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Research Article

Quantification of Size Segregated Particulate Matter Deposition in Human Airways

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Abstract

Background: Air pollution has become a significant concern in both urban and rural sectors due to its catastrophic effect on human health and the environment. Particulate matter (PM) is crucial among criteria pollutants and is well correlated with human mortality and morbidity. Based on aerodynamic size, PM is classified into coarse (PM_{10}) and fine ($PM_{2.5}$ and PM_1). A recent study by World Health Organization showed that PM has caused 7 million premature deaths globally. Also, the International Agency for Research on Cancer (IARC) identified PM as carcinogenic as it is directly related to lung cancer. Human airway is the primary pathway for PM to enter the human body. Hence the study on coarse and fine PM deposition in the human respiratory tract is essential for health risk assessments.

Materials and Methods: Hourly measurements of PM_{10}, $PM_{2.5}$ and PM_1 are measured during a winter using Grimm aerosol spectrometer near an arterial roadside in Chennai city of Tamil Nadu, India. PM deposition in the human airway is investigated using the Multiple-Path Particle Deposition Model (MPPD) version 3.04. In MPPD model, the stochastic structure which depicts the real human lung is considered. The deposition in MPPD model is assessed for three size fractions, i.e. PM_{10}, $PM_{2.5}$ and PM_1 under different breathing scenarios viz. nasal, oral, and oronasal.

Results: Highest total deposited mass rate obtained from the MPPD model for PM_{10}, $PM_{2.5}$, and PM_1 are 942 ng min^{-1}, 345 ng min^{-1}, and 104 ng min^{-1}, respectively. The maximum deposited mass rate is also assessed in the head (PM_{10} = 904 ng min^{-1}; $PM_{2.5}$ = 244 ng min^{-1}; PM_1 = 57 ng min^{-1}), tracheobronchial (PM_{10} = 284 ng min^{-1}; $PM_{2.5}$ = 60 ng min^{-1}; PM_1 = 24 ng min^{-1}) and pulmonary (PM_{10} = 32 ng min^{-1}; $PM_{2.5}$ = 89 ng min^{-1}; PM_1 = 27 ng min^{-1}) regions. In the head region, maximum deposition is caused by nasal breathing; whereas, tracheobronchial (TB) and pulmonary regions, the oral breathing leads to higher deposition. Results also showed that for all PM sizes the lobe wise depositions are in the following order: right upper > left lower > left upper > right middle > right lower. Further, the airway clearance results indicated that PM removal is faster in the TB region than the alveolar region.

Conclusion: PM_{10} has a higher deposition in the head region whereas $PM_{2.5}$ and PM_1 deposition is higher in the TB and pulmonary regions. This indicates that PM deposition inside lungs is influenced by its size and several other deposition mechanisms viz. inertial impaction, sedimentation, diffusion and interception. Further, this study results can be utilized for assessing health risks such as oxidative potential and toxicity of deposited PM.

Keywords: Air pollution, Deposition, Human airway, Particulate matter, MPPD model

Introduction

Globally air pollution has become a crucial concern due to its adverse effects on human health and environment.[11,18,25] Many countries and international agencies have laid

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legislation and standard limits to mitigate air pollution. In India, National Ambient Air Quality Standards are enacted to protect public health by reducing the current air pollutants concentration. At present the standard limits are levied for eight crucial pollutants viz. particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxide, sulfur dioxide, carbon monoxide, ozone, ammonia, and lead. Among the eight pollutants, PM is considered a most toxic, since it causes an average of 9,91,600 premature deaths annually. Across the nation, North India experiences alarming premature mortality at the rate of >0.2 deaths per square kilometers.[30] This is due to its complex physio-chemical composition which holds the toxic effects.[12,20,40] PM physical properties include its size, mass and number concentration. The size of PM ranges from few Nanometres to 100 micrometers.PM with an aerodynamicdiameter of less than 10μm, 2.5μm, and 0.1μm are coarse PM, fine PM and ultrafine PM respectively.[18] Mass metric is utilized for coarse and fine PM while the number concentration is considered for ultrafine PM.[13, 23, 33, 34] The chemical nature of PM is highly variable and is dependent upon the source of origin.[26, 32, 39] However most of the PM will be composed of carbon compounds (organic carbon and elemental carbon), ions (Ca^{2+}, Cl^{-}, Mg^{2+}, K^{+}, NH_4^{+}, NO_3^{-}, $PO_4^{3-}$and SO_4^{2-}) and elements (Al, As, Ba, Br, Ca, Cd, Cl, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, S, Sc, Se, Si, Sr, Ti, V and Zn).[21, 31, 35, 45] Both the physical and chemical properties of PM will vary spatially and temporally due to the influence of several meteorological parameters such as wind, temperature, pressure and humidity.[6,41,42]

PM having a size less than 10μm can easily enter the human respiratory tract through the nose and mouth.[3] The inhalability of PM depends upon the particle size, wind speed and the orientation of nose or mouth towards the air streamline. Inhalability of fine particles is usually high when compared to coarse particles. This is due to the inability of coarse particles to take a sharp turn with the air streamlines while entering the nose or mouth.[43] After entering the human respiratory tract, PM will get settled in different regions viz. head, tracheobronchial (TB) and pulmonary. Settling of PM inside the respiratory tract is influenced by several deposition mechanisms such as sedimentation, diffusion, and impaction.[46] All these mechanisms are dependent on the lung geometry, breathing pattern and properties of PM. The lung geometry influences the airflow and the PM motion. The inhalation-exhalation duration, pause duration, breathing frequency, lung volume, and PM properties such as shape, density, electrical charge and hygroscopicity are crucial in deposition.[5,19,22]

This deposited PM is capable of causing short-term and long-term human health effects. The available PM epidemiological studies are positively associated with respiratory diseases, cardiovascular diseases, cerebrovascular diseases, and kidney diseases.[2,4,8,16,28,29] Hence, quantification of PM deposition in the human airway is essential. So far only few studies have measured the deposition of PM entering through the mouth and oronasal (combined oral and nasal). Thus, a study comparing the deposition of PM through the nose, mouth and oronasal will be essential and informative for the other health assessment studies. By understanding the need and importance, this study aims to quantify and compare the deposition of PM (PM_{10}, $PM_{2.5}$ and PM_1) entering into the human respiratory tract by means of nasal, oral and oronasal. In the present study, the deposited doses are found using the multiple path particle dosimetry (MPPD) model.

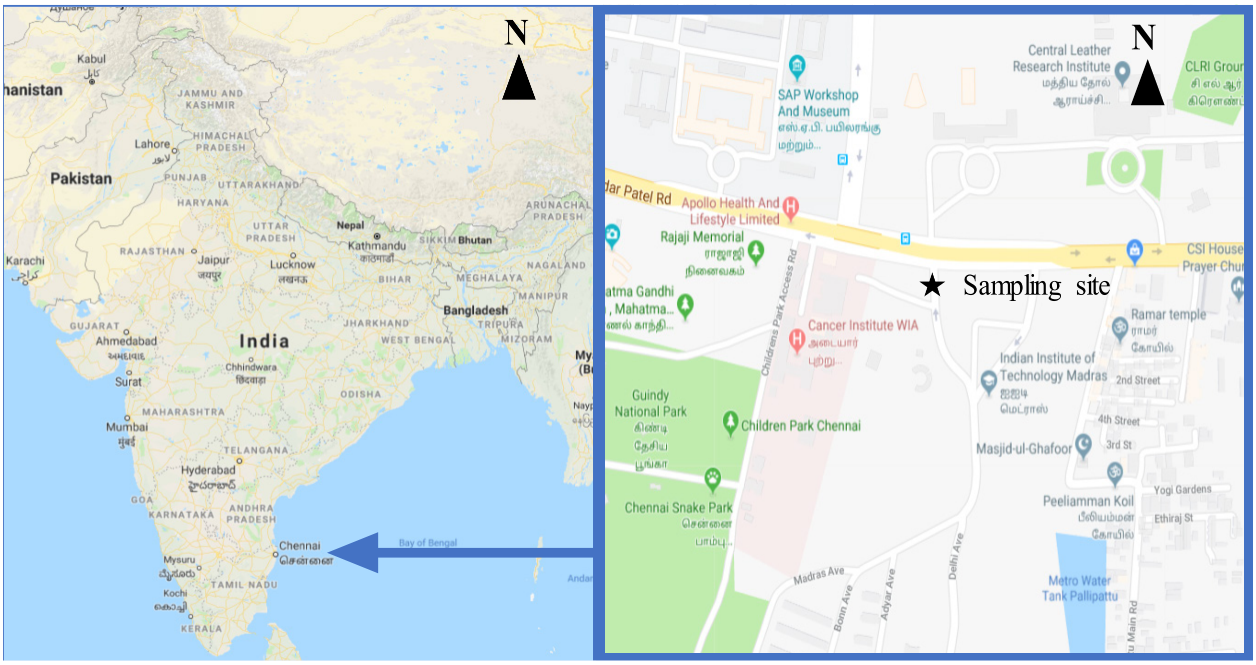

Figure 1.Location of sampling site

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Materials and Methods

PM sampling is carried out during 2009 winter season near a busy traffic road side at Chennai city, Tamil Nadu, India (Figure 1). PM mass concentration is monitored in three size fractions viz. PM_{10}, $PM_{2.5}$ and PM_1 using portable dust monitors (Model - GRIMM-107). In the present study the total deposition, regional deposition, lobe-specific deposition and clearance of PM under different breathing scenarios (oral, nasal and oronasal) are quantified using multiple path particle dosimetry (MPPD) model versions 3.04. MPPD model is jointly developed by Applied Research Associates, Inc. and The Hamner Institutes for Health Sciences in collaboration with the National Institute of Public Health and the Environment (RIVM), the Netherlands, and the Ministry of Housing, Spatial Planning and the Environment, the Netherlands. The MPPD model calculates the deposition and clearance in the human respiratory tract for PM having aerodynamic size between 0.001 μm and 100 μm. All deposition calculations are based on the deposition efficiencies for various mechanisms viz. impaction, sedimentation, diffusion and interception within the respiratory tract. Since the model is based on multiple path method, it calculates the region-specific, lobe-specific and generation specific depositions. The clearance calculations are based on the three-compartment model. Further, the selection of lung geometry plays a vital role in the accuracy of deposition and clearance calculations. In MPPD, symmetric (Yeh-Schum Single Path, Yeh-Schum 5-Lobe, Age-specific symmetric model, Age-specific 5-lobe model, Weibel symmetric model, and PNNL symmetric model) and asymmetric (Stochastic model and PNNL asymmetric model) lung geometries are available. The asymmetric stochastic model is selected for the better accuracy in calculation and realistic PM deposition. For running the MPPD model the parameters such as species, model, functional residual capacity, upper respiratory tract volume, body orientation, breathing frequency, tidal volume, breathing scenario, PM concentration and exposure condition should be specified. The options/values entered in the model are given in the Table 1.

Results and Discussion

PM Concentration

Continuous size-segregated PM mass concentrations are measured during a winter period. Then the average of hourly concentration is considered for the deposition assessment. The average values used in the deposition assessment are 131.20 μg m^{-3} (PM_{10}), 66.9 μg m^{-3} ($PM_{2.5}$) and 54.43 μg m^{-3} (PM_1). Detailed PM physical and chemical characterization, source apportionment and traffic characterization in the study area can be found in our previous studies.[35-38]

Total Deposition Fraction

The total deposition fraction is the fraction of inhaled PM that are deposited in the entire human airways. Otherwise, the total deposition fraction can be defined as the sum of all regional (head, TB and pulmonary) deposition fractions. Total deposition fraction of PM_{10}, $PM_{2.5}$, and PM_1 under various breathing scenarios are quantified and presented in Table 2.

Table 1.Model parameters and its options/values selected in the MPPD model

Parameter	Options/Values
Species	Human
Model	Stochastic lung
Functional residual capacity	3300 ml
Upper respiratory tract volume	50 ml
Body orientation	Upright
Breathing frequency	12 per minute
Tidal volume	625 ml
Breathing scenario	Oral, Nasal and Oronasal
Exposure condition	Constant exposure

Table 2.Deposition fraction in human airways under different breathing scenarios

Region	Size	Breathing scenarios		
		Nasal	Oral	Oronasal
Head	PM_{10}	0.9185	0.4867	0.762
	$PM_{2.5}$	0.4854	0.0252	0.3174
	PM_1	0.1391	0.0082	0.0851
TB	PM_{10}	0.0347	0.2889	0.1503
	$PM_{2.5}$	0.0809	0.1191	0.0965
	PM_1	0.0547	0.0591	0.0565
Pulmonary	PM_{10}	0.0039	0.0321	0.0167
	$PM_{2.5}$	0.1206	0.1777	0.144
	PM_1	0.0604	0.0652	0.0624
Total	PM_{10}	0.9571	0.8077	0.929
	$PM_{2.5}$	0.6869	0.322	0.5579
	PM_1	0.2542	0.1325	0.204

Total deposition in the whole respiratory tract is predominant in nasal breathing for all three PM fractions. Among the three sizes, PM_{10} has a high deposition in the human respiratory tract via nasal, oral and oronasal routes. The second highest total deposition is contributed by $PM_{2.5}$ and the least is attributed to PM_1. Like coarse PM, the fine PM ($PM_{2.5}$ and PM_1) deposition is highly noted in nasal breathing followed by oronasal and oral breathing. The deposition fraction under nasal and oral breathing conditions in our study are similar to the results obtained using Inhalation, Deposition and Exhalation of Aerosols in the Lung (IDEAL) model (Hofmann, 2011)and physical factors such as fluid dynamics, particle properties, and

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deposition mechanisms. Current particle deposition models may be grouped into two categories referring to the region of interest in the lung, i.e. either deposition in the whole lung (whole lung models. Another study also has similar deposition fractions for the PM with aerodynamic sizes 1 µm and 2.5 µm.[17]

Regional Deposition

Regional deposition can be useful in assessing the PM deposition in each region viz. head, TB and pulmonary. The percentage deposited in each region of the human airway is quantified and given in Table 3. Head deposition results showed that PM_{10} through nasal breathing has the highest deposition (96% of inhaled PM) when compared to other breathing scenarios and sizes. The lowest deposition percentage in the head region is contributed through oral breathing for all sizes (PM_{10} = 60%; $PM_{2.5}$ = 8%; PM_1 = 6%). In TB region, oral breathing deposition (PM_{10} = 36%; $PM_{2.5}$ = 37%; PM_1 = 44%) is dominant than nasal (PM_{10} = 4%; $PM_{2.5}$ = 12%; PM_1 = 21.5%) and oronasal (PM_{10} = 16%; $PM_{2.5}$ = 17%; PM_1 = 28%).For all breathing scenarios, PM1 has the highest deposition (21.52-45%) in the TB region followed by $PM_{2.5}$ (12-37%) and PM_{10} (4-36%). The least deposition in the TB region is contributed through nasal breathing. Pulmonary region is highly deposited by both fine PM sizes i.e. $PM_{2.5}$ (18-55%) and PM_1 (24-55%) under all breathing scenarios. Highest pulmonary deposition is recorded in $PM_{2.5}$ via oral breathing scenario. Further for all breathing scenarios, PM_{10} is recorded with the lowest deposition (0.4-1.8%) in pulmonary region. It is observed that coarse PM deposition is high in the upper region (head) of respiratory tract whereas fine PM deposition is found to be maximum in lower regions.[10,15,24] This is due to the various deposition mechanisms that are dominant in each region of airways. Due to inertial impaction the coarse PM will get settled in the head region and the fine PM experience diffusion and sedimentation mechanisms causing it to settle in the deeper part of lungs.[7,22,46]

Table 3.Regional size-segregated deposition percentage for different breathing scenarios

Region	Size	Breathing scenario		
		Nasal (%)	Oral (%)	Oronasal (%)
Head	PM_{10}	95.97	60.26	82.02
	$PM_{2.5}$	70.67	7.83	56.89
	PM_1	54.72	6.19	41.72
TB	PM_{10}	3.63	35.77	16.18
	$PM_{2.5}$	11.78	36.99	17.30
	PM_1	21.52	44.60	27.70
Pulmonary	PM_{10}	0.41	3.97	1.80
	$PM_{2.5}$	17.56	55.19	25.81
	PM_1	23.76	49.21	30.59

Regional Mass Deposition Rate

Regional mass deposition rate for different particle size and breathing scenario are given in Table 4. The total deposited mass rate is high in PM_{10} for all breathing scenarios. This is due to the fact that PM_{10} being larger in size possess high mass. Next to PM_{10}, the $PM_{2.5}$ and PM_1 have high total deposited mass rate. Breathing through the nose has a high total deposition rate followed by oronasal and oral breathing. PM_{10} has a high deposition rate in the head region through nasal breathing. In the TB region, oral breathing contributed to higher deposition rate. PM_{10} and $PM_{2.5}$ are highly deposited in the TB region. In the pulmonary region, $PM_{2.5}$ is highly deposited in all breathing scenarios viz. nasal, oral and oronasal. Except for oral breathing, PM_1 contribute second highest in the pulmonary breathing. It is observed that nasal breathing leads to high deposition rate in the head region and less in the TB and pulmonary regions. But in the case of oral breathing, the deposition rate is higher in TB and pulmonary regions.

With respect to size, coarse PM has high deposition rate in head regions whereas fine PM fractions are deposited maximum in TB and pulmonary regions. The deposited mass rate in our study is comparable with previous findings. In the earlier study, the deposition rate in the head region varies from 3.6-5.2 µg min^{-1} for PM_{10}, 1.3-1.8 µg min^{-1} for $PM_{2.5}$, and 0.41-0.58 µg min^{-1} for PM_1.Also, the TB region deposition ranges from 0.07-0.10 µg min^{-1} for PM_{10}, 0.12-0.16 µg min^{-1} for $PM_{2.5}$, and 0.04-0.05 µg min^{-1} for PM_1. The main variation in the deposition rate is due to the difference in exposure concentrations, and the model used.[10]

Table 4.Size-segregated PM deposition mass rate under different breathing scenarios

Region	Size	Breathing scenario		
		Nasal (ng min^{-1})	Oral (ng min^{-1})	Oronasal (ng min^{-1})
Head	PM_{10}	903.80	478.90	749.80
	$PM_{2.5}$	243.60	12.62	159.30
	PM_1	56.80	3.36	34.72
TB	PM_{10}	34.13	284.20	147.80
	$PM_{2.5}$	40.58	59.77	48.43
	PM_1	22.32	24.11	23.07
Pulmonary	PM_{10}	3.79	31.58	16.43
	$PM_{2.5}$	60.52	89.15	72.23
	PM_1	24.64	26.62	25.48
Total	PM_{10}	941.72	794.68	914.03
	$PM_{2.5}$	344.70	161.54	279.96
	PM_1	103.76	54.09	83.27

Regional Deposited Mass Rate per Unit Area

Regional deposited mass rate per unit area are shown in Figure 2. Head region experiences the maximum PM mass deposition per unit area than TB and pulmonary regions. In the head region, PM_{10}contributed larger mass deposition rate per unit area. Breathing through the oral route resulted in the highest PM_{10} deposition of 3.09 ng min^{-1} cm^{-2}. The nasal and oronasal breathing resulted in the deposition of 2.97 and 1.71 ng min^{-1} cm^{-2} respectively. In case of fine PM, the mass deposition per area is high through nasal breathing ($PM_{2.5}$ = 0.8 ng min^{-1} cm^{-2} and PM_1 = 0.18 ng min^{-1} cm^{-2}) followed by oronasal (0.36 and 0.07 ng min^{-1} cm^{-2}) and oral (0.003 and 0.002 ng min^{-1} cm^{-2}). In TB and pulmonary regions, the oral breathing contributed to maximum deposition per unit area in all size fractions. PM_{10} and $PM_{2.5}$ have high mass deposition per cm^{-2} in TB and pulmonary regions, respectively. The PM_{10} deposition in TB region ranges from 0.003 to 0.024 ng min^{-1} cm^{-2}, while the $PM_{2.5}$ in pulmonary region recorded between 4.36 x 10^{-5} and 6.43 x 10^{-5} ng min^{-1} cm^{-2}.

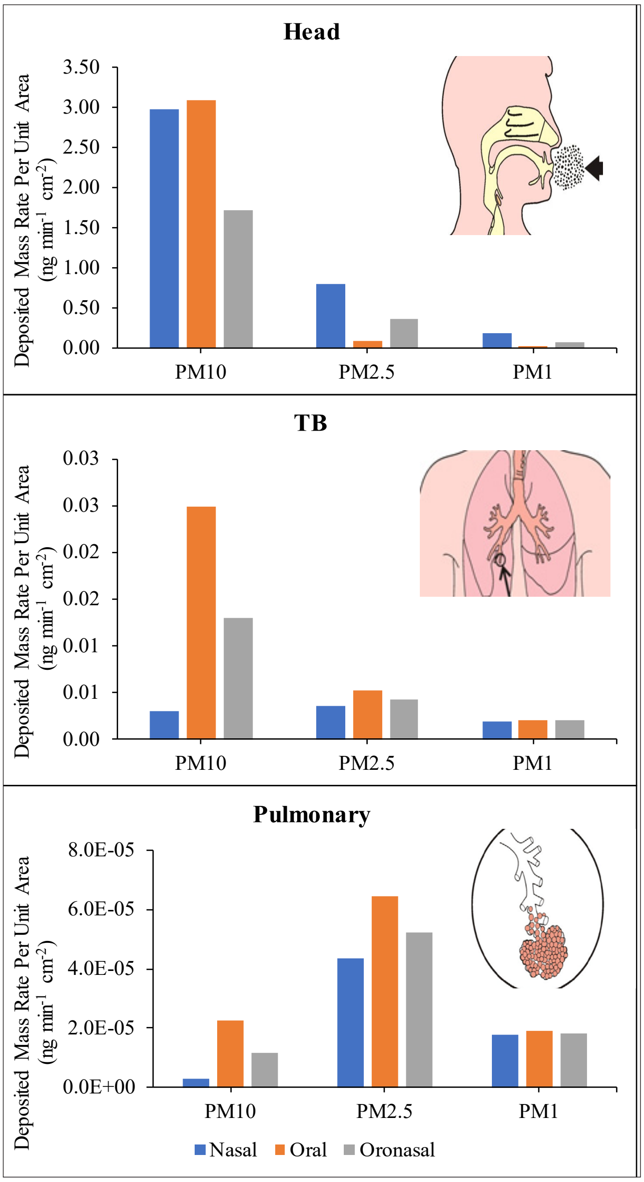

Figure 2.Deposited mass per unit area (ng $min^{-1}cm^{-2}$)

Lobar Deposition

Using the stochastic lung model, lobe wise i.e. left lower (LL), left upper (LU), right lower (RL), right middle (RM) and right upper (RU) deposition are quantified and presented in Table 5. For all the PM sizes and breathing scenario, right upper lobe experiences maximum deposition among all lobes. The lobar deposition is in the order of right upper > left lower > left upper > right middle > right lower. Further the oral breathing leads to higher PM_{10}, $PM_{2.5}$ and PM_1 deposition in all five lobes whereas nasal breathing has the lowest deposition. It is also observed that the deposition of PM_1 is similar in all breathing scenarios but in case PM_{10} and $PM_{2.5}$, the deposition varies. The lobar deposition results of our study are very much comparable with previous study results.[1, 14]

Clearance of Deposited PM

Deposited PM is cleared from the human respiratory tract through the clearance. The clearance of size-segregated deposited PM in TB and alveolar regions are shown in the Figure 3.

Clearance in the TB region is high in all size fractions when compared to the alveolar region. PM_{10} has the maximum removal (94% of deposited PM) in the TB region during the 48 hours post-exposure period. Same with $PM_{2.5}$ and PM_1 is 91%. The PM removal in the alveolar region is only 3% during the post-exposure days. For the given PM size, the clearance percentage is found to be same for all breathing routes. The clearance is mainly attributed to four mechanisms such as mucociliary transport, phagocytosis, lymphatic system and dissolution.[44] In the TB region the fast clearance is due to the mucociliary transport mechanism. In the alveolar region, deposited PM is removed by slow mechanisms such as phagocytosis, lymphatic system, and dissolution.[22, 44]

Conclusion

PM pollution has attracted much attention worldwide due to its complex nature and its effects on human and the environment. The essential studies such as PM deposition in human airways and its related effects are scarce in India. Hence to address the existing gap in the Indian scenario, this study aims to quantify the size-segregated PM deposition in human airways considering different breathing scenario viz. nasal, oral and oronasal. PM measurements in different sizes (PM_{10}, $PM_{2.5}$, and PM_1) are measured near the busy traffic road during the winter season in Chennai city. The seasonal hourly average concentration of PM_{10}, $PM_{2.5}$, and PM_1 are taken as constant mass exposure concentration in this study. To quantify the PM deposition in human airways, MPPD model is utilized. With the help ofthe MPPD model, the deposition in human airways are quantified in terms of total and regional (head, TB and pulmonary) deposition. Further, the deposited mass rate, deposited mass rate per unit area and lobar depositions are derived from the model.

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Table 5.Lobar deposition fraction for different breathing scenarios

Breathing scenario	Size	Lobe				
		LU	LL	RU	RM	RL
Nasal	PM_{10}	0.0067	0.0094	0.0103	0.002	0.0014
	$PM_{2.5}$	0.0437	0.0598	0.0663	0.0139	0.0092
	PM_1	0.0242	0.032	0.037	0.0075	0.0049
Oral	PM_{10}	0.056	0.0786	0.0856	0.0165	0.0114
	$PM_{2.5}$	0.0644	0.0881	0.0976	0.0204	0.0136
	PM_1	0.0261	0.0346	0.04	0.0081	0.0053
Oronasal	PM_{10}	0.0291	0.0409	0.0445	0.0086	0.0059
	$PM_{2.5}$	0.0522	0.0714	0.0791	0.0166	0.011
	PM_1	0.025	0.0331	0.0382	0.0077	0.005

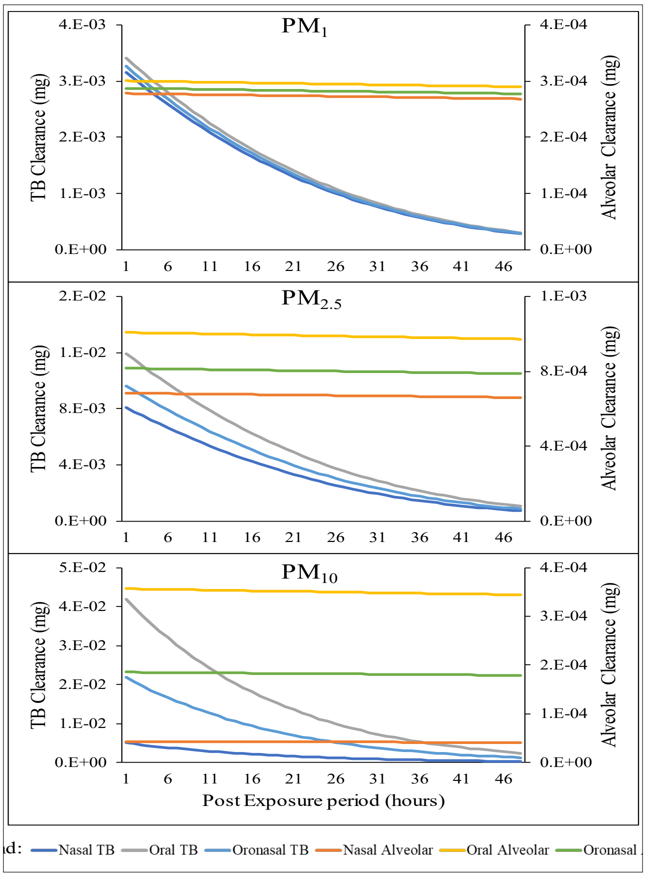

Figure 3.Clearance during post-exposure days

Results showed that PM_{10} has highest total deposition fraction in the human airways followed by $PM_{2.5}$ and PM_1. Nasal breathing leads to higher total deposition of PM_{10}, $PM_{2.5}$, and PM_1 than oral and oronasal breathing. The regional deposition analysis showed that PM_{10} has the highest deposition rate in the head and TB regions ranging from 478.9 to 903.8 ng min^{-1} and 34.1-284.2 ng min^{-1} respectively. Similarly, in the pulmonary region $PM_{2.5}$ is deposited maximum between 60.5-89.1ng min^{-1}. This shows the influence of breathing scenario is evident in the regional depositions. The nasal breathing is attributed to high deposition in the head region but in the TB and pulmonary region, oral breathing leads to maximum deposition. The deposited mass per unit area results indicated that oral deposition contributes to the highest in the head (3.09 ng min^{-1} cm^{-2} of PM_{10}), TB (0.02 ng min^{-1} cm^{-2} of PM_{10}) and pulmonary (6.43 x 10^{-5} ng min^{-1} cm^{-2} of $PM_{2.5}$) regions. Further, the oral breathing leads to high PM_{10}, $PM_{2.5}$ and PM_1 deposition in all five lobes. Deposited PM in the TB and pulmonary regions are assessed for the clearance during the post-exposure days. The airway clearance in the TB region is fast and about 91-94% of the deposited particles are removed after 48 hours. Alveolar clearance is observed to be very slow because only 3% of PM are removed during the post-exposure period. Our study has yielded significant results that are essential for human toxicological studies.

Conflict of Interest: None

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