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PM_{10} Exposure and Cardiorespiratory Mortality – Estimating the Effects and Economic Losses in São Paulo, Brazil

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ABSTRACT

Air pollution is an important health risk concern and an economic burden, notably on low- and middle-income countries. The aim of this study was to determine the mortality burden of cardiovascular and respiratory diseases, specifically, the relative risk due to air pollution and the economic valuation derived from life-years lost within the population of São Paulo, Brazil. This study was conducted using a retrospective Health Impact Assessment (HIA) approach via daily time series of cardiovascular and respiratory deaths for the population of São Paulo from 2000 to 2011. The effects of particulate matter smaller than 10 µm (PM_{10}) were estimated with Poisson generalized additive models. The single-day lag effects of air pollutant exposure were estimated for 0–3-day lags. Therefore, we obtained the years of life lost (YLL) through the disability-adjusted life years (DALY) method to estimate the burden of disease due to air pollution in São Paulo. The value of a life year (VOLY) was then applied to convert the YLL component to economic loss. The results showed an association between PM_{10} and cardiovascular and respiratory mortality, lagging 3 days. The YLL totaled 231,691.8 years, meaning an overall economic loss of more than US$14.1 billion. In conclusion, knowledge regarding the costs of premature deaths related to air pollution can be used to improve public policy and to facilitate decision making in the context of scarce resources.

***Keywords**:* Particulate matter; Air pollution; Health effects; Economic valuation; Costs.

INTRODUCTION

Air pollution exposure has been associated to a large range of adverse health effects, as overall, circulatory and respiratory mortality (Lee *et al*., 2014; Smargiassi *et al*., 2014; Khaefi *et al*., 2017).

The air pollution effects on health could occur in the day of exposure or on consecutive days, named lag structures (Braga *et al*., 2001; Martins *et al*., 2006). In a recent study, Costa *et al.* (2016) found that single-day lag and cumulative effects up to 5 days pointed out relevant increases in mortality in elderly population in association with air pollutant levels, including particulate matter smaller than 10 µm (PM_{10}) (Costa *et al*., 2016).

Vehicles are the main sources of PM_{10} and target of a large range of international public policies. Air pollutants and noise can cause external costs in the range of 1,700–1,800 million CHF each year in Swiss transport system (Vienneau *et al*., 2015).

In Brazil, Miraglia and Gouveia (2014) have estimated the cost of premature deaths due to air pollution in 29 Brazilian capital cities and the result was a loss of US$1.7 billion annually (Miraglia and Gouveia, 2014). Considering predictive scenarios of reduced concentration of particulate matter smaller than 2.5 µm ($PM_{2.5}$) in order to achieve the World Health Organization (WHO) standards, São Paulo city in Brazil would avoid more than 5,012 premature deaths and savings of around US$15.1 billion annually (Abe and Miraglia, 2016). The economic studies involving air pollution impacts on health are scarce, mainly in Latin America where policy makers are often confronted with the need of quantifying the cost of a polluted air.

In Brazil, São Paulo is the most developed urban area. The gross domestic product is US$195 billion and is the most polluted city in the country (MMA, 2014; SEADE, 2014). In this sense, a comprehensive approach to deal with this issue is highly recommended. An integrated assessment is required to improve the policy making process for air

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quality control. However, it has not been a simple procedure, often surrounded by economics conflicts and barriers. In this way, one recommended methodology is the "Health Impact Assessment" (HIA). The HIA methodology is derived from the WHO general method (WHO, 2000) and is useful to quantify a range of impacts, including the effects of air pollution exposure on health. In this study, we aimed to determine the mortality burden of cardiovascular and respiratory diseases, considering the relative risk and the economic costs derived from life-years lost in São Paulo's population in order to improve pollution control policies.

METHODS

Locale of Study and Population

São Paulo city is located at 23°32′50″S and 46°38′09″W in the state of São Paulo, Brazil. The total area of the municipality is 1,523 km^2 and is at an altitude of 799 m (2,621 ft.) above sea level with a humid subtropical climate. Its population is approximately 12,038,175 inhabitants in 2016, and the regional Human Development Index was 0.805 in 2010, presenting 678 public health facilities. It has a vehicle fleet of about 7,590,181 in 2015 (IBGE, 2016).

Type of Study and Health Data

A retrospective HIA was performed using a time series study and the numbers of daily cardiovascular (I00-I52, International Classification of Diseases, 10th Revision) and respiratory (J00-J99) deaths were accessed from the Mortality Information System of the Brazilian Public Health System database (DATASUS), among subjects of both sexes at all ages, living in São Paulo, Brazil. The study period was between January 1, 2000, and December 31, 2011. We selected mortality data by the main cause of death of the residents living in the study area.

Environmental Data

Environmental Company of the State of São Paulo provided air pollutant data (CETESB, 2016) for 16 monitoring stations throughout the city. We have chosen stations that had measured PM_{10} concentrations and we have analyzed the trend and variability of pollutant concentrations. Abe and Miraglia (2016) already used these data in another study. Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo (IAG/USP), provided daily averages for minimum temperature and relative humidity.

Modeling Design

Associations between daily counts for each death cause and daily 24-hr average ambient PM_{10} levels were analyzed using Poisson generalized linear models. This model was fitted to estimate single-day lag effects of PM_{10} exposures on lag 0 through 3 days. All Poisson regression analyses were conducted in the SPSS software, version 21 (IBM Statistics). Statistical significance was set at $p < 0.05$. The model was adjusted for day of the week, minimum temperature and average relative humidity (Conceição *et al.*, 2001). We used cubic smoothing spline functions for temperature and relative air humidity to account for the non-linearity of meteorological variables.

The coefficient value exponent provided by Poisson regression was used to calculate the relative risks (RR) of cardiorespiratory mortality in association with PM_{10} exposure concentrations on the same day of the event (lag 0), one day (lag 1), two days (lag 2) and three days (lag 3) prior to the event.

The expression RR = exp(β × X) provides the increase in the relative risk (RR), where β is the coefficient given by the Poisson regression and X means the increase in the concentration of the pollutant. In this case, an increase of 10 $\mu g\ m^{-3}$ in PM_{10} levels was adopted. We calculated the relative risk of mortality with 95% confidence intervals (CI). Additionally, we determined increases in the relative risk for a 10 $\mu g\ m^{-3}$ in PM_{10} concentration as percentage values. This model has been used by several studies worldwide (Zanobetti *et al.*, 2003; Romieu *et al.*, 2012; Costa *et al.*, 2016; Nascimento *et al.*, 2016; Shi *et al.*, 2016).

Economic Valuation

Currently, there has been a growing concern in the creation of methodologies to express trade-offs among economic costs and deaths (Pascal *et al.*, 2013). A method to achieve the value of postponed deaths is termed Value of a Statistical Life (VSL). A valuable key finding is that the VSL rely on health outcomes and consider other characteristics of the risk of death, such as age, time bounded by exposure and death and features of the underlying risk (Cropper *et al.*, 2011; Dekker *et al.*, 2011).

In consequence, to achieve a standard indicator, we applied the disability-adjusted life years (DALY) method to evaluate the burden of disease due to air pollution in São Paulo (Murray and Lopez, 1996; Miraglia *et al.*, 2005). This method involves two elements: years of life lost (YLL), due to premature death, and years of life lived with disability (YLDs) (Miraglia *et al.*, 2005). In this study, we only assessed the YLL component of DALY. We proceeded with YLL estimation through the WHO updated methodology (WHO, 2016).

The calculation formula of burden in terms of YLL is described in Eq. (1):

$$
\begin{aligned}
YLL_s &= \frac{KC_e^{r\_}}{(r+\_)^2}\Big[e^{-(r+\_)(L+\_)}\big[-(r+\_)(L+\_)-1\big] \\
&\quad -e^{-(r+\_)\_}\big[-(r+\_)\_-1\big]\Big] \\
YLL_s &= \frac{KC_e^{r\alpha}}{(r+\beta)^2}\Big[e^{-(r+\beta)(L+\alpha)}\big[-(r+\beta)(L+\alpha)-1\big] \\
&\quad -e^{-(r+\beta)\alpha}\big[-(r+\beta)\alpha-1\big]\Big]
\end{aligned}
\tag{1}
$$

r is the discount rate, K is the age-weighting modulation factor, C is a constant, α is the age at death, L is the standard expectation of life at age α, and β is the parameter from the age-weighting function. The values adopted for the parameters r, K, C, and β are respectively 3%, 1, 0.1658, and 0.04, as recommended by the Global Burden of Disease (Murray and Lopez, 1996).

In addition, we considered the value of a life year (VOLY) €50,000 to express the economic terms of YLL (Bickel and Friedrich, 2005). The conversion factor for American dollars was 1.2195 (February 28, 2018) which means an equivalent VOLY of US$60,975.00. We considered the relative risk obtained from lag 0 of PM_{10} exposure for all the economic valuation. The standard life expectancy considered was 82.5 years (female) and 80.0 years (male), according to WHO template. The attributable deaths due to PM_{10} was applied to respiratory diseases in all ages and cardiovascular diseases to adults with minimum age of 30 years.

Federal University of São Paulo Ethical Committee approved this study under process number 250.107.

RESULTS

Meteorological and Pollutant Data

Considering the period between 2000 and 2011, there were 96,845 deaths due to respiratory diseases and 265,654 deaths derived from cardiovascular diseases in São Paulo city. Table 1 shows the average values, minimum and maximum of the meteorological variables PM_{10} concentration average in the whole period was 42.04 µg m^{-3}, with a minimum of 8.26 µg m^{-3} and maximum of 168.98 µg m^{-3} (Table 1).

Relative Risk and Lag Function

We used the values of the coefficients, obtained through Poisson regression to obtain the percent of change in RR according to an increment of 10 µg m^{-3} in PM_{10} concentrations (Fig. 1). The effects of exposure to PM_{10} were seen to be significant in all days ($p < 0.001$), with the following values: cardiovascular deaths at lag 0 (%RR = 1.113%; 95% CI = 0.89–1.33); lag 1 (%RR = 0.966%; 95% CI = 0.75–1.19); lag 2 (%RR = 0.734%; 95% CI = 0.51–0.96) and lag 3 (%RR = 0.560%; 95% CI = 0.34–0.78); and respiratory deaths at lag 0 (%RR = 2.173%; 95% CI = 1.81–2.54); lag 1 (%RR = 2.181%; 95% CI = 1.82–2.55); lag 2 (%RR = 1.936%; 95% CI = 1.57–2.30) and lag 3 (%RR = 1.597%; 95% CI = 1.23–1.96).

Economic Valuation

Table 2 shows measures of mortality cases and the burden of disease and injury attributable to air pollution in terms of YLL. It can be observed that respiratory and cardiovascular deaths attributable to PM_{10} correspond to more than US$5.7 billion to US$8.4 billion, respectively between the 2000–2011 period. The total for both causes in all the period sums more than US$14 billion, only considering PM_{10} exposure in São Paulo city.

DISCUSSION

According to the World Bank, air pollutant exposure is the third most important premature death health risk in low- and lower-middle-income countries (WBG, 2016). In 2013, nearly 5.5 million deaths were associated with air pollution, an increase from 4.8 million in 1990 and it costs the world's economy more than $5.1 trillion in welfare losses (WBG, 2016). Very few time series studies have addressed HIA of PM_{10} effects on cardiovascular and respiratory mortality displacement and the associated costs. In China, Yang *et al.* (2016) found that the mean daily YLL was 248 for deaths from cardiovascular disease associated with 10 µg m^{-3} increases in NO_2, SO_2 and PM_{10} levels. Another study in China revealed the mean daily cardiovascular and respiratory deaths were 83 and 14, respectively, from 2006 to 2011, with the corresponding daily YLL of 1,026.4 years and 139.2 years, respectively (Huang *et al.*, 2018).

Our findings using retrospective HIA study suggest that in São Paulo city, PM_{10} is associated with a considerable number of cardiovascular and respiratory deaths. Considering 2000–2011 study period, more than 93,486 respiratory and 138,205 cardiovascular YLL could be associated to PM_{10} exposure. According to Miraglia *et al.* (2005) respiratory events corresponded respectively to 18.6% and 36.2% of total deaths in the elderly and children in the population of

Table 1. Minimum, maximum, means and standard error (SE) of temperature, relative humidity and PM_{10} concentration between 2000 and 2011 in São Paulo.

Year	Minimum Temperature (°C)			Relative Humidity (%)			PM_{10} (µg m^{-3})		
	Mean ± SE	Maximun	Minimun	Mean ± SE	Maximun	Minimun	Mean ± SE	Maximun	Minimun
2000	14.87 ± 0.20	21.30	–0.20	79.44 ± 0.48	95.90	45.67	49.19 ± 1.09	126.60	15.23
2001	15.54 ± 0.18	21.00	3.70	79.46 ± 0.39	95.70	54.70	47.84 ± 1.06	168.98	14.01
2002	16.03 ± 0.17	21.80	3.70	78.81 ± 0.43	96.60	51.20	50.06 ± 1.12	140.28	15.18
2003	15.23 ± 0.18	21.50	3.70	79.06 ± 0.48	96.08	45.54	47.49 ± 1.21	133.94	9.62
2004	14.77 ± 0.17	20.60	4.10	81.01 ± 0.41	97.29	52.29	41.79 ± 1.03	118.48	11.96
2005	15.44 ± 0.16	21.00	5.20	80.96 ± 0.41	94.46	50.54	37.57 ± 0.87	89.19	11.92
2006	15.06 ± 0.18	21.20	4.30	79.76 ± 0.45	96.04	49.50	39.11 ± 1.00	119.34	11.36
2007	17.04 ± 0.17	22.38	6.35	73.46 ± 0.52	98.79	40.40	45.43 ± 0.97	105.11	13.49
2008	16.33 ± 0.14	21.72	9.16	66.30 ± 0.52	99.58	41.41	39.00 ± 1.01	98.80	13.12
2009	15.70 ± 0.18	21.40	4.60	73.39 ± 0.48	99.19	46.33	32.37 ± 0.63	76.09	9.49
2010	15.15 ± 0.19	21.20	0.90	70.12 ± 0.61	93.78	35.74	37.87 ± 1.04	130.79	8.26
2011	14.94 ± 0.19	21.20	2.40	88.04 ± 0.48	99.31	54.27	36.70 ± 0.86	106.38	8.49

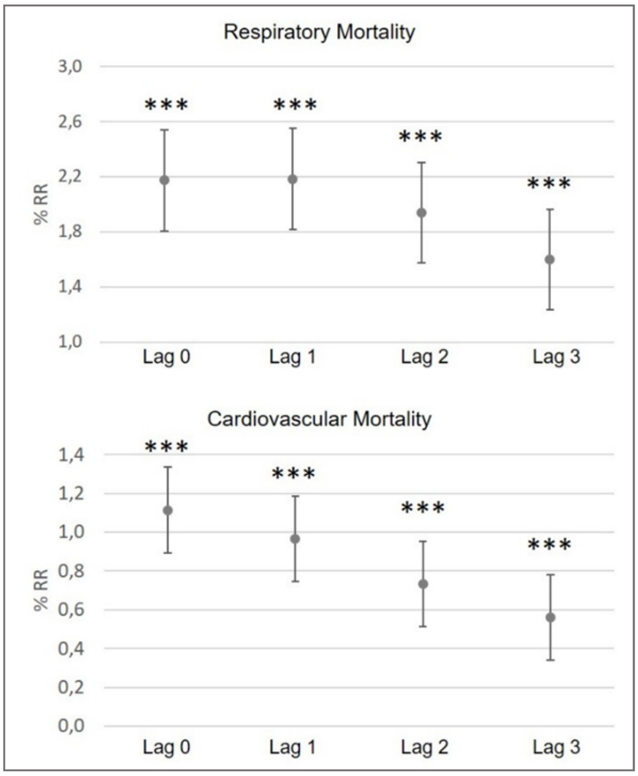

Fig. 1. Increase in relative risk according to increment of 10 µg m^{-3} (95% CI) in the concentrations of PM_{10}.

São Paulo. In the same study, the authors reported that cardiovascular diseases in the elderly corresponded altogether to 47.3% of total deaths in this age group. Elderly and children are the most affected groups, however, pollutants affect all ages in the population, and the exposure could result in a comprehensive decrease in the health status. As reported by Perez *et al.* (2013), road-traffic-related pollution exposure was responsible of 15% of all asthma episodes and the authors found similar patterns for coronary heart diseases in older adults. Moreover, concerning cardiovascular mortality cases and myocardial infarction, there is also a large amount of outcomes regarding acute and chronic health (Franklin *et al*., 2015; Pope *et al*., 2015).

In recent times, some cities have been looking for shifting their focus away from vehicles and coming up to greener, citizen-focused mobility opportunities that may also be healthier (Rojas-Rueda *et al*., 2016). The policy instruments for vehicles restrictions must include, ensuring public transport availability, cycling infrastructure and secure pedestrian areas. According to Rojas-Rueda *et al*. (2016), polices to encourage active transportation are associated with health benefits in the six European cities, as a result of the implementation of active transportation policies that support the use of bicycles and walking. Moreover, in São Paulo city, air pollution has a causal dose-dependent association with absenteeism (Silva *et al*., 2012).

HIA is useful for health management of governmental authorities to determine the need for action and to address potential public health concerns arising from air pollutant exposure (Hadei *et al*., 2017). An HIA study of our group

Table 2. YLL from respiratory and cardiovascular diseases attributable to exposure to PM_{10} and the economic valuation, in euro and dollars, per year.

Year	Respiratory YLL	Economic valuation (€)	Economic valuation (US$)	Cardiovascular YLL	Economic valuation (€)	Economic valuation (US$)	Total (US$)
2000	9,145.0	457,250,000.00	557,616,375.00	14,060.6	703,030,000.00	857,345,085.00	1,414,961,460.00
2001	8,646.9	432,345,000.00	527,244,727.50	13,260.6	663,030,000.00	808.565.085,00	1.335.809.812,50
2002	9,280.9	464,045,000.00	565,902,877.50	13,733.9	686,695,000.00	837,424,552.50	1,403,327,430.00
2003	8,905.7	445,285,000.00	543,025,057.50	12,944.5	647,225,000.00	789,290,887.50	1,332,315,945.00
2004	8,092.3	404,615,000.00	493,427,992.50	11,685.4	584,270,000.00	712,517,265.00	1,205,945,257.50
2005	6,502.9	325,145,000.00	396,514,327.50	9,807.3	490,365,000.00	598,000,117.50	994,514,445.00
2006	7,269.4	363,470,000.00	443,251,665.00	10,406.5	520,325,000.00	634,536,337.50	1,077,788,002.50
2007	8,247.5	412,375,000.00	502,891,312.50	12,162.4	608,120,000.00	741,602,340.00	1,244,493,652.50
2008	6,792.8	339,640,000.00	414,190,980.00	10,673.0	533,650,000.00	650,786,175.00	1,064,977,155.00
2009	6,182.8	309,140,000.00	376,996,230.00	8,884.1	444,205,000.00	541,707,997.50	918,704,227.50
2010	6,991.2	349,560,000.00	426,288,420.00	10,366.8	518,340,000.00	632,115,630.00	1,058,404,050.00
2011	7,429.4	371,470,000.00	453,007,665.00	10,219.8	510,990,000.00	623,152,305.00	1,076,159,970.00
Total	93,486.8	4,674,340,000.00	5,700,357,630.00	138,205.0	6,910,245,000.00	8,427,049,875.00	14,127,401,407.50

has led us to consider scenarios of preventive action and associated avoidable costs. As the main point of analysis,if the $PM_{2.5}$ WHO standards (2005) had been reached in São Paulo city, life expectancy would have increased by 15.8 months due to a 266,486 life years' gain and it could represent an economy of more than US$15 billion annually (Abe and Miraglia, 2016). As a comparison, the present study indicates an economic loss of more than US$3.3 billion in São Paulo city due to actual PM_{10} levels. In this sense, any measure concerning diminishing of air pollutants' levels will have a worthy Return On Investment (ROI) in both economic and health figures terms.

A Belgian study conducted a similar analysis where the authors concluded that a 10% reduction of pollutants mean a potential annual hospital cost saving of €13.2 million (Devos *et al*., 2015). If WHO annual guidelines for PM_{10} and $PM_{2.5}$ were met, more than triple these amounts would be saved (Devos *et al*., 2015).

As shown in Fig. 1, air pollutant effects could be verified even after 3 days of the prior exposure, meaning a persistent effect. Another study in Brazil verified the effect of $PM_{2.5}$ exposure on population health in the city of 260,000 inhabitants called Volta Redonda, in Rio de Janeiro state. The authors declared that a 5 µg m^{-3} decrease in $PM_{2.5}$ concentration would entail a decrease of 76 hospitalizations and it would lead to savings of around R$84,000.00 annually (approximately US$26,040.00; conversion data: February 28, 2018), in light of a costs reduction related only to hospitalization due to pneumonia, acute bronchitis, bronchiolitis and asthma (Nascimento *et al*., 2016). They also verified the $PM_{2.5}$ effects in a lag model, demonstrating an association between $PM_{2.5}$ and health effects even 7 days after the prior exposure. A large study estimated the mortality attributable to PM_{10} in 29 Brazilian metropolitan areas assessing economic outcome of air pollution. It has resulted in 20,050 premature deaths and representing a loss of $1.7 billion annually (Miraglia and Gouveia, 2014).

Zanobetti *et al*. (2003) has concluded that PM_{10} effect (per 10 µg m^{-3}) in distributed lag models has an effect estimates increased to 4.2% (95% CI = 1.08–7.42) for respiratory deaths and to 1.97% (95% CI = 1.38–2.55) for cardiovascular deaths. Moreover, the authors confirmed that most of the air pollution effect is persistent for more than a month after exposure (Zanobetti *et al*., 2003). For the day of exposure, our study showed an increase of 2.173% and 1.113% in respiratory and cardiovascular deaths, respectively, considering lag 0 per 10 µg m^{-3}. The effect was decreasing until the third lag day; however, it showed significant association, as other studies have that demonstrated the persistent long-term effect of air pollution in health (Fig. 1).

Air pollution effects and economic costs are a crucial issue recognized worldwide. The World Bank estimates 5.5 million lives were lost in 2013 due to diseases associated with outdoor and household air pollution, causing human suffering and reducing economic development. The costs of those deaths, globally, are estimated about US$225 billion in lost labor income in 2013 and more than US$5 trillion in welfare losses, highlighting economic burden of air pollution (WBG, 2016).

Despite the fact that São Paulo city has been decreasing the PM_{10} mean concentrations over the study period (at the beginning of the study was 49.19 µg m^{-3} ± 1.09 Standard Error (SE) (2000) and the mean concentration at the end of study period was 36.7 µg m^{-3} ± 0.86 SE (2011); Table 1), due to national and regional restrictive public policies, more efforts will be needed to diminish mortality and morbidity associated with air pollution. Urgent action is now required to strengthen the public policies against the increase of air pollutants and to facilitate decision making in the context of limited resources. In this sense, a prospective HIA study could be useful in order to highlight health priorities and prevent economic expenditures.

The improvement of public policies with respect to pollutant levels are highly required once the premature deaths in Brazil means an overload in health system and serious economic losses (Miraglia and Gouveia, 2014).

Limitations and Positive Aspects of the Study

Few studies have examined the air pollution impact on YLL and its economic valuation. Moreover, there are very few studies for evaluating the chronic effects of air pollution in São Paulo, and this could be useful to stakeholders. Furthermore, the public national health data obtained by DATASUS system has some boundaries, as there may be underreporting, data insertion problems, technological limitations and people training. In addition, the meteorological and pollutant data represent an average and may present distortions within the actual data. Although $PM_{2.5}$ concentration was more suitable to consider in health analysis, $PM_{2.5}$ data was not available. Finally, the economic data used a European statistical life value because there is no similar national study that reflected an adequate value; however, life values should be equal all over the world.

CONCLUSIONS

The present study confirms the impact of PM_{10} on health and the resulting economic burden, which significantly hamper the progress and well-being of developing countries. We found evidence of an association between PM_{10} and cardiovascular and respiratory mortality, even after a displacement of three days. The YLL totaled 231,691.8 years, meaning an overall economic loss of more than US$14.1 billion for the city of São Paulo. The knowledge gained from this study must be considered in formulating and prioritizing public policies, thereby minimizing these impacts.

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AUTHOR CONTRIBUTIONS

S.G.E.K.M. had the original idea and design the study; K.C.A., G.M.S.S. and M.S.Z.S.C conducted the database collection and performed the analysis; S.G.E.K.M. and K.C.A. conducted the data analysis and interpretation, prepared the text and provided critical revision of the manuscript, which was revised and approved by all authors.

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