Evaluation of Serum and Urinary Neopterin Levels as a Biomarker for Occupational Exposure to Crystalline Silica

Mohammadi H, Dehghan SF, Golbabaei F, Ansari M, Yaseri M, Roshani S, Divani R

Department of Occupational Health, School of Public Health, Tehran University of Medical Sciences, 1Department of Occupational Health, School of Public Health, Shahid Beheshti University of Medical Sciences, 2Department of Clinical Biochemistry, Faculty of Medicine, Tehran University of Medical Sciences, 3Epidemiology and Biostatistics, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran

Abstract

Background: Crystalline silica is a commonly used mineral in various industries and construction activities, and it is so important introducing potential biomarkers to identify early indicators of biological effects in its high-risk occupational exposures.

Aim: The present study was aimed to assess the blood and urinary neopterin as an early biomarker of exposure in the workers of an insulator manufacturing plant who are exposed to crystalline silica.

Subjects and Methods: This analytical descriptive study was done among two groups of exposed workers (n = 55) and unexposed office workers (n = 38) of an insulator manufacturing plant. Statistical software R was used to determine sample size and select the participants by random sampling among nonsmoker workers. Sampling of airborne silica in breathing zone of participants was done based on the National Institute for Occupational Safety and Health method 7601. The urinary and blood samples were collected and prepared for analysis by high-performance liquid chromatography to determine the level of urinary and serum neopterin. All of the statistical analyses were carried out using SPSS 22.

Results: The airborne silica concentration was significantly different between two exposed and unexposed groups (P < 0.001, 0.27 [0.11] vs. 0.0028 [0.0006] mg/m³, respectively). The urinary neopterin in exposed group is significantly higher than the unexposed one (P < 0.001, 97.67 [30.24] vs. 55.52 [2.18] µmol/mol creatinine, respectively). Neopterin level of serum in exposed group is higher than the unexposed group, and there is a significant difference between them (P < 0.001, 6.90 [2.70] vs. 2.20 [1.20] nmol/l, respectively). The positive significant correlations were found between silica exposure concentration with urinary and serum neopterin (P < 0.001, r = 0.36 and 0.59, respectively).

Conclusions: Considering the sensitively and easily measurement of neopterin in biological fluid and also the statistically significant positive relationships which were found between the airborne silica concentration and neopterin levels in the present study, the serum and urinary neopterin levels can be considered the potential biomarkers of silica exposure for doing further comprehensive studies in this area.

Keywords: Airborne, biomarker, crystalline silica, neopterin, occupational exposure

How to cite this article: Mohammadi H, Dehghan SF, Golbabaei F, Ansari M, Yaseri M, Roshani S, et al. Evaluation of serum and urinary neopterin levels as a biomarker for occupational exposure to crystalline silica. Ann Med Health Sci Res 2016;6:274-9.
Airborne hazards such as dust, vapors, and fumes are present in many workplaces.[1] The risk of exposure to crystalline silica is a great concern worldwide. The term “silica” refers to the silicon dioxide (SiO$_2$) found in amorphous (noncrystalline) or crystalline form. As one of the most abundant minerals, silica exists in different materials and in the crust of the earth. Free crystalline silica can be found in three polymorphs including alpha-quartz, cristobalite, and tridymite.[3] While silica is a commonly used mineral in various industries and construction activities, exposure to silica dust can result in respiratory disorders.[2] The health hazards associated with occupational exposure to crystalline silica include silicosis, lung cancer, tuberculosis, chronic bronchitis, kidney disease, tooth abrasion, and autoimmune diseases such as rheumatoid arthritis.[1] Silicosis is classified into three clinical and pathologic varieties including acute, accelerated, and chronic silicosis. The chronic type occurs after 10–20 years, the accelerated one occurs after 5–10 years, and the acute one develops within several weeks to 5 years. As the disease progresses, some symptoms including shortness of breath, severe coughing, fatigue, loss of appetite, chest pain, and fever may happen. The concentration of exposure to silica is a determinative factor for developing silicosis.[4] Workers of various workshops and industries depending on their jobs are at risk to diseases associated with silica dust exposure. Workers engaged in insulator manufacturing are one of them who at risk of silica exposure. An electrical silicon-based insulator is applied as a high electrical resistance structure in power transmission towers, at the junction of cables and tower. During most of its manufacturing processes such as milling, mixing, pressing, assembling, cutting, grinding, and extruding equipment, there is the possibility of emitting silica particles.[5]

The diagnosis of silicosis is usually possible when someone has been involved, and the disease has progressed. Therefore, it is important introducing potential biomarkers to identify early indicators of biological effects before other clinical manifestation in the high-risk occupational exposures. It should be noted that the International Agency for Research on Cancer has classified the silica as a carcinogen agent, causing the lung cancer. Given the fact that the silica is extremely hazardous substances, assessing the silica particles in the workplaces under risk is so critical.[6]

Many workers are exposed to silica particles in the wide variety of occupations so that they are at risk of damage to DNA and lipids peroxidation through oxidative stress.[7] Silicosis can be considered as a chronic inflammation in which activated immune cells secrete toxins, causing damage to the lung tissue and development of the lung cancer.[8,9] Therefore, continuous monitoring of the early manifestations of exposure to silica appeared in workers may provide valuable information about worker’s health status, resulting in the prevention of disease progression.[10] Neopterin, a pteridine derivative and a by-product of the guanosine triphosphate-biopterin pathway,[11] is known as a biomarker of oxidative stress resulted in the response of immune system cells to inhaled silica particles.[12,13] Neopterin, as a marker of immune activation, is produced by activated macrophages and is released during or after sepsis, elective surgery, and severe trauma.[14] Studies show that high neopterin levels may be a marker of viral, bacterial, and parasitic infections,[15] a prognostic biomarker in intensive care,[16] and also as a marker in coronary disease activity.[11]

According to literatures, cytokines produced by exposure to crystalline silica lead to activating the immune system and producing the neopterin.[13] Exposure of lung cells to silica particles causes the activation of immune system mechanism and release the neopterin produced by stimulated macrophages and monocytes.[16,17] A study by Altindag et al. indicated that the concentration of urinary neopterin in exposed participants was significantly higher than that of the unexposed group, demonstrating the importance of neopterin as a marker of early effects associated with silica exposure.[13] Since the neopterin can be considered a biomarker of exposure to silica and due to the severe health hazards of crystalline silica, the present study was conducted to assess the serum and urinary neopterin in the workers of an insulator manufacturing plant who are exposed to crystalline silica. So by this way, it is possible to add this biological monitoring in periodic medical examinations to prevent the adverse effects resulting from exposure to silica. The purpose of the study was to assess the serum and urinary concentrations of neopterin between exposed and unexposed workers and then to investigate the correlation between workers’ exposure to silica and the concentration of neopterin, as a potential biomarker for silica.

Subjects and Methods
Sample size determination
This analytical descriptive study was done among two groups of exposed and unexposed workers of an insulator manufacturing plant from June to August 2015. Statistical software R 3.2.2 (2015; R Development Core Team, Auckland University, New Zealand) was used to determine sample size and select the participants by random sampling among nonsmoker workers. A list of all workers ($n = 181$) involving their history exposure level to silica was provided. To have 90% power to detect 0.70 µg/ml difference between the each exposed group with the unexposed group, when the type I error assumed to be 0.05 and the standard deviation assumed to be 0.65 µg/ml, sample size was calculated to be 18 in each exposed and unexposed groups. As there were five exposed groups which compared with one unexposed group, it was decided to change the ratio to 4:1 in unexposed group compared with each exposed group. In this way, the final sample size has been determined 11 in each exposed group (total = 55) and 44 in unexposed group. Forty-four male healthy and nonexposed office employees to crystalline
silica, who their age and work experience were in accordance with exposed participants, were selected through simple random sampling. There were some data missing including six participants from unexposed group.

A signed informed consent had been obtained from all participants. Workers who have suffered from any infectious disease, autoimmune diseases and other inflammatory diseases, and malignant diseases and were under any other special medical treatment and also have work experience <2-year-old were excluded from the study. Ethical approval was granted by the Research Ethics Committee of Tehran University of Medical Sciences.

Measurement of the concentration of airborne silica
National Institute of Occupational Safety and Health Method 7601[13] was used for sampling of airborne silica in breathing zone of all exposed and unexposed participants to evaluate the status of their respiratory exposure (sampling time: 6–8 h). The collected samples were carried to the laboratory for quantitative analysis. The stock and working solutions prepared according to method were used to plot the calibration curve. To prepare the samples for spectrophotometric analysis, silica standard solutions were filtered through the mixed cellulose ester filters (MCE-37 mm, 0.8 µm; SKC, Pennsylvania, USA). Finally, samples were analyzed by spectrophotometer (Unico SpectroQuest Model SQ2800 Single Beam UV/Visible Scanning Spectrophotometer, Ottawa, Canada).

Measurement of the blood and urinary neopterin levels
Blood and urine samples were taken from all participants in the early morning before work, and then they were transferred into 15 and 50 ml polyethylene tubes, respectively. Samples were stored immediately in an ice box and carried to the laboratory. All blood and urine samples were stored at −20°C until analysis. These biological samples were prepared for analysis by high-performance liquid chromatography (Merck Hitachi model L-7420 HPLC-UV, Midland, ON, Canada, equipped with RP18 column, absorbance wavelength of 353 nm). To analyze the biomarkers in serum and urine samples, calibration standard solutions were prepared, and the calibration curve was plotted based on the obtained data ($R^2 = 0.9992$, linear dynamic range: 1–2000 ng/ml). Using the obtained model, limit of detection and limit of quantification were computed, 0.0089 and 0.029 ng/ml, respectively. Since the urinary neopterin is reported in terms of urinary creatinine, the creatinine level was also determined by Kinetic Jaffe methods.

### Results
Table 1 shows some demographic characteristics of study participants. There is no significant difference between the exposed and unexposed groups regarding the age and work experience ($t$-test, $P = 0.89$ and 0.14, respectively).

The time-weighted average concentration of silica for exposed and unexposed participants can be seen in Table 2. The significant difference was found between two groups regarding the silica level exposure ($P < 0.001$). The highest silica concentration (0.36 [0.13] mg/m$^3$) was related to glazing workers, and the lowest concentration (0.11 [0.04] mg/m$^3$) was obtained for the workers of subordinate and small parts of the factory [Table 2]. According to results, the exposure concentration of silica was significant difference between workers of all parts of factory and unexposed ones ($P < 0.001$).

The concentration of urinary neopterin ($\mu$mol/mol creatinine) in both groups is presented in Table 3. The urinary neopterin in exposed group is significantly higher than the unexposed one (Mann–Whitney, $P < 0.001$). According to findings, the highest urinary concentration of neopterin (139.77 [14.95] $\mu$mol/mol creatinine) was related to glazing workers, and the lowest one (55.52 [2.18] $\mu$mol/mol creatinine) was obtained for unexposed group. The urinary concentration of neopterin was significantly different between exposed and unexposed groups in all parts of factory ($P < 0.001$).

Table 4 indicates the serum level of neopterin (nmol/l) in both groups. Based on results, neopterin level of serum in exposed group is higher than the unexposed group, and there is a significant difference between them (ANOVA, $P < 0.001$). As it can be seen in Table 4, the highest and lowest serum concentrations of neopterin (7.80 [0.20] and 2.20 [1.20] nmol/l) were obtained for glazing workers and unexposed group,

### Table 1: Some demographic data of study participants

| Demographic variables | Exposed group (n=55) | Unexposed group (n=38) | $P$ |
|-----------------------|----------------------|------------------------|-----|
|                       | Minimum | Maximum | Mean (SD) | Minimum | Maximum | Mean (SD) |       |
| Age (year)            | 23      | 45      | 37.29 (3.79) | 23      | 46      | 37.52 (5.56) | 0.89  |
| Work experience (year)| 2       | 18      | 12.91 (3.74) | 4       | 20      | 11.47 (4.15) | 0.14  |
respectively. The concentration of neopterin in serum was significantly different between exposed and unexposed groups in all parts of factory ($P < 0.001$).

Table 5 illustrates the relationship of silica concentration, age, and work experience with serum and urinary neopterin. Findings demonstrate that there was no significant correlation between these two these demographic variables and urinary and serum neopterin (Pearson correlation test, $P > 0.06$). The positive significant correlations were found between silica exposure concentration and urinary and serum neopterin ($P < 0.001$, $r = 0.36$ and 0.59, respectively).

**Discussion**

Crystalline silica is one of the most important minerals in various industrial activities worldwide. The concentration exposure of silica is a determinative factor in the development of silicosis. The diagnosis of silicosis is possible when it has progressed and person has been involved. Therefore, it is important to propose appropriate biomarkers to identify the high-risk exposures. Wächter et al. first introduced the neopterin as a marker of immune system activation. The present study was conducted to evaluate the blood and urinary level of neopterin as a potential biomarker of silica exposure.

The blood and urinary neopterin levels in workers exposed to silica were compared to those of unexposed participants from an insulator manufacturing plant. According to demographic data, there was no significant difference between the exposed and unexposed groups regarding the variables of age and work experience ($P > 0.14$). The concentrations of airborne silica for exposed and unexposed participants were 0.27 (0.11) mg/m$^3$ and 0.0028 (0.006) mg/m$^3$, respectively ($P < 0.001$). American Conference of Governmental Industrial Hygienists has recommended the threshold limit value of 0.025 mg/m$^3$ for respirable silica crystalline. Yassin et al. (2005) conducted a study to determine the occupational exposure to airborne silica for 7206 American workers between 1988 and 2003. The mean of silica concentration was reported 0.77 mg/m$^3$ that it is higher than the mean concentration obtained in the present study.

The highest and lowest value of urinary neopterin was obtained 139.77 (14.95) and 55.52 (2.18) µmol/mol creatinine, respectively, for glazing workers and unexposed group. The measurements of neopterin in serum showed that the maximum level of this variable was 7.80 (2.45) µmol/L for glazing workers and minimum level was 2.20 (1.20) µmol/L for unexposed one. Normal value of neopterin in urine for 26–35-year-old men is 101 (33) µmol/mol creatinine and for 36–45-year-old men is 109 (28) µmol/mol creatinine. Normal value of neopterin in serum for 19–75-year-old people is 5.3 (2.7) nmol/L. Increased concentrations of neopterin have been shown that can induce the formation of reactive oxygen and nitrogen species. High level of neopterin can contribute to endothelial injury and risk of infection.

Based on results, a significant increase in the serum and urinary neopterin levels of exposed groups was found. According to the literature, on the one hand, silica has proven to change immunological functions, T-lymphocytes, neutrophils, and immunoglobulin; and on the other hand, several studies have introduced neopterin as a sensitive marker of cellular immunity. Therefore, the present study can be a useful approach to evaluate the occupational exposure to airborne silica.
immune activation in humans.[13,27] Therefore, it can be stated that the observed differences in neopterin levels between two exposed and unexposed groups may be related to the effect of crystalline silica on pulmonary cells which is followed by the activation of immune system cells and stimulation of macrophages and monocytes, and subsequently increased secretion of neopterin.

The release of neopterin by macrophages is related to the ability of the cells to produce toxic metabolites, especially reactive oxygen species (ROS). Thus, neopterin is not only a marker for activated cell-mediated immunity but also it is a monitor of oxidative stress as a result of immune activation.[13] Silica exposure can lead to the lung inflammation in which activated immune cells secrete toxins, causing damage to lung tissue.[8,9]

The present finding is in line with Wachter et al.[20] A study by Prakova et al. demonstrated that the level of serum neopterin in workers exposed to silica was significantly higher than that of the unexposed participants; thus, they introduced the neopterin as a potential marker of effect for crystalline silica exposure.[12]

Results of the present study also indicated that there was no significant relationship for the age and years of work with serum and urinary levels of neopterin. The study of Altindag et al. in a foundry industry showed that the age of participants had no significant relationship with serum and urinary levels of neopterin.[13] However, normal values of urinary neopterin in healthy people somewhat rely on age and sex of participants.[23,24]

Determination of neopterin levels which can be of importance in the progression of various diseases such as inflammatory diseases,[24] for example, due to silica exposure, but for making a definitive conclusion about the findings of the present study, the further comprehensive studies are certainly necessary to consider more confounding factors such as existence of any form of cardiovascular disease, renal impairment, sepsis, surgery, and severe trauma. Moreover, to confirm the results, it also needs to monitor the other biomarkers closely associated with neopterin levels such as oxidative stress-related parameters.[13]

The health hazards associated with silica exposure can highly dependent on particle size. Particles in the size range 0.5–5 µm cause a significant and fibrogenic effect of oxidative stress, since they are too small and can reach the alveoli and they are digested by the alveolar macrophages and it resulted in the cellular immune responses.[12,29] However, silica particle size distribution is not considered in the present study.

High reactivity of crystalline silica is due to surface – SiOH groups which are formed when SiO2 becomes hydrated. Silica dust trigger producing ROS from alveolar macrophages, which overwhelms antioxidant defenses of the lung and contribute to lipid peroxidation and an increased likelihood of lung injury and DNA damage.[28-30] Therefore, in some studies, plasma/serum malondialdehyde levels as an index of lipid peroxidation, 8-hydroxydeoxyguanosine as an oxidative stress marker, and erythrocyte reduced glutathione levels as an index of antioxidant status were investigated in silica-exposed participants.[28-30] Moreover, more attention has been given to assay of in-vitro DNA strand breakages resulting from the biologic interactions of oxygen radicals generated by silica particles,[30,31] Gulubian et al. (2006) performed a comprehensive review on suitable biomarkers of silicosis and coal worker’s pneumoconiosis and introduced the number of ideal biological markers of them.[32] They concluded that “the determination of serum neopterin levels may be a useful early biomarker following exposure to crystalline silica if combined with other biomarkers.”[32]

Conclusion

According to literatures, increased concentration of neopterin in body fluids such as serum and urine can provide useful information about the activation of immune system. High production of neopterin can help identifying and predicting the immunologic changes in some diseases. Findings of this study indicated that there are the statistically significant positive relationships between the silica concentration and serum and urinary neopterin among participants, so higher exposure level to silica displayed higher this biomarker values.

Neopterin is a biologically stable biomarker, and the measurement of neopterin in human biological fluids can be sensitively and easily performed. Furthermore, it has been also found to be a strong predictor of disease progression,[14] so it can be suggested as a potential indicator for determining the early health effects resulted from silica exposure. However, further studies in larger populations are recommended for more accurate assessment of the risk threatening workers exposed to crystalline silica.

Acknowledgments

This study was the part of a M.S. thesis supported by Tehran University of Medical Sciences (Grant no: 94-04-27-29488).

Financial support and sponsorship

This study was financially supported by Tehran University of Medical Sciences.

Conflicts of interest

There are no conflicts of interest.

References

1. Lumens ME, Spee T. Determinants of exposure to respirable quartz dust in the construction industry. Ann Occup Hyg 2001;45:585-95.
2. Mohammadi H, Golbabaei F, DehghanSF, Normohammadi M.
Assessment of occupational exposure to crystalline silica in an Insulator industry: Determination the risk of mortality from silicosis and lung cancer. JHSW 2017;47(1):45-52. [In Persian].

3. Morman SA, Plumlee GS. The role of airborne mineral dusts in human disease. Aelolian Res 2013;9:203-12.

4. Azari MR, Rokni M, Salehpour S, Mehrabi Y, Jafari MJ, Moaddeli AN, et al. Risk assessment of workers exposed to crystalline silica aerosols in the east zone of Tehran. Tanaffos 2009;8:43-50.

5. Mohammadi H, Alimohammadi I, Roshani S, Pakzad R, Abdollahi MB, Dehghan SF. The effect of occupational noise exposure on blood and biochemical parameters: A case study of an insulator manufacturer in Iran. Electron Physician 2016;8:1740-6.

6. Liu Y, Steenland K, Rong Y, Hnizdo E, Huang X, Zhang H, et al. Exposure-response analysis and risk assessment for lung cancer in relationship to silica exposure: A 44-year cohort study of 34,018 workers. Am J Epidemiol 2013;178:1424-33.

7. Peluso ME, Munnia A, Giuse RW, Chellini E, Ceppi M, Capacci F. Oxidatively damaged DNA in the nasal epithelium of workers occupationally exposed to silica dust in Tuscany region, Italy. Mutagenesis 2015;30:519-25.

8. Greenberg MJ, Waksman J, Curtis J. Silicosis: A review. Dis Mon 2007;53:394-416.

9. Frankel A, Blake L, Yates D. Late-breaking abstract: Complicated silicosis in an Australian worker from cutting engineered stone countertops: An embarrassing first for Australia. Eur Respir J 2015;46:PA1144.

10. Shulte PA. The role of biomarkers in the prevention of occupational disease. In: Mendelsohn ML, Peeters JP, Normandy MJ, editors. Biomarkers and Occupational Health: Progress and Perspectives. Washington (USA): Joseph Henry Press; 1995.

11. Kaski JC, Avanzas P, Arroyo-Exceptigure R. Neopterin – A forgotten biomarker. J Am Coll Cardiol 2003;42:1142-3.

12. Prakova G, Gidikova P, Slavov E, Sandeva G, Stanilova S. The potential role of neopterin as a biomarker for silicosis. Trakia J Sci 2005;3:37-41.

13. Altindag ZZ, Baydar T, Isimer A, Sahin G. Neopterin as a new biomarker for the evaluation of occupational exposure to silica. Int Arch Occup Environ Health 2003;76:318-22.

14. Baydar T, Yuksel O, Sahin TT, Dikmen K, Girgin G, Sipahi H, et al. Neopterin as a prognostic biomarker in intensive care unit patients. J Crit Care 2009;24:318-21.

15. Ruokonen I, Ilkka L, Niskanen M, Takala J. Procalcitonin and neopterin as indicators of infection in critically ill patients. Acta Anaesthesiolog Scand 2002;46:398-404.

16. King NJ, Thomas SR. Molecules in focus: Indoleamine 2,3-dioxygenase. Int J Biochem Cell Biol 2007;39:2167-72.

17. Munn DH, Mellor AL. Indoleamine 2,3-dioxygenase and tumor-induced tolerance. J Clin Invest 2007;117:1147-54.

18. National Institute of Occupational Safety and Health (NIOSH). Silica, crystalline, by VIS. Method 7601. In: NIOSH Manual of Analytical Methods. Atlanta (GA): NIOSH; 2003.

19. Wachter H, Fuchs D, Hausen A, Reibnegger G, Werner ER. Neopterin as marker for activation of cellular immunity: Immunologic basis and clinical application. Adv Clin Chem 1989;27:81-141.

20. Wachter H, Fuchs D, Hausen A, Reibnegger G, Weiss G, Werner ER, et al. Neopterin Biochemistry-Methods of Clinical Application. Berlin (Germany): De Gruyter; 1992.

21. ACGIH. 2015 TLVs and BEIs: Threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati, OH: American Conference of Governmental Industrial Hygienists; 2015.

22. Yassin A, Yebesi F, Tingle R. Occupational exposure to crystalline silica dust in the United States, 1988-2003. Environ Health Perspect 2005;113:255-60.

23. Friedrich W. Vitamins. New York (USA): Walter de Gruyter; 1988.

24. Fuchs D. Neopterin. Available from: http://www.neopterin.net/neopterin_e.pdf. [Last accessed on 2016 Jul 25].

25. Kusaka Y, Cullen RT, Donaldson K. Immunomodulation in mineral dust-exposed lungs: Stimulatory effect and interleukin-1 release by neutrophils from quartz-elicited alveolitis. Clin Exp Immunol 1990;80:293-8.

26. Lindenschmidt RC, Driscoll KE, Perkins MA, Higgins JM, Maurer JK, Belfiore KA. The comparison of a fibrogenic and two nonfibrogenic dusts by bronchoalveolar lavage. Toxicol Appl Pharmacol 1990;102:268-81.

27. Altindag ZZ, Sahin G, Isimer A, Akpek G, Kansu E. Dihydropteridine reductase activity and neopterin levels in leukemias and lymphomas: Is there any correlation between these two parameters? Leuk Lymphoma 1999;35:367-74.

28. Orman A, Kahraman A, Cakar H, Ellidokuz H, Serteser M. Plasma malondialdehyde and erythrocyte glutathione levels in workers with cement dust-exposure [corrected]. Toxicology 2005;207:15-20.

29. Azari MR, Ramazani B, Mosavian MA, Movahadi M, Salehpour S. Serum malondialdehyde and urinary neopterin levels in glass sandblasters exposed to crystalline silica aerosols. Int J Occup Hyg 2011;3:29-32.

30. Shi X, Mao Y, Daniel LN, Saffiotti U, Dalal NS, Vallyathan V. Silica radical-induced DNA damage and lipid peroxidation. Environ Health Perspect 1994;102 Suppl 10:149-54.

31. Liu HH, Lin MH, Liu PC, Chan CI, Chen HL. Health risk assessment by measuring plasma malondialdehyde (MDA), urinary 8-hydroxydeoxyguanosine (8-OH-dG) and DNA strand breakage following metal exposure in foundry workers. J Hazard Mater 2009;170:699-704.

32. Gulumian M, Borm PJ, Vallyathan V, Castranova V, Donaldson K, Nelson G, et al. Mechanistically Identified Suitable Biomarkers of Exposure, Effect, and Susceptibility for Silicosis and Coal-Worker’s Pneumoconiosis: A Comprehensive Review. J Toxicol Environ Health B Crit Rev 2006; 9(5):357-95.