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Biomonitoring of 20 trace elements in blood and urine of occupationally exposed workers by sector field inductively coupled plasma mass spectrometry

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ABSTRACT

A sector field inductively coupled plasma mass spectrometry method for the determination of Ag, Al, As, Ba, Be, Cd, Co, Cr, Cs, Cu, Fe, Mn, Ni, Pb, Se, Sr, Tl, U, V and Zn in whole blood and urine was designed. Microwave-assisted digestion with concentrated nitric acid was used for blood samples. Urine samples were analyzed after 1/50 (v/v) dilution with 5% (v/v) nitric acid. For beryllium the necessity of medium resolution mode (R=4000) was shown. Method validation was performed using blood and urine reference materials and by analyzing of spiked samples. For the designed method relative standard deviation (RSD) for the concentration range 0.01–1.0 μg/L was 5–10%. RSD did not exceed 3% when trace elements concentrations were above 1.0 μg/L. Method detection limits (3σ): Ag 0.7 ng/L, Al 16 ng/L, As 3.4 ng/L, Ba 0.02 ng/L, Be 1.5 ng/L, Cd 7.7 ng/L, Co 1.0 ng/L, Cr 2.8 ng/L, Cs 9.8 ng/L, Cu 27 ng/L, Fe 1.1 ng/L, Mn 1.8 ng/L, Ni 17 ng/L, Pb 13 ng/L, Se 0.07 ng/L, Sr 5.7 ng/L, Tl 0.2 ng/L, U 0.1 ng/L, V 0.7 ng/L and Zn 1.2 ng/L.

A developed method was applied for trace element biomonitoring of occupationally exposed workers of a beryllium processing enterprise. For preliminary risk assessment technological surface dust had been analyzed by inductively coupled plasma optical emission spectrometry. Based upon results of 50 blood and 40 urine samples analyses occupational exposure evaluation was performed. Exposure risks were found not to exceed acceptable ranges. Possible health hazards were found for Be and also Al, Cr, Mn. Occupational health and safety recommendations for the biomonitored enterprise medical care unit were issued as a result of the current investigation.

1. Introduction

Nowadays, monitoring of chemical exposure to toxic metals is a problem of top priority [1]. In the Russian Federation most common mean of such monitoring, especially in industry, is chemical monitoring, first of all assessment of hazardous components in the ambient air [2]. However, absorption of most toxicants is highly dependent on the intake pathways, e.g. via inhalation, by oral intake, and through skin [3–6]. Thus, only complex investigations consisting of both chemical and biological monitoring [7–9], are able to supply objective occupational exposure information [3].

Unfortunately, biomonitoring as a system of exposure risk evaluation for toxic metals and other compounds has not yet gained enough attention in the Russian Federation. Nowadays, only the blood lead toxicity threshold is strictly defined for employees occupationally exposed to this metal [10]. However, an analysis of work-related health disorders in the Russian Federation showed that the most frequent cases of metal-induced intoxications are also related to chromium, manganese, nickel, mercury, cadmium and other metals [2,11].

Conventional media for evaluation of essential trace element deficiencies and exposure to toxic metals are blood [9,12–16] and urine [6,12,17–20]. As alternative substrates hair [21–24], saliva [23], nails [25,26] and in rare cases even breast milk [27] are used. However, the informational content of these media still remains questionable [5]. For instance, according to [9] hair is an inappropriate biomarker for the monitoring of copper, manganese, strontium and lead.

An important task to solve when preparing for trace element biomonitoring is choosing a sensitive, selective and accurate quantification technique which also has enough productivity for

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analysis of large numbers of samples [28,29]. At present, atomic absorption spectrometry (AAS) [11,19,22,30], inductively coupled optical emission spectrometry (ICP-OES) [31] and inductively coupled plasma mass spectrometry (ICP-MS) [6,9,12–16,18,21,25] are most commonly employed for biomonitoring purposes.

Multielement biomonitoring studies often show rather dispersed values of reference concentrations of some elements depending on living location, occupation, dietary habits, smoking etc. It should be noted that published data for some trace elements (e.g. beryllium, thallium, cadmium etc) reference values acquired using ICP-MS are often significantly lower than presented in more recent studies based on AAS and ICP-OES [18]. It is related to the proximity of beryllium, thallium and cadmium reference concentrations to AAS and ICP-OES limits of detection. That may cause inaccuracy and significant systematic errors [6,18]. ICP-MS is more sensitive and allows more accurate assessment of lower concentration compared to other techniques. Thus, ICP-MS is gradually replacing other trace element assessment techniques in the field of clinical chemistry [8,32,33].

Double focusing sector field inductively coupled plasma mass spectrometry (SF-ICP-MS) is one of the most selective variants of ICP-MS [8,17,34]. It allows effective correcting for most spectral interferences. That is why SF-ICP-MS was applied for method development and biomonitoring studies in the current investigation.

The aim of this study was to develop a method for blood and urine trace element determination using double focusing sector field inductively coupled plasma mass spectrometry and to perform a biomonitoring of a beryllium processing enterprise for occupational exposure evaluation using this method. Although beryllium is really hazardous for human health [35,36], we did not find any multielement biomonitoring data for beryllium processing plants. Twenty trace elements were determined in 50 blood and 40 urine samples of 50 workers.

2. Materials and methods

2.1. Instrumentation

A sector field inductively coupled plasma mass spectrometer Thermo Scientific™ Element 2 (Thermo Scientific, Germany) was used for trace element determination in blood and urine samples. A Meinhard type glass concentric nebulizer and quartz cyclonic spray chamber were used for sample introduction. Trace element determination in surface contamination was performed using an inductively coupled plasma optical emission spectrometer Optima 2100 DV (PerkinElmer, USA). Ultrapure water preparation was carried out using a Milli-Q® Advantage A10 system (Millipore, France). A microwave system Start D (Milestone, Italy) was employed for blood sample preparation.

2.2. Standards and chemicals

Calibration solutions were prepared daily from multielement certified stock standard solution (10 mg/L, ICP-MS Calibration Standard, High-Purity Standards™, USA) using gradual dilution with 5% (v/v) nitric acid (prepared from 65% HNO_3 Suprapur®, Merck, Germany). For method validation reference materials (RM), Seronorm™ Trace Elements Whole Blood L-1 (REF 210305, LOT 1003193, Sero AS, Norway), Seronorm™ Trace Elements Whole Blood L-3 (REF 210105, LOT 1003191, Sero AS) and Seronorm™ Trace Elements Urine (Ref 201205, Lot 0511545, Sero AS), were analyzed. For within run quality control, Seronorm™ RM were analyzed after each 10 samples. Yttrium (1000 μg/mL Yttrium in 2% (v/v) HNO_3, Inorganic Ventures, USA) was employed as an internal standard. Ultrapure hydrochloric acid (Reaktiv, Russia) was used for technological surfaces contamination sampling. High-purity argon (99.999%, Lentekhgaz, Russia) was used for ICP maintenance.

2.3. Samples

The study was performed as a part of annual medical examination. All examinees were informed of the investigation and volunteered to participate. Biological fluids were taken from 50 adults (26 males and 24 females) working at a beryllium processing enterprise. The age was in the range 24–57 years. All subjects worked at the enterprise under study for at least 5 years.

Great care was taken to avoid contamination during all analytical stages – biological media sampling, transportation, storage, sample preparation and analysis. Blood sampling was performed using vacuum test-tubes (Vacutest®, Vacutest KIMA, Italy) with lithium heparinate (1400–1500 U/tube) as anticoagulant. Blood was taken from an elbow vein in the morning hours after fasting overnight. Urine samples (24 h excretion) were collected by subjects into sterile polyethylene containers after careful instruction by a clinic doctor. Collected biomaterial was frozen at – 20 °C and transported to the laboratory.

In the laboratory, blood and urine samples were thawed at +4 °C and subjected to pretreatment. Blood samples were digested in closed vessels with concentrated nitric acid (0.5 mL of blood was mixed with 2 mL of 65% HNO_3, Suprapure®, Merck, and 6 mL of Milli-Q® water) using a microwave sample preparation system Start D (25 min, 190 °C, 950 W). After the digestion samples were diluted to the final volume of 25 mL with Milli-Q® water. Urine samples were analyzed after 1/50 (v/v) dilution with 5% (v/v) solution of nitric acid (Suprapure®, Merck).

Sampling of technological surfaces contamination was performed by wiping them with cotton tampons moistened with 2% (v/v) hydrochloric acid. Total surface of 30 dm^2 was used for surface dust sampling. On each investigated surface 3 separate sites of 10 dm^2 were chosen for sampling and each site was wiped in two mutually perpendicular directions. After that all three tampons were combined into a single sample, packed into polyethylene film and transported to the laboratory. Samples consisting of combined tampons were put into quartz crucibles, treated with 20 mL of nitric acid (5:1) and left for 24 h. Acquired extracts were diluted with deionized water to the final volume of 50 mL and subjected to ICP-OES analysis. Optical emission was measured at the following wavelengths: Al 396.153 nm, Be 234.861 nm, Cr 267.716 nm, Mn 257.610 nm, Fe 238.204 nm, Ni 231.604 nm, Cu 327.393 nm, Zn 206.200 nm, V 292.464 nm, Cd 228.802 nm and Pb 220.353 nm.

Blank solutions and RM were prepared using the same techniques, chemicals and materials as for real blood, urine and surface dust samples.

2.4. Study limitations

Current study has several limitations. The group under study ($n=50$) was relatively small as only most heavily exposed employees had participated. A control group was to be formed from unexposed employees of the same enterprise (e.g. working in the administration department). However, a number of unexposed workers turned out to be too small for statistical comparison. Therefore, obtained results for occupationally exposed workers were compared mainly to the previously published data on trace element reference concentrations for unexposed population. First of all, recent results of ICP-MS studies were taken into account. And finally, only exposure period, smoking and alcohol consumption, but not dietary habits, were considered when choosing the examinees.

3. Results and discussion

3.1. SF-ICP-MS method optimization

Nowadays, SF-MS-ICP is often referred as one of the most profound methods of trace element determination due to its high selectivity, extremely low detection limits and possibility to perform multielement assessments in a single run [8,28,29,32,33]. Nevertheless, complicated sample matrices of blood and urine pose serious problems for the determination of many trace elements, first of all, due to spectral interferences, e.g. ^{111}Cd – ^{75}As^{36}Ar^{+}, ^{95}Mo^{16}O^{+}; ^{59}Co – ^{43}Ca^{16}O^{+}, ^{23}Na^{36}Ar^{+}, ^{19}F^{40}Ar^{+}; ^{55}Mn – ^{110}Cd^{2+}, ^{39}K^{16}O^{+}, ^{15}N^{40}Ar^{+}, ^{19}F^{36}Ar^{+}; ^{77}Se^{+} – ^{61}Ni^{16}O^{+}, ^{37}Cl^{40}Ar^{+}, ^{59}Co^{18}O^{+}, ^{40}Ar^{36}Ar^{1}H^{+}. After an assumption of possible spectral interferences the following working isotopes and resolution modes were chosen:

- low resolution (R=300) – ^{208}Pb and ^{238}U,
- medium resolution (R=4000) – ^{27}Al, ^{137}Ba, ^{9}Be, ^{111}Cd, ^{59}Co, ^{52}Cr, ^{133}Cs, ^{63}Cu, ^{55}Mn, ^{60}Ni, ^{205}Tl, ^{51}V and ^{66}Zn,
- high resolution (R=10000) – ^{109}Ag, ^{75}As and ^{77}Se.

According to the previously published data [34,37] and manufacturer's guidelines [38], low resolution mode was recommended for the determination of beryllium in biological fluids. However, our experimental data showed considerable spectral interference when beryllium concentrations were below 0.1 μg/L (Fig. 1). Observed interference may be attributed to ^{27}Al^{3+} and ^{18}O^{2+}. Element ionization energies are E_1=1313.9 kJ/mol, E_2=3388.3 kJ/mol for oxygen; E_1=577.5 kJ/mol, E_2=1816.7 kJ/mol, E_3=2744.8 kJ/mol for aluminum; E_1=1520.6 kJ/mol, E_2=2665.8 kJ/mol for argon while isotope abundances of ^{18}O and ^{27}Al are 0.205% and 100% respectively. Consequently, Al^{3+} must be the most important source of the interference. Precise masses for ^{9}Be, ^{18}O and ^{27}Al are 9.0122, 17.9992 and 26.9815 respectively, i.e. precise measured mass to charge ratios for ^{9}Be^{+}, ^{18}O^{2+} and ^{27}Al^{3+} are 9.0122, 8.9996 and 8.9938. A resolving power of at least 715 is required to separate the ^{9}Be peak with equal interference signals of ^{18}O^{2+} and ^{27}Al^{3+}. Indeed, no spectral interferences were observed for beryllium (Fig. 2) when higher resolution was used, ensuring result accuracy. Accounting for spectral interferences also provided much more stable blank values, i.e. in this case middle resolution mode provided nearly the same beryllium limit of detection compared to low resolution. Thus, it may be stated that medium resolution should be used for beryllium assessment in blood and urine due to the spectral interferences, observed at lower resolution.

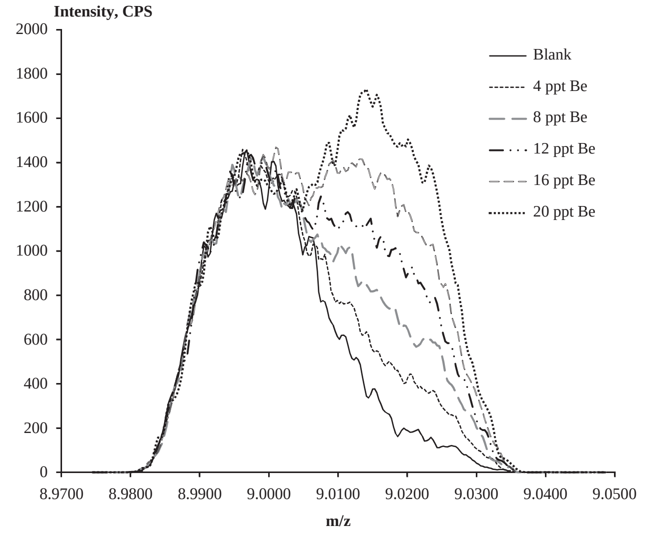

Fig. 1. Mass spectrum of m/z=9 at low spectral resolution (R=300). Solutions were injected immediately after preparation (Blank 5% HNO$_3$).

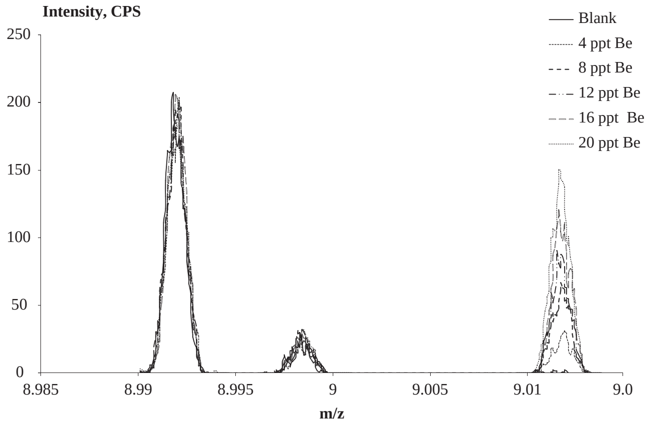

Fig. 2. Mass spectrum of m/z=9 at medium spectral resolution (R=4000). From the left to the right: ^{27}Al^{3+}, ^{18}O^{2+} and ^{9}Be^{+}. Solutions were injected immediately after preparation (Blank 5% HNO$_3$).

After mass analyzer resolution modes for all analytes had been chosen, ICP conditions were optimized: RF power – 1150 W, argon cooling flow – 16.4 mL/min, plasma flow – 0.73 mL/min, transport flow – 0.91 mL/min.

After ICP conditions were optimized we turned to analyses of real samples. Important source of error when analyzing complicated organic-rich and saline samples is ionization altering [15] and possible nebulizer clogging [34,39]. Ionization interferences were mainly observed for urine samples as both saline background of urine and its organic composition are highly dependent on patient liquid consumption. Yttrium (1 μg/L) was applied as internal standard to cope ionization interferences.

Blood and urine reference materials were analyzed for method validation. Acquired results matched target values (Table 1). Silver, cesium, barium, strontium, iron, uranium and copper were spiked into real blood and urine samples, and these were employed for validation as no reference values were available from a RM manufacturer. Recovery was found in the range 91–111% depending on the element.

Relative standard deviations (RSD) for the concentration range 0.01–1.0 μg/L were 5–10%. RSD did not exceed 3% when trace elements concentrations were above 1.0 μg/L. Method detection limits (MDLs) were determined using the 3σ criterion by tenfold measuring of corresponding blank solution. MDLs evaluated for urine/blood are presented below: Ag 0.7/0.6 ng/L, Al 15/16 ng/L, As 3.4/2.9 ng/L, Ba 0.01/0.02 ng/L, Be 1.5/1.2 ng/L, Cd 7.7/7.2 ng/L, Co 0.8/1.0 ng/L, Cr 2.8/2.5 ng/L, Cs 9.8/8.7 ng/L, Cu 25/27 ng/L, Fe 1.1/0.7 ng/L, Mn 1.5/1.8 ng/L, Ni 15/17 ng/L, Pb 13/11 ng/L, Se 21/23 ng/L, Sr 0.07/0.05 ng/L, Tl 0.2/0.1 ng/L, U 0.1/0.1 ng/L, V 0.6/0.7 ng/L, Zn 1.2/1.1 ng/L. As blank analytical signals for both matrices were quite close due to the same dilution factor, higher MDLs values were chosen for analytical data evaluation.

3.2. Application of the designed method

The designed method was used for the biomonitoring of occupationally exposed workers of a metallurgical enterprise processing beryllium-containing materials. Preliminary hygienic evaluation was performed based on the results of floor, wall and technological surfaces contamination with analyses by ICP-OES. Beryllium

Table 1
Analysis of reference materials, Seronorm™ trace elements.

Element	Whole blood L-1		Whole blood L-3		Urine	
	Measured concentration (μg/L)	Reference value (μg/L)	Measured concentration (μg/L)	Reference value (μg/L)	Measured concentration (μg/L)	Reference value (μg/L)
Al	7.8–11.2	7.0–15.4	97–110	98–126	106–118	88–112
As*	5.8–6.2	2.7–8.7	31.4–32.6	27.1–34.7	141–145	130–154
Be*	0.007–0.011	0.009–0.027	10.8–11.2	11.0–13.8	3.3–3.9	4.5–5.3
Cd	0.46–0.76	0.59–0.75	10.5–11.3	11.1–13.5	4.5–5.1	3.8–5.4
Co	0.13–0.23	0.12–0.34	10.5–10.9	9.3–13.3	8.7–8.9	8.8–11.2
Cr	0.53–0.63	0.58–1.06	34.1–36.5	33.5–41.1	19.8–21.4	17.1–22.3
Cu	595–602	601–689	2203–2287	2195–2607	70–76	not certified
Mn	19.6–20.4	16.3–23.9	45.2–46.8	44.7–54.7	11.7–12.5	9.5–15.1
Pb	14.4–15.2	13.8–15.8	584–596	594–682	34.0–34.4	35.1–45.5
Se	63.7–70.2	35–115	268–272	160–360	59.9–60.3	52.4–64.8
Tl*	0.002–0.008	0.004–0.012	30.2–31.0	27.7–34.1	8.43–8.79	8.58–9.94
V*	0.6–0.8	0.7–1.5	13.2–13.6	10.6–15.4	24.5–28.3	22.4–28.0
Zn	5058–5128	4552–5260	8822–8956	8573–10189	1077–1079	984–1352

* Measured values for real urine samples were considerably lower than reference concentration of RM, additional spiking of real urine samples was employed for validation.

Table 2
Trace element analysis: results of 50 blood samples trace element analysis

Element	Mean (μg/L)	Median (μg/L)	SD (μg/L)	C_{min} (μg/L)	C_{max} (μg/L)	% below MDLs	Reference concentration (μg/L)
Ag	0.045	0.388	0.311	0.125	1.52	0	0.03–2.7 [3]
Al	261	248	64	160	411	0	40–73 [52]
As	3.13	2.68	1.85	1.10	10.0	0	0.2–23 [10]
Ba	84.5	83.1	14.7	57.1	123	0	50–90 [3]
Be	0.036	0.035	0.019	0.004	0.079	0	<0.008–0.04 [12]
Cd	2.17	2.01	0.834	0.857	5.56	0	0.1–4.7 [10]
Co	0.788	0.546	0.766	0.175	4.194	0	0.04–0.8 [13]
Cr	6.65	6.24	3.84	1.14	14.3	0	0.7–2.8 [3]
Cs	1.72	1.72	0.62	0.89	3.34	0	1.5–6.7 [13]
Cu	803	839	149	538	1081	0	720–1800 [13]
Fe	4.07×10^5	4.06×10^5	0.67×10^5	2.3×10^5	5.8×10^5	0	$(4.89–6.11)\times10^5$ [37]
Mn	13.6	12.7	3.5	7.7	23.5	0	7.7–11.2 [37]
Ni	159	99.9	216	5.23	1169	0	<0.28–1.5 [37]
Pb	28.4	25.8	9.23	16.4	54.4	0	5–83 [13]
Se	163	158	37.5	99.8	268.1	0	58–234 [10]
Sr	53.8	31.4	101	19.0	718	0	10–77 [13]
Tl	0.023	0.022	0.008	0.011	0.047	0	<0.01–0.05 [13]
U	0.040	0.034	0.024	$<$MDL	0.12	12	<0.003–0.006 [13]
V	0.576	0.515	0.227	0.241	1.11	0	0.016–0.11 [13]
Zn	5570	5593	809	3747	6908	0	4400–8600 [10]

surface concentration was found in the range from 0.5 to 870 μg/dm^2 whilst according to [40] surface dust cleanup criterion for beryllium is 51 μg/dm^2. In separate samples, elevated concentrations (above 500 μg/dm^2) of iron, aluminum, zinc, copper and manganese were found. There were lesser amounts of lead, cadmium, vanadium and nickel: their surface concentration ranged between 0.1 and 10 μg/dm^2. Thus, preliminary chemical monitoring supported possible health hazard from beryllium and other toxic metals and showed the necessity of biomonitoring to control the health status of exposed personnel. For that purpose 50 blood and 40 urine samples were analyzed. The results of trace element analysis of blood and urine are presented in Tables 2 and 3 respectively.

As was already stated in the 'Study limitations' section, obtained results for occupationally exposed workers were compared mainly to the previously published data on trace element reference concentrations for unexposed populations. According to the literature, biological media reference concentrations for the most of essential (Fe, Cu, Zn, Se, Co, Mn) and also some of toxic trace elements (Cd, Hg, Pb, As) are quite strictly defined [1,3,10,41,42]. However, for some essential (Ni, V, Si) and many toxic trace elements (Ag, Be, Tl, Al, U) there are either no attested ranges of reference concentrations [18] or reference concentrations from different sources are often contradictory to each other [1,10,37,41,43–50]. Nevertheless, such data can be employed for occupational exposure evaluation [5].

Comparison of acquired results (Tables 2 and 3) to the published data [1,3,20,43–46] showed that concentrations of such toxic elements as Pb, Cd, Tl, As, and U in both blood and urine samples were within normal range, i.e. no occupational exposure was observed. For 80% of the samples, blood aluminum level exceeded 200 μg/L. For 12%, a 2 to 3-fold excess of this element was found. Elevated aluminum levels were also observed for the most of urine samples if compared to Skalny (1–20 μg/L) [10], Tietz (3–10 μg/L) [41] and Kaletina (5 μg/L) [3] but were in a good agreement with [51].

Elevated blood vanadium concentration was observed for all samples; for 40% of workers, the excess found to be considerable [12]. However, no elevated vanadium levels were found in urine when compared to previously published data [18,51].

Elevated blood chromium levels, as compared to data from [1,3,10,33,41], were observed for 80% samples and, for 10 subjects,

Table 3
Trace element analysis: results of 40 urine samples trace element analysis

Element	Mean (μg/L)	Median (μg/L)	SD (μg/L)	C_{min} (μg/L)	C_{max} (μg/L)	% below MDLs	Reference concentration (μg/L)
Ag	0.030	< MDL	0.073	< MDL	0.336	62.5	0.3–3 [10]
Al	54.7	44.3	47.0	10.5	223	0	1–20 [10]
As	18.2	16.8	9.90	3.56	49.1	0	1–375 [18]
Ba	33.6	28.2	27.5	0.122	102	0	0.1–14 [18]
Be	0.040	0.037	0.017	0.014	0.13	0	< 0.009 [18]
Cd	1.13	1.02	0.590	0.229	2.51	0	0.1–4.7 [10]
Co	0.908	0.233	3.43	0.052	20.8	0	1.0–2.0 [41]
Cr	1.81	0.441	6.88	< MDL	41.7	2.5	< 0.06–1 [18]
Cs	4.07	3.65	2.30	0.786	9.59	0	1.4–11.9 [18]
Cu	7.96	7.55	4.42	0.848	21.3	0	4–30 [18]
Fe	59.1	41.3	61.5	0.670	331	0	2–70 [41]
Mn	1.08	0.401	1.60	< MDL	5.86	7.5	0.5-9.8 [41]
Ni	1.43	0.657	2.07	< MDL	8.15	22.5	< 0.032–7.2 [18]
Pb	1.38	0.482	1.95	< MDL	7.33	15	0.02–4.8 [18]
Se	98.8	99.5	40.8	34.1	180	0	3–60 [18]
Sr	151	155	73.0	25.0	308	0	11–675 [18]
Tl	0.176	0.179	0.091	0.032	0.431	0	< 0.01–1.44 [18]
U	< MDL	< MDL	0.0015	< MDL	0.007	92.5	< 0.004–0.02 [18]
V	0.072	0.043	0.089	< MDL	0.338	17.5	< 0.08–0.24 [18]
Zn	252	184	189	24.7	912	0	5–850 [10]

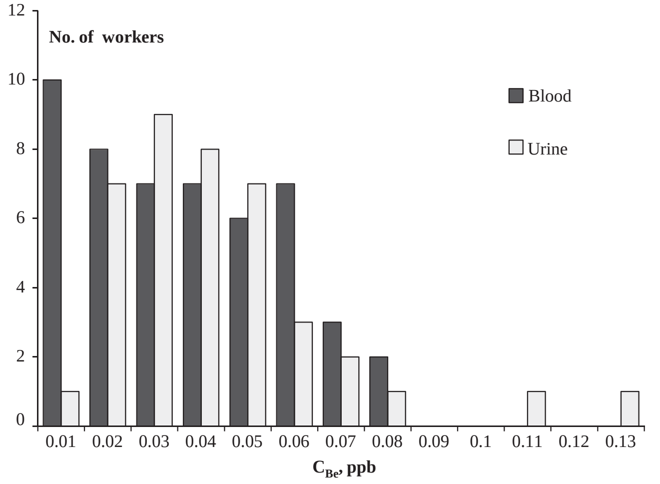

Fig. 3. Distribution of beryllium in blood (n=50) and urine (n=40) samples of occupationally exposed workers.

considerable excess over reference values was found. Chromium urine excretion was also elevated [18,51]. Blood manganese for 3 patients was found on the lower limit of toxic concentration. At the same time, levels of most essential trace elements (Fe, Cu, Zn, Co and Se) matched reference ranges [12,14,18,41]. A few individual cases of deficiency were found only for zinc and copper.

Blood beryllium level did not exceed 0.1 μg/L. However, blood beryllium level of exposed workers was considerably higher than in general population, when compared to the data from [10,13]. Beryllium exposure was also supported with elevated beryllium excretion with urine observed for all patients. Compared to [18,20] no values below MDLs were observed. Consequently, subtoxic beryllium exposure may be concluded. Patterns of blood and urine beryllium distribution are presented in Fig. 3.

Risk of aluminum, chromium and manganese exposure was also found possible. However, it was shown that occupational exposure remained within acceptable ranges. Still, more attention to occupational health and safety is required. As a result of the current investigation, risk groups of trace element exposure were determined, and occupational safety recommendations were prepared for the medical care unit of the biomonitored enterprise.

4. Conclusion

A SF-ICP-MS method of 20 trace elements determination in blood and urine was developed. Spectral interferences with $^{27}Al^{3+}$ and possibly $^{18}O^{2+}$ were observed for both digested blood and diluted urine samples when beryllium concentration did not exceed 0.1 μg/L. Use of medium resolution mode (R=4000) allowed effective coping of observed interferences.

The method was applied for trace element biomonitoring of a beryllium processing enterprise. Based upon 50 blood and 40 urine samples, occupational exposure assessment was found not to exceed acceptable ranges. Besides beryllium, possible health hazards may be posed from aluminum, chromium and manganese. Occupational health and safety recommendations for the medical care unit of the biomonitored enterprise were issued as a result of the current investigation.

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