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The Correlation between Radon (Rn^{222}) and Particulate Matters (PM_{10}, $PM_{2.5}$, $PM_{1.0}$) in Subway Tunnel in Seoul.

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Abstract

Radon (Rn^{222}) is a radioactive gas and is found at high concentrations underground. Investigations were done in many years specifically on public transportations such as in the subway stations, concourses and platforms for these are located underground areas. This study correlates the Rn^{222} concentrations with the Particulate Matter (PM) concentration for the gas could be attached or trapped inside these particles. It was done on the opening subway tunnel of Miasageori Station going to Mia Station (Line 4) last August 2016. Based on the result, the Rn^{222} were more influenced on the mass ratio (%) of PM present in the air instead of its mass concentration ($\mu g/m^3$). As the PM_{10} mass ratio increases (42.32 ± 1.03%) during morning rush-hours, radon starts to increase up to 0.97 ± 0.03pCi/L. But during the afternoon Rn^{222} concentrations decreased while the composition were stable at 22.96 ± 3.0%, 39.04 ± 0.6% and 38.01 ± 0.3% in PM_1, $PM_{2.5}$ and PM_{10} respectively. It was then assumed that it could be the composition of the morning hours of the station were influencing the concentration of the radon.

Keywords: Radon, Subway, Indoor Air Quality, Health

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1. Introduction

Radon (Rn^{222}) is a radioactive gas from a decaying chain of uranium (U) and radium (Ra) (BIER, 1999; Font et al., 1999) which could be found at contaminated soil or sediments. The danger of this particular radioactive gas is that it decays to other radon progenies which emits alpha and beta particles and once inhaled or exposed for long periods of time could increase the risk of lung cancer if exposed for a long periods of time (Lubin et al, 2004; Krewski et al, 2005; Darby et al, 2005). Aside from introducing radon in the environment through groundwater (Skeppstrom and Olofsson, 2007), it could be introduced through air diffusion. From a thin porous sediment, radon diffuses in the air at a steady rate. In caves, if the air pressure is low or reduced, it will pull air from the cave and thus carrying radon gases through the environment (Whittlestone et al, 2003). This is because radon naturally soil and accumulated underground such as caves (Bezek, 2013) or even urbanized areas such as metropolitan city could be also at risk of high exposure in underground facilities (such as basement, subway stations, parking lots). In Korea, most radon studies conducted in indoor environments such as building, residential houses and also in subway system (Lee, et al, 2012). Metropolitan subway system is the most convenient and efficient way for common passengers to travel and most of these are underground. In fact subway system takes up to 36.2% of all means of public transportation (Seoul Metropolitan Government, 2013).

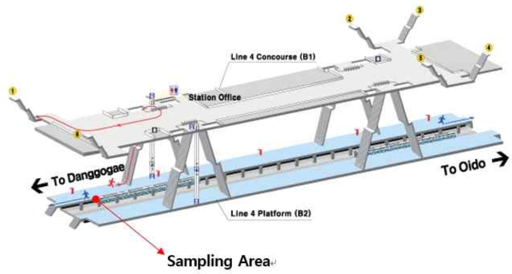
Underground subway and tunnels are somehow the manmade caves of the modern times. Concerns on radon exposure risk were only established mainly on the mine workers (International Commission on Radiological Protection, 1981) excluding tunnel workers. Moreover, many studies were conducted in subway stations with concerns of radon concentrations (Jeon et. al, 2006; Yoon, et al, 2010) present in air and water (Lee, et al, 2004), with the installation of platform screen doors (Jeon et al, 2012), and with exposure of the inhabitants such as its station staffs (Song et al, 2010). Comparing to the outdoor conditions, underground subway systems are different in terms of characteristics due to a close system which could trap air pollutants. Aside from radon, indoor air quality in subway systems were commonly assessed with its particulate matter (PM) concentrations (Adams, et al, 2001; Moreno, et al, 2015, Kwon, et al, 2016). PM are mixtures of solid particles like dust, dirt or smoke and liquid droplets present in the air. Different diameter sizes of PM such as ≥10μm (PM_{10}), ≥2.5μm ($PM_{2.5}$), ≥1.0μm ($PM_{1.0}$), could cause some health problems when large amounts are inhaled. Most of the previous study on PM in Korea were done in tunnels and cabins (Park, et al, 2012; Kim et al, 2014; Jeong, et al, 2016), source identification (Park, et al, 2014), mass ratio (Lee et al, 2016) and chemical profiles (Ma, et al, 2015) while radon determination were done separately. Rn^{222} and PM correlations were not fully investigated in underground subway tunnels unlike other studies that deal with atmospheric radon and aerosol which were frequently conducted.

The purpose of this study is to assess the concentration of Rn^{222} in an underground subway tunnel and correlated with particulate mass ratio. This experiment would like to determine if the particulate matter could trap and carry Rn^{222} gas inside the subway tunnel in Seoul. Through this correlation we could see if PM contributes the concentration of the said radioactive gas. Recent studies are concerned on the ticketing booth, concourse platform and cabin were both passenger and subway staff stayed during the day. Here we examined the radon build-up which will give more characteristics of the subway tunnel. Due to device availability, only one station was used in this study. The data presented here could not represent the whole subway stations of Seoul and its corresponding radon and particulate matter concentrations. Ventilation and train operations were not monitored in the study as well as monitoring the ambient PM concentrations from outside sources. Interpretation of the data is only limited to the concentrations of the two primary parameters of the study, thus information of other studies were used for comparison.

2. Materials and Methods

To determine the concentrations of Rn^{222} a monitoring device was used (FRD1600, RadonFTLab). This monitor could be easily placed anywhere, had a forced air fan or internal pump and could detect from 0.05 ~ 99.99 pCi/L with accuracy of <±3% at 10pCi/L powered with a 5V DC adaptor. Sampling intervals on the monitor ranged up to 1 hour, and for this particular study 10min time interval was used to collect large data on real-time setting.

The particulate matter were monitored through an optical particle counter (GRIMM SKY-OPC Model 1.129, Germany). This device measured fine dust for mass or count distribution from 0.25 ~ 32μm. Also it had a real-time data collection starting at 6 seconds, could be operated with 12V DC and had a user-friendly software. The Sky-OPC was connected to a laptop to directly save the data.



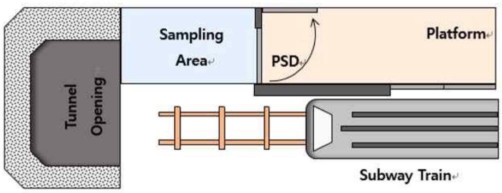


Fig. 1. Schematic Diagram of thesampling area of the experiment. (Above) Sampling was done between the platform and tunnel opening where it is separated with platform screen doors (PSD) (Image by disability.seoul.go.kr). (Below) This area can only be accessible to authorized personnel.

The study was conducted on the opening subway tunnel of Miasageori Station going to Mia Station (all stations are in Line 4) last August 2016. The station is a side platform type where two opposing tracks are in the center while the platforms are in each side link with station's concourse (Figure 1). This specific line was chosen due its less popular on metropolitan subways being investigated through the years (such as Seoul). Additionally the station was assessed with a previous study which found radon concentrations for 2 ~ 4 pCi/L (Jeon et. al, 2006) and also source profiles of particulate matter were done (Ma, et. al, 2015)Due also to limited monitors, the investigation could only choose one station. The devices were placed on an area that passengers could not easily access in to and where the trains could operate freely without the disturbance of the researchers when data transferring were conducting (Fig. 1).

The main purpose of the study was to investigate if ^{222}Radon could be influence on air pollutants such as particulate matter. The best way was to compare its specific time periods were phenomenon such as increasing concentrations of both radon and PM were considered. But the number of days of data gathering were the not the same such as PM concentrations were monitored 4.5 days while Rn^{222} concentrations were monitored in a week.The intended investigatory time was the maximum of four days due to administration restrictions but the RadonFTLab were prolonged to one week due to power interruptions in the station itself.After collection of Rn^{222} and PM 24 hour data collection, these were converted to hourly and daily average to determine its measurement on specific time. Furthermore mass ratio of particulate matter ($PM_{1.0}/PM_{10}$, $PM_{2.5}/PM_{10}$) and below is the equation for the mass ratio of PM_{10}.

$$\%PM_{10} = 1 - (\%PM_{1.0} + \%PM_{2.5})$$

where$\%PM_{1.0}$ and $\%PM_{2.5}$ are mass concentration of 1μm and 2.5μm divided by the mass concentration of PM_{10}.

3. Results and Discussions

3.1 Particulate Matter Concentrations

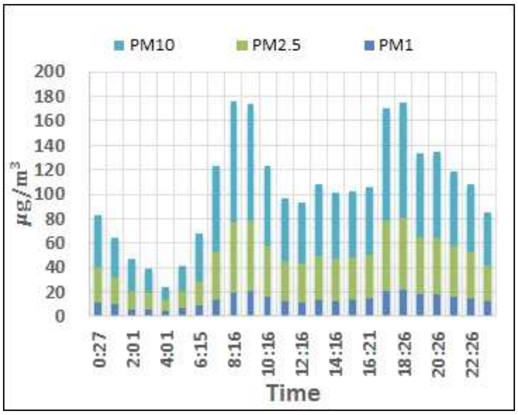
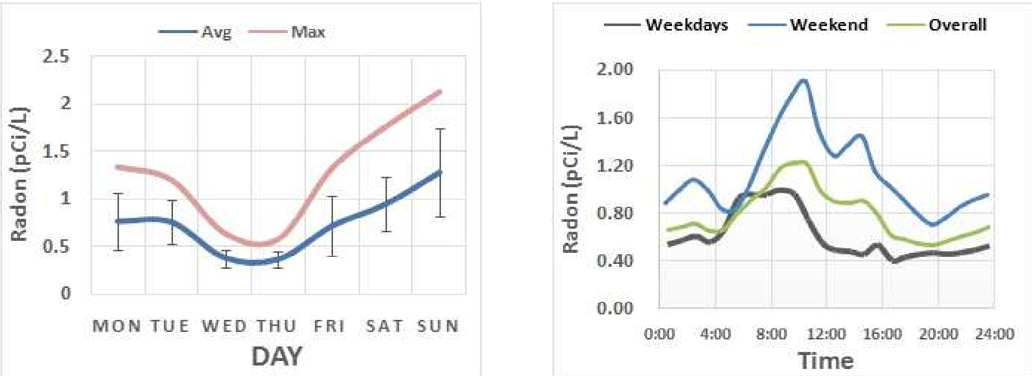


Fig. 2. Particulate Matter in the subway stations. After 4 days of data collection, the concentrations were aside to each specific recorded time; (A) PM_1, (B) $PM_{2.5}$, (C) PM_{10}.

As shown in Fig. 2 all sizes of particulate matter were reaching its respective maximum concentration with two specific time periods. These time periods were at 08:46 ± 00:29 and at 17:41 ± 00:13 with maximum values of $PM_{1.0}$ were 22.17 ± 3.26 μg/m³ and 22.07 ± 1.48 μg/m³ respectively. Additionally, maximum concentrations of $PM_{2.5}$ and PM_{10} were seen also with the same time periodsat values of 64.74 ± 7.34 μg/m³ and 60.99 ± 4.91 μg/m³ for $PM_{2.5}$; at values of 109.33 ± 10.45 μg/m³ and 100.13 ± 11.61 μg/m³ for PM_{10}. During these time intervals, it is also the rush-hour periods of subway operations (8:00 – 10:00 AM and 6:00 to 8:00 PM) which corresponds to increase number of train in operation (Son, et al, 2014). Overall the average concentrations were 14.5 ± 0.47 μg/m³, 37.85 ± 0.89 μg/m³, and 60.49 μg/m³, in $PM_{1.0}$, $PM_{2.5}$ and PM_{10} respectively (Table1).

Table 1. Maximum and minimum concentrations of Particulate matter with response to time.

μg/m³	PM_1	$PM_{2.5}$	PM_{10}	Time (24 hour)
1st Max	22.17 ± 3.26	64.74 ± 7.34	109.33 ± 10.45	08:46 ± 00:29
2nd Max	22.07 ± 1.48	60.99 ± 4.91	100.13 ± 11.61	17:41 ± 00:13
Min	6.10 ± 3.08	10.2 ± 4.62	16.16 ± 6.50	05:30 ± 00:24
Average PM	14.59 ± 0.46	37.85 ± 0.89	60.50 ± 1.64	



A B

Fig. 3. Radon Concentration under the subway. (A) Average Radon concentration every day; (B) Overall Radon Concentration.

3.2 Radon Concentrations

For the Rn^{222} concentrations there were different concentrations depending on the time of the week. On the weekdays, average concentrations were at decreasing manner, starting from 0.76 ± 0.30 pCi/L on Monday to as low as 0.36 ± 0.09 pCi/L on Thursday. But as seen in Fig. 3A, these average concentrations dramatically changed on the weekends (starting Friday) from 0.72 ± 0.32 pCi/L to as high as 1.28 ± 0.46 pCi/L (Sunday).

The highest maximum radon concentration per day was calculated on Sunday at the value of 2.13 ±0.38 pCi/L while the lowest concentration per day was at the value of 0.06 ± 0.41 pCi/L during the sixth day. Based on the data, there was a pattern on the increase and decrease of the concentration on a daily basis (Table 2). During weekdays there were low concentrations of ^{222}Radon (Monday to Thursday) while it gradually increase on the weekends (Friday to Sunday), but all concentrations did not exceed to the guidelines of the WHO for radon exposure (4.0 pCi/L) and lesser range with the previous study (at values of 2 ~ 4.0 pCi/L) obtained in this particular station (Jeon et al, 2006). The minimum values of radon were random when it comes to a specific time during the day. Ventilation also served as suppresser of harmful pollutants in tunnels and Rn^{222} gas also was in lower concentrations which were based on previous studies (Yoon et al, 2010; Jeon, et al, 2012). On the contrary, the maximum values during the day were seen to increase between 08:00 AM to 12:00 PM on the weekends. During the sampling time of the middle of the week, there were data that was loss due to power interruptions.

In Fig. 3B the ^{222}Radon concentrations during the weekdays were increasing at its average (0.92 ± 0.48pCi/L) approximately at 05:39 AM, maintained maximum average (0.99± 0.38pCi/L) nearly at 08:39 AM, and started to decrease (0.54± 0.41pCi/L) estimated at 11:39AM. At the weekdays, it seems the average concentrations were decreasing during lunch time, but on the weekends it started increasing (0.83 ± 0.13pCi/L), then stable to its highest value (1.90 ± 0.32pCi/L), and then started to decrease (0.79 ± 0.07pCi/L) at the approximate hours of 05:26 AM, 10:26AM, 06:26PM respectively. Weekend activities on the subway stations might influence the concentration of Rn^{222} for the data shows maximum average were constant from morning until before evening. On the overall average the concentrations started increasing from 0.80 ± 0.38pCi/L (at 05:36 AM), reached its maximum average of 1.22 ± 0.53pCi/L (at 09:36 AM), and started to decrease to 0.79 ± 0.36pCi/L (at 05:34 PM).

3.3 Correlation between PM and Radon

In Fig. 4A, mass concentrations of particulate matter in all sizes were superimposed with the overall average concentration of Rn^{222}. Weekday concentrations were used in both PM and radon gas to have a 4-day data correlation. All concentrations of particulate matter were decreasing form 12:00AM until it were completely at its lowest concentration before 05:00 AM. This is due to the fact the operations in the subway were finished on midnight until its first early train which were operated at 05:30AM. During the time of operations all sizes of particulate matter increased in the morning rush-hour (from 08:00 AM to 09:00 AM) and the afternoon rush-hour (05:00 PM to 06:00 PM). During this time the subway is full of

Table 2. Radon concentrations on a daily basis.

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
(pCi/L)	0.76 ± 0.30	0.76 ± 0.23	0.38 ± 0.09	0.36 ± 0.09	0.72 ± 0.32	0.95 ± 0.28	1.28 ± 0.46
Max	1.34 ± 0.18	1.20 ± 0.19	0.64 ± 0.24	0.58 ± 0.17	1.33 ± 0.30	1.76 ± 0.37	2.13 ± 0.38
Min	0.49 ± 0.04	0.52 ± 0.12	0.20 ± 0.09	0.25 ± 0.05	0.30 ± 0.06	0.06 ± 0.41	0.72 ± 0.09

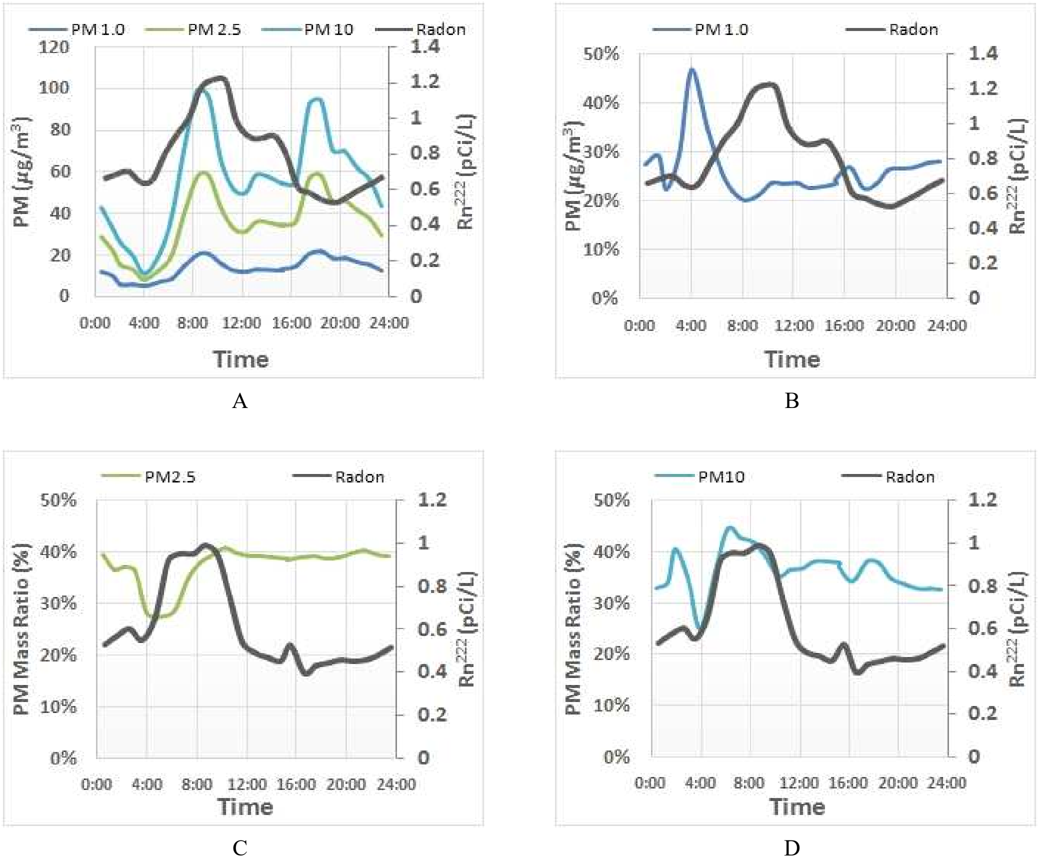


Fig. 4. Correlation of Radon and PM concentrations; (A) Radon compared with mass concentration of particulate matter; Radon concentrations correlated with (B) $PM_{1.0}$; (C) $PM._{2.5}$; (D) PM_{10}.

passengers who commuters due to their daily time-in (08:00 AM to 09:00 AM) and −out (05:00 PM to 06:00 PM).Since people are commuting on these hours, the number of train operations are increased to accommodate the increasing number of passengers.

On the other hand, radon concentrations were different. As the radon trend is superimposed with the particulate matter concentrations, the dangerous gas were slightly increase from 0.53 ± 0.17pCi/Lto 0.65 ± 0.31pCi/Lat late and no train operations (Fig. 4A). It gradually increased as the morning rush hour came during the day and accumulated until it decreased hours after the the morning maximum mass concentrations of all PM sizes. It appeared that PM mass concentrations influenced the ^{222}Radon concentrations but during the afternoon maximum mass concentration of PM, the gas concentrations were merely unaffected which had the lowest average concentration (0.40 ± 0.16pCi/L) at 04:36 PM.

Mass ratios of particulate matter were all calculated and compared with the ^{222}Radon gas concentrations. Between 12:00 AM to 01:30 AM there were increasing fluctuations (27.6 ± 5.55% to 31.0 ± 5.92%) of mass concentrations of $PM_{1.0}$ and further increases at 46.7 ± 0.00% during 04:01 AM (Fig.4B). $PM_{2.5}$ mass ratio concentrations found to be constant and had a slight decrease down to 28.3 ± 0.20% at the same time $PM_{1.0}$ at its maximum mass ratio (Fig.4C). Based on the results, fine inhalable particulate matter did not affect the rate of increase of ^{222}Radon gas concentrations

Table 3. Percent Composition of particulate matter during rush hours

Time	PM_1	$PM_{2.5}$	PM_{10}	Radon (pCi/L)
8:00 – 9:00 AM	21.15± 2.95%	36.52 ± 0.83%	42.32 ± 1.03%	0.97 ± 0.03
5:00 – 6:00 PM	22.96 ± 2.95%	39.04 ± 0.60%	38.01 ± 0.29%	0.44 ± 0.01

while PM_{10} was seen to be influential. The mass ratio of PM_{10} calculated were ranges from 2.5 μm ≥ 10.0 μm and found two significant peaks at approximately between 02:01 AM ~ 03:01 AM (40.5 ± 0.10%) and 06:15 AM ~ 07:15 AM (44.7 ± 15.08%). Rn^{222} concentrations had three significant peaks and the first two simultaneously increased as mass ratio of PM_{10} increased (Fig.4D). This could mean that the large diameter of particulate matter could trap and carry radon gases through the subway tunnels. On the overall daily average the mass ratio of PM_{10}, $PM_{2.5}$, $PM_{1.0}$ were 36.3 ± 4.07%, 37.44 ± 3.79%, and 26.2 ± 5.43% respectively. However the weekday radon concentrations maintained at low values (0.44 ± 0.01pCi/L) during the afternoon rush-hours as the PM_{10} mass ratio decreased (Table 3).

In previous study conducted in open-air, radon concentration were influenced by the physiochemical properties of particulate matter (Zoran, et al, 2013). Another previous study found that characterizing the elements the PM would pinpoint the source of radon gas in the air (Crawford, et al, 2011). In our study, it exhibits the same phenomena were the radon concentration were increase as the mass ratio of PM_{10} but during the afternoon radon starts to decrease and could be that the characteristics of this particulate matter did not have the capability or potential to carry radon in the air. Atmospheric concentrations were also correlated with radon on the previous study and found that potassium was likely to influence radon concentrations (Crawford, 2011). Potassium were also present in another local study on characteristic of PM were done on this particular station (Miasageori) but other large concentration of elements like magnesium, calcium and iron that are abundant on the platforms (Ma, et al, 2015). If the other's assumptions were correct radon concentrations were low during the afternoon rush-hours due to less concentration of potassium, but this would be the assumption and could not be proven for data on PM characteristics on that time is not available.

4. Conclusions

Radon and particulate matter characteristics in a subway tunnel were determined and correlated. Radon concentrations were found to have different maximum peak time than the mass concentrations of PM which were influenced by rush-hour train operations. All sizes of particulate matter had two maximum peaks throughout the day which corresponds with morning and afternoon rush-hours of subway operations while the radon gas has a gradual yet one peak after the morning rush-hour. Only by calculating the mass ratio of each sizes of particulate matter, PM_{10} was potential to trap and carry Rn^{222} concentrations due to its larger diameter size compared fine inhalable particulate matter. Furthermore the composition of the particulate matter should also be investigated for source identification of radon gases inside the subway tunnels.

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