RESEARCH ARTICLE

Costs of attributable burden disease to PM$_{2.5}$ ambient air pollution exposure in Medellín, Colombia, 2010–2016 [version 1; peer review: awaiting peer review]

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Abstract

Introduction: The impact of PM2.5 ambient air pollution exposure on morbimortality has been documented; however, for Latin American cities, there are no calculations of the economic burden. The objective of the study was to estimate the costs of attributable burden disease to PM2.5 ambient air pollution exposure in Medellín, Colombia.

Methods: The costs were assessed using the cost-of-illness approach and the human capital approach, which include direct medical costs and indirect costs due to loss of productivity. To estimate the value of the lost years of production the salaries established in the Great Integrated Household Survey carried out in September 2016 by the National Administrative Department of Statistics of Colombia were used. The PYWL were calculated taking as a reference the 57 years to age of death for female and 62 years for male. For both, an alternative scenario was proposed to account for the cost of working years by changing the reference age to 80 years.

Results: A total of 5540 potential years of working life lost due to premature deaths attributed to exposure to PM2.5 was calculated. The costs of attributable morbimortality to PM2.5 exposure in Medellín totaled 86,0 million dollars in baseline scenario and 281,2 million dollars in alternative scenario. Which represented 0.091% of the gross domestic product of Colombia and 0.627% of that from the Department of Antioquia. The highest percentage of the costs associated with the loss of productivity originated in the premature death of the population over 50 years of age, both due to chronic and acute events.

Discussion: The costs of mortality represented 80% of the total. PM2.5 ambient air pollution exposure generates significant costs associated with the loss of years of working life, due to acute infections and

chronic diseases of respiratory tract and ischemic heart diseases

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Introduction

The impacts of air pollution on morbidity and mortality indicators at the global, regional, and local levels have been extensively documented. The most relevant information, coming from empirical research, establishes the adverse effects of pollutants PM10, PM2.5, and ozone on acute and chronic events, particularly in children and older adults.[1] These impacts have been measured in the last decade in terms of the burden of attributable disease to air pollution, which involves the measurement of disability-adjusted life years (DALYs), that is, the sum of potential years of life lost due to premature death and years lived with disability.[2]

At the international level, there are estimates from the Institute for Health Metrics and Evaluation (IHME) of the University of Washington, whose annual reports establish the DALYs attributable to ambient air pollution, specifically related to exposure to PM2.5. In its 2017 report, from a sample of 195 countries, the IHME identified air pollution as one of the main causes of the global burden of disease; for the year 2015 the IHME calculated that long-term exposure to air pollution by fine particulate matter (PM2.5) caused 4.2 million deaths and 103.1 million years of healthy life lost, accounting for 7.6% of total global mortality.[2]

Seen in this way, air pollution has become a public health problem, increasingly involving the population living in large cities around the world. This problem also manifests itself in an economic burden that compromises significant society resources, related to disease care and productivity losses due to mortality and premature disability attributable to air pollution.

At the global level, for the year 2013, the economic burden of exposure to ambient air pollution by PM2.5 was established at 3.5 billion dollars, strictly associated with the loss of well-being due to premature mortality. In terms of productivity losses, the burden amounted to 144 billion dollars a year. These productivity losses were most costly in South Asia and Sub-Saharan Africa regions, which comprised 0.39% and 0.23% of the gross domestic product (GDP) in 2013, respectively. In Latin America and the Caribbean, where the effects appear to be relatively lower, this economic burden represented 0.09% of GDP in 2013.[3]

In Colombia, as can be seen below, few studies have documented the economic burden derived from the impact on morbidity and mortality caused by air pollution. All of this even though exceptional levels of air pollution have been registered in cities like Medellín, with daily and annual concentrations that exceed the reference values established in the respective guide of the World Health Organization (WHO).[4] Indeed, for the period 2010–2016, in this city, the levels of PM10 and PM2.5 reached daily averages of 68.2% and 35.8 µg/m3.[1]

At the national level, it is possible to underscore the pioneering research by Larsen, which estimated morbidity and mortality costs attributable to exposure to PM2.5 ambient air pollution, amounting to 2275.7 million dollars in 2002.[5] With some methodological changes, ten years later, the World Bank (WB) updated Larsen's study, estimating the economic burden at 6319.1 million dollars in 2010.[6] In 2018, the National Planning Department (DNP, by its Spanish acronym) reported that it had updated these studies, with a nationwide cost measurement of 4449.6 million dollars in 2015, due to morbidity and mortality attributable to urban air pollution.[7]

In a recent study by the National Institute of Health (INS, by its acronym in Spanish) of Colombia, the economic burden due to mortality attributable to exposure to ambient and indoor air pollution by pm2.5 in the country was established at 160 million dollars for the year 2016, which represented about 0.05% of that year's GDP. This baseline scenario was accompanied by low estimates of 84.5 million dollars and high estimates of 462.9 million dollars.[8]

For the city of Medellín, there are no estimates of the economic burden of attributable morbidity and mortality to air pollution. Based on the Local attributable burden disease to PM2.5 ambient air pollution study in Medellín,[9] we established the costs of it. We expected that the assessment of the economic burden will provide relevant information for decision makers and analysts of this problem, in the sense of promoting the economic assessment of ongoing actions or potential air pollution containment programs in the city.

Methods

Type of study and population

A descriptive study of the costs of morbidity and mortality attributable to PM2.5 ambient air pollution was carried out in the city of Medellín for the period 2010 to 2016. Medellín is located in Aburra Valley in the Andes Mountains to the central-western of Colombia and an estimated population of around 2.9 million people. Additionally, it has the fastest demographic growth in the country, with a growth rate twice that of other cities. The attributable burden to PM2.5 was estimated for the five events documented in the Global Burden of Disease study, carried out by the IHME, in which the

respective population attributable fractions are reported for the case of Colombia: chronic obstructive pulmonary disease (J40–J47); malignant neoplasms of respiratory and intrathoracic organs (C30–C39); acute myocardial infarction (I20–I25); cerebrovascular diseases (I60–I69), and acute respiratory infection (J00–J06; J09–J18; J20–J22; H10–H13; H65–H75).[2]

Data source

The supporting information for the calculation of attributable morbidity and mortality was taken from two official sources for the period 2010–2016 in the city of Medellín: 1) Individual Records of Health Services Provision (RIPS, by its Spanish acronym), consolidated and validated by the Municipal Health Secretariat, corresponding to outpatient, hospitalization and emergency services for each of the five events, according to age and sex; 2) Single Registry of Affiliates, Births and Deaths module (RUAF-ND), included in the Comprehensive Social Protection Information System, managed by the Ministry of Health and Social Protection, for the five events, according to age and sex.

Assessment of morbidity costs

In estimating costs, the social perspective was partially adopted, with the aggregation of the costs of treated morbidity and the costs of lost productivity due to premature mortality. For attributable morbidity, the direct medical costs associated with health care and the costs due to loss of productivity associated with sick leaves were estimated, leaving out the calculation of direct non-medical costs and the valuation of intangible costs associated with the pain and suffering of patients and families. The information for this morbidity costing was taken from the RIPS billing module, which allowed the calculation of the unit costs for each of the five events studied in Medellín, according to age and sex. The consolidated values for each year were expressed in 2016 pesos, according to official annual inflation reports for the study period.[5,10-20]

Assessment of mortality costs

Human capital and willingness-to-pay approaches are commonly used to value the impact of premature mortality.[17,21] The willingness approach, recommended by the WB and the IHME,[3,22] captures the valuation of welfare losses due to premature mortality, that is, the valuation not only of production losses, which is typical of the human capital approach, but also broader valuations of human life, associated with the enjoyment derived from the subjectivity and experience of each person. In Colombia, there are no estimates of this type, which is why the human capital approach was adopted to establish the economic burden of mortality.

In this study, the days lost due to morbidity and the years of life lost due to premature mortality are valued, from the wages by sex and age groups. In the approach adopted, it is usual to assume as price vector the *per capita* income[3,22,23] or the current legal monthly minimum wage,[24] in the understanding that they are a good approximation to the remuneration of the productive effort that workers carry out. It is evident that in both cases the productivity differentials, which originate from the profile by sex and age group of the workers, are being ignored. This is contrary to the human capital approach itself, which has indeed documented the cycle of productivity that occurs as age, education, and work experience increase.[25]

Estimates were made for all cases of mortality attributed to air pollution identified in the analysis of the burden of morbidity and mortality, regardless of whether these losses corresponded to the employed or unemployed population. These are, in all cases, potential losses in productivity that impose an economic burden on society. Thus, the cost of premature deaths was based on the present value (PV) of wages or income corresponding to the potential years of work lost (PYWL) due to deaths. Under this approach, the expected loss of income for the average person in each age group and sex was valued according to equation 1[3,22]:

$$VP(I) = \sum_{i=0}^{n} \frac{I(1+g)^i}{(1+r)^i}, \tag{1}$$

where n and I are the expected number of years of work and the average *per capita* labor income in a particular age group and sex; g is the annual growth rate of labor income (labor productivity), and r is the social discount rate.

The PYWL were calculated taking as a reference the age of death at the midpoint of the intervals of the age groups considered, the retirement age for women (57 years) and the retirement age for men (62 years), defined by Colombian law.[26] The values of the PYWL were estimated based on the monthly salary reports and the number of hours worked per month from the Great Integrated Household Survey, concerning the Medellín metropolitan area, carried out by the National Administrative Department of Statistics (DANE, by its Spanish acronym) in September 2016.[25] Although the survey is conducted month by month, September was chosen to avoid seasonal variations in labor data throughout the year.

For the assessment of PYWL, baseline salaries were considered, that is, without discounting social security and other contributions made by the workers. These salaries were adjusted to their full-time equivalent value. In consideration of the years lost, these salaries were projected based on the growth rate of labor productivity (g) of 2% per year, as calculated in the specialized literature for the period 2000–2018.[27]

The present value of these wages was calculated, as it appears in Equation 1, applying the discount factor $[1/(1+r)^n]$, with a discount rate r of 3% per year. This rate was assumed in consideration of the recommendations of the IHME[3,22] and the Institute for Health Technology Assessment (IETS) of Colombia,[15] so that the results were comparable with similar studies at the local and global level.

For the generation of results and graphs, the commercial software, Microsoft Excel® (RRID:SCR_016137) licensed by the University of Antioquia, was used. A free office suite alternative that could also be used for this process would be LibreOffice.

Research ethics

This project was approved by the Ethics Committee of the National School of Public Health of Universidad de Antioquia as declared in minutes No. 141 of April 29, 2016. All procedures performed in this project followed ethical standards contemplated in Resolution 8430 of the Ministry of Health and Social Protection of Colombia, and International Ethical Guidelines for Health-related Research Involving Humans of 2016 of the Council for International Organizations of Medical Sciences.

Results

In the study period 2010–2016, Medellín recorded a total of 5,540 potential years of working life lost due to premature deaths attributable to exposure to PM2.5 ambient air pollution. On average, the PYWL were about 791 per year. From this calculation the costs of premature deaths in Medellín were estimated for each event by sex and age group. The data for each year are in millions of 2016 dollars (see Table 1).

The indirect costs of premature mortality, the direct medical costs of disease care, and the total costs of premature morbidity and mortality are presented below.

Indirect costs of premature mortality

As recorded in Table 1, in the seven years under study, attributable premature deaths to pm2.5 pollution generated, in Medellín, a total cost of 29.5 million of 2016 dollars. Throughout the period, these costs registered a relatively stable behavior, averaging about 4.2 million dollars annually.

The costs in men and women due to attributable premature death to air pollution also registered, throughout the period, a relatively stable behavior with only a slight decrease in 2014 for men, which marked a similar fall in the total costs.

According to data in Table 1, it is evident the great importance of the costs in the group of men compared with the group of women. In their order, they add up, for the entire period, 22.7 and 6.8 million dollars, which represent 76.9% and 23.1% of the total, respectively.

Table 1. Potential years of working life lost and costs of attributable premature mortality to pm2.5 ambient air pollution, by sex, Medellín 2010–2016.

Year	Men			Women			Total		
	pywl	Costs*	% Costs	pywl	Costs*	% Costs	pywl	Costs*	% Costs
2010	661	3.5	15.4	267.0	1.2	17.2	928.0	4.7	15.9
2011	650	3.6	15.6	264.0	1.2	17.2	914.0	4.8	15.9
2012	597	3.3	14.6	223.0	1.0	15.2	820.0	4.3	14.7
2013	554	3.2	14.1	162.0	0.8	12.1	716.0	4.0	13.7
2014	515	2.9	12.8	184.0	0.9	13.3	699.0	3.8	12.9
2015	536	3.0	13.1	179.0	0.8	12.4	715.0	3.8	13.0
2016	575	3.2	14.3	173.0	0.9	12.7	748.0	4.1	13.9
Period	4088	22.7	76.9	1452.0	6.8	23.1	5540.0	29.5	100.0

pywl: Potential years of working lost.
*Values in millions of of 2016 dollars.

Table 2. Costs of attributable premature mortality to pm2.5 ambient air pollution, by sex and acute and chronic events, Medellín 2010–2016.

Event type	Year	Men		Women		Total	
		Costs*	% Costs	Costs*	% Costs	Costs*	% Costs
Acute	2010	2.9	15.6	1.0	17.4	3.9	16.1
	2011	3.0	16.1	1.0	17.4	4.0	16.4
	2012	2.6	14.1	0.8	14.6	3.4	14.2
	2013	2.7	14.3	0.7	12.0	3.4	13.7
	2014	2.4	13.1	0.8	14.0	3.2	13.3
	2015	2.5	13.2	0.7	12.3	3.2	13.0
	2016	2.5	13.6	0.7	12.4	3.2	13.3
	Period	18.6	76.9	5.7	23.1	24.3	100.0
Chronic	2010	0.6	14.6	0.2	16.3	0.8	15.0
	2011	0.5	13.1	0.2	16.4	0.7	13.9
	2012	0.7	16.8	0.2	17.8	0.9	17.1
	2013	0.5	13.5	0.2	12.4	0.7	13.3
	2014	0.5	11.6	0.1	9.9	0.6	11.2
	2015	0.5	13.1	0.2	13.1	0.7	13.0
	2016	0.7	17.2	0.2	14.0	0.9	16.4
	Period	4.0	76.8	1.3	23.2	5.3	100.0

*Values in millions of 2016 dollars.

From 35 to 39 years, a growing gradient in costs is evident for both sexes, although in the group of women it is flatter. In the case of men, on the other hand, the gradient is much more pronounced, to the extent that the costs of premature deaths in men aged 50 and over represent about 2.2-times the costs in the group of men under 35 years of age and in the one from 35 to 44 years old.

According to Table 2, the costs of premature mortality due to acute events attributable to air pollution, which in Medellín totaled about 24.2 million dollars, represented 81.9% of the total costs for the period 2010-2016. The remaining 18.1% of these costs were due to premature deaths from chronic events.

The greatest contribution of costs for acute events was also observed in the groups of men and women. However, both in acute and chronic events, the group of men had a greater contribution to the costs of premature mortality, attributable to air pollution, with values of 18.6 and 4.1 million dollars, which represented, in their order, 76.9% and 76.8% of the costs of each event.

Throughout the seven years, no significant variations in costs attributable to chronic events were observed, except for slight increases in 2012 and 2016, years in which the highest values of these costs were recorded. In contrast to the above, costs for acute events registered a downward trend in the post-2011 tranche (see Table 2).

In relation to the specific events that make up the chronic and acute groups, ischemic heart diseases and acute lower respiratory infections contributed the most to the total of these costs: 12.5 and 9.4 million dollars respectively; cerebrovascular diseases are the ones with the lowest contribution, with 2.3 million dollars (see Table 3).

Regarding the costs of these specific events by age groups, Table 3 shows once again the positive gradient of the attributable economic burden to air pollution according to specific causes of premature mortality. Overall, for three of the five events, it was evidenced that the oldest age groups contributed the most to the total economic burden.

The foregoing, as expected, was particularly true in the case of chronic events, such as chronic respiratory diseases and malignant neoplasms of respiratory and intrathoracic organs, whose costs came from the population aged 50 and over in 67.5% and 53.0%, respectively.

Table 3. Costs of attributable premature mortality to pm2.5 ambient air pollution, by age group and specific acute and chronic events, Medellín 2010–2016.

Age groups	Ischemic heart disease		Cerebrovascular diseases		Acute lower respiratory infections		Malignant neoplasms of respiratory and intrathoracic organs		Chronic respiratory diseases	
	Costs*	% Costs	Costs*	% Costs	Costs*	% Costs	Costs*	% Costs	Costs*	% Costs
< 35	1.1	8.3	0.5	22.6	4.9	51.7	0.3	9.7	0.2	7.0
35 to 39	1.1	8.7	0.3	12.0	1.0	10.7	0.2	6.6	0.2	7.5
40 to 44	1.6	13.2	0.3	13.1	0.7	7.9	0.3	9.0	0.1	3.1
45 to 49	2.8	22.8	0.4	19.1	1.1	11.9	0.6	21.7	0.4	14.9
50 and over	5.9	47.0	0.8	33.2	1.7	17.8	1.6	53.0	1.6	67.5
Total	12.5	100.0	2.3	100.0	9.4	100.0	3.0	100.0	2.5	100.0

*Values in millions of 2016 dollars.

Although the previously described behavior of costs by age group is similar in the remaining acute events, it is relevant to note how, in the case of acute lower respiratory infections, the cost gradient is more pronounced after 35 years of age, so that the costs in the population under this age are comparable to those of the population aged 50 and over.

As reported in the methods section, the human capital approach to mortality costs implies adopting the retirement age limits to measure the PYWL, which results in underestimation given that it omits the elderly group. This circumstance is especially relevant in the context of this study, since the impacts on mortality due to air pollution are usually concentrated in this population. In this sense, an alternative scenario is proposed that allows to count the cost of the years of working life of this population group, shifting the reference age to 80 years for this group only.

In this alternative scenario, the mortality costs for the period 2010–2016 amounted to a total of 224.7 million of 2016 dollars. The distribution by sex and age was not significantly different from what was described in the baseline scenario previously reported, except for what corresponds to the elderly group. Likewise, 61.1% of these costs were concentrated in the group of men.

The gradient of these costs is evident as age increases. Thus, 78.5% of these costs are concentrated in adults aged 55 and over.

Direct medical costs of disease care
Care for morbidity events attributed to air pollution by PM2.5 generated, in the aggregate of 2010–2016, a total cost of 52.3 million of 2016 dollars. These costs showed a growing trend until 2013, then fell to levels of the beginning of the period, reaching in the seven years, an average of 7.5 million dollars per year (see Table 4).

The aforementioned trends in the costs of attributable morbidity to PM2.5 ambient air pollution show the same behavior in the costs of medical care for men and women, especially in the latter group. Thus, the costs remain higher in women than in the male population. In fact, slightly more than half (53.2%) of the total costs for the period originated in the medical care for the group of women, which amounted to 27,8 million dollars.

Table 5 shows, for each year of study, the costs of patients treated for the different events, by sex and age group. Throughout the period, for both acute and chronic events, the costs of medical care registered a relatively stable behavior. Acute events totaled 27 million dollars, slightly higher than the costs of care for chronic events, which totaled 25.4 million dollars.

Costs according to sex and types of events showed a behavior similar to that already referenced for the total of 2010–2016. They were stable throughout the period and revealed a similar distribution for acute and chronic events in men and women. However, as observed for the entire period, in the group of men, the costs of care for acute events (13.1 million dollars) were slightly higher than the costs for chronic events (11.4 million dollars).

Table 4. Costs of attributable morbidity to pm2.5 ambient air pollution, by sex, Medellín 2010–2016.

Year	Men		Women		Total	
	Costs*	% Costs	Costs*	% Costs	Costs*	% Costs
2010	3.5	14.4	3.6	12.9	7.1	13.6
2011	3.7	15.2	4.1	14.7	7.8	15.0
2012	3.8	15.4	4.5	16.0	8.3	15.7
2013	3.8	15.3	4.5	16.1	8.3	15.7
2014	3.3	13.4	3.7	13.5	7.0	13.4
2015	3.3	13.5	3.8	13.8	7.1	13.7
2016	3.1	12.8	3.6	13.0	6.7	12.9
Average	24.5	46.8	27.8	53.2	52.3	100.0

*Values in millions of 2016 dollars.

Table 5. Costs of attributable morbidity to pm2.5 ambient air pollution, by sex and acute and chronic events, Medellín, 2010–2016.

Event type	Year	Men		Women		Total	
		Costs*	% Costs	Costs*	% Costs	Costs*	% Costs
Acute	2010	1.8	13.8	1.8	12.7	3.6	13.3
	2011	1.9	14.7	2.0	14.5	3.9	14.6
	2012	2.0	15.0	2.1	15.5	4.2	15.3
	2013	2.0	14.9	2.1	15.1	4.1	15.0
	2014	1.8	13.9	1.9	13.9	3.7	13.9
	2015	1.8	13.9	2.0	14.2	3.8	14.1
	2016	1.8	13.8	1.9	14.0	3.7	13.9
	Period	13.1	48.8	13.8	51.2	27.0	100.0
Chronic	2010	1.7	15.1	1.8	13.1	3.5	14.0
	2011	1.8	15.8	2.1	14.9	3.9	15.3
	2012	1.8	15.9	2.3	16.5	4.1	16.2
	2013	1.8	15.8	2.4	17.1	4.2	16.5
	2014	1.5	12.9	1.8	13.0	3.3	12.9
	2015	1.5	12.9	1.9	13.4	3.4	13.1
	2016	1.3	11.6	1.7	12.0	3.0	11.8
	Period	11.4	44.7	14.0	55.3	25.4	100.0

*Values in millions of of 2016 dollars.

For the period 2010–2016, chronic respiratory diseases (22.7 million dollars) and acute lower respiratory infections (21.4 million dollars) were the largest contributors (84%) to the total costs of attributable morbidity to air pollution. The contributions of the three remaining events did not individually exceed 6% of the total of these costs.

Table 6 shows in detail the estimated costs for the five events of interest by age groups. The pattern is similar to that reported for the aggregate of costs for the period. Except for one of the events, in the remaining four, more than 75% of the costs were concentrated in the population aged 55 and over. Only in the case of acute lower respiratory infections was a more equal participation observed in the contribution of extreme age groups: 34.5% in those under 35 years of age and 54.8% in adults aged 55 and over.

Due to the low impact of these indirect costs, only those corresponding to the consolidated period 2010–2016 were estimated, according to age groups and sex. For the seven years, the costs of lost productivity associated with the five

Table 6. Costs of attributable morbidity to pm2.5 ambient air pollution, by age group and specific acute and chronic events, Medellín 2010–2016.

Age groups	Ischemic heart disease		Cerebrovascular diseases		Acute lower respiratory infections		Malignant neoplasms of respiratory and intrathoracic organs		Chronic respiratory diseases	
	Costs*	% Costs	Costs*	% Costs	Costs*	% Costs	Costs*	% Costs	Costs*	% Costs
< 35	0.03	1.2	0.3	9.9	7.4	34.5	0.1	4.5	1.3	5.6
35 to 39	0.03	1.3	0.05	1.6	0.3	1.5	0.06	2.3	0.3	1.3
40 to 44	0.1	4.4	0.08	2.6	0.5	2.2	0.08	3.1	0.6	2.8
45 to 49	0.2	7.5	0.08	2.5	0.7	3.1	0.2	6.1	0.7	3.0
50 to 54	0.2	9.9	0.3	8.1	0.8	3.9	0.2	9.0	1.4	6.4
55 and older	1.8	75.6	2.4	75.3	11.7	54.8	2.0	75.1	18.4	80.9
Total	2.4	100.0	3.2	100.0	21.4	100.0	2.7	100.0	22.7	100.0

*Values in millions of 2016 dollars.

Table 7. Total costs of attributable mortality and morbidity to pm2.5 ambient air pollution exposure, Medellín 2010–2016.*

	Baseline scenario		Alternative scenario	
	Costs	%	Costs	%
Mortality costs	29.5	34.3	224.7	79.9
Morbidity costs	56.5	65.7	56.5	20.1
Total costs	86.0	100.0	281.2	100.0
% of Colombia's GDP	0.028		0.091	
% of Antioquia' GDP	0.192		0.627	

*Costs in millions of 2016 dollars.
Representative market rate = 2808.3 COP; Colombia's GDP in 2016 = 307,581.8 million USD; Antioquia's GDP in 2016 = 44,874.8 million USD.

events under study totaled 4.1 million dollars. The distribution of these costs according to sex does not show marked differences: 51.2% for women and the remaining 48.8% for men.

In total costs, as well as those corresponding to men and women, those corresponding to extreme age groups prevail. No less than 60% of the costs for sick leaves are concentrated in adults aged 55 and over.

Total costs of morbidity and premature mortality

According to consolidated data in Table 7, for the period 2010-2016, in the baseline scenario, premature deaths and attributable morbidity to PM2.5 pollution amounted a total cost of 86 million dollars in Medellín. In the alternative scenario, these costs totaled, for the entire period, a value of 281.2 million dollars. In this alternative scenario, mortality costs represented 79.9% of the total, while morbidity costs represented the remaining 20.1%. The total costs corresponding to the alternative scenario, which amounted to nearly 281 million dollars, represented 0.091% of Colombia's GDP in 2016 and 0.627% of Antioquia's GDP in the same year.

Discussion

The findings of this research are supported by methodologies validated by experts and international organizations with extensive experience in the areas of health economics and environmental epidemiology. The costing procedures adopted are among the options suggested by the theoretical approaches and the empirical procedures provided by the specialized literature.

This research agrees, in this sense, with the methodological approaches applied in calculating the costs of attributable premature mortality to air pollution, carried out by the WB and the IHME in their 2016 global report,[3] which also validate the human capital approach applied in this research.

In this methodological aspect, it also agrees with the study of the national aggregate of mortality attributed to pm2.5 ambient air pollution, carried out in 2018 by the INS[8]; also with international studies, such as the one reported by the Ministry of Social Development of Chile[28] and the one reported by Guo et al. in China.[29]

Regarding the assessment of the morbidity costs, this study provides an added plus compared to what is usually observed in the national and international literature. Much of the reports at the global level can be applied only to the costing of premature mortality, leaving aside the cost of morbidity. The abovementioned INS study did not report the morbidity cost either, focusing exclusively on mortality costs. At the national level, in the study by Larsen,[5] as well as in its updates of 2014[6] and 2017,[7] estimates are made of the two components, that is, premature mortality and morbidity attributed to air pollution.

With regard to morbidity, it would also be necessary to specify the methodological concordances and differences of this study when compared to those at the national and international level, in terms of valuation of morbidity costs. In the study of Medellín, the cost-of-illness approach from the field of health economics was adopted to estimate the morbidity cost, based on information validated by official and governing institutions of the city's health care system. The national studies already referred to, that is, those by Larsen,[5] Golub et al.,[6] and the DNP,[7] proceed in the same way in the cost of morbidity. The WB and the IHME,[3,22] although they do not advocate the effective measurement of these morbidity costs, they do privilege, in their recommendations, the willingness-to-pay approach.

However, these organizations show the uncertainties and variability in the estimates of morbidity costs with a willingness-to-pay approach. Overall, they recognize the lack of a standard framework for the valuation of these costs and, therefore, they do not measure them in their reports on the economic environmental burden. This is understandable from the perspective of international comparability of estimates, given that for a wide range of countries there may be a lack of data on health expenditures and medical treatment costs. This is compounded by differences between countries in health care systems, contractual forms, and payment and billing schemes between patients, care providers, and public institutions.

This study is the first research in the city of Medellín aimed at estimating the costs of the burden of morbidity and mortality attributed to PM2.5 ambient air pollution. Its realization required a prior and novel effort to estimate the burden of morbidity and mortality attributable to air pollution in this city, for which standard methodologies from the IHME and WHO were adopted.[2,30]

According to the findings of this research, in the period 2010–2016, the costs of morbidity and mortality attributed to pm2.5 pollution totaled in the city of Medellín about 281.2 million dollars: 80% of these costs corresponded to the premature mortality component, and the remaining 20% to medical care and productivity losses due to morbidity.

In relative terms, these figures do not differ from the reports of national and international studies. In the abovementioned report of the Organization for Economic Cooperation and Development (OECD),[31] it is reported that the impacts of morbidity represented 27% of the total costs, although this figure requires caution, since the component of mortality comes from the willingness-to-pay approach. Similar caution should be taken when mentioning the WB and IHME report of 2016,[22] which includes studies from Nicaragua and China where morbidity costs may represent 44% of the total morbidity and mortality costs. In a more recent study concerning Egypt, which incorporates a detailed review of the literature, Larsen[32] establishes that this proportion would be in the range of 10% to 30% of the total cost.

Experts from the OECD, as well as those from the IHME and the WB, agree in reporting a minimum proportion of 10% for morbidity costs contribution to the total morbidity and mortality costs. Of the three national studies that addressed the valuation of morbidity costs attributed to air pollution, for this component with a cost-of-illness approach and for mortality with a willingness-to-pay approach, Larsen[5] and Golub et al.[6] estimated a proportion of 21%. In the most recent one by the DNP,[7] whose methodological approach adopts the two previous ones, the morbidity costs reported for 2015 represent 13.1% of the total costs of morbidity and mortality attributed to pm2.5 ambient air pollution.

In the period 2010–2016, Medellín registered a slight downward trend in the costs of premature mortality, especially in what corresponds to the group of men; this trend reverts as of 2015, which coincides with the rebound in the number of PYWL. This circumstance may be associated with the PM2.5 pollution episodes that have occurred since that year in the city of Medellín. By then, the daily concentration levels of this particulate matter during the first quarter of 2015 and 2016 reached values higher than three-times the WHO reference levels.[1]

The costs of premature mortality concentrated to a greater extent in the group of men (61.1%) and in the extreme age population groups, particularly in adults aged 55 and over (78.5%). In the group of men, more than in that of women, there was an increasing gradient in the costs of premature mortality as age increased. This behavior reflects the combined effects of the wage differential and the ages at which deaths occur. Men earn higher wages and the effects of air pollution fall more heavily on the young and elderly populations.

According to the types of events that are the object of this study, the results of mortality costs should be addressed in greater detail. When measurements are made based on retirement ages, acute events represent about 81.9% of total costs for the period 2010-2016. Upon including ages over 60 in the estimation of these costs, acute events represent 65.4%. In both scenarios, the mortality costs of this type of event are higher when compared to those of chronic events.

It should be noted that, in the group of acute events, the costs of deaths associated with ischemic heart diseases stood out, reaching a participation of 42% with respect to the total costs for the period. This pattern of distribution for premature mortality costs is in line with the findings reported in the INS study[8] at the national level, with respect to a higher participation of mortality costs due to acute events. That study reveals a participation of nearly 48% for mortality costs associated with ischemic heart diseases in the total costs for 2016.

The costs of morbidity attributed to PM2.5 ambient air pollution in the city of Medellín reached a value of 56.5 million dollars in the period 2010–2016. Of these, 92.7% corresponded to direct costs of health care, and the remaining 7.3% corresponded to costs of lost working days due to sick leaves. These morbidity costs represented nearly 20% of the total costs for the period, and showed, in their component of health care costs, a trend contrary to the costs of premature mortality, with an increasing trend in the first years and a decrease since 2013, which shows a lack of sensitivity to the episodes of PM2.5 ambient air pollution registered in the city in 2015 and 2016.

The consolidated estimate of these costs, seen in its distribution by sex, showed a different behavior from that registered for mortality costs, with a more even distribution between men and women. When analyzed according to the patients' age, the marked gradient that was observed for mortality costs was not seen, although the pattern of higher incidence in the extreme groups was present, particularly in those aged 55 and over, whose total costs represented about 70.4% in women and 68% in men.

This pattern reflects two situations widely documented in the specialized literature[33,34]: on the one hand, the fact that women, compared to men, seek medical care more frequently and adhere more regularly to ongoing care; and on the other hand, there is also evidence that morbidity, especially the chronic kind, due to a strictly biological effect, tends to be more pronounced in the elderly. In fact, in the total health care costs, those corresponding to the care of chronic respiratory diseases represented 43%, while those of acute lower respiratory infections added a participation of 41%.

The costs of morbidity and mortality attributable to PM2.5 air pollution in Medellín totaled, for the entire period, 281.2 million dollars, with an annual average of 40.2 million dollars. These annual costs represented 0.013% of the national GDP in 2016 and 0.091% of the GDP of the Department of Antioquia in the same year. These are relative calculations lower than the proportions estimated in the national studies by Larsen (0.78% of the national GDP),[5] by Golub *et al.* (1.12% of the national GDP),[6] and the DNP (1.5% of the national GDP).[7]

Measurements of the cost of premature mortality assumed from the human capital approach support greater comparability. In effect, these costs, in the case of Medellín, annually represented 0.011% of the national GDP and 0.072% of the departmental GDP. Meanwhile, these mortality costs, with a similar human capital approach, were calculated by the INS[8] for the national level at 0.05% of the 2016 GDP. It should be noted that these productivity losses due to premature mortality were estimated by the WB and IHME[3] at 0.09% of the 2013 GDP in Latin America and the Caribbean.

The foregoing shows consistency in the estimates made in this research for the costs of premature mortality from the human capital approach, but at the same time shows that the valuation of mortality costs with this approach, when compared to the willingness-to-pay approach, underestimates the true environmental costs.

In this sense, it is worth mentioning that the economic burden derived from air pollution goes beyond the costs of morbidity and mortality attributed to exposure to PM2.5. It should be taken into consideration that other pollutants (O_3, SO_x, NO_x, and CO_2), as well as their synergistic effects, also negatively impact the health of the population. Additionally, it is evident that several of these pollutants also pose an economic burden in terms of the deterioration of production processes and public and private infrastructure, constituting a hindrance to economic development and the quality of life of the population.

These limitations are typical of the restrictions in the scope of all studies about economic burden attributed to air pollution. Regarding the Medellín study, it is worth mentioning other limitations concerning the information base and the cost estimation methodology, specifically related to the values of the population attributed fraction and the valuation of mortality costs. It is imperative to make progress in epidemiological research, through cohort studies that allow documenting, for the local context, the real attribution of morbidity and mortality to air pollution. Likewise, it is convenient to carry out studies on the statistical value of life related to the risks of mortality due to air pollution at the local or national level.

Regarding the estimation of morbidity costs, this study did not make any progress in the component of indirect costs or production losses incurred by patients and relatives due to effects of disease and the search for effective medical care. There was also no information available to value the intangible costs associated with having a disease. Studies on disease should be encouraged for events specifically associated with air pollution, incorporating local information on sick leaves, reduction of productive capacity, and willingness to pay to avoid suffering and pain associated with those illnesses.

Nonetheless, beyond the above limitations, this study offers a valid informative basis on the costs of morbidity and mortality attributed to PM2.5 ambient air pollution in the city of Medellín. In this sense, the results may constitute supporting material to establish priorities in public policy decisions regarding the general objectives of local development and the policy options aimed at containing air pollution in the city. The valuation of these costs will facilitate the economic evaluation, either cost-effectiveness or cost-benefit, of those policy actions that involve the health and environment sectors.

Data availability
Underlying data
Zenodo. Underlying data for 'Costs of attributable burden disease to PM2.5 ambient air pollution exposure in Medellín, Colombia, 2010–2016. http://doi.org/10.5281/zenodo.5138785 (Nieto-López et al. 2021).

The dataset contains the following files:

- Attributable mortality to PM2.5 ambient air pollution in Medellin.xlsx

- Cost of Years of Work Life Lost in Medellin 2010-2016, Alternative Scenario.xlsx

- Cost of Years of Work Life Lost in Medellin 2010-2016, Baseline Scenario.xlsx

- Costs of Attributable morbidity to PM2.5 ambient air pollution in Medellin, 2010-2016.xlsx

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Primary health data are publicly available at: https://www.sispro.gov.co/Pages/Home.aspx

Acknowledgments

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