Urinary Metal Levels in a Chilean Community 31 Years After the Dumping of Mine Tailings

Sandra Cortés,1,2 Lucía del Carmen Molina Lagos,1 Soledad Burgos,3 Héctor Adaros,4 Catterina Ferreccio1,2

1 Departamento de Salud Pública, Pontificia Universidad Católica de Chile, Santiago, Chile
2 Center for Advanced Chronic Diseases (ACCDIS), Departamento de Salud Pública, Facultad de Medicina, Pontificia Universidad Católica de Chile
3 School of Public Health, University of Chile, Santiago, Chile
4 Chañaral’s Hospital, Atacama Region, Chile

Introduction

Mining is an important economic activity in many countries. In Latin America, it is a growing industry which, in part, national incomes depend, as is the case in Chile. Recently, the health risks related to mining have been evaluated due to increased awareness and concern. Environmental risks for the general population are equally important, especially considering vulnerable subgroups such as women and children. There has been increased attention on the evaluation of the physical, chemical, biological, ergonomic and psychosocial health hazards associated with mining. Until now, the focus has been on chemical risks, but heavy metal exposure is especially important due to the abundant worldwide evidence on the adverse health effects associated with mining activities.1-5

Mine tailings contain high concentrations of chemicals and elements that alter the environment. Therefore, they must be transported and stored in dams or reservoirs, where contaminants slowly decant at the bottom, the water is recovered or evaporated, and the material remains as a stratified deposit of fine solid material.4 Mine tailings are an important source of heavy metal contamination in the environment. Metals such as arsenic, lead, chromium, cadmium, copper, zinc and nickel have been found in mine tailings throughout the world. Communities living around the tailings may be exposed to heavy metals through different exposure routes, such as ingestion of contaminated water and inhalation/ingestion of tailing dust.4,7 Previous studies have found urinary levels of arsenic exceeding permissible occupational exposures in people residing in close proximity to mine tailings in Mexico, and high concentrations of heavy metals in hair samples of children residing in close proximity to mine tailings in Italy. Such heavy metals exposure may induce poor

Background. Between 1938 and 1975, the city of Chañaral, located in the north of Chile, received 200 megatons of unregulated mining waste, which created an artificial beach 10 kilometers long and covering an area larger than 4 km². In 1983, this deposit was classified as a serious case of marine pollution in the Pacific Ocean, according to the Organization for Economic Cooperation and Development. In 1989, dumping ceased due to a judicial order. Until now, the effects of this pollution on the population living around these mine tailings has been unknown.

Objective. To determine the prevalence of exposure to metals by dust from mine tailings in Chañaral, a city located in the northern mining area of Chile.

Methods. The level of urinary metals in a representative sample of adults from Chanaral was determined.

Results. Urinary levels of total arsenic (44.6 μg/L), inorganic arsenic (17.0 μg/L) and nickel (2.8 μg/L) were higher than in other areas of Chile. Levels of copper (17.9 μg/L), mercury (1.6 μg/L) and lead (0.9 μg/L) exceeded international values. Of the total subjects, 67.5%, 30.4%, 29.4%, 16.9%, 13.2 and 9.3% presented with high levels of copper, nickel, total arsenic, inorganic arsenic, mercury and lead, respectively.

Conclusion. Thirty-one years after suspension of the discharge of mining waste, the local population in this area remains exposed to metals from the mine tailings. Surveillance and remedial actions addressing the Chañaral mine tailings are needed.

Patient Consent. Obtained

Ethics Approval. The protocols and informed consent documents were approved by the Ethics Committee for Human Research of the School of Medicine of the University of Chile.

Competing Interests. The authors declare no competing financial interests.

Keywords. heavy metals, urinary metals, Chile, mining waste, mine tailings, arsenic, nickel, copper, lead, mercury

J Health Pollution 10: 19–27 (2016)
respiratory health, lung cancer, and neurodevelopmental disorders, as well as various other health disorders.\textsuperscript{8,9}

In Chile, a total of 603 mine tailings were reported in 2015, and 216 of these (35.8\%) were active and associated with mining enterprises in current production. The remaining contained abandoned waste (64.2\%), posing a risk for people living near them. From the total number of mine tailings, 81.1\% are located in northern Chile, between the Arica and Atacama region, and the largest is located along the coast of Chañaral.\textsuperscript{6} Depending on location, mining tailings and associated superficial waters may contain several chemical elements such as silica, aluminum, copper, chromium, nickel, lead, zinc, and mercury.\textsuperscript{10-14}

The city of Chañaral is located in the north of Chile, 1000 km from Santiago, the capital, and has a population of approximately 13,500 inhabitants (Figure 1). Copper mining is the city’s main economic activity and the two most important mines are Potrerillos and El Salvador, located approximately 100 and 120 km east of Chañaral. The Potrerillos mine operated from 1926 to 1959 and the El Salvador mine opened in 1959 and remains in operation today. From 1938 to 1975, untreated waste materials from these two mines were dumped into the Salado River which carried them into the Chañaral Bay on the Pacific coast. Between 1975 and 1989, waste was instead deposited 15 km north of Chañaral Bay, contaminating the coastline and the ocean. In 1983, Chañaral was classified as a serious case of marine pollution in the Pacific Ocean according to the Organization for Economic Cooperation and Development.\textsuperscript{15} In 1989, dumping ceased due to a judicial order, and subsequently waste material has been stored in closed tanks near the mine.\textsuperscript{16}

During the time the disposal of the waste was permitted, more than 220 megatons of material was accumulated in the bay (mainly porphyry copper type minerals), forming a 10 km artificial beach, covering an area of more than 4 km\textsuperscript{2}, with an estimated depth of 10 to 15 meters. This beach is located across the bay from the city, resulting in the coastline moving approximately one km.\textsuperscript{16} These mine tailings are mainly composed of active chemical elements including arsenic, nickel, and copper. These elements experience changes that facilitate their migration, solubilization, and progressive transformation.\textsuperscript{17} In 2006, Dold measured the metal contents and chemical activity in the mine tailings and identified an oxidation zone at the top of the tailings with liberation of divalent metal cations, such as Copper\textsuperscript{(2+)}, Nickel\textsuperscript{(2+)}, and Zinc\textsuperscript{(2+)} (up to 2265 mg/L, 18.1 mg/L, and 20.3 mg/L, respectively).\textsuperscript{17} Based on these findings, it is plausible that residents of Chañaral may be exposed to copper, nickel, and zinc suspended in dust. Furthermore, the presence of H\textsubscript{2}SO\textsubscript{4} (sulfuric acid) or HCl (hydrochloric acid) neo-formations indicate an acidic environment within the tailings, meaning that the sedimentable dusts from the tailing sands have acidic and corrosive properties. However, arsenic

| Abbreviations |
|----------------|
| CDC | Centers for Disease Control and Prevention |
| ICP-MS | Inductively coupled plasma mass spectrometry |
| DL | Detection limit |

\textcopyright Cortés et al.
released from sulphur is immobilized and remains at the bottom of the tailings and in the sediments, where it is dissolved in the sea.\textsuperscript{17}

Although waste material is no longer deposited in Chañaral Bay, its accumulation and transformation in the environment may continue to represent a risk to human health and surrounding ecosystems.\textsuperscript{18-28} Arid conditions in the region and lack of rain precipitation limiting the removal of salt from soil may exacerbate exposure.\textsuperscript{18} In addition, the population in Chañaral is characterized by high social vulnerability, with the highest unemployment rates in the region (11.5\% vs 3.7\% in the nearby city of Caldera) and the lowest annual per capita spending on health in the region (US $42 in Chañaral vs US $146 in Diego de Almagro, 61 km north), a condition that could worsen the potential adverse health effects of exposure to mine tailings in this population.\textsuperscript{29,30}

The mine tailings in Chañaral represents a unique scenario due to the lack of mitigation projects and poor environmental control. This makes it difficult to make a comparison with other cities with or without nearby mine tailings. These characteristics, followed by the scarcity of policies addressing the problem and the remoteness of universities and high quality toxicology laboratories, constitute a scenario that complicate the study of the tailings and their potential health risks to Chañaral’s population. Chañaral represents a typical case of a contaminated site that calls for an integral approach with available and well-known methodologies. Although this is not the intention of the present study, we will consider a few specific elements from those methodologies.

Our study was conducted 31 years after the prohibition of the dumping of mining waste into the Bahia. The aim was to determine the prevalence of urinary metals such as copper, nickel, mercury, arsenic and lead, and establish cut-off points for future surveillance of exposures in order to improve the quality of life of the inhabitants of Chañaral and enhance their health.

**Methods**

**Population and Sample**

The total adult population in Chañaral between the ages of 18-65 years old was estimated to be 8,851 inhabitants in 2007 when this study was conducted. We recruited a sample population of 205 individuals, considering at least 190 to achieve statistical significance and 10\% for replacements.

The sample was selected in three stages. First, a list of blocks and residences was developed and random number generation was used to select blocks. Subsequently, the third house clockwise from the north corner of the selected block was chosen. In each residence, an adult that met the selection criteria was selected using a Kish grid.\textsuperscript{31} One subject from each of the predefined residences was invited to participate in the study.

Eligibility criteria included: (1) age 18-65 years, (2) a minimum of 8 years of education, (3) absence of mental illness, and (4) residence in the city for at least 3 years. Subjects were excluded if they had a history of occupational exposure to the mining industry.

A questionnaire was used to collect information about demographics (age, sex, education level, place of residence), exposure to metals (employment history, daily activities, proximity to potential sources of exposure), and lifestyle (active and passive smoking, consumption of alcohol, consumption of fish and shellfish). Questions regarding socioeconomic variables were taken from the 2002 Chilean census. Metal exposure questions were developed by the research team and later validated in 20 volunteers who met the study inclusion criteria, but who lived outside of Chañaral in a coastal region that was not exposed to mining waste. Modifications were made to the questionnaire based on respondent feedback.

**Collection and Analysis of Metals in Urine**

Participants provided a single sample of urine in two separated flasks. Urine samples were collected by households, and researchers were present during the sample collection and provided detailed instructions. Samples were kept at 4°C during the first four hours after the collection. Nitric acid was added to one of the flasks (flask 2) and both flasks were frozen at -20°C in Chañaral. Samples without nitric acid (flask 1) were transported to the laboratory in Santiago. Samples were analyzed with inductively coupled plasma mass spectrometry (ICP-MS) for total arsenic, copper, nickel, and lead. Mercury was measured by the laboratory of the Metropolitan Regional Health Authority with atomic absorption spectroscopy. Samples with arsenic levels higher than 50 μg/L were analyzed at the Public Health Institute to measure inorganic arsenic and its metabolites. There, samples with nitric acid (flask 2) were analyzed by hydride generation atomic absorption spectrophotometry (Perkin-Elmer).

All laboratory activities were performed in accordance with the requirements imposed by ISO 17025 (http://www.iso.org/iso/catalogue_detail.htm?csnumber=30883). The detection limit (DL) for each metal was calculated independently using 10 urinary samples.

**Statistical Analysis**

Urinary metal concentrations are expressed in μg per liter of urine (μg/L). Levels below the DL had an imputed
Research

Urinary Metal Levels in a Chilean Community

value corresponding to half of the DL (DL/2), as proposed by the Centers for Disease Control and Prevention (CDC) for population studies in the United States over a similar study period. We chose not to present creatinine-adjusted results because our reference values were obtained from studies focused on environmental exposure in the general population and provided unadjusted values. However, creatinine-adjusted levels were analyzed and this did not change the results (data not shown).

Median metal concentrations by sex, age group, distance (meters) to tailings, residence in the north, consumption of fish and shellfish, and occupational exposure to metals were compared using the Kruskal-Wallis test.

As an indicator of metal exposure, the 95th percentile level of urinary metals for the residents of Chañaral were compared with other populations described in the literature by reviewing studies from the period 2005–2010 that measured urinary metals in adults. These studies included adults from the general population (not occupationally exposed to metals) of similar ages, as in our study. Reference values for copper, lead and nickel were defined as 13 µg/L, 2.6 µg/L and 4.1 µg/L, respectively. We defined the reference value for total arsenic using national expert opinion (50 µg/L), but for inorganic arsenic, an occupational reference from the United States was used (35 µg/L).

Multivariate models were used to evaluate the risk factors for high metal levels in urine. Levels higher than the reference value were defined as high metal exposure. Multivariate models were adjusted for covariates.

The protocols and informed consent documents were approved by the Ethics Committee for Human Research of the School of Medicine of the University of Chile (#977) compliant with the Declaration of Helsinki.

Results

A total of 215 residents of Chañaral were invited to participate in the study and 205 agreed to participate (95.3%). The mean age was 43.6 years (± 11.2). More than half of the participants were women (67.3%). Of the total participants, 23% had a middle school level of education (8 years or less of education), and 7% had more than 12 years of education. The mean distance between homes and mine tailings was 1560 meters (range 100-6000 meters). Among study participants, 24.4% reported contact with chemical agents at work, including 5.4% who smelted lead to make fishing weights. More than half (54.9%) reported regularly eating fish and shellfish (Table 1).

Almost all participants (204) provided adequate urine samples (adequate volume and lack of contamination). Table 2 presents the percentage of samples exceeding the DL and descriptive statistics.

For each metal, there were individual samples that exceeded the established environmental reference values. Inorganic arsenic levels exceeded occupational reference values. The most commonly elevated levels were for copper and nickel, with 67.5% and 30.4% of samples exceeding the reference values, respectively.

The highest copper levels were found

| General Characteristics (n)               | Total (205) | Men (67) | Women (138) |
|-------------------------------------------|-------------|----------|-------------|
| Age (years) (mean ± SD)                   | 43.6 ± 11.2 | 45.1 ± 11.3 | 42.9 ± 11.1 |
| < 44 years                                | 52.2        | 29.2     | 70.8        |
| 45-59 years                               | 38.4        | 34.6     | 65.4        |
| > 60 years                                | 9.4         | 36.8     | 63.2        |
| Years of residence in Chañaral (mean ± SD)| 33.7 ± 13.8 | 31.8 ± 13.8 | 34.6 ± 13.8 |
| 8 years or less of education (%)          | 23.4        | 25.4     | 22.5        |
| Number of blocks between home and mine tailings (range 1-60) | 15.6 ± 12.5 | 14.8 ± 12.1 | 15.9 ± 12.6 |
| Smelts lead fishing weights (%)           | 5.4         | 10.5     | 2.9         |
| Consume fish or shellfish (%)             | 54.9        | 59.1     | 52.9        |

Table 1 — Participant Demographics (No significant differences by sex using Kruskall-Wallis test)
in people younger than 44 years old, living in the northern area of the city and working in small-scale fishing. In the multivariate analysis, residence in the northern area of the city was a risk factor for having a urinary copper level higher than the reference value of 13 µg/L.

Preparation of fishing weights was identified as a risk factor for an elevated mercury level (Table 3). Preparing lead fishing weights was also associated with higher concentrations of nickel and lead, but the association did not reach significance. We found that people living fewer than 1000 meters from the tailings had a two times higher risk of showing a urinary nickel level above the reference value (4.1 µg/L) (odds ratio = 2.5; 95%, confidence interval = 1.08 - 5.82) (data not shown). In the multivariate analysis, fish and shellfish consumption remained a statistically significant predictor for having a urinary arsenic level >50 µg/L (odds ratio = 2.3; 95%, confidence interval = 1.05 - 4.87) (data not shown).

### Discussion

This is the first study to determine levels of multiple metals in urine samples of adults living in Chañaral in order to assess their current exposure.

Urinary metal concentrations indicate that Chañaral residents are exposed to metals, possibly from the mine tailings in Chañaral Bay, even though mine waste discharge ceased 31 years prior to the present study. The study confirms the findings of Dold, who reported in 2006 that mine tailings undergo various chemical transformations facilitating the migration and solubilization of metals, making them more bioavailable. The chemical composition of these mine tailings is a mineral surface of eriochalcite (Copper(II) chloride·water) and halite (NaCl), strongly enriched with copper at levels.
between 1000 to 24100 mg/kg. Other metals in the mine tailings included nickel (5-370 mg/kg) and arsenic (30-281 mg/kg). These results suggest that residents living in Chañaral have been exposed to copper and nickel suspended in dust carried by wind from the mine tailings to the city. In our study, the copper and nickel levels found in study subjects were consistent with findings reported by Dold.17

Metal levels in other matrices such as soil, food, or dust in suspension were not evaluated in this pilot study. For exploratory information only, drinking water samples were collected from the residences of volunteer participants (n=10). The highest levels found for nickel (5.6 µg/L), arsenic (7.6 µg/L), copper (10.4 µg/L), and lead (1.3 µg/L) were within the national drinking water standards.38 Regarding food exposure, key informants indicated that locally-harvested seafood is not consumed in Chañaral due to obvious discoloration by copper. We were not able to obtain data on metals in foods more frequently consumed in the area.

Although all metals were elevated in some urine samples (Table 2), the prevalence of copper exposure, with 67.5% of subjects exceeding the reference level, deserves further attention. These copper levels have not been previously reported in the international literature on environmentally-exposed populations, and further investigation is necessary to develop better biomarkers for monitoring at the population level.39-41

We did not collect blood samples to measure lead, which is the preferred method of assessing recent lead exposure. We use urinary lead level as a qualitative indicator of chronic exposure, as has been done previously in the United States.32 This is the first publication of general population data on urinary lead levels in Chile. Notably, the highest urinary lead level (58 µg/L) was found among people who stated that they smelted lead for small-scale fishing, an activity unrelated to the exposure to mine tailings. Moreover, when these subjects were excluded from the analyses, the population mean level of lead was comparable to other international studies.32

In addition, this is the first study in Chile to publish data on mercury levels in a general and non-occupational population from a coastal location. The 95th percentile for mercury (6.3 µg/L) in subjects living in Chañaral exceeds values reported in the United States (4 µg/L) and Germany (1 µg/L), although it is somewhat similar to levels reported in Brazil (mean of 5.6 µg/L, range 0.2 to 36.1 µg/L).32,33,42

### Table 3 — Urinary Metal Levels by Demographics, Place of Residence, and Lifestyle

* Significant difference p-value <0.05; Kruskal-Wallis non-parametric test

| Characteristics                      | Copper | Mercury | Nickel | Lead | Total Arsenic |
|--------------------------------------|--------|---------|--------|------|---------------|
| Male (n=67)                          | 21.7   | 1.4     | 2.7    | 1.1  | 42.8*         |
| Female (n=138)                       | 16.8   | 1.7     | 2.8    | 0.8  | 28.8          |
| <44 years old (n=106)                | 18.6   | 1.8     | 2.6    | 0.9  | 37.9          |
| 45-59 years old (n=78)               | 16.4   | 1.6     | 2.6    | 0.9  | 29.9          |
| >60 years old (n=19)                 | 16     | 0.6     | 2.9    | 0.4  | 25.5          |
| Northern sector residence (n=63)     | 22.7*  | 2       | 2.8    | 0.8  | 28.6          |
| Another sector residence (n=141)     | 16.5   | 1.4     | 2.7    | 0.9  | 35.9          |
| Lives <1000 m from waste site (n=80) | 18.6   | 1.5     | 2.6    | 0.8  | 34.7          |
| Lives >1000 m from waste site (n=79) | 17.7   | 1.8     | 2.9    | 0.9  | 30.9          |
| Smelts lead fishing weights (n=4)    | 34.9*  | 5.65*   | 5.1    | 4.25 | 69.8          |
| Consumes fish and/or shellfish (n=112)| 17.2   | 1.9     | 2.6    | 0.9  | 35.0          |

### Table 2

| Characteristic | Urinary Metal Level (µg/L) |
|---------------|----------------------------|
|               | Copper | Mercury | Nickel | Lead | Total Arsenic |
| Male (n=67)   | 21.7   | 1.4     | 2.7    | 1.1  | 42.8*         |
| Female (n=138)| 16.8   | 1.7     | 2.8    | 0.8  | 28.8          |
| <44 years old| 18.6   | 1.8     | 2.6    | 0.9  | 37.9          |
| 45-59 years old| 16.4  | 1.6     | 2.6    | 0.9  | 29.9          |
| >60 years old| 16     | 0.6     | 2.9    | 0.4  | 25.5          |
| Northern sector residence (n=63) | 22.7*  | 2       | 2.8    | 0.8  | 28.6          |
| Another sector residence (n=141)   | 16.5   | 1.4     | 2.7    | 0.9  | 35.9          |
| Lives <1000 m from waste site (n=80)| 18.6 | 1.5     | 2.6    | 0.8  | 34.7          |
| Lives >1000 m from waste site (n=79)| 17.7 | 1.8     | 2.9    | 0.9  | 30.9          |
| Smelts lead fishing weights (n=4)  | 34.9*  | 5.65*   | 5.1    | 4.25 | 69.8          |
| Consumes fish and/or shellfish (n=112)| 17.2 | 1.9     | 2.6    | 0.9  | 35.0          |
Residence in the northern area of Chañaral, which is strongly affected by air masses that bring dust from the mine tailings, is the best proxy for exposure. In fact, subjects living in proximity to the mine tailings had higher urinary copper levels than those not living nearby, suggesting that the main source of exposure in the area could be the mine tailings.

This study used ICP-MS, a poly-elemental technique, to simultaneously measure various chemical elements at a low cost. This method is ideal for monitoring metal exposure in a population.\(^4\) Additionally, this method of screening allows researchers to select complementary methodologies on a case-by-case basis, according to the context of the exposure being evaluated. On this occasion, the study focused on speciation of arsenic in subjects with high total arsenic values, significantly reducing costs.

The use of the 95th percentile as an indicator to monitor a population is strongly recommended by a number of international authors.\(^3,2,31\) This technique allows results to be compared across exposed populations and to measure changes in exposure levels due to environmental interventions. Values reported in this study can be used in the future to assess the impact of subsequent interventions in the area by comparing post-intervention metal levels in a representative sample of the adult population.

The adverse health effects related to chronic exposures to copper, nickel, and arsenic are more varied and multisystemic than the effects evaluated in this population. Preliminary findings showed the prevalence of cough, asthma, chronic obstructive respiratory syndrome and dyspnea to be higher than the national prevalence (18.4%, 27.0%, 46.6% and 37.7% vs 8.1%, 10.1%, 25.7%, 18.6%, respectively). Other findings reported differences in lipid profiles, with higher levels of cholesterol > 200 mg/L, triglycerides > 200 mg/L and high-density lipoprotein cholesterol than the national level (64.4%, 51.5% and 69.5% vs 43.3%, 35.2% and 47.3%, respectively) (data not shown). This suggests that the probability of disease and alterations in organs and systems in the population in Chañaral and others sites affected by mining wastes is high and additional studies of this issue are needed. However, the health risk assessment methodologies employed in the present study provide an opportunity to obtain more and better information from sites affected by mining.

**Conclusion**

The urinary levels of copper, nickel, and arsenic found in residents of the city of Chañaral confirm significant exposure to these metals 31 years after the cessation of the dumping of mine tailings in the area.

Effective interventions to stop emissions from tailings are needed to prevent further exposure to Chañaral’s population. This study provides a reference point to assess the effect of future interventions in the area that effect a change in exposure profile. Questions regarding health effects associated with the exposure identified in the present study, in particular the interaction of these various metals and their health effects, require further in-depth studies.

**Acknowledgments**

Special thanks to Dr. Paulina Pino, Director of the Doctoral Program in Public Health, and Dr. Kyle Steenland, for their cooperation and continued support through the Fogarty Program award (International Training and Research Program in Environmental and Occupational Health) to the University of Chile, School of Public Health.

Thank you to Professor Jorge Quense A, Institute of Geography (Pontificia Universidad Católica de Chile) for his help making maps and to Rosario Toro for reviewing the final version. Special thanks to Professor Germán Corey. His dedicated comments undoubtedly improved the final version.

Finally, we are grateful to the Chañaral community for their participation.

**References**

1. Donoghue AM. Occupational health hazards in mining: an overview. Occup Med [Internet]. 2004 [cited 2016 Apr 5];54(5):283-9. Available from: http://occmed.oxfordjournals.org/content/54/5/283.full.pdf+html
2. Celebi A, Ozdemir S. Mining wastewater management and its effects on groundwater and ecosystems. Water Sci Technol [Internet]. 2014 [cited 2016 Apr 5];70(9):1481-7. Available from: http://wst.iwaponline.com/content/70/9/1481 Subscription required to view.
3. Lopes G, Costa ET, Penido ES, Sparks DL, Guilherme LR. Binding intensity and metal partitioning in soils affected by mining and smelting activities in Minas Gerais, Brazil. Environ Sci Pollut Res [Internet]. 2015 Sep [cited 2016 Apr 5];22(17):13442-52. Available from: http://link.springer.com/article/10.1007%2Fs11356-015-4613-5 Subscription required to view.
4. Schonfeld SJ, Winde F, Albrecht C, Kielkowski D, Liefersink M, Patel M, Sewram V, Stoch I, Whitaker C, Schuz J. Health effects in populations living around the uraniferous gold mine tailings in South Africa: gaps and opportunities for research. Cancer Epidemiol [Internet]. 2014 Oct [cited 2016 Apr 5];38(5):628-32. Available from: http://www.cancerepidemiology.net/article/S1877-782X(14)00106-4/abstract Subscription required to view.
5. Gibb H, O’Leary KG. Mercury exposure and
Research

Urinary Metal Levels in a Chilean Community

health impacts among individuals in the artisanal and small-scale gold mining community: a comprehensive review. Environ Health Perspect [Internet]. 2014 Jul [cited 2016 Apr 5];122(7):667-72. Available from: http://ehp.niehs.nih.gov/wp-content/uploads/122/7/ehp.1307864.pdf

6. Castilla JC, Nealler E. Marine environmental impact due to mining activities of El Salvador copper mine, Chile. Marine Pollut Bull [Internet]. 1978 Feb [cited 2016 Apr 6];9(3):67-70. Available from: https://www.researchgate.net/publication/222857319_Marine_environmental_impact_due_to_mining_activities_of_EL_Salvador_copper_mine_Chile Subscription required to view.

12. Gonzalez C, Parra R, Klenovcanova A, Imris I, Sanchez M. Reduction of Chilean copper slags: a case of waste management project. Scandinavian J Metall [Internet]. 2005 Apr 11 [cited 2016 Apr 5];34(2):143-9. Available from: http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0692.2005.00740.x/abstract Subscription required to view.

13. Narvaez J, Richter P, Toral J. Preliminary physical chemical characterization of river waters and sediments affected by copper mining activity in Central Chile: application of multivariate analysis. J Chil Chem Soc [Internet]. 2007 Sep [cited 2016 Apr 5];52(3):1261-5. Available from: http://www.scielo.cl/scielo.php?pid=S0717-97072007000300016&script=sci_arttext

14. Copaja SV, Diaz G, Toro R, Tessada R, Miranda P, Morales JR. Determination of mining activity of river sediments of three Chilean basins by particle induced x-ray emission (PIXE). J Chil Chem Soc [Internet]. 2012 [cited 2016 Apr 6];57(4):1400-3. Available from: http://www.scielo.cl/scielo.php?pid=S0717-97072012000400014&script=sci_arttext

15. OECD environmental performance reviews: Chile [Internet]. Paris, France: Organization for Economic Cooperation and Development; 2005 [cited 2016 Apr 6];216 p. Available from: http://www.keepeek.com/Digital-Asset-Management/oecd/environment/oecd-environmental-performance-reviews-chile-2005_9789264009684-en#page19

16. Lopez OM, Ahumada GS, Miller AH, Ahumada PS. Chanaral 1833-2000: una historia en el desierto. Copiapo, Chile: University of Atacama; 2000. 243 p. Spanish.

17. Dold B. Element flows associated with marine shore mine tailings deposits. Environ Sci Technol [Internet]. 2006 Feb 1 [cited 2016 Apr 6];40(3):752-8. Available from: http://pubs.acs.org/doi/abs/10.1021/es051475z?mobileUi=0&journalCode=esth Subscription required to view.

18. Castilla JC, Nealler E. Marine environmental impact due to mining activities of El Salvador copper mine, Chile. Marine Pollut Bull [Internet]. 1978 Feb [cited 2016 Apr 6];9(3):67-70. Available from: https://www.researchgate.net/publication/222857319_Marine_environmental_impact_due_to_mining_activities_of_EL_Salvador_copper_mine_Chile Subscription required to view.

19. Castilla JC. Environmental impact in sandy beaches of copper mine tailings at Chanaral, Chile. Marine Pollut Bull [Internet]. 1983 Dec [cited 2016 Apr 6];14(12):459-64. Available from: http://www.sciencedirect.com/science/article/pii/0025326X83900462 Subscription required to view.

20. IARC monographs on the evaluation of carcinogenic risks to humans. Vol. 84. Some drinking-water contaminants and disinfectants, including arsenic [Internet]. Lyon, France: International Agency for Research on Cancer; 2004 [cited 2016 Apr 6]. 526 p. Available from: http://monographs.iarc.fr/ENG/ Monographs/vol84/mono84.pdf

21. Environmental health criteria 200: copper [Internet]. Geneva, Switzerland: World Health Organization; 1998 [cited 2016 Apr 6]. 180 p. Available from: http://www.inchem.org/documents/ehc/ehc/ehc200.htm

22. Environmental health criteria 108: nickel [Internet]. Geneva, Switzerland: World Health Organization; 1991 [cited 2016 Apr 6]. 180 p. Available from: http://www.inchem.org/documents/ehc/ehc/ehc108.htm

23. Toxicological profile for copper [Internet]. Atlanta, Georgia: Agency for Toxic Substances and Disease Registry; 2004 Sep [cited 2012 Oct 7]. 314 p. Available from: http://www.atsdr.cdc.gov/toxprofiles/tp132.pdf

24. Toxicological profile for nickel [Internet]. Atlanta, Georgia: Agency for Toxic Substances and Disease Registry; 2005 Aug [cited 2012 Oct 7]. 397 p. Available from: http://www.atsdr.cdc.gov/toxprofiles/tp15.pdf

25. IARC monographs on the evaluation of carcinogenic risks to humans. Vol. 58. Beryllium, cadmium, mercury, and exposure in the glass manufacturing industry [Internet]. Lyon, France: International Agency for Research on Cancer; 1993 [cited 2016 Apr 6]. 453 p. Available from: http://monographs.iarc.fr/ENG/Monographs/vol58/mono58.pdf

26. Lead and lead compounds: lead and inorganic lead compounds (group 2b) organolead compounds (group 3). In: IARC monographs on the evaluation of carcinogenic risks to humans. Overall evaluations of carcinogenicity: an updating of IARC monographs volumes 1 to 42: Suppl 7 [Internet]. Lyon, France: International Agency for Research on Cancer; 1987 [cited 2016 Apr 6]. p. 230-2. Available from: https://monographs.iarc.fr/ENG/Monographs/Suppl7/Suppl7.pdf

27. Myers GL, Davidson PW. Prenatal methylmercury exposure and children: neurologic, developmental, and behavioral research. Environ Health Perspect [Internet]. 1998 Jun [cited 2016 Apr 6];106(Suppl
28. Steenland K, Boftetta P. Lead and cancer in humans: where are we now? Am J Ind Med. 2000 Sep;38(3):295-9.

29. Censo 2002: síntesis de resultados [Internet]. Santiago, Chile, Empresa Periodística La Nación S.A.; 2003 Mar [cited 2016 Apr 6]. 50 p. Available from: http://www.inc.cl/c2002/sintonisencensal.pdf Spanish

30. Matute I. Diagnósticos regionales con enfoque DSS: serie fichas de datos de comunas seleccionadas. Región Atacama [Internet]. Santiago, Chile: Departamento de Epidemiología Ministerio de Salud, Gobierno de Chile; 2009; cited 2016 Apr 6]. 20 p. Available from: http://info.sereisaludatacama.cl/documents/epidemiologia/Diagnosticos%20de%20salud/ATACAMA.pdf Spanish

31. WHO STEPWise approach to chronic disease risk-factor surveillance [Internet]. Geneva, Switzerland: World Health Organization; [updated 2008 Oct; cited 2012 Oct 7]. 445 p. Available from: http://www1.paho.org/english/ad/dpc/nc/panam-steps-manual.pdf

32. Third national report on human exposure to environmental chemicals [Internet]. Atlanta, Georgia: Centers for Disease Control and Prevention; 2005 Jul [cited 2012 Oct 7]. 475 p. Available from: http://www.cdc.gov/research/centers-and-institutes/center-for-excellence-in-environmental-health-tracking/Third_Report.pdf

33. Wilhelm M, Ewers U, Schule C. Revised and new reference values for some trace elements in blood and urine for human biomonitoring in environmental medicine. Int J Hyg Environ Health [Internet]. 2004 Jan [cited 2016 Apr 6];207(1):69-73. Available from: http://www.sciencedirect.com/science/article/pii/S1438463904702655 Subscription required to view.

34. Goulle JP, Mahieu L, Castermant J, Neveu N, Bonneau I, Laine G, Bouige D, Lacroix C. Metal and metalloid multi-elementary ICP-MS validation in whole blood, plasma, urine and hair. Forensic Sci Int [Internet]. 2005 Oct 4 [cited 2016 Apr 6];153(1):39-44. Available from: http://www.fsiournal.com/article/S0379-0738(05)00208-2/abstract Subscription required to view.

35. Heitland P, Koster HD. Biomonitoring of 37 trace elements in blood samples from inhabitants of northern Germany by ICP-MS. Trace Elem Med Biol [Internet]. 2006 Dec [cited 2016 Apr 6];20(4):253-62. Available from: http://www.sciencedirect.com/science/article/pii/S0946672X06001283 Subscription required to view.

36. Ohashi F, Fukui Y, Takada S, Moriguchi J, Ezaki T, Ikeda M. Reference values for cobalt, copper, manganese, and nickel in urine among women of the general population in Japan. Int Arch Occup Environ Health [Internet]. 2006 Nov [cited 2016 Apr 6];80(2):117-26. Available from: http://link.springer.com/article/10.1007%2F00420-006-0109-4

37. Arsenic and its inorganic compounds: TLV® chemical substances 7th edition documentation [Internet]. Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists; 2001 [cited 2016 Apr 6]. 5 p. Available from: https://www.acgih.org/forms/store/ProductFormPublic/arsenic-and-its-inorganic-compounds-tlv-r-chemical-substances-7th-edition-documentation Subscription required to view.

38. Reglamento de los servicios de agua destinados al consumo humano [Internet]. Santiago, Chile: Ministerio de salud publica; 1969 Dec 19 [cited 2016 Apr 6]. Available from: http://www.leychile.cl/Navesar%3bIDNorma%3d197226 Spanish

39. Araya M, Olivares M, Pizarro F, Gonzalez M, Speisky H, Uauy R. Gastrointestinal symptoms and blood indicators of copper load in apparently healthy adults undergoing controlled copper exposure. Am J Clin Nutr [Internet]. 2003 Mar [cited 2016 Apr 6];77(3):646-50. Available from: http://ajcn.nutrition.org/content/77/3/646.long

40. Araya M, Olivares M, Pizarro F, Llanos A, Figueroa G, Uauy R. Community-based randomized double-blind study of gastrointestinal effects and copper exposure in drinking water. Environ Health Perspect [Internet]. 2004 Jul [cited 2016 Apr 6];112(10):1068-73. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1247379/