한국환경보건학회지, 제31권 제4호(2005)
Kor. J. Env. Hlth., Vol. 31, No. 4, pp 316~321(2005)

Effect of Airborne Lead Concentration Characterized by Size on Blood Lead and Their Relationships

Dong Uk Park† · Kwon Chul Ha*

Department of Environmental Health, Korea National Open University, Seoul, Korea
**Department of Health Science and Biochemistry, Changwon National University Changwon, Korea*
(Received June 23, 2005; Accepted July 23, 2005)

납 흡수에 영향을 미치는 요인 분석: 납 크기 특성과 혈액중 납과의 관계

박동욱† · 하권철*

한국방송통신대학교 환경보건학과, *창원대학교 보건 · 생화학과

요 약

4개 업종(축전지제조업, 광명단 제조업, 2차 제련업, 라디에타 제조업)에서 근무하는 총 100명의 근로자를 대상으로 8단계다단충돌기(eight stages personal cascade impactor)에 의한 입자 크기별 납농도를 측정하였다. 크기별 납 농도는 총납(PbA), 흡입성납(IPM-PbA), 흉곽성납(TPM-PbA), 호흡성납(RPM-PbA), 1 μm 미만의 납($Pb_{1\mu}$) 그리고 1 μm 이상의 소화성납(Pb_{ing})이었다. 동일한 근로자(100명)를 대상으로 혈액에서 납농도를 측정하였다. 혈액 중 납은 원자흡광광도계(atomic absorption spectrometry)의 Zeeman effect graphite furnace를 이용하여 분석하였다. 총납의 노출농도는 노출기준(50 ug/m^3)을 크게 초과하였다. 평균 호흡성 납 노출농도(115.7 ug/m^3) 총 납의 노출기준을 훨씬 초과하였다. 1 μm 미만의 납($Pb_{1\mu}$) 노출농도의 범위는 0.7에서 492.2 ug/m^{3}이나 되었다. 근로자의 46%가 혈액 중 납 농도 40 ug/dL을 초과하였다. 60 ug/dL을 초과한 경우도 13%나 되었다. 입자 크기가 큰 납인 총납, 흡입성 납 그리고 호흡성 납 농도는 혈액 중 납 농도와 유의한 상관을 보였다($p<0.0001$). 그러나 가장 높은 상관은 1 μm 미만의 납($Pb_{1\mu}$)과 혈액 중 납과의 관계였다. T-test에서 50 ug/m^3 이상의 호흡성 납을 나타낸 근로자 그룹과 50 ug/m^3 이하의 근로자 그룹간에의 혈액 중 납 농도는 유의한 차이가 있는 것으로 나타났다($p=0.000$). 이러한 연구결과는 입자크기 구분이 없는 현재의 총납에 의한 노출기준과 측정방법은 미세 납 먼지에 노출되는 근로자의 납 흡수를 보호하는데 한계점이 있다는 것을 의미한다. 향후 납 입자크기는 물론 근로자의 개인적인 위생과 작업내용 등을 변수로 납 흡수에 영향을 미치는 종합적인 요인을 찾아내는 연구를 진행할 필요가 있다.

주요어: 8단계다단충돌기, 호흡성 납, 미세 납, 혈액 중 납, 납의 크기별 특성

I. Introduction

In 1978, the U.S. Occupational Safety and Health Administration (OSHA) established a permissible exposure limit (PEL) of 50 μg/m^3 to limit worker's blood lead (PbB) levels to 40 μg/dL.[1)]

OSHA PEL was based on only the measurement of total particle without considering respirable lead particle size. OSHA PEL have been used in Korea with same basis for establishment. Unlike airborne lead that particle size is not considered, most aerosols have dual Threshold Limit Values (TLV), such as total and respirable particulate mass, in order to consider the difference of absorption due to particle size.[2)]

Airborne lead, an aerosol that could have a diverse size distribution, is taken using total mass sampling without particle size selective criteria. It has been well known that fine lead particles are more easily absorbed into the body than coarse lead particles.

Several previous studies had reported that the particle size distribution assumed in the OSHA

†Corresponding author : Department of Environmental Health, Korea National Open University, Seoul, Korea
Tel: 82-2-3668-4707, Fax: 82-2-741-4701
E-mail: pdw545@knou.ac.kr

model was likely found to be incorrect.[3-8)]

If the OSHA model was to be directly applied to the actual particle-size distributions, significantly lower levels of lead in the blood would be predicted for a given air lead exposure.[4,8)]

These studies criticized that PEL has been no longer effective tool because it completely couldn't protect worker to fine lead particle. Our two previous works concluded that the contribution of respirable lead particles to lead absorption would be greater than that of PbA.[9,10)]

We already suggested the assumption that lead respirable fractions (RPM-PbA) should be added to current PEL to protect workers from exposure to fine lead particles generated by numerous lead operations. This study was designed to prove this assumption that measurement of RPM-PbA is necessary with another basis. The specific objectives of this study was: 1) to examine relationship between lead concentrations based on size characteristics, 2) to examine whether lead concentrations by size influence (PbB) and to examine whether personal hygiene-related and work-related characteristics influence.

II. Material and Methods

1. Sampling and analysis of airborne lead

Personal samples were taken from 100 workers randomly selected in four industries. Samples were taken using the Marple personal cascade impactor (Model 298, Anderson Sampler, Inc., U.S.A.) with air drawn by personal pumps (Model MSA 87004, MSA, USA). Sampling was carried out for regular work duration of 8 hours. The air sampling equipment was fitted to the subject on starting, removed or switched off during the break, and finally removed at the end of the day. The cascade impactor had cut-points (particle size for 50% collection) of 21.3 μm, 14.8 μm, 9.8 μm, 6.0 μm, 3.5 μm, 1.55 μm, 0.93 μm, and 0.52 μm. The pump and sampling train were calibrated at 2 l/min before and after sampling. Mylar substrate (Anderson Stock #C-290-MY, Anderson Sampler, Inc., USA) was thinly coated with silicone grease (Dow Corning 316 Silicone Release Spray, Dow Chemicals, USA) to prevent the bounce of lead particles. The substrate and polyvinyl chloride (PVC) backup filter (5 μm pore size, Anderson Stock # F-290-p5, Anderson Sampler, Inc., USA) for each stage were pretreated by a microwave digestion system (Model MDS-2000, CEM Corp, USA). The lead mass was quantified using atomic absorption spectroscopy (Model Spectra 300 plus, Varian Corp, Australia). The amount of lead particles collected by each stage was corrected for internal particle losses using inlet-sampling efficiencies as determined by Rubow *et al.* (1987).[11)] One field blank per 10 cascade impactor samples was taken to correct the results of cascade impactor samples. In addition, recovery test was performed to correct the analytical results. The recovery rates ranged from 98.6 to 102.5%. Mylar substrates were spiked with the amounts of lead, corresponding to 0.1, 0.25, 0.5, 1, and 2 times the occupational health standard at air volume of 400 liter. External quality control was performed by participation in the inter-laboratory Proficiency Analytical Testing (PAT) quality program organized by the U.S. National Institute for Occupational Safety and Health (NIOSH)/American Industrial Hygiene Association (AIHA). Our results were always evaluated as acceptable.

2. Lead particle size determination

From the size distribution of lead particles collected on the cascade impactor, the PbA concentration was calculated by summing the collected lead particles at each stage and dividing the sum by the air volume sampled. The proportion of lead particles ≤ 1 μm or > 1 μm (designated as ingestible) was computed using a regression equation for the relationship between the cut-point diameter and the cumulative percentage of lead particles collected on each stage of the impactor. According to OSHA CPA model, the lead concentration were split into two quantities based on Ashford *et al.*, (OSHA model) 1 um size criterion for the change from respirable to ingestible lead, i.e., PbA < 1 um and PbA 1 um.[11)]

Concentrations of IPM-PbA, TPM-PbA and RPM-PbA were calculated using the methods proposed by Hinds.[13)] Each mass fraction for a size interval of an impactor stage was estimated from the regression equation between collection efficiencies of each lead particle mass and AD defined by ACGIH

using a trapezoidal rule.

3. Blood lead (PbB) analysis

From 100 workers who matched the airborne lead samples, whole blood samples were taken in a lead-free vacuum tube (Monoject, Sherwood Medical) containing ethylenediamine tetracetic acid (EDTA) as the anticoagulant. After pretreatment with a 1:4 solution of 0.1% Triton X 100 (Merck, scintillation grade) and 1.25% ammonium dihydrogen phosphate (Merck, puratronic grade),[12] lead concentration in whole blood (PbB) was analyzed with Zeeman effect graphite furnace atomic absorption spectrometry (Spectra AA-300/400 Zeeman, Varian, Australia, Pty Ltd). External quality control for blood lead was performed by the use of National Institute of Standard and Technology (NIST)'s standard reference material (SRM 955 B : 5.01-54.43 μg/dL). Accuracy ranged from 96.5% to 105.0%.

4. Data analysis

Statistical testing was carried out using SPSS 10.0 Standard Version. Correlation analysis was performed to examine the relationship between lead concentration by size and lead in blood.

T-test and ANOVA was used to determine if differences of PbB between personal hygiene – related and work-related characteristics was detected. To perform this statistical analysis, PbA and RPM-PbA were categorized into two variables, ≥50 ung/m^3 and <50 ung/m^3, respectively.

III. Result

Exposure to PbA greatly exceeds 50 ug/m^3 of Korean PEL. Even exposure to RPM-PbA was as much as 115.7 ug/m^3, which is over 2 times as higher as Korea PEL for PbA. Lead concentrations characteriged by the size selective-selective sampling were shown in Table 1. Mean of lead concentration smaller than 1 um ($Pb_{1\mu}$) ranged from 0.7 to 492.2 ug/m^3. The average PbB was near 40 ug/dL for Korean compliance level. 46% of workers showed PbB concentration higher than 40 ug/dL. Workers whose blood level exceeded 60 ug/dL were as much as 13%. Table 2 summarizes the result of correlation coefficients between environmental lead concentration characterized by size and PbB. Significant correlations among all lead concentrations were found. In particular, highly significant correlation coefficients among lead concentration with large size were observed ($p< 0.0001$).

PbA, IPM-PbA and $PbA_{ingestible}$ were weakly correlated with PbB, respectively. In particular, correlation coefficient between PbB and $Pb_{1\mu}$ of fine lead concentrations was the highest compared to other lead concentration. This result indicated fine lead particle significantly influenced the absorption of lead. In contrast, RPM-PbA and TPM-PbA were not significantly correlated with PbB. Worker's personal-related activity such as smoking habit and wearing personal protective equipment (PPE) were not significantly related to the level of PbB.

Table 1. Age, smoking habit, working duration, lead exposure and PbB examined from 100 lead workers

	N	Median	Range	Mean (SD)
Age	100	34.5	17-62	34.4(11.6)
Working duration, month	100	25.0	1-243	41.7(47.5)
PbA, ug/m^3	100	70.5	4.1-11,390	655.0(1,626)
IPM-PbA, ug/m^3	100		3.7-9,125.2	476.5(1234.1)
TPM-PbA, ug/m^3	100		3.2-6,400.3	253.8(773.7)
RPM-PbA, ug/m^3	100	13.7	2.0-3,373.0	115.7(419.2)
$Pb_{ingestible}$, ug/m^3	100		1.7-10,899	623.3(1576.9)
$Pb_{1\mu}$, ug/m^3	100		0.7-492.2	28.8(75.4)
PbB, ug/dL	100	34.4	7.3-113.5	38.6(23.0)

Abbreviation: IPM-PbA = Inhalable Particulate Mass; TPM-PbA = Thoracic Particulate Mass; RPM-PbA = Respirable Particulate Mass; $Pb_{ingestible}$ = particles > 1 μm; $Pb_{1\mu}$= particles ≤ 1 μm; PbB = Lead in blood.

Table 2. Correlation matrix between lead concentration by size and PbB

	PbA	IPM-PbA	TPM-PbA	RPM-PbA	$Pb_{ingestible}$	$Pb_{1\mu}$	PbB
PbA	1	0.996**	0.944**	0.792**	0.999**	0.667**	0.227*
IPM-PbA	-	1	0.969**	0.839**	0.994**	0.691**	0.210*
TPM-PbA	-	-	1	0.941**	0.938**	0.740**	0.167
RPM-PbA	-	-	-	1	0.783**	0.719**	0.136
$Pb_{ingestible}$	-	-	-	-	1	0.641**	0.215*
$Pb_{1\mu}$	-	-	-	-	-	1	0.392*
PbB	-	-	-	-	-	-	1

**: $p<0.001$, *: $p<0.05$.

Abbreviation: IPM-PbA = Inhalable Particulate Mass; TPM-PbA = Thoracic Particulate Mass; RPM-PbA = Respirable Particulate Mass; $Pb_{ingestible}$ = particles > 1 μm; $Pb_{1\mu}$ = particles ≤ 1 μm; PbB = Lead in blood.

On the contrary, the work-related factor that significantly affected the level of PbB was working activity within metabolic rate categories. Significant difference of PbB level among categories of working activity was detected (p=0.001). Thus, the higher metabolic rate for working activity, the higher PbB level (p=0.001).

IV. Discussion

Correlation matrix between exposure to lead concentration by size and PbB supported OSHA's PEL for total lead without considering lead particle size. Current OSHA's lead PEL was still based on CPA model that PbA and PbB relationship originally proposed by Bernard and subsequently modified by Ashford *et al.* of MIT Center for Policy Alternatives (CPA) to include the effects of particle size and job tenure[11] To take particle size into account, CPA assumed (designated as Assumption C) that the first 12.5 ug/m^3 of airborne lead is composed of smaller particles that are less than 1.0 um in diameter, and all additional airborne lead is present in particles larger than 1.0 um. Current PEL for lead is based on only total lead without considering size selective criteria while other aerosols have dual PEL such as total and RPM. Several previous studies had reported that the particle size distribution assumed in the OSHA model was likely found to be incorrect for not only battery plants[5] but also for primary smelter plants,[13] capacitors, and lead powder plants.[6] If the OSHA model was to be directly applied to the actual particle-size distributions, significantly lower levels of lead in the blood would be predicted for a given air lead exposure.[3,5,7-8]

Tsai *et al.* (1997) concluded that concentrations of lead particles ≤ 1 μm ($Pb_{1\mu}$) increased along with increasing PbA concentrations. These results are contrary to CPA assumption, which states that concentrations of lead particles ≤ 1 μm ($Pb_{1\mu}$) are relatively constant.

Park *et al.* (2002) reported that in high temperature operations like secondary smelting and radiator plants, the variations of fine lead particles such as RPM-PbA and $Pb_{1\mu}$ predicted by PbA concentration were either not significant, or very low, while they were significant in other industries with coarse lead particles.

They suggested that worker's exposure to fine lead particles might not be effectively monitored because the current PbA sampling does not consider size-selective criteria.

The conclusions of these studies reported so far were based on the assessment on the size characteristics of airborne lead concentrations. We analyzed the relationship between lead concentration characterized by size and PbB level to examine whether PEL could be effective for protecting workers from exposure to lead particle.

In our previous study,[10] simple linear regression model indicated that the lead absorption could be estimated from RPM lead concentrations with higher slope coefficient than that from PbA concentrations (model p=0.0001, ordinary least squares R^2= 0.35). When the RPM-PbA was controlled, the partial correlation coefficient between PbA concentrations and PbB levels greatly decreased from

Table 3. The results of univariate analysis between PbB and several factors including person-related and work-related characteristics

		No of sample	PbB, ug/dL
Smoking	Yes	48	36.57
	No	22	26.98
	p-value		0.537
PPE	Yes	24	36.02
	No	57	39.38
	p-value		0.537
Operating temp.	High	31	45.12
	Low	69	35.64
	p-value		0.057
Working activity	Light	18	41.86
	Moderate	64	33.07
	High	18	54.86
	p-value		0.001
PbA (ug/m^3)	<50	43	19.63
	>50	57	106.81
	p-value		0.064
RPM-PbA (ug/m^3)	<50	76	51.32
	>50	24	126.33
	p-value		0.000

Abbreviation: PPE = Personal Protective Equipment; RPM-PbA = Respirable Particulate Mass.

0.56 to 0.20 (p=0.053). Our previous study concluded that contribution of RPM lead particles to the lead absorption would be greater than that of PbA.

In correlation analysis of this study, PbA, IPM-PbA and small lead particle concentrations was significantly correlated with lead in blood. In contrast, RPM showed no significant correlation with lead in blood, which is different from what we found better relationship between them in previous study.

In correlation matrix of this study, RPM-PbA concentration higher than 50 ug/m^3 showed significant higher PbB than RPM-PbA lower than 50 ug/m^3 (p=0.000) while PbA did not indicate significant difference PbB (Table 3). However, PbA with higher than 50 ug/m^3 was not significant (p=0.065). Small lead particle ($Pb_{1\mu}$) significantly influences lead in blood in not only correlation analysis but also mean comparison by T-test. This study also supported our previous conclusions that contribution of RPM-PbA to the lead absorption would be greater than that of PbA and worker's exposure to fine lead particles might not be effectively monitored.

V. Conclusion

Statistical T-test of this study concluded that RPM-PbA higher than 50 ug/m^3 showed significant higher PbB than RPM-PbA lower than 50 ug/m^3. Small lead particle ($Pb_{1\mu}$) significantly influenced PbB in not only correlation analysis but also mean comparison by T-test. These results proved that fine and respirable lead particle significantly influences the absorption of lead We concluded that exposure to fine lead particles with diverse size distribution might not be effectively monitored by the current PbA sampling method without considering lead size. Future study is needed to examine if person-related (e.g. hygiene behaviors) and work-related factors (e.g. work load, work practice, operation temperature) might affect the lead absorption using multivariate analysis.

Acknowledgement

This work was supported by Research Foundation of Korea National Open University. Author greatly appreciate this support.

References

1. Occupational Safety and Health Administration(OSHA) : United States Department of Labor 29 CFR 1910 and 1025 Occupational exposure to lead, Final Standard. Federal Register, **43**, 54354, 1978.
2. American Conference of Governmental Industrial Hygienists (ACGIH) : Threshold limit values and physical agents and biological exposure indices, ACGIH. Cincinnati, OH, 2005.
3. Froines, J. R., Liu, W. C., Hinds, W. C. and Wegman, D. H. : Effect of aerosol size on the blood lead distribution of industrial workers. *American Journal of Industrial Medicine*, **9**(3), 227-237, 1986.
4. Froines, J. R., Baron, S., Wegman, D. H. and O'Rourke, S. : Characterization of the airborne concentrations of lead in U.S. industry. *American Journal of Industrial Medicine*, **8**(1), 1-17, 1990.
5. Hodgkins, D. G. : The effect of lead-in-air particle size

on the lead-in-blood levels of lead-acid battery workers. A dissertation submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy (Industrial Health) in the university of Michigan, 1990.
6. Hodgkins, D. G., Hinkamp, D. L., Robins, T. G., Schork, M. A. and Krebs, W. H. : Influence of high past lead-in-air exposures on the lead-in-blood levels of lead-acid battery workers with continuing exposure. *J. Occup. Med.*, **33**(7), 797-803, 1991.
7. Hodgkins, D. G., Robins, T. G., Hinkamp, D. L., Schork, M. A. and Krebs, W. H. : A longitudinal study of the relation of lead in blood to lead in air concentrations among battery workers. *Br. J Ind Med*, **49**, 241-248, 1992.
8. Tsai, C. J., Shih, T. S. and Sheu, R. N. : Characteristics of lead aerosols in the different work environments. *Am. Ind. Hyg. Assoc. J.*, **58**, 650-656, 1997.
9. Park, D. U. and Paik, N. W. : Effect on blood lead of airborne lead particles characterized by size. *Ann. Occup. Hyg.*, **46**, 237-243, 2002.
10. Park, D. U. and Paik, N. W. : Exposure to Lead and Its Particles Size Distribution. *Journal of Occupational Health*, **46**, 225-229, 2004.
11. Ashford, N. A., Gecht, R. D., Hattis, D. B. and Katz, J. I. : The effects of OSHA medical removal protection on labor costs of selected lead industries. Cambridge. MA: Massachusetts Institute of Technology, Center for Policy Alternatives, 1977.
12. Jacobson, B. E., Lockitch, G. and Quigely, G. : Improved samples preparation for assurate determination of low concentrations of lead in whole blood by graphite furnace analysis. *Clinical Chemistry*, **37**(4), 515-519, 1991.
13. Hinds, W. C. : Data analysis. IN Cascade Impactor Sampling and Data Analysis, eds, J. P., Lodge, T. L., Chan, Chapter 3, American Industrial Hygiene Association, Akron, OH. 1986.