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BASIC RESEARCH

Lean diesel technology and human health: a case study in six Brazilian metropolitan regions

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OBJECTIVE: Due to their toxicity, diesel emissions have been submitted to progressively more restrictive regulations in developed countries. However, in Brazil, the implementation of the Cleaner Diesel Technologies policy (Euro IV standards for vehicles produced in 2009 and low-sulfur diesel with 50 ppm of sulfur) was postponed until 2012 without a comprehensive analysis of the effect of this delay on public health parameters. We aimed to evaluate the impact of the delay in implementing the Cleaner Diesel Technologies policy on health indicators and monetary health costs in Brazil.

METHODS: The primary estimator of exposure to air pollution was the concentration of ambient fine particulate matter (particles with aerodynamic diameters $<2.5\ \mu m$, [PM2.5]). This parameter was measured daily in six Brazilian metropolitan areas during 2007-2008. We calculated 1) the projected reduction in the PM2.5 that would have been achieved if the Euro IV standards had been implemented in 2009 and 2) the expected reduction after implementation in 2012. The difference between these two time curves was transformed into health outcomes using previous dose-response curves. The economic valuation was performed based on the DALY (disability-adjusted life years) method.

RESULTS: The delay in implementing the Cleaner Diesel Technologies policy will result in an estimated excess of 13,984 deaths up to 2040. Health expenditures are projected to be increased by nearly US$ 11.5 billion for the same period.

CONCLUSIONS: The present results indicate that a significant health burden will occur because of the postponement in implementing the Cleaner Diesel Technologies policy. These results also reinforce the concept that health effects must be considered when revising fuel and emission policies.

KEYWORDS: Vehicular emission; Health costs; Environmental policies.

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INTRODUCTION

Sanitation, immunization and antibiotics, and improved nutrition have increased life expectancy and dramatically changed the patterns of disease in many countries. Along with these benefits, however, development, including economic development, population growth, industrial development, urbanization, and increased use of motorized transportation, has been accompanied by global environmental deterioration, which poses a threat to current and future human health, especially in developing and underdeveloped countries. Economic disadvantage (areas with low socioeconomic status) augments the deleterious effects of air pollution on human health, a situation designated as environmental inequity (1). Environmental quality has been considered to be dependent on regional characteristics, among which social and economic factors play a pivotal role (2,3). Environmental disparities may increase as the result of the expansion of the interest of the automotive industry, predominantly diesel engine manufacturers, in the growing markets in Latin America, Africa, and Asia, where environmental and health policies are not strongly consolidated (4).

Due to their high toxicity, diesel emissions have been subjected to increasingly restrictive regulations over the last several decades at a cost of higher investments in fuel (low sulfur content) and engine technologies in developed countries (5). Sulfur is a naturally occurring component of crude oil and is found in both gasoline and diesel. When

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No potential conflict of interest was reported.

these fuels are burned, sulfur is emitted as sulfur dioxide (SO_2) or sulfate particulate matter (6).

Since 1993, the European Union (EU) has established standards to regulate the quality of automotive fuels and vehicle emissions to combat the atmospheric pollution caused by emissions from motor vehicles. A series of directives resulted in the progressive introduction of increasingly stringent standards (EURO standards) that define the acceptable limits for exhaust emissions of vehicles sold in EU member states (7).

Unfortunately, the benefits of cleaner technologies are lagging in less developed regions. In the USA, trucks sold after 2007 emit 0.01 g/bhp-hr[1] PM, and in Germany, trucks can emit only 0.02 g/kWh[2] (defined in the EURO V standard). In contrast, in Brazil, India, and China, the allowed level of emissions is 0.1 g/kWh PM (EURO III standard) (8). These differences in emissions standards mean that heavy-duty diesel engines produced by the same manufacturer emit markedly different levels of pollutants depending on the regional market in which the engines are sold. Economic issues have been evoked to support the aforementioned ''regulatory differences'' in environmental emission standards. The trade-offs associated with these regulatory differences are relevant to the situation in Brazil because the implementation of a policy requiring cleaner diesel technologies (CDT; Euro IV standards for vehicles produced in 2009 and low sulphur diesel; diesel with 50 ppm of sulphur) was postponed until 2012 without a comprehensive analysis of the health consequences (9).

To evaluate the health impact of the decision to delay implementation of the CDT policy, we estimated the monetary health costs of the non-abatement of ambient PM2.5 emissions due to this postponement in Brazil.

MATERIALS AND METHODS

Air pollution analysis and emission source determination. We selected fine particles (particles with aerodynamic diameters less than 2.5 µm – PM2.5) as the estimator of exposure to air pollution. Diesel emissions contribute significantly to ambient PM2.5 concentrations in urban areas, and this class of pollutant exhibits a robust association with adverse health effects, especially lung cancer and cardio-respiratory diseases (10,11).

During 2007-2008, we performed daily measurements of the ambient levels of PM2.5 in six Brazilian metropolitan regions: Curitiba, São Paulo, Belo Horizonte, Rio de Janeiro, Recife, and Porto Alegre. These cities have a combined population of 46,811,100 inhabitants (25% of the Brazilian population) and generate 37.3% of the country's Gross National Product (12,13).

The daily concentration of particulate matter (PM2.5) was obtained by a gravimetric method using a Harvard sampler with a PM2.5 impactor (Air Diagnostics and Engineering Inc., Harrison, ME, USA) at a flow rate of 10 $L.min^{-1}$ using a polycarbonate membrane. Each membrane was weighed before and after sampling using an ultra-microbalance (Mettler Toledo UMX2, readability 1 µg, Zurich, Switzerland) to determine the daily mass trapped by each membrane, allowing the calculation of the daily mean concentration of PM2.5 (13). The black carbon concentrations were measured using the reflectance method (14) using the same membranes, and 1/3 of the membranes were submitted to X-ray fluorescence spectrometry (15) and ion chromatography (16) analysis to determine the concentrations of the predominant chemical elements (Na, Al, Si, P, S, K, Ca, Ti, V, Fe, Ni, Cu, Zn, and Pb), nitrates and sulfates. The daily mean concentrations of PM2.5 were used to calculate the annual daily mean of PM2.5 as described by the WHO (30). All of the samplers were installed in central areas of the metropolitan regions at least 200 m from major traffic routes.

Sources and their relative contributions to the ambient PM2.5 concentrations were identified using receptor modeling techniques based on the chemical characteristics of the particles collected at the receptor sites (in this case, the different metropolitan areas). In addition, PMF (positive matrix factorization), a factor analysis method, was applied to identify sources and determine the contribution of each identified source to the ambient concentration of PM 2.5 (17). The data used in this study were obtained from a recent research project conducted by our group (18).

Delay in the adoption of the CDT policy and estimate of the ambient PM2.5 concentrations. The non-abatement of ambient PM2.5 concentrations due to the delay in the adoption of more stringent emissions standards was estimated by considering the Total Emissions Inventory agreed upon by the Brazilian Ministry of Environment and truck manufacturers and oil companies operating in Brazil (19). The projected reduction in the PM2.5 concentration that would have been achieved if the CDT policy had been implemented and those expected considering the delay are presented in Figure 1 (20).

Estimation of the health consequences of the implementation of the CDT policy. The differences between the emissions curves presented in Figure 1 are assumed to be proportional to the changes in the proportion of PM2.5 generated by diesel engines for each metropolitan area. The delay in the decline in the level of diesel-generated particles was computed until 2040 based on the present ambient concentrations of PM2.5 and the relative contribution of diesel to PM2.5 determined for each study site.

The impact on morbidity of the additional PM2.5 due to the delay in the implementation of the CDT policy was estimated in terms of hospitalizations due to respiratory and cardiovascular events. The impact was determined separately for different age groups, employing coefficients from time series studies (Table 1), favoring studies that were conducted locally (21-26). Functions associating increases in air pollution with adverse health effects may be derived based on short-term or long-term exposures. When there is no clear evidence of a chronic effect, the short-term dose response is preferable and more conservative. For PM2.5, long-term cohort studies have provided solid evidence of cumulative effects. Therefore, we used the annual mean PM2.5 concentration, as recommended by the WHO (30). For mortality studies, we decided to consider the coefficients that associate chronic exposure to PM2.5 with all causes of mortality in adults to avoid possible bias in establishing the cause of death based on death certificates (WHO).

Respiratory and cardiovascular hospital admissions. The numbers of respiratory and cardiovascular hospital admissions in the public health system for each metropolitan area for 2007 were obtained from the Brazilian Health Ministry Database (27) and are presented in Table 2.

Hospital admissions in the private health system are not routinely registered in Brazil. We estimated the number of

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[1] grams/brake horsepower/hour

[2] grams/kilowatt hour

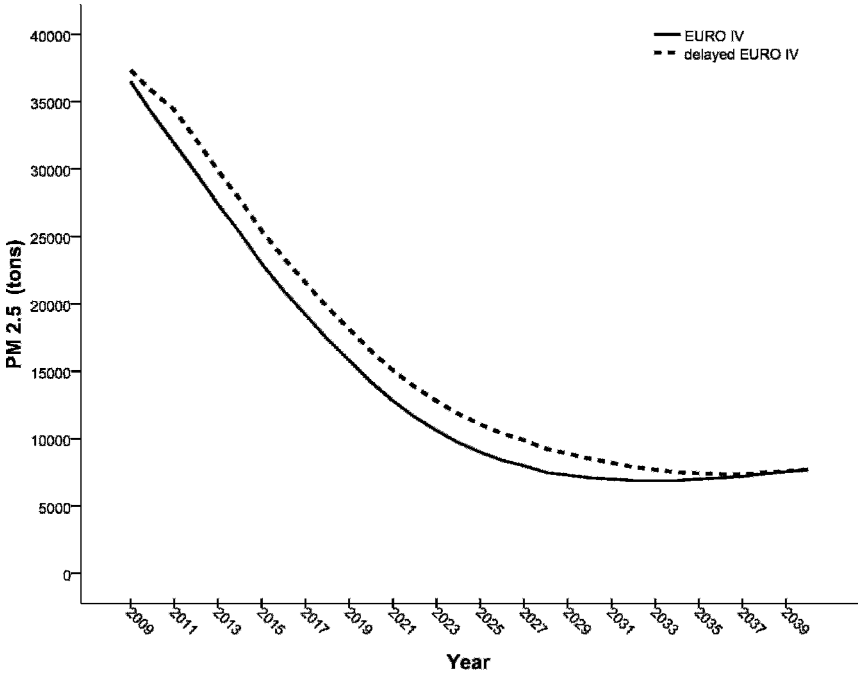

Figure 1 - Graphic representation of the estimated PM2.5 emissions for the six Brazilian metropolitan areas (in tons per year) considering the implementation of or the delay in the adoption of the EURO IV standards for diesel emissions.

hospital admissions in the private system by extrapolation based on the health insurance coverage rate (28) of the private system for each metropolitan area (as presented in Table 6- Supplemental Data). The number of hospital admissions in the private health system was computed based on the relationship described in the following equation (1):

$$N_{PS} = N_{Public}\left(\frac{1}{1-CR} - 1\right) \qquad (1)$$

Where:

N_{PS} is the number of hospital admissions in the private system,

N_{public} is the number of hospital admissions in the public system, and

CR is the proportion of the population with access to private health insurance.

After determining the baseline number of hospital admissions for the relevant health outcomes and the age groups of interest and after establishing the coefficients that relate changes in the PM2.5 concentration to hospital admissions, the projected morbidity effects of the delay in implementing the CDT policy were computed using the following equation (2):

Table 1 - The age groups considered in this study and the corresponding risk coefficients relating PM2.5 concentrations to a given health effect.

Age group (years)	Respiratory (increase per µg/m^3)	Cardiovascular (increase per µg/m^3)
0 to 4	0.0047 (21,23)	
40 to 59	0.0024 (26)	0.0016 (26)
60 to 69	0.0044 (22)	0.0024 (22,24)
over 69	0.0063 (25)	0.0027 (24)

$$\left[\mathrm{Hadm}\left(\Delta\ \mathrm{Conc_{year}}\right)\right] = \left[\exp\left(\beta * \left(\Delta\mathrm{Conc_{year}}\right) - 1\right] * \mathrm{Totadm}\ (2)$$

Where:

Table 2 - Total number of hospital admissions (2007) to the public health system attributable to respiratory and cardiovascular diseases according to age and metropolitan area.

Metropolitan area	Age group (years)	Number of Hospital Admissions	
		Respiratory	Cardiovascular
São Paulo	0-4	41.842	nihil
	40-59	12.600	36.854
	60-69	6.981	22.868
	>69	14.739	29.796
Rio de Janeiro	0-4	23.644	nihil
	40-59	8.190	19.295
	60-69	4.206	12.410
	>69	7.480	16.956
Belo Horizonte	0-4	12.140	nihil
	40-59	3.647	10.604
	60-69	2.239	5.672
	>69	4.728	7.115
Curitiba	0-4	6.123	nihil
	40-59	3.056	9.315
	60-69	2.193	5.842
	>69	4.104	6.414
Porto Alegre	0-4	10.089	nihil
	40-59	6.601	12.008
	60-69	4.139	7.823
	>69	6.893	10.335
Recife	0-4	11.027	nihil
	40-59	2.535	6.820
	60-69	1.679	4.140
	>69	3.596	5.155

Hadm (Δ Conc$_{year}$) = hospital admissions due to the delay in reducing the ambient concentration of PM2.5 in a given year;

β = coefficient relating PM2.5 to hospital admissions (Table 1);

Δ Conc$_{year}$ = difference between the predicted concentration of PM2.5 that would have been achieved if the CDT policy had been implemented and the estimated concentration of PM2.5 given the delay; and

Totadm = total hospital admissions for a given year.

Equation (2) was used to estimate the effects of the additional PM2.5 on the different health outcomes listed in Table 2. The value of Hadm (Δ Conc$_{year}$) was integrated over 40 years, as shown in Figure 1.

Mortality

The effects of the delay in implementing the CDT policy were also expressed in terms of mortality. Data on mortality due to natural causes in individuals over 40 years of age were obtained from DATASUS (29). The most recent data available were for 2007 and are presented in Table 3. The additional mortality burden due to the delay in implementing the CDT policy was estimated as suggested by the WHO (30) using the following equation:

$$[\mathrm{M}(\Delta \mathrm{Conc}_{year})] =]\left(\Delta \mathrm{Conc}_{year}\right) * 0.006 * \mathrm{TotalM} \quad (3)$$

Where:

M (Δ Conc$_{year}$) = number of deaths in a given year due to the delay in reducing the concentration of PM2.5;

Δ Conc$_{year}$ = difference between the predicted concentration of PM2.5 that would have been achieved if the CDT policy had been implemented and the estimated concentration of PM2.5 given the delay;

0.006 = relative risk of adult mortality for each 1.0 $\mu g/m^3$ of PM2.5; and

TotalM = the baseline mortality counts for each metropolitan area, as presented in Table 3.

Economic valuation of the health effects expected to occur as a consequence of the delay in the implementation of the CDT policy. Morbidity costs were estimated in terms of the direct costs of hospital admissions due to respiratory and cardiovascular diseases in both the public and private health systems and in terms of indirect costs (productivity loss). The mean cost of hospital admissions for respiratory and cardiovascular diseases for each age group was obtained from DATASUS (31). The cost of hospital admissions in the private health system was not available and was estimated to be three times higher than the public cost based on data from the Hospital das Clínicas of the Faculdade de Medicina da Universidade de São Paulo. The cost associated with lost productivity considers the number of days of absence due to hospitalization (data were obtained from DATASUS (31)) and the mean gross income for each age group (data obtained from the IBGE (the Brazilian Statistical and Geographic Agency), which was responsible for the public economic census conducted in 2000 (32)).

Table 3 - Total number of deaths per year (2007) in the six studied Brazilian metropolitan regions.

Metropolitan region	Number of deaths/year
São Paulo	82,542
Rio de Janeiro	61,430
Belo Horizonte	16,830
Curitiba	12,971
Porto Alegre	20,471
Recife	15,407

The economic valuation of mortality was performed based on the disability-adjusted life years (DALY) method (33), which combines an ambient factor, in this case the PM2.5 concentration, with a health indicator (mortality) to estimate the number of years of life lost through premature mortality relative to Brazilian life expectancy. The number of (DALY) (33) was calculated using an equation that estimates years of life lost (YLL), the DALY component that refers to time lost due to premature mortality. The YLL was estimated based on the age at death and the life expectancy in southeastern Brazilian. We assumed an equal proportion of male and female deaths. The values of the other parameters (the discount rate and the age-weighted modulation factor) were adopted as recommended by Murray and Lopez (33). The total years of life lost were converted into monetary values as described previously (34), and the values for the years of life lost (YLL) were provided by ExternE (35). The life expectancy values were obtained from the IBGE (the Brazilian Statistical and Geographic Agency) (12) for each metropolitan region.

RESULTS

Source. Our approach indicated that diesel sources contributed approximately 40% of the total mass of PM2.5, considering both primary and secondary aerosol formation. This estimate was consistent with that of the São Paulo State Sanitation Agency (CETESB) and previous studies focused on the city of São Paulo (37-38).

Hospital Admissions and Mortality

Table 4 presents the estimated excess hospital admissions due to respiratory and cardiovascular diseases in the public and private health systems and the estimated excess mortality for the six metropolitan areas for the years 2009 to 2040 resulting from the delay in the implementation of the CDT policy.

Health and mortality costs

Table 5 presents the costs associated with the excess hospital admissions due to respiratory and cardiovascular diseases attributable to PM2.5.

Mortality costs due to respiratory and cardiovascular diseases attributable to PM2.5 were estimated based on the total years of life lost (YLLs). For the period 2009-2040, the non-abatement of PM2.5 accounted for 162,878 YLLs, which represents a total cost of US$ 11.4 billion.

DISCUSSION

Our results indicate that considerable health and economic burdens resulted from the delay in implementing the CDT policy. Air pollution in urban areas has negative health effects, including difficulty breathing, wheezing, coughing, eye irritation, aggravation of pre-existing respiratory and cardiac diseases, and even premature death. Effects on pregnancy and fetal development have also been reported (39). Increases in hospital admissions and medication use in

Table 4 - Total Number of Hospital Admissions (HA) due to Respiratory and Cardiovascular diseases in the Public (PHS) and Private Health Systems (PrHS) and Total Number of Deaths in the six Brazilian Metropolitan Areas between 2009 and 2040 attributable to PM2.5.

Total Number of Hospital Admissions (HA) in the Public (PHS) and Private Health Systems (PrSH) and the Total Number of Deaths for the period 2009-2040							
	Belo Horizonte	**Curitiba**	**Porto Alegre**	**Recife**	**Rio de Janeiro**	**São Paulo**	**Total**
Total number of HA-PHS	1,596	1,244	2,000	843	3,487	9,379	18,549
Total number of HA-PrHS	1,113	649	703	288	2,354	9,530	14,638
Total Number of Deaths	866	668	1,041	533	3,641	7,235	13,984

areas with moderate or high levels of air pollution are commonly reported in different parts of the world (40).

The use of motorized transportation in Brazil increases every year. According to DENATRAN (National Traffic Department), the Brazilian fleet has doubled in the last ten years; there are currently almost 65,000,000 registered vehicles in Brazil, including cars, trucks, buses and motorcycles (41). The states of São Paulo, Minas Gerais, and Paraná have the largest fleets, with nearly 20, 7, and 5 million cars, respectively.

Although this growth in motorized transportation is a result of and an indicator of the growing economy and a higher standard of living, it is accompanied by environmental and social challenges, including air pollution and traffic congestion, which pose threats to the health and well-being of the residents.

It is clear that this growth in motorization will increase economic and health costs. To address these problems, different countries have conducted economic valuations of public health endpoints to substantiate environmental and health politics (42). The translation of the social and health benefits of cleaner fuel and vehicle regulations into monetary amounts is necessary to direct the decision-making process regarding actions that have the potential to affect air quality in urban areas (43).

Unfortunately, in Brazil, the decision to postpone the adoption of the CDT policy was not based on any cost-benefit analysis. The displacement of the curve for the reductions in diesel emissions (Figure 1) agreed upon by industries and the Brazilian authorities was considered not to be significant. However, the more detailed analysis of the health consequences of this delay performed in our study indicated that because of the large number of exposed people, the delay in implementing the CDT policy will be responsible for a considerable number of hospitalizations and a presumable excess of approximately 14,000 premature deaths. Most likely, the authorities that approved the postponed implementation of the CDT policy would have made a different decision if the health consequences had been fully considered in the decision-making process.

Because cost-benefit analyses may be highly influenced by regional characteristics, in the present investigation, we collected primary data to minimize uncertainties in the estimates. For example, the concentration response curves for morbidity preferentially used data from local studies. Costs were obtained directly from the Health System databank. A comprehensive sampling and chemical analysis of the particle composition and source apportionment techniques were applied to determine the contribution of the present diesel technology to ambient particle levels in the areas of study.

Vehicles, fuels, air pollution, and health should be treated and analyzed as a system. Changes in fuel composition can immediately impact air pollution and consequently influence air pollution control (44-45). There are many examples of how cleaner diesel fuel contributes to reductions in air pollution. In Hong Kong, a one-weekend intervention study that required all power plants and road vehicles to use fuel oil with a low sulfur content led to an immediate decrease in the level of ambient sulfur dioxide (SO_2) and provided direct evidence that this type of change has immediate and long-term health benefits, thus reducing mortality rates (46).

Donald McCubbin and Mark Delucchi evaluated the health costs of a kilogram of various air pollutants, including CO, NOx (Nitric oxides), PM2.5, SOx (sulfur oxides), and VOCs (volatile organic compounds). They estimated health costs based on such factors as hospitalization, chronic illness, asthma attacks, and lost work days for US urban areas. These researchers found that the ranges in health costs per kilogram were from US$0.01 to US$0.10 for CO, US$1.59 to US$23.34 for NOx, US$14.81 to US$225.36 for PM2.5, US$9.62 to US$90.94 for SOx, and US$ 0.13 to US$ 1.45 for VOCs (47).

In the Indian context, the health cost of urban air pollution was estimated to be US$ 1.4 billion (48).

Our results are consistent with the results of previous studies and indicated that the sulfur content of diesel represents a considerable source of ambient fine particles and that considerable health benefits would result from implementing the CDT policy. Indeed, a previous study performed in São Paulo indicated that the use of improved

Table 5 - Total costs in US$ of the hospital admissions (PHS and PrHS) due to respiratory and cardiovascular diseases attributable to PM2.5 between 2009-2040 in the six metropolitan areas.

	Total costs in US$ of hospital admissions (PHS and PrHS) due to respiratory and cardiovascular diseases attributable to PM2.5 for the period 2009-2040					
	Belo Horizonte	**Curitiba**	**Porto Alegre**	**Recife**	**Rio de Janeiro**	**São Paulo**
PHS	1,400,466	1,188,968	1,845,497	606,468	2,825,747	9,322,799
PrHS	2,931,933	1,861,553	1,946,366	622,914	5,723,134	28,418,886
Total	4,332,399	3,050,521	3,791,863	1,229,382	8,548,881	37,741,685

Table 6 - Percentage of the population with private health insurance coverage.

Metropolitan area	Percentage of the population with private health insurance coverage
São Paulo	50.4
Rio de Janeiro	40.3
Belo Horizonte	41.1
Curitiba	34.3
Porto Alegre	26.0
Recife	25.5

diesel technology exhibited the best cost-benefit ratio among all other policies considered to reduce the health effects of air pollution (49). Interestingly, although this report was fully available when the decision to delay the implementation of the CDT policy was made, the relevant authorities did not consider the recommendations presented in that report. This failure to consider published data-based recommendations indicates that the health consequences of industrial and fuel policies are not usually considered in situations in which economic pressures are high.

In conclusion, our results indicate that it is necessary to increase the level of awareness about the health consequences of policies that regulate transportation and fuel technology and that human health must play a role in the environmental agenda in urban areas.

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AUTHOR CONTRIBUTIONS

André PA designed the research plan, supervised and participated in the field experiments and the acquisition of the air monitoring data, and participated in the data analysis and the writing of the paper. Miraglia SG designed the research plan and participated in the data analysis and the estimation of the monetary health costs. Veras MM designed the research plan and participated in the data analysis and the writing of the paper. Saldiva PH coordinated the study, designed the research plan, and participated in the writing of the paper. All authors have read and approved the final version of the manuscript.

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