venues were visited per day over a period of 2–4 weeks. Visits took place during peak times according to the local context in each country. Samples purposefully included venues within a 1 hour travelling distance of each local office. No exclusion criteria regarding other sources of PM (eg, open fires, candles etc) were applied during sampling and data collection as precise interior details were unavailable prior to the data collection visit and it was considered desirable to maximize sample size at that point. Venues that recorded obvious combustion sources other than smoking were excluded at the analysis stage to remove venues where non-SHSPM sources may contribute significantly to the measured PM concentrations. Table 1 presents some brief details of current smoking restrictions in each of the six countries where measurements were carried out, together with some geographical data on the main location of sampling.

Data Collection

PM2.5 data were collected with a Dylos DC1700 Air Quality Monitor (Dylos, Inc) over a 4-week period in February/March 2014. This instrument uses a light scattering technique to measure the number of particles in two particle size ranges: more than 0.5 µm and more than 2.5 µm. All data presented in this article relate to particles in the size range between 0.5 µm and 2.5 µm and were generated as mass concentrations using equations specific to SHS aerosol presented in Semple et al. The monitor was placed in a small bag with the inlet protruding to the outside to allow air to be pulled into the device. To prevent airflow resistance space was left around the bottom vent. Researchers visited each venue as customers and carried out sampling in an unobtrusive manner. Covert data collection was agreed upon based on advice from past researchers who highlighted the delays and difficulties that an open approach to owners can present, and who justify the approach as ethical in that it does not involve personal /human data. Venue managers were thus not consented, however researchers carried an official letter describing the study plus evidence of ethical approval and contact details. Data collection was carried out at a table or space within each venue that was as central as possible, at least 1 meter away from any doors, windows, or obvious potential sources of PM2.5. Observational measurements were recorded in addition to PM2.5 in order to yield data comparative data, such as number of patrons, number of cigarettes actively burning, food availability, “no-smoking” signage and presence of other possible PM2.5 sources such as coal fires and candles, using a standardized template every 15 minutes from entry to departure the data. The recording sheet is available—Supplementary File 1, and raw data may be provided on request.

The Dylos were switched on to start the logging process at the beginning of each series of visits and were left to measure and log 1-minute particle number concentrations for the duration of the sampling process. AQM assessment was conducted continuously for a minimum of 30 minutes inside each venue and the device left running between venues to allow PM2.5 measurement in outdoor air to provide comparative data. A minimum of 30 minutes of outside air sampling was undertaken each day. Exact entry and exit time for each venue and time spent outside in ambient air were recorded and provided to those carrying out analysis.

Analysis

Data was downloaded to a PC txt.file using the Dylos Logger software at the end of each sampling day and sent to the analysis teams in Edinburgh and Aberdeen. Dylos particle number concentrations were then converted to equivalent PM2.5 mass concentrations and corrected for nonlinearity of response using a previously published method. Entry and exit times for each venue were matched to the sampling day record sheets and an average PM2.5 concentration was then calculated for each venue. A similar process was followed to generate an outdoor PM2.5 daily average for. Data were entered to a country specific database (Microsoft Excel). This contained PM2.5 measurements and observational record data (observed customer / staff smoking, presence of open fires and candles, “no-smoking” signage, and a subjective assessment of SHS levels on a four-point scale: none/ low/ medium/ high). Feedback graphs presenting real-time measurement data were generated for the local teams to use in future discussions with local policy makers. An example graph is provided in Figure 1.

Ethical Approval

Ethical approval was obtained from the Ethics Advisory Group of the International Union Against Tuberculosis and Lung Disease,

Results

A total of 626 venues were visited across the six countries (Mexico \(n = 80\); Pakistan \(n = 100\); Indonesia \(n = 135\); Chad \(n = 105\); Bangladesh \(n = 96\); and India \(n = 110\)). The most common classification for venues was restaurant (60% \(n = 373\)) followed by bars (14% \(n = 90\)), cafés (12% \(n = 73\)) and hotels (10% \(n = 61\)). A small number were classified as mixed venues or were unclassified by the observer (5% \(n = 29\)). Food was available in the majority of venues (89% \(n = 557\)). The median (Inter-quartile range [IQR]) number of patrons per establishment was 14 (8–25).

Customer smoking was observed in just under a third of venues visited (31% \(n = 193\)) with considerable variation between the six countries. Chad (72% \(n = 76\)) and Indonesia (46% \(n = 62\)) were the countries where smoking was observed most frequently, followed by Pakistan (20% \(n = 20\)) and Mexico (29% \(n = 23\)), with Bangladesh (9% \(n = 9\)) and India (5% \(n = 5\)) having considerably lower rates. Staff smoking in venues was not observed in Mexico or India with a small number of occasions in Bangladesh (\(n = 1\)) and Pakistan (\(n = 4\)). It was more common in Chad (\(n = 16\)) and Indonesia (\(n = 28\)) mirroring the customer smoking observations.

SF signs were evident in the majority of venues visited in Mexico (81% \(n = 65\)) Elsewhere signage implementation was more variable, ranging from 51% (\(n = 49\)) in Bangladesh and 43% in India (\(n = 48\)) to lower rates in Pakistan (29% \(n = 29\)); Indonesia (16% \(n = 22\)); and Chad (9% \(n = 9\)).

PM Measurements

Table 1 shows the median and IQR \(\text{PM}_{2.5}\) inside and outside measurements grouped by country. Outdoor air pollution in all six countries is much higher than would be measured in high income countries such as the United Kingdom, United States, and Australia where outdoor \(\text{PM}_{2.5}\) concentrations tend to be generally less than 20 \(\mu g/m^3\) except during major pollution events or at particularly polluted locations. The median values in Pakistan, Indonesia, Chad, Bangladesh, and India are all above the WHO 24-hour Air Quality Guidance for \(\text{PM}_{2.5}\) (25 \(\mu g/m^3\)) with only Mexico below this limit. \(\text{PM}_{2.5}\) values inside the venues are broadly similar or lower to those outside in Mexico, Indonesia, India, and Bangladesh; concentrations in venues in Pakistan and Chad were markedly higher than those measured outside.

Table 2 shows results for each country after excluding venues where there was an open fire or candles burning (\(n = 157\)) analyzed by the difference between inside and outside \(\text{PM}_{2.5}\) values as measured on that day. Positive values indicate that indoor air was worse than that measured outdoors and therefore suggestive of an indoor source of \(\text{PM}_{2.5}\) emissions.

Table 3 shows analysis by observed smoking (either customer or staff smoking) and compares the inside-outside \(\text{PM}_{2.5}\) value for

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**Table 2.** \(\text{PM}_{2.5}\) Concentrations Measured Inside and Outside Venues by Country

<table>
<thead>
<tr>
<th>Country</th>
<th>Count</th>
<th>(\text{PM}_{2.5}) ((\mu g/m^3)) inside</th>
<th>(\text{PM}_{2.5}) ((\mu g/m^3)) outside</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Median 25th percentile 75th percentile</td>
<td>Median 25th percentile 75th percentile</td>
</tr>
<tr>
<td>Mexico</td>
<td>80</td>
<td>18 14 25</td>
<td>19 10 26</td>
</tr>
<tr>
<td>Pakistan</td>
<td>100</td>
<td>69 44 132</td>
<td>34 30 52</td>
</tr>
<tr>
<td>Indonesia</td>
<td>135</td>
<td>32 12 148</td>
<td>29 12 47</td>
</tr>
<tr>
<td>Chad</td>
<td>105</td>
<td>51 31 81</td>
<td>34 13 39</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>96</td>
<td>119 2 183</td>
<td>146 2 182</td>
</tr>
<tr>
<td>India</td>
<td>110</td>
<td>37 23 65</td>
<td>49 31 80</td>
</tr>
</tbody>
</table>

\(\text{PM}_{2.5}\) = fine particulate matter.
Discussion

Providing the tobacco control community in LMICs with effective and accessible methods to assess compliance with local and national SF legislation is essential to generate data to engage policymakers, the media and the public with a view to address any weaknesses in SF protection. This article presents the results from a study in more than 600 hospitality venues across six countries and three continents.

Overall, smoking was observed in nearly one-third of venues but this varied substantially between the countries. SF was found to be well observed in the Indian and Bangladeshi venues visited, where less than 10% had customers actively smoking. Smoking was evident in the majority of venues in Chad (72%) and nearly half of venues in Indonesia (46%) with a more mixed picture in Mexico (29%) and Pakistan (20%). Staff smoking was also a considerable problem in Indonesia and Chad. Compliance with SF signage rules was generally found to be low with only Mexico having high levels (81%). Signage was not evident in the majority of venues visited in India, Pakistan, Indonesia, and Chad. The primary explanation for the variation in the observed level of smoking by patrons and/ or staff in the six countries would appear to be the difference in the presence, robustness, stage of implementation, and effectiveness of enforcement of SF legislation.

India and Bangladesh have national legislation and implementation and enforcement are well developed particularly in the metropolitan areas where this study was undertaken. The current Indian law is weaker than that in Bangladesh in permitting Designated Smoking Areas (DSAs) within larger hospitality venues (restaurants with >30 seats; hotels with >30 rooms) yet the majority of venues in this study sample were below this threshold. Pakistan’s national law and the sub-national legislation in Bali (Indonesia) and Mexico City are robust though enforcement is not yet as advanced as in Dhaka or Delhi. At the farther end of the spectrum of observed smoking, Chad has national SF legislation in place but enforcement at present is weak and violations are common, explaining the greater number of smokers in venues where in theory this is banned.

Objective assessments of PM levels were obtained using a simple, low-cost air quality monitor. After excluding venues with open fires and candles burning, the comparison of indoor PM with levels measured outdoors indicated that venues where smoking was observed had significantly higher levels of airborne PM compared to those where smoking was not observed. By subtracting the outdoor PM value from the indoor value this methodology seeks to define the quantity of SHS-derived PM in each venue. The mean difference in SHS-derived PM between smoking observed and SF venues was 34 µg/m³. One-quarter of venues where smoking was observed had PM concentrations more than 64 µg/m³ greater than those measured outdoors, indicating that smoking greatly increases the level of fine PM in these settings. This appears to correspond with the levels found in previous studies of hospitality settings in Scotland and the wider United Kingdom prior to the implementation of SF laws in 2006 and 2007 that found median SHS-PM concentrations of between 80 µg/m³ and 170 µg/m³ that then reduced to between 0 to 10 µg/m³ after SF laws were enacted.

Strengths and Limitations

The authors acknowledge several limitations to the study and suggest these are borne in mind in considering the study results. Firstly, lead data collectors received training in using the Dylos and software, while the core analysis was conducted by a team with prior expertise. Access to a simplified form of the software and an online guide in use and data analysis is therefore essential to realize the potential of this low-cost methodology to increase access to AQM in LMICs. A second limitation is that information about additional indoor sources of smoke, such as fires, candles, and cooking ranges, was not available at the time of venue selection and so these venues were excluded from the dataset during analysis. In addition, it is known that the response of photometric particle counters such as the Dylos used in this study are influenced by high (>95%) humidity environments measured in this study though it is recommended that future work simultaneously records humidity levels and, where required, applies a correction factor to the particle concentration data gathered. A further sampling consideration is venue selection. The primary focus of the study was feasibility testing of the methodology and thus the sampling objective was to obtain as much observational and air quality data from each country within the project period and with the resources available. As such, a sample size was not generated, and selected venues were not stratified, for example, by district. In terms of the secondary objective—using the data to examine compliance with SF legislation in each country—the sample in each country is clearly skewed towards the urban centers where

Table 3. Difference Between Inside and Outside PM Concentrations by Country

<table>
<thead>
<tr>
<th>Country</th>
<th>Count</th>
<th>PM₁₀ (µg/m³) (inside–outside)</th>
<th>Median</th>
<th>25th percentile</th>
<th>75th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico</td>
<td>51</td>
<td>2</td>
<td>−2</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Pakistan</td>
<td>98</td>
<td>24</td>
<td>4</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>96</td>
<td>0</td>
<td>−2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Chad</td>
<td>49</td>
<td>8</td>
<td>−6</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Bangladesh</td>
<td>65</td>
<td>0</td>
<td>−39</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>110</td>
<td>−10</td>
<td>−30</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

PM₁₀ = fine particulate matter.
measurements were performed and so may not be representative of all hospitality venues.

It should be noted that India was the only country with the legislative exemption of DSAs in certain sizes of venue. Again, as the capacity of venues (and thereby whether they included DSAs) was not screened prior to the study a small proportion (>10%) of the Indian venues included DSAs. The overall small proportion of Indian venues where smoking was observed therefore included some of these venues with DSAs and the Indian data should therefore be considered in this context. The data and results of this study overall suggest there is major potential for the Dylos to be used to gather data to demonstrate the inadequacy of DSAs in protecting people from SHS.

Lastly, it is worth noting that the majority of venues where smoking was observed were in two countries, Chad and Indonesia. The potential for any clustering effect either upon the subjective assessments or the comparison of observations and PM$_{2.5}$ results was not considered as part of the analysis.

This is one of the first studies to use PM$_{2.5}$ as a marker of SHS in cities with very high outdoor air pollution levels. Outdoor PM$_{2.5}$ concentrations in all countries except Mexico exceeded the WHO 24h guidance value of 25µg/m$^3$ with median outdoor values in Bangladesh approaching 150 µg/m$^3$. Despite this, statistically significant differences in objectively measured PM$_{2.5}$ concentrations between smoking and nonsmoking venues were clearly observed. This suggests that this simple, cheap protocol can be used to reliably assess SHS-derived PM$_{2.5}$ levels indoors even in highly polluted urban environments. As previously discussed, guidance in using the device and analyzing the data is a pre-requisite and developing an online guide is a recommendation of this study.

Data from this study indicates that this method of objectively measuring SHS can provide a valuable addition to observed data on factors including presence of smokers, smoke and smoking-related equipment. In this study, when observers subjectively rated venue SHS levels as “medium” or “high” the objectively assessed levels confirmed that the PM$_{2.5}$ was substantially higher than the measured outdoor level. However in over half of the venues where smoking was observed the observers’ subjective rating of SHS levels was “none” or “low,” suggesting that subjective assessment may underestimate SHS in many venues. In addition, in a country such as India where the SF law is weaker and allows DSAs in hospitality venues of larger capacity then an objective measurement of PM$_{2.5}$ has the potential to demonstrate the presence of SHS even when active smoking may not be observed.

Conclusions

This study suggests that AQM is a viable method for improving knowledge about SHS exposure and compliance with local and national SF legislation in hospitality venues in LMICs. Additionally the results suggest that this low-cost methodology can provide reliable information about indoor air quality and SHS even in cities with high levels of outdoor air pollution. It is proposed therefore that this method can be used to enhance the quality and quantity of SHS data and provide stronger evidence to strengthen SF protection in LMICs. Simplified, accessible software and usage and analysis guidance is needed to enable this.

The results indicate that compliance with SF legislation varies between countries and suggest the need for stronger enforcement in cities where indoor smoking was observed. Venues where smoking was observed had on average significantly higher PM$_{2.5}$ levels, that is, poorer indoor air quality, compared to venues where smoking was not observed. The PM$_{2.5}$ levels in venues where smoking was present were substantially higher than the already high outdoor air pollution levels in these cities. Given that there is no risk free level of exposure to tobacco smoke the indoor PM$_{2.5}$ concentrations due to SHS are cause for concern.

### Supplementary Material

Supplementary File 1 can be found online at http://www.ntr.oxfordjournals.org

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### Declaration of Interests

None declared.

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