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Fundão tailings dam failure in Brazil: Evidence of a population exposed to high levels of Al, As, Hg, and Ni after a human biomonitoring study

Ana Carolina Cavalheiro Paulelli [a], Cibele Aparecida Cesila [a], Paula Pícoli Devóz [a], Silvana Ruella de Oliveira [a], João Paulo Bianchi Ximenez [a], Walter dos Reis Pedreira Filho [b], Fernando Barbosa Jr. [a,*]

[a] Departamento de Análises Clínicas, Toxicológicas e Bromatológicas, Faculdade de Ciências Farmacêuticas de Ribeirão Preto, University of São Paulo, Ribeirão Preto, SP, Brazil

[b] Fundação Jorge Duprat Figueiredo de Segurança e Medicina do Trabalho, Ministério do Trabalho e Previdência Social, São Paulo, SP, Brazil

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ABSTRACT

Background: On November 5th, 2015, the Fundão mine tailings dam in Minas Gerais State, Brazil, failed, releasing more than 50 million m^3 of mud, rich in toxic metals. After that, a massive environmental disaster began with the mud wave flowing more than 600 km, until the mouth of Doce River, in Espírito Santo State, and finally reaching the Atlantic Ocean. A vast area was contaminated, affecting the ecosystem and several communities. Despite the tremendous environmental disaster, little is known concerning the population's exposure to toxic elements yet.

Methods: Thus, a cross-sectional study was for the first time conducted in three communities directly affected by the disaster (Regência, Povoação, and Campo Grande) in Espírito Santo State, to evaluate the levels of 11 chemical elements (Al, As, Cd, Co, Cu, Hg, Mn, Ni, Pb, Se, and Zn) in blood. Sample analysis ($n = 300$) was performed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Results: Our data show high levels of exposure to Al, As, Hg, and Ni. Mean values in blood were 60 μg/L (ranging from 9 to 434 μg/L), 10.9 μg/L (ranging from 5.81 to 269 μg/L), 6.4 μg/L (ranging from 0.05 to 103 μg/L) and 2.7 μg/L (ranging from 0.08 to 21 μg/L) for Al, As, Hg and Ni, respectively. Moreover, after applying a multiple regression model, we found community, drinking water, fish, seafood consumption, and smoking habits associated with metal/metalloid levels in their body. Well and tap water intake were identified as important sources of exposure to aluminum and nickel.

Conclusions: Our findings represent health risks to the groups living in the areas affected by the tailings dam failure, calling for further studies to evaluate the potential health effects of high exposure to metals and remediation actions from public health Brazilian authorities.

1. Introduction

On November 5th, 2015, the Fundão mine tailings dam in Minas Gerais state, Brazil, failed, and released more than 50 million m^3 of mud contaminated with toxic metals/metalloids. A vast environmental disaster occurred with the toxic mud wave reaching the Doce River and then flowing >600 km from the Minas Gerais state, Espírito Santo State to the Atlantic Ocean in only two weeks, affecting the ecosystem and several riverside communities living in the whole affected area.

After the event, numerous studies were carried out to investigate the extension of the environmental contamination to toxic elements (AMBIOS, 2019; Coelho et al., 2020; Girotto et al., 2020; Gomes et al., 2019; Hatje et al., 2017; Segura et al., 2016). High levels of Fe, As, Hg, Mn, and other elements in sediments, soil, and water samples from the Doce River were observed (Hatje et al., 2017). Besides, episodes of heavy rain, rainfall-runoff, erosion, remobilization, transport of toxic particles, seasonal wind and currents have been promoting chronic contamination with continuous detection of high levels of toxic metals in zooplankton, marine foods (crustaceans and fish), and river water (Bianchini, 2016; GIAIA, 2016; Hatje et al., 2017; Marta-Almeida et al., 2016; Rudorff et al., 2018).

Despite the extensive tragedy to the environment with a wide

* Corresponding author.
E-mail address: fbarbosa@fcfrp.usp.br (F. Barbosa Jr.).

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ecosystem contamination by toxic elements, little was evaluated of the possible exposure to toxic elements in populations living in the affected areas. A very preliminary human biomonitoring study was conducted by our group in Barra Longa District, Minas Gerais State, one of the first areas affected by mud waves, with 11 volunteers. High levels of exposure to Al, As, Cd, Cu, Pb, Mn and Ni (Vormittag et al., 2021) were detected, providing the earliest evidence that populations living in the areas affected by the toxic mud could be at high risk of exposure to toxic elements.

Thus, in the present study, an extended human biomonitoring study has been conducted with 313 volunteers living in the communities of Regência, Povoação, and Campo Grande at the Espírito do Santo state, more than 600 km from the mine tailings dam. The levels of eleven elements (Al, As, Cd, Co, Cu, Hg, Mn, Ni, Pb, Se, and Zn) in whole blood were evaluated in the study groups, as well the factors associated with the exposure. To the best of our knowledge, this study is the first extensive human biomonitoring with populations affected by the Fundão dam failure in Brazil.

2. Material and methods

2.1. Study area and population

A cross-sectional study was conducted with a population of 313 volunteers (Age ranged from 8 to 78 years) living in the area affected by the Fundão dam failure in the Doce River (Espírito Santo, Brazil). The study area compose three communities (Regência, Povoação, and Campo Grande) located more than 600 km from the dam failure: Regência (19°38′47.5″S 39°49′54.6″W), Povoação (19°34′58.0″S 39°47′20.9″W) (Linhares, Espírito Santo) and Campo Grande de Barra Nova (19°00′24.1″S 39°44′13.3″W) (São Mateus, Espírito Santo) (Fig. 1). The eligibility criteria were to reside in one of the three regions in the study, before, during, and after the event. Men and women, children, adults and the elderly were included. The project was approved by the Ethics Committee of the School of Pharmaceutical Sciences of Ribeirão Preto (Protocol n. 407).

2.2. Disclosure and questionnaire application

For each community the representative sample population was calculated based on Arya et al. (2012) (Arya et al., 2012), 95% confidence level, 50% prevalence and 7% of admissible error. The total population used in the sample size formula was 4651 individuals, according to the total number of residents in each region (1204 in Regência, 3247 in Povoação and 200 in Campo Grande) (Gonçalves, 2014; IBGE, 2010). Three hundred and thirteen composes the group of study (Regência: 171, Povoação: 68 and Campo Grande: 74).

Participation in the project was promoted in several ways including broadcasting it from automobile-based speaker systems, using community-based presentations and leveraging local social media. Due to the lack of health evaluation after the rupture of the Fundão dam, the adherence of the volunteers to participate in the study was huge.

Community meetings were made prior to collection, explaining the procedures and benefits of participating in the study. After agreeing to

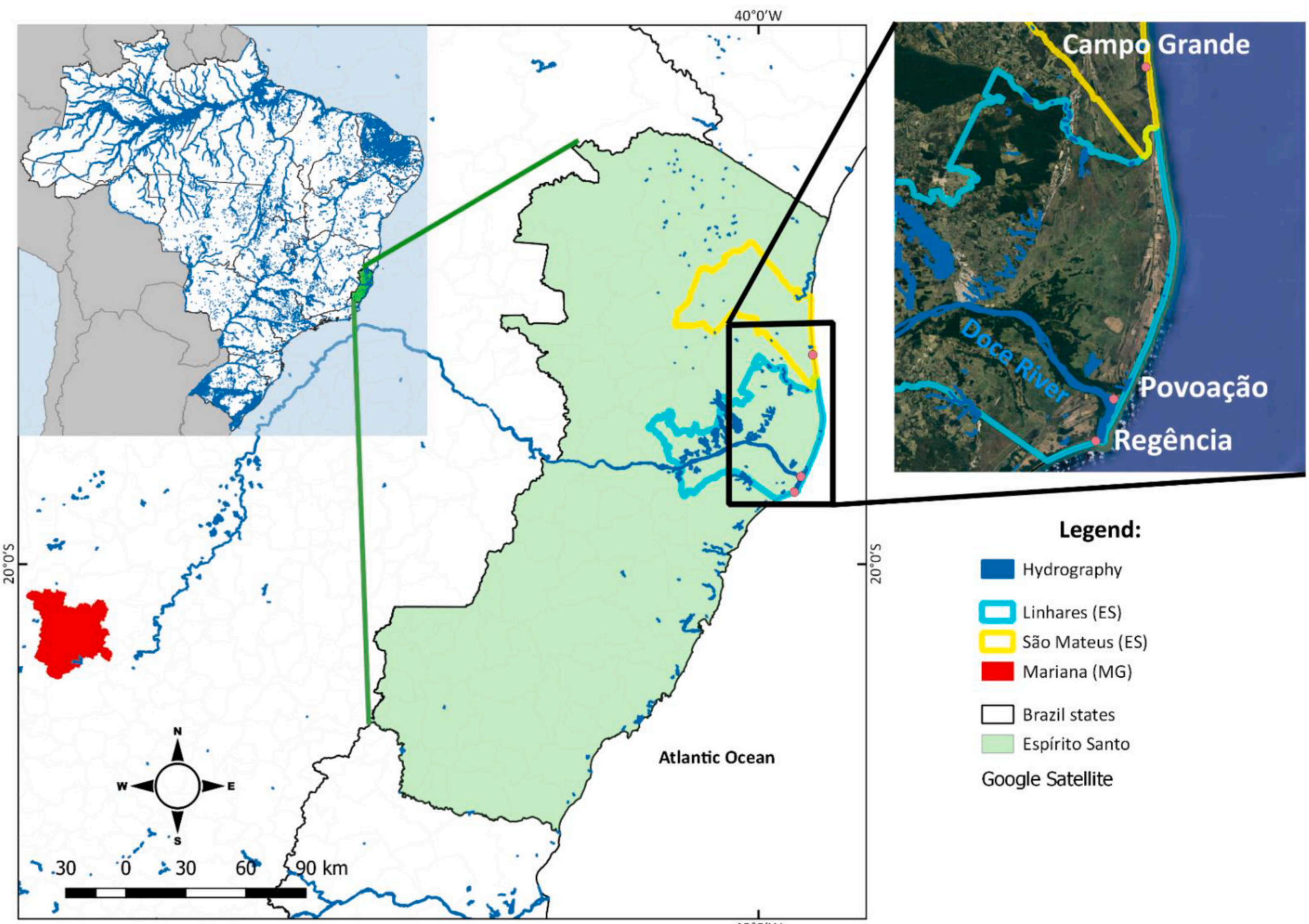

Fig. 1. Study area in Espírito Santo State, Brazil: Communities of Regência, Povoação and Campo Grande. The area represented in red color (Mariana district) is the region of the dam failure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

participate in the study and signing the written informed consent, the volunteer was invited to respond an interviewer-administrated questionnaire, which included sociodemographic and lifestyle topics, such as age, sex, ethnicity, body mass index, house annual income, educational level (Less Elementary, Elementary, Middle, High, College or Above), time living in the region, previous occupation work, dental amalgam fillings, and dietary topics (food frequency questionnaire) including the quantity, type of water consumed, frequency consumption of milk and dairy products, fruits, vegetables, fish, seafood, cereals, nuts, carbohydrates, meat, rice, teas, supplements/vitamins.

Participants were also asked whether they have had any health issues since the disaster. Among the spontaneously reported health conditions, one finds: mental disorders (60%), malaise (40%), skin lesions (38%), gastrointestinal disorders (30%), bone diseases (25%), as the most prevalent.

2.3. Sample collection

After answering the questionnaire, residents were asked if they were willing to provide blood samples. Of the 313 recruited volunteers who signed the consent form and answered the questionnaire, three hundred agreed to provide blood samples. Thus, whole blood samples (5 mL) were collected from 157 women and 143 men (n = 300) in "trace metals free" evacuated tubes (BD Vacutainer®) containing EDTA as anticoagulant. Samples were immediately stored in a freezer at −20 °C and then transported in a cool box to the laboratory and kept at this temperature until the analysis.

2.4. Chemical analysis

Samples were analyzed according to the method proposed by Batista et al. (2009). Briefly, blood was dilute 1:50 (0.05 mL of blood + 9.5 mL of 0.5% v/v HNO_3 and 0.01% v/v Triton X-100) prior to analysis. The following elements were measured: Aluminum (Al), arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se) and zinc (Zn).

Analyses were performed by using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) equipped with Quadrupole Ion Deflector (NexION® 2000, PerkinElmer, Shelton, CT, USA).

In order to verify the accuracy of our data, reference blood samples obtained from the Institut National de Sante' Publique (INSP) du Quebec in Quebec, Canada as part of the external quality assessment schemes (EQAS) were also analyzed. Found values were always in good agreement with target values (*t*-test, 95%).

The method detection limits (MDLs) were Al: 0.05 μg/L; As: 0.02 μg/L; Cd: 0.003 μg/L; Co: 0.01 μg/L; Cu: 0.09 μg/L; Hg: 0.01 μg/L; Mn: 0.05 μg/L; Ni: 0.02 μg/L; Pb: 0.02 μg/L; Se: 0.5 μg/L and Zn: 0.5 μg/L. The MDLs were obtained as 3 times the Standard Deviation of 20 consecutive measurements of the diluted (1:50 v/v) base blood sample.

2.5. Statistical analysis

Simple and multiple linear regression was used to test associations between the concentration of metals/metalloids in Blood: Al, As, Cd, Co, Cu, Hg, Mn, Ni, Pb, Se, and Zn and potential covariates. As covariates, the consumption of fish, seafood, water (mineral, tap, and well), tea, and alcohol, as well as current smoking status and dental amalgam, were analyzed as categorical variables.

First, descriptive statistics were run, aiming to describe the general characteristics of the participants. One-way ANOVA followed by Tukey posthoc analyses was applied when comparing mean levels of metals in blood between the communities. The potential relationship between the metals/metalloids in the blood of the population were estimated by Spearman correlations.

The log concentration of metals/metalloids were compared among the categorical and continuous covariates by simple linear regression. Covariates that met the significance criteria of $P < 0.20$ were included in the multiple regression model to determine potential confounding. Finally, multiple regression modeling was used to assess the effect of significant covariates on the log concentration of metals/metalloids and to identify the sources of exposure. The statistical analyses were performed with RStudio (version 1.1.456), and all tests considered $P < 0.05$ as statistically significant.

3. Results and discussion

3.1. Characteristics of the study population

Table 1 presents the socio-demographic characteristics of the study population. Most volunteers considered their race as pardo (68.69%), 7.03% had less than elementary schooling, 23.64% elementary, 24.28% middle, 30.9 high, and 7.03% college or above. The population of the

Table 1
Socio-demographic characteristics of the population assessed in this study (continuous variables).

Characteristic	Overall (n = 313)	Campo Grande (n = 74)	Povoação (n = 68)	Regência (n = 171)
Female (%)	165 (52.72)	39 (52.72)	49 (72.06)	77 (45.03)
Age (years), median (range)	41 (8–78)	39 (10–77)	41.5 (10–78)	41 (8–77)
BMI (kg/m^2), median (range)	25.72 (14.38 - 45.24)	25.51 (15.43–45.24)	26.22 (14.38–41.75)	25.74 (15.23–42.72)
Race (%)				
White	33 (10.54)	5 (6.76)	6 (8.82)	22 (12.87)
Pardo	215 (68.69)	58 (78.38)	55 (80.88)	102 (59.65)
Black	40 (12.78)	5 (6.76)	4 (5.88)	31 (18.13)
Caboclo	17 (5.43)	3 (4.05)	–	14 (8.19)
Education (%)				
Less Elementary	22 (7.03)	4 (5.41)	15 (22.06)	3 (1.75)
Elementary	74 (23.64)	25 (33.78)	17 (25.0)	32 (18.71)
Middle	76 (24.28)	20 (27.03)	17 (25.0)	39 (22.81)
High	97 (30.99)	22 (29.73)	12 (17.65)	63 (36.84)
College or Above	22 (7.03)	1 (1.35)	2 (2.94)	19 (11.11)
Food/Water consumption (%)				
Mineral Water	193 (61.66)	19 (25.68)	23 (33.82)	151 (88.30)
Tap water	96 (30.67)	10 (13.51)	51 (75.00)	35 (20.47)
Well water	74 (23.64)	56 (75.68)	7 (10.29)	11 (6.43)
Tea	44 (14.06)	7 (9.46)	7 (10.29)	30 (17.54)
Fish	82 (26.20)	39 (52.7)	17 (25.0)	26 (15.20)
Seafood	88 (28.12)	45 (60.81)	17 (25.0)	26 (15.20)
Fishing (%)	123 (39.30)	52 (70.27)	13 (19.12)	58 (33.92)
Water activity (%)	160 (51.12)	55 (74.32)	14 (20.59)	91 (53.22)
Alcohol (%)	27 (8.63)	3 (4.05)	1 (1.47)	23 (13.45)
Smoking (%)	38 (12.14)	8 (10.81)	7 (10.29)	23 (13.45)
Amalgam (%)	102 (32.59)	19 (25.68)	20 (29.41)	63 (36.84)

Regência community had the highest level of education with 36.8% with concluded high school and 11.1% with complete college or above. In Campo Grande, 52.7% of the volunteers were women, whereas, in Povoação and Regência, women were 72.06% and 45.03%, respectively. The large majority were born in the region. Body mass index (BMI) ranged between 14.38 and 45.24 kg/m^2. The categorized as underweight and obese represented 31.8% and 20.7%, respectively. Taken from the whole population in the study, few people reported alcohol consumption (8.63%) or cigarette smoking (12.14%), and 32.59% reported the presence of dental amalgams.

3.2. Levels of metals and metalloids in blood

Table 2 shows mean, minimum and maximum values for all metals and metalloids in the study in blood samples from the volunteers of Regência, Povoação, and Campo Grande. Highly significant differences in As, Co, Hg, Mn, Ni, Pb, Se, and Zn levels were observed between the three communities (ANOVA; $p < 0.0001$).

Statistically significant differences in the mean blood levels of some elements were found according to gender, age, education, and smoking habits. For example, Mn levels were statistically higher in women, whereas Pb and Zn levels were higher in men (data not shown). Higher Mn levels in females were previously reported in other studies (Freire et al., 2015; Lee and Kim, 2012; Nunes et al., 2010). Lee and Kim (2014) correlated the absorption mechanism between iron and manganese with increased levels of Mn in women's blood compared with men. Two main reasons were reported, one is the reduction in ferritin in women of childbearing age compared to higher ferritin levels in menopausal women; another is the upregulation of iron absorption in late gestation, which increases the levels of Mn (Lee and Kim, 2012, 2014; Margrete Meltzer et al., 2010; Takser et al., 2004). Moreover, the higher the age, the higher was Cd, Al, Pb levels. Lower education and smoking habits were associated with higher levels of Pb and Cd. Cd levels among smokers were almost three times higher than levels observed in non-smokers. On the other hand, Cd and Pb levels were 20% and 50% lower in volunteers with superior education compared to less elementary and elementary groups, respectively. Pb, As, and Al levels were higher, whereas Zn levels were lower in the lesser household income groups.

For Cd, Co, Cu, Pb, Mn, and Se the mean values were in good

Table 2
Levels of metals and metalloids (μg/L) in blood of the study population (n = 300).

Metals/Metalloids	Overall	Campo Grande	Povoação	Regência	Reference ranges[Ω]
Mean (min-max) μg/L					
Al	60 (9–434)	65 (27.13–293)	54 (8.9–268)	61 (11.7–434)	–
P10	29.2	33.7	20.2	31.1	
Median	59.9	61.4	52.2	61.1	
P95	153	128	169	140	
As[$]	10.93 (5.81–268)	9.83 (6.19–38.7)	8.48 (5.81–12.7)	12.6 (6.4–268)	0.1–12.5[1,2,7]
P10	7.3	7.2	6.8	7.9	
Median	10.7	8.9	8.5	12.3	
P95	17.0	16.1	11.4	19.2	
Cd	0.13 (0.01–1.4)	0.14 (0.06–0.83)	0.15 (0.04–0.89)	0.13 (0.01–1.4)	0.06–1.7[1,2,3,4,5,7]
P10	0.06	0.08	0.06	0.05	
Median	0.13	0.13	0.15	0.12	
P95	0.41	0.24	0.36	0.45	
Co[#,$]	0.39 (0.05–3.7)	0.4 (0.29–1.1)	0.34 (0.16–1.3)	0.41 (0.05–3.7)	0.0005–2.090[6]
P10	0.20	0.32	0.19	0.16	
Median	0.37	0.39	0.36	0.35	
P95	1.68	0.54	0.54	2.2	
Cu	856 (439–1780)	891 (633–1426)	864 (439–1569)	836 (534–1780)	495–1989[1,6,7]
P10	677	725	675	665	
Median	835	890	828	808	
P95	1262	1132	1270	1269	
Hg[*,#]	6.4 (0.05–103)	15 (1.6–71)	4.7 (0.23–29.4)	4.9 (0.05–103)	0.10–12.40[3,7]
P10	1.4	4.6	1.4	1.2	
Median	6.7	16.9	5.4	5.8	
P95	40.9	58.7	25.3	26.1	
Mn*	10.4 (5.2–46.6)	11.8 (7.4–22.2)	9.8 (5.2–21.5)	10 (5.2–46.6)	6.9–18.4[1,4]
P10	6.7	8.9	6.6	6.5	
Median	10.5	11.8	10.4	9.6	
P95	18.2	17.5	14.9	19.3	
Ni[*,#]	2.7 (0.08–21)	3.6 (1.3–14.8)	2.4 (0.6–21)	2.5 (0.08–12.5)	<0.12–3.9[1]
P10	1.3	2.0	1.3	0.98	
Median	2.8	3.3	2.4	2.8	
P95	7.4	11.6	5.1	2.2	
Pb[*,#]	21.9 (3.4–129)	28.5 (6.6–118)	20.9 (7.9–111)	19.9 (3.4–129)	1.3–163[1,2,3,5,7]
P10	10.3	11.8	11.2	10.0	
Median	21.4	28.6	20.9	17.9	
P95	68.7	81.4	38.7	58.6	
Se[*,#]	108 (67–185)	120 (77–185)	102 (69–173)	104 (67–162)	68–245[1,7]
P10	83.5	99	79.6	82.8	
Median	107	121	98.8	104	
P95	153	155	139	142	
Zn[#,$]	4578 (1513–8659)	4025 (1577–5250)	4090 (1513–5828)	4917 (2741–8659)	3518–122,94[6]
P10	3588	3229	3411	3674	
Median	4613	4395	4275	4782	
P95	7312	5066	5031	7613	

Significant interactions (mean values) were detected by one-way ANOVA followed by Tukey posthoc analyses and were designated by * when a significant difference between Campo Grande and Povoação was detected, by # when a significant difference between Campo Grande and Regência was detected, or by $ when a significant difference between Povoação and Regência was detected. [Ω]Reference ranges in the Brazilian population: [1](Nunes et al., 2010), [2](Takeda et al., 2017), [3](Kuno et al., 2013), [4](Freire et al., 2015), [5](Kira et al., 2016), [6](Rodrigues et al., 2009)[7](Almeida Lopes et al., 2019). P10 and P95 represent 10th and 95th percentiles, respectively.

agreement with baseline values established for other Brazilians living in different geographic regions.(Castilhos et al., 2015; Freire et al., 2015; Kira et al., 2016; Kuno et al., 2013; Nunes et al., 2010; Rodrigues et al., 2009; Takeda et al., 2017). However, moderate to high levels of exposure were found for other elements in the study. Al levels ranged from 9 to 434 μg/L (mean of 60.4 μg/L). These values are higher than the reference values established in other countries (ATSDR, 2008; JECFA, 2007; Karwowski et al., 2018). According to the ATSDR (ATSDR, 2008), serum levels in healthy individuals range from 1 to 3 μg/L. Studies evaluating the levels of aluminum in blood for healthy and non-environmentally exposed populations in Brazil are very scarce. On the other hand, the Al reference range fifth–95th percentile in a healthy French population was found as 1.28–6.35 μg/L (Goullé et al., 2005). Moreover, the median Al level in an adult healthy Swedish population was 14.6 μg/L (Schultze et al., 2014). These reference values are much lower than the levels found in the present study.

As levels in the study group ranged from 5.81 to 268 μg/L. Found values were much higher than those previously established as baseline levels for other Brazilians living in different geographic regions of the country (Almeida Lopes et al., 2019; Nunes et al., 2010; Takeda et al., 2017). Moreover, all volunteers in three communities had As levels higher than the upper limit reference for As (6.1 μg/L) in non-environmentally exposed Brazilian populations (Nunes et al., 2010; Takeda et al., 2017), Spanish (Bocca et al., 2019), and French (Goullé et al., 2005). Arsenic is a toxic element found in the environment in different chemical forms (inorganic and organic species). Inorganic forms are much more toxic than arsenorganicals. The inorganic species, mainly present in water samples due to their solubility, is the most toxic and has the highest absorption rate (at least 95%). The organic species (including arsenobetaine and arsenocholine), insoluble in water and present mainly in seafood, are less toxic with an absorption rate of 75–85% (ATSDR, 2007).

Mean Hg levels were 6.4 μg/L for the whole study group. From Campo Grande, 59% of volunteers had Hg levels higher than 12.4 μg/L, which is the upper reference level for Hg in other Brazilian populations (Almeida Lopes et al., 2019; Kuno et al., 2013; Takeda et al., 2017) and is probably associated with higher fish and seafood consumption (details below). Moreover, blood levels exceeding 65.0 μg/L were observed in some volunteers from Campo Grande and Regência. Due to its persistence and anthropogenic activities (such as informal gold mining, *garimpo* and industrial processes), large amounts of Hg are found in the environment. Hence human exposure to Hg and its health effects have been constant and extensively studied for more than 20 years (Batista et al., 1996; Harada, 1995; Malm, 1998). Mercury's main target organ is the brain. Its neurotoxicity is well known, and the first cases occurred after contaminated seafood intake in Minamata city, Japan (Harada, 1995; Khoury et al., 2015).

Mean Ni and Zn levels are within the range observed in other Brazilian populations (Nunes et al., 2010). Volunteers from Regência had the higher Zn mean levels (4917 μg/L) compared with Campo Grande (4025 μg/L) and Povoação (4090 μg/L). However, 54.6%, 57.4%, and 24% of the volunteers from Campo Grande, Povoação, and Regência had Zn levels <3500 μg/L (the lower reference level found in other Brazilian groups). On the other hand, 35.2%, 11.4% and 23.9% of volunteers from Campo Grande, Povoação and Regência, respectively, presented Ni levels higher than 3.9 μg/L, the upper limit reference found in other Brazilian groups (Nunes et al., 2010).

In a pilot study, our group evaluated the levels of toxic metals in a small group of 11 subjects (children and adults) living very close to the dam failure area in the Minas Gerais State (Vormittag et al., 2021). This preliminary study observed high levels of exposure to aluminum, arsenic, cadmium, copper, lead, manganese, nickel, and zinc deficiency in the population's body. Conversely, the present study has also observed higher levels of exposure to aluminum, arsenic, and nickel. Interestingly, the current study population lives more than 600 Km far from the previous study group, but a comparable pattern of exposure in both groups was found. In contrast, mean Zn levels in the present study were higher than those previously observed by Vormittag et al. (2021) (Vormittag et al., 2021) but still much lower than the reference levels identified in other Brazilian groups (Almeida Lopes et al., 2019; Rodrigues et al., 2009). Zinc deficiency in some volunteers is probably a consequence of changes in the diet components in which the population was submitted after the disaster, with a reduction of meat and fish consumption or other important zinc sources (Bianchini, 2016).

We consider it too premature to associate the high exposure to toxic metals with any health consequences yet. However, to list potential health problems associated with the disaster, we asked the participants to describe if they were experiencing any health disorders after the disaster. Among the spontaneously reported health situations, one finds Mental disorders (60%), Malaise (40%), skin lesions (38%), gastrointestinal disorders (30%), Bone pain (25%) as the most prevalent. Since exposure to moderate to high levels of As and Ni are usually associated with skin lesions (Larese et al., 2007; Quansah et al., 2015; Tseng, 1977; Tseng et al., 1968), it is reasonable to believe that reported skin problems by more than 1/3 of the population could be in part associated with the high levels of As and Ni exposure observed in the present study. However, further studies are necessary to confirm this hypothesis.

3.3. Correlations between metal/metalloids in blood samples

Fig. 2 shows the Spearman correlations obtained for all elements in the study. Several positive and moderate correlations were observed with special highlights to Hg and Se levels (0.484, $p < 0.01$), Hg and Pb (0.417, $p < 0.01$), As and Zn (0.406, $p < 0.01$) and Ni and Mn (0.441, $p < 0.01$). The correlations between some elements are preliminary evidence of similar sources of exposure.

3.4. Preliminary identification of the sources of exposure

In Regência and Povoação, 88.3% and 75.7% of the volunteers reported drinking predominantly mineral water, respectively, while in Campo Grande, 75.7% reported drinking tap and/or well water and occasionally mineral water. Most residents of Campo Grande (81%) reported performing water activities, including fishing, swimming and/or surfing. In Regência and Povoação, people generally used to swim and/or surf. Fish (52.7%) and seafood (60.81%) consumption were higher in Campo Grande than Povoação (25.0%), and Regência (15.2%) and 14% of volunteers from the three groups used to drink tea prepared with tap or well water.

Blood mercury, Se, Pb, and Zn levels were significantly higher ($p < 0.05$) in volunteers eating seafood > 2x/week. Higher levels of As, Hg, and Se in the blood are commonly observed in people eating seafood and fish more often (Almerud et al., 2021; Carneiro et al., 2014; Cunha et al., 2018; Dórea, 2009; Dórea and Barbosa, 2007; Grotto et al., 2011; Snoj Tratnik et al., 2019). In seafood, arsenic is present mainly in less toxic forms (arsenobetaine, arsenocholine, arsenolipids, etc.) (Batista et al., 2012; Navas-Acien et al., 2011), unlike mercury predominates in fish and seafood in a very toxic form (methylmercury) (Batista et al., 2011; Dórea, 2009; Dórea and Barbosa, 2007; Grotto et al., 2011).

Table 3 shows the multivariate regression coefficients (Beta coefficient, 95% confident interval) of several potential sources of exposure and metal/metalloid levels in blood separated by the study's three groups (communities). Moderate correlations between Al ($\beta = 0.32$, $p = 0.03$) and Ni ($\beta = 0.23$, $p = 0.03$) and to drink of tap and well water was observed in Campo Grande and Povoação communities, respectively. Hg levels were associated with seafood consumption ($\beta = 0.28$, $p = 0.01$) in the Campo Grande group. As and Se levels are also associated with seafood consumption in Povoação and Regência groups. Despite this association, even for those volunteers who reported not to eat seafood or fish at all, the mean levels of As in blood were still high (compared to established background levels), 10.9 μg/L (ranging from 5.8 to 268). Moreover, no statistical differences in As levels were found between the

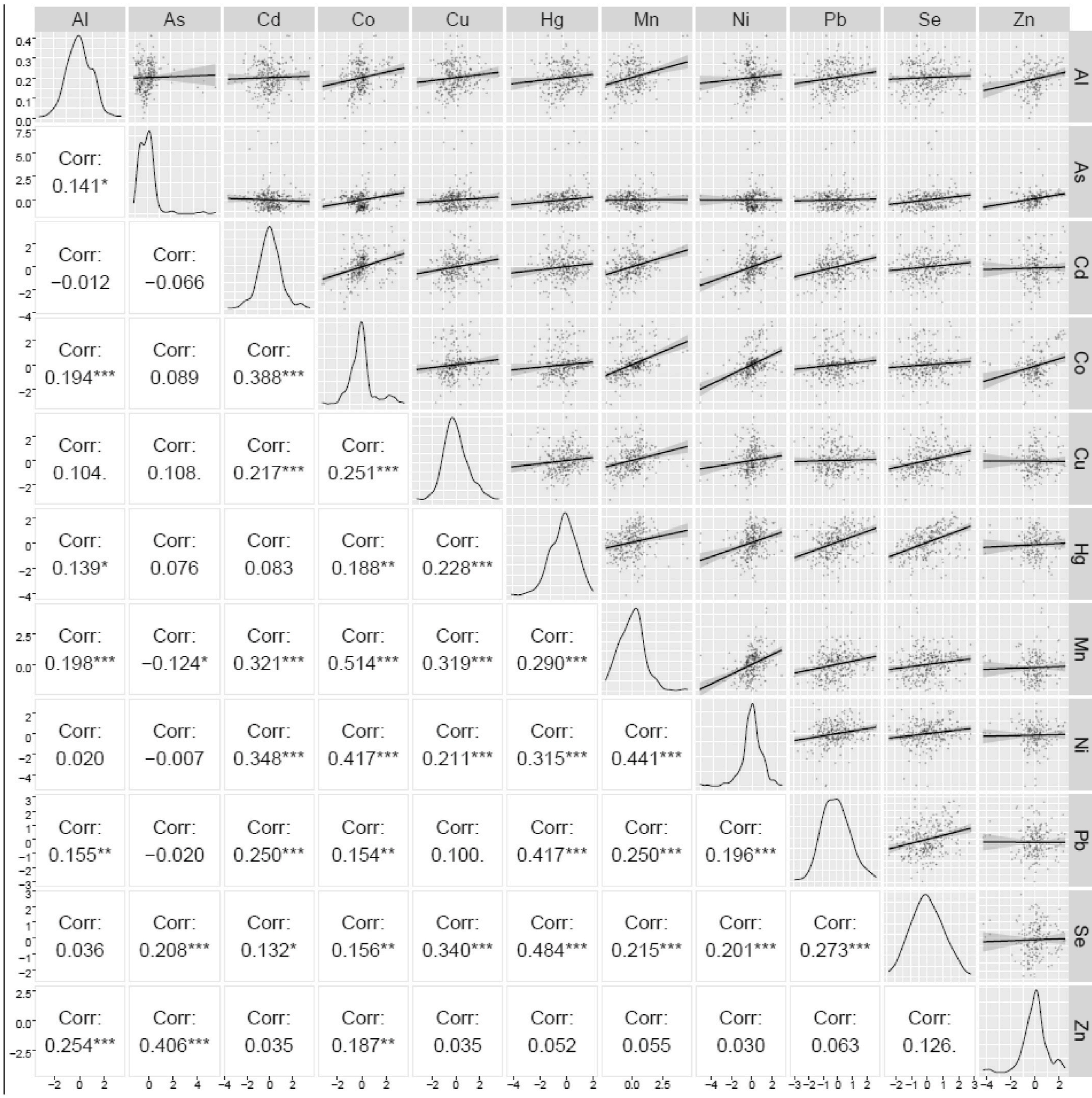

Fig. 2. Evaluation of correlation between the elements in whole blood. Spearman's rank correlation coefficients (R).

seafood/fish eaters group and no eaters ($p > 0.05$). Contrary, the group who reported not to eat fish and seafood had much lower levels of Pb and Se in blood compared to those reporting the consumption once a week or more ($p < 0.05$). This finding demonstrates that seafood and fish are also important sources of lead and selenium to this population, whereas other relevant sources of exposure to arsenic are present. A simple comparison between the volunteers divided by the type of water they reported to drink shows that those who reported drinking from well and/or tap water had higher levels ($p < 0.05$) of arsenic, nickel, manganese, and zinc in blood than who reported drinking only mineral water. Thus, well and/or tap water are sources of arsenic and other elements to this population. Moreover, higher levels of As in water samples were also found in other geographic areas affected by the toxic mud (Bianchini, 2016; Carvalho et al., 2017; dos Reis et al., 2019; Gomes et al., 2019; Hatje et al., 2017; Quadra et al., 2019; Silva et al., 2018).

After the Fundão tailings dam failure, many families drilled artesian wells due to insecurity in consuming water from the supply service. Furthermore, in Campo Grande, there was no water supply service, and the predominance was to drink well water. Water infiltrates the soil and can transport metals, a process known as leaching (Twarakavi and Kaluarachchi, 2005; Wirmvem et al., 2017). The increase in the leaching of metals to the water table is associated with the season, rainfall, precipitation, and temperature (Alves et al., 2019; Twarakavi and Kaluarachchi, 2005; Wirmvem et al., 2017). Moreover, other factors can also contribute to the elevation of metals in the waters, including storms, sea currents, rains, wind-induced resuspension, and the oxidizing condition of rivers. These factors can result in mobilization of the chemical elements (As, Fe, Cr, Cu, Hg, Pb, and Zn), which were already present

Table 3
Multivariate linear regression model for the log-transformed elements in whole blood and explanatory variables (potential sources of exposure) separate by region of sampling.

Metal/ metalloid	Covariates	β-coefficients	P-value	Adj. R-squared
Campo Grande				
Al	tap water	0.32	0.03	0.31
Zn	tap water	−0.63	0.00	0.36
Hg	Seafood	0.28	0.01	0.42
Povoação				
As	Seafood	0.35	0.00	0.43
Ni	Seafood	0.29	0.03	0.27
	well water	0.23	0.05	
Se	seafood	0.32	0.03	0.06
Regência				
Se	fish consumption	0.17	0.04	0.18
	well water	−0.22	0.01	

before the rupture from the Fundão dam to the hydrological system, contaminating water bodies (Hatje et al., 2017; Marta-Almeida et al., 2016; Pimentel et al., 2003; Santolin et al., 2015).

Since the water used to drink by the population seems to be an important source of exposure to toxic elements, further studies with a metal/metalloid profile in distinct water samples collected in the study region are mandatory.

3.5. *Study's strengths and weaknesses*

This study provides the levels of eleven toxic and essential elements, measured in the whole blood of 300 volunteers affected by the Fundão dam failure in Brazil. Moreover, our data indicate that many groups, even living far from the origin of the disaster, could be at serious risk of exposure to toxic metals/metalloids. We also acknowledge limitations in this study. For example, the number of volunteers can be considered relatively small. Moreover, inclusion of a control group living in the same geographic area, with the same lifestyle and diet habits, but not affected by toxic mud, would provide better baseline/reference levels of elements in the blood.

4. Conclusion

To the best of our knowledge, this study is the first to evaluate the levels of toxic and essential elements in a large population living in an area affected by the Fundão tailings dam failure in Minas Gerais, Brazil. Although the studied regions are almost 600 km distant from the Fundão dam, the communities were considerably affected by the passage of iron ore tailings through the Doce River and the Atlantic Ocean, increasing the exposure to toxic metals/metalloids.

Although, is still premature to associate the high levels of exposure to Al, As, Hg, and Ni with some of the self-reported health injuries, our findings represent an elevated risk to the health of communities living in the surrounding areas affected by the Fundão tailings dam failure. Thus, further studies to evaluate the potential toxic effects associated with the exposure and actions by public health Brazilian authorities to reduce the exposure are required.

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Declaration of competing interest

The authors declare that they have no conflict of Interest.

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