

Simultaneous determination and variability over time of Cr, Cu, Zn, As, Se, Sr, Cd, Sb, Hg, Tl, and Pb concentrations in fingernail samples by ICP-MS method

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Abstract

This study aimed to determine 11 metal(oid)s in fingernails using inductively coupled plasma-mass spectrometry (ICP-MS) and to demonstrate the intra-day reproducibility and time-dependent variability of the measurements. Fingernail samples without nail polish were taken from the female subject in the research team twice in 2020 and three times in 2023. The nails of both hands were combined in a nail pool (n=5). Simultaneous determination of Cr, Cu, Zn, As, Se, Sr, Cd, Sb, Hg, Tl, and Pb was carried out with 3 consecutive intra-day readings. The mean relative standard deviation (RSD) of 3 consecutive intraday measurements was 5.26%, and Kendall's W value was 0.99. Kruskal-Wallis test showed no significant difference between the three measurements ($p < .05$). Spearman rho values and p-values of repeated measurements in a 3-year period were found to be ⁵²Cr ($r_s = 0.884$, $p = 0.000$), ⁶³Cu ($r_s = -0.862$, $p = 0.000$), ⁶⁶Zn ($r_s = -0.436$, $p = 0.104$), ⁷⁵As ($r_s = -0.840$, $p = 0.000$), ⁷⁸Se ($r_s = 0.524$, $p = 0.045$), ⁸⁸Sr ($r_s = 0.022$, $p = 0.938$), ¹¹¹Cd ($r_s = 0.273$, $p = 0.325$); ¹²¹Sb ($r_s = 0.822$, $p = 0.000$), ²⁰¹Hg ($r_s = 0.316$, $p = 0.251$), ²⁰⁵Tl ($r_s = 0.165$, $p = 0.557$) and ²⁰⁸Pb ($r_s = 0.197$, $p = 0.483$), respectively. Intraday measurements of fingernail samples by ICP-MS showed high reproducibility and analytical precision. All elemental levels were within the reference ranges. The highest value was ⁶⁶Zn 117.843 µg/g and the lowest value was ²⁰⁵Tl 0.0035 µg/g. Accordingly, fingernails can be used in biomonitoring of metal(loid) exposure and diagnosis of poisoning in terms of public health and forensic toxicology.

Keywords: Age of sample, heavy metal, exposure window, forensic medicine

1. Introduction

Metal(loid)s exposure and toxicity have become an increasingly dangerous and interdisciplinary problem. Chromium (Cr), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), strontium (Sr), cadmium (Cd), antimony (Sb), mercury (Hg), thallium (Tl), and lead (Pb) are found in different concentrations in all ecosystems, in air, soil, water, and the food chain due to environmental contamination and in cosmetic products [1–6]. Therefore, humans are exposed to the pollutant and toxic effects of these elements through both natural and anthropogenic sources, as well as industrial activities [7,8]. Many cases of poisoning caused by As, Tl, Pb, Hg, and Cd have been reported in the literature [2,6,9,10]. Cu, Se, and Zn are essential in some physiological reactions; however, they become toxic due to increased exposure or pathological metabolism [2]. Clinical, forensic toxicological, and chemical analyses are essential for determining exposure to these elements and

evaluating their toxicity, both for public health and for effective risk management and preventive policies [10–12].

Nails are essential biomarkers used for biomonitoring of metal(loid) exposure and toxicological analyses. Due to their cutaneous structure with keratinized cells, human fingernails and toenails can accumulate xenobiotics over long periods [10,13–15]. Analytical, forensic toxicological, and pharmacological studies of fingernails provide additional information on the retrospective detection and long-term exposure of metalloid elements, as well as drugs and illicit substances [1,2,4,5,7,9,10,13–18]. Besides, nails are richer in alpha-keratins containing cysteine residues due to the disulfide groups they contain than other biological samples; they retain more metal(loid) and reflect a longer exposure window [15]. The retrospective exposure window for fingernails is approximately 3-5/6

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months; they grow an average of 3 mm (1.9–4.4 mm) per month, and the growth rate is related to finger length [14]. The detection window varies between 2 and 4 months, depending on the growth rate and length of the nails. Therefore, nowadays, the determination of metal(loid)s in fingernails may provide essential data for the biomonitoring of these elements, the diagnosis of intoxication, and the timing of exposure.

On the other hand, many chemical, clinical, and medical investigations have been carried out for decades to determine metal(loid)s in various biological samples other than nails. However, multielement metal(loid) analyses in fingernails began in the 1980s and have been performed more widely and easily in recent years with the aid of techniques such as inductively coupled plasma-mass spectrometry ICP-MS [19–23]. In recent years, ICP techniques with atomic emission spectrometry (AES) and mass spectrometry (MS) detectors have been preferred instead of flame atomic absorption spectrometry (FAAS) and electrothermal atomic absorption spectrometry (ETAAS) techniques in metal(loid) analysis [2]. Since ICP-MS is a highly sensitive technique, it is preferred for clinical toxicology related to metal(loids) in forensic cases for investigating and monitoring occupational or environmental exposure in poisonings or deaths [2]. These analyses can be performed using the ICP-MS technique, even with a small nail sample of 20 mg [2]. In research conducted in this area, it is generally seen that toenail samples are used. However, fingernail samples are easier to collect than toenails, and fingernails should be analyzed, especially in cases where no other biological sample can be obtained. However, fingernails have been less studied in literature, and there is a research gap in this subject. Therefore, this study aimed to determine the simultaneous quantification of Cr, Cu, Zn, As, Se, Sr, Cd, Sb, Hg, Tl, and Pb elements in fingernails by the ICP-MS technique and to indicate the intra-day reproducibility and time-dependent variability of the measurements.

Table 1. ICP-MS analytical method parameters.

Parameter	Value
RF power	1500 W
RF matching	1.80 V
S/C temperature	2 °C
Sample Depth	10 mm
Nebulizer gas	1.03 L/min
Make up gas	0.00 L/min
Nebulizer Pump	0.10 rps
Internal standards	⁶ Li, ⁴⁵ Sc, ⁷² Ge, ⁸⁹ Y, ¹¹⁵ In, ¹⁵⁹ Tb, ²⁰⁹ Bi
Analysed metals	⁵² Cr, ⁶³ Cu, ⁶⁶ Zn, ⁷⁵ As, ⁷⁸ Se, ⁸⁸ Sr, ¹¹¹ Cd, ¹²¹ Sb, ²⁰¹ Hg, ²⁰⁵ Tl and ²⁰⁸ Pb
Oxide Ratio	(156/140) 1.289%
Doubly Charged Ratio	(70/140) 1.333%
Tuning solvent	⁵⁸ Ce, ²⁷ Co, ⁷ Li, ⁸⁹ Y, ²⁰⁵ Tl
Readings	3

2. Materials and methods

2.1. Standards and reagents

In this study, 10 µg/mL multi-element standard solution (VHG-LICV1A-100, LGC Standards) was used for chromium (Cr), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), strontium (Sr), cadmium (Cd), antimony (Sb), thallium (Tl), and lead (Pb). For mercury (Hg), a 1000 µg/mL single-element standard solution (Agilent Technologies, USA) was used. For microwave solubilization of the fingernails, 60% HNO₃ (Ultrapur, Merck KGaA Darmstadt-Germany) and 30% H₂O₂ (Suprapur, Merck KGaA Darmstadt-Germany) were used. European Reference Material (fish muscle, ERM-BB422) was used for accuracy and precision studies of the ICP-MS method.

2.2. Instrumentation

ICP-MS analyses of Cr, Cu, Zn, As, Se, Sr, Cd, Sb, Hg, Tl, and Pb were performed at Izmir Katip Çelebi University Central Research Laboratory. ICP-MS (7800, Agilent Technologies Inc., USA) devices combined with a cooler (Chiller, Agilent G3292A), autosampler (Agilent SPS4), vacuum pump system, and Mass Hunter 4.4 software were used in the analysis. Pure water (18.2 MΩ.cm conductivity, TOC<10 ppb), used in the preparation of the solutions, was obtained from Human Power I, Human Corporation, K.

2.3. ICP-MS analytical method parameters

Simultaneous determination of Cr, Cu, Zn, As, Se, Sr, Cd, Sb, Hg, Tl, and Pb in current and aged fingernails was performed by the ICP-MS technique. After the hands were brushed and washed with deionized water, nail samples were taken and stored in a closed sample container until subjected to microwave processing. Approximately 0.06 g of fingernail samples were weighed into polytetrafluoroethylene (PTFE) tubes and then treated with 8 mL HNO₃ (60%, Sigma-Aldrich) and 2 mL H₂O₂ (30%, Sigma-Aldrich). After waiting for the gas release in the fume hood, the Teflon tubes were closed, and the samples were dissolved in a microwave digestion system (Ethos Easy, Milestone Srl., IT). In this study, a microwave digestion program was employed, consisting of two stages. In the first stage, the power range was 0–1800 W, and the temperature increased from 30 °C to 200 °C in 15 min. In the second stage, the power was maintained at 1800 W for 15 min, with the temperature kept at 200 °C. After microwave digestion, the sample solutions were diluted to 25 mL with ultrapure water. The sample solutions prepared were analyzed using an ICP-MS instrument via an autosampler. ICP-MS instrument parameters are given in Table 1.

In our study, all metal(loid)s were measured in He mode using high-purity helium gas to minimize possible interferences. The collision/reaction cell (CRC) was operated in collision mode, where helium effectively reduces polyatomic interferences through kinetic energy discrimination (KED). The reagent blanks were analyzed alongside the samples to ensure data accuracy and eliminate potential contamination; these blanks were used as the blank in the calibration curve. The standard addition method was used to verify the accuracy of the process. Multi-element analytical standard solution (VHG-LICV1A), including Ag, Al, As, Ba, Be, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, Se, Sr, Ti, Tl, U, V, Zn (10 mg/mL) and Ca, Fe, K, Mg, Na (1000 mg/mL) was used for calibration. A single-standard Hg solution (10000 µg/mL in 5% HNO₃, 100 mL, Agilent Technologies) was used for Hg only. The oxide/doubly charged ratios were below the acceptable threshold of 2.5%, so the instrument's performance was considered satisfactory. After digestion, the internal standard solution (0.5 µg/mL) was introduced into the instrument simultaneously with the sample via a peristaltic pump. Therefore, the internal standard solution eliminates potential variations related to the instrument during analysis. The instrument's performance was also evaluated using a tuning solution before analysis.

2.4. Ethics committee approval and sample analysis procedure

Ethics committee approval (2022/16-25) was obtained from the Clinical Research Ethics Committee of Çanakkale Onsekiz Mart University before the study. Fingernail samples were provided by the same female subject on the research team in Çanakkale/Türkiye. Written informed consent was obtained from the participants included in the study.

The samples analyzed in this study were taken at different time points and analyzed at various times. The term "sample age" refers to the time interval between when the samples were taken and when they were examined. The fingernails were collected on five dates (30.08.2020, 27.09.2020, 18.03.2023, 11.10.2023, and 07.11.2023). Analyses were performed on two dates in 2023 (27 March 2023 and 22 November 2023). Samples were stored in separate cardboard boxes at room temperature. All samples were sent to the laboratory for analysis in 2023. The age of the samples was calculated in days, considering the time between the date of collection and the date of analysis. The participant collected the samples by cutting them with a stainless-steel cutting tool. All fingernail samples were unpolished. Fingernails cut from the right and left fingers were combined in a nail pool. Each nail pool was

considered as one sample (n=5). The masses of the fingernail pools were measured.

2.5. Analysis and comparison of Cr, Cu, Zn, As, Se, Sr, Cd, Sb, Hg, Tl, and Pb

In this study, the elements ⁵²Cr, ⁶³Cu, ⁶⁶Zn, ⁷⁵As, ⁷⁸Se, ⁸⁸Sr, ¹¹¹Cd, ¹²¹Sb, ²⁰¹Hg, ²⁰⁵Tl and ²⁰⁸Pb were analyzed quantitatively. The results obtained in this study were compared with the reference values of previous studies in Table 2 [2,5,15].

2.6. Statistical analysis

Data was obtained from the five nail samples by taking three repeated readings for each element. The analyses for the determination of elemental levels in the samples were performed on the same day, by the same person, on the same instrument, in the same mode, and with three consecutive repeated readings/measurements of the signals from the same sample. A measurement spectrum was obtained from the instrument software by averaging the results of these three consecutive measurements. The relative standard deviation between measurements relative standard deviation (RSD) and the concordance coefficient (Kendall's W) were calculated to determine the reproducibility and accuracy of the measurements and whether it is appropriate to take the average of the measurements of these three consecutive repeated readings as the exposure value of each element in nail samples. Additionally, the Kruskal-Wallis test was used to compare the measurement results and their averages. The intra-individual variability of the amount of metal(loid)s in nail samples within a specific period is discussed in the literature with the concepts of "reproducibility over time" or "stability over time" [18,24–26]. Spearman's rank correlation coefficients were calculated using the elemental concentrations found in three repeated measurements on the same day of 5 samples collected from the same person at different times by ICP-MS [26]. Intraday measurements were evaluated for agreement and precision, and inter-annual measurements were assessed for intra-individual time-dependent variability. Spearman correlation, Kruskal-Wallis, and Mann-Whitney U tests were applied to compare the elemental levels in the nails of different age groups to examine the intra-individual intra-day and intra-individual inter-annual variability of elemental amounts. $p < 0.05$ was considered statistically significant. The correlations between the variables studied were interpreted in terms of magnitude as follows: < 0.20 was interpreted as "very weak", correlations between 0.20-0.39 as "weak", correlations between 0.40-0.59 as "moderate", correlations between 0.60-0.79 as "strong", and correlations greater than 0.80 as "very strong". Statistical evaluations were performed using free and open software (Jamovi Desktop, 2025, Version 2.6.44).

Table 2. ICP-MS analysis results and reference ranges for 11 metals/metalloids in aged and current fingernails [n=5, (TriPLICATE readings/measurements n=15)].

Elements mode]	[He Sample (Days)	Age	Concentration (TriPLICATE Measurements) (µg/g)			Mean (µg/g)	Median (µg/g)	SD	Spearman's Correlation (rho)	Range (µg/g)	Published Ranges (µg/g)		
			Replicate 1	Replicate 2	Replicate 3						[5]	[2]	[15]
⁵² Cr	1150		0.3665	0.3647	0.3807	0.3706	0.3665	0.0072	0.884* (0.000)	0.365–0.579	0.224–3.20	0.18–0.76	0.03–1.89
	939		0.5608	0.5786	0.5157	0.5517	0.5608	0.0265					
	Aged Cr Samples					0.4612	0.4482	0.0926					
	41		0.3388	0.3561	0.3535	0.3495	0.3535	0.0076					
	14		0.3304	0.3254	0.3328	0.3295	0.3304	0.0031					
	9		0.1345	0.1259	0.1258	0.1287	0.1259	0.0041					
	Current Cr Samples					0.2692	0.3304	0.0998					
All Cr Samples					0.3460	0.3535	0.1351		0.126–0.579				
⁶³ Cu	1150		4.3502	4.3817	4.4829	4.4049	4.3817	0.0566	-0.862* (0.000)	4.086–4.483	4.2–17	4.3–9.4	3.9–12.4
	939		4.086	4.1848	4.4103	4.2270	4.1848	0.1357					
	Aged Cu Samples					4.3160	4.36595	0.1368					
	41		4.4109	4.4359	4.4932	4.4467	4.4359	0.0345					
	14		4.6417	4.5691	4.7371	4.6493	4.6417	0.0688					
	9		5.801	6.0998	6.2559	6.0522	6.0998	0.1887					
	Current Cu Samples					5.0494	4.6417	0.7236					
All Cu Samples					4.7560	4.4829	0.6713		4.086–6.256				
⁶⁶ Zn	1150		97.5053	102.1464	104.4316	101.3611	102.1464	2.8817	-0.436 (0.104)	97.505–125.483	80–191	83–143	72–182
	939		112.0139	111.6038	125.4828	116.3668	112.0139	6.4481					
	Aged Zn Samples					108.8640	108.0177	9.0130					
	41		116.9085	126.1908	123.9958	122.3650	123.9958	3.9610					
	14		98.6218	101.3871	105.7922	101.9337	101.3871	2.9527					
	9		117.8429	125.8456	128.3619	124.0168	125.8456	4.4848					
	Current Zn Samples					116.1052	117.8429	10.7569					
All Zn Samples					113.2087	112.0139	10.7007		97.505–128.362				
⁷⁵ As	1150		0.0536	0.0534	0.0557	0.0542	0.0536	0.0010	-0.840* (0.000)	0.03–0.056	0.065–1.09	0.024–0.404	0.005–0.086
	939		0.0296	0.0313	0.035	0.0320	0.0313	0.0023					
	Aged As Samples					0.0431	0.0442	0.0113					
	41		0.0553	0.0566	0.0569	0.0563	0.0566	0.0007					
	14		0.057	0.056	0.0581	0.0570	0.057	0.0009					
	9		0.0762	0.0782	0.072	0.0755	0.0762	0.0026					
	Current As Samples					0.0629	0.057	0.0090					
All As Samples					0.0550	0.056	0.0139		0.03–0.078				
⁷⁸ Se	1150		1.0318	0.854	1.1461	1.0106	1.0318	0.1202	0.524** (0.045)	0.536–1.146	0.62–1.53	0.47–1.06	0.44–0.91
	939		0.6059	0.6712	0.5363	0.6045	0.6059	0.0551					
	Aged Se Samples					0.8076	0.7626	0.2236					
	41		0.8553	0.9979	0.9518	0.9350	0.9518	0.0594					
	14		0.9001	0.9872	0.8406	0.9093	0.9001	0.0602					
	9		0.4312	0.4068	0.4811	0.4397	0.4312	0.0309					
	Current Se Samples					0.7613	0.8553	0.2335					
All Se Samples					0.7798	0.854	0.2307		0.407–1.146				
⁸⁸ Sr	1150		1.8157	1.7402	1.9733	1.8431	1.8157	0.0971	0.022 (0.938)	1.367–1.973	0.17–1.39	0.28–1.00	0.28–1.64
	939		1.3671	1.642	1.3811	1.4634	1.3811	0.1264					
	Aged Sr Samples					1.6532	1.6911	0.2208					
	41		1.3933	1.2063	1.2801	1.2932	1.2801	0.0769					
	14		0.594	0.4552	0.501	0.5167	0.501	0.0577					
	9		2.1789	2.1231	1.9259	2.0760	2.1231	0.1085					
	Current Sr Samples					1.2953	1.2801	0.6420					
All Sr Samples					1.4385	1.3933	0.5455		0.455–2.179				

¹¹¹ Cd	1150	0.0402	0.0367	0.04	0.0390	0.04	0.0016	-0.273 (0.325)	0.03–0.04	0.013–0.438	0.011–0.137	0.009–0.196
	939	0.032	0.0365	0.0296	0.0327	0.032	0.0029					
	Aged Cd Samples				0.0358	0.0366	0.0039					
	41	0.0305	0.0261	0.0287	0.0284	0.0287	0.0018					
	14	0.0375	0.0333	0.0307	0.0338	0.0333	0.0028					
	9	0.0591	0.052	0.0523	0.0545	0.0523	0.0033					
	Current Cd Samples				0.0389	0.0333	0.0115					
All Cd Samples				0.0377	0.0365	0.0094	0.026–0.059					
¹²¹ Sb	1150	0.0187	0.0179	0.0172	0.0179	0.0179	0.0006	0.822*	0.017–0.026	0.014–0.128	0.014–0.086	0.012–0.196
	939	0.0262	0.0242	0.023	0.0245	0.0242	0.0013					
	Aged Sb Samples				0.0212	0.02085	0.0034					
	41	0.0171	0.0179	0.0177	0.0176	0.0177	0.0003					
	14	0.0171	0.0164	0.0171	0.0169	0.0171	0.0003					
	9	0.016	0.0129	0.0142	0.0144	0.0142	0.0013					
	Current Sb Samples				0.0163	0.0171	0.0016					
All Sb Samples				0.0182	0.0172	0.0035	0.013–0.026					
²⁰¹ Hg	1150	0.235	0.2535	0.2304	0.2396	0.235	0.0100	0.316	0.076–0.254	0.028–0.311	0.09–0.56	0.06–0.83
	939	0.0755	0.0824	0.0812	0.0797	0.0812	0.0030					
	Aged Hg Samples				0.1597	0.1564	0.0803					
	41	0.0337	0.0248	0.032	0.0302	0.032	0.0039					
	14	0.0406	0.0329	0.0323	0.0353	0.0329	0.0038					
	9	0.1322	0.1452	0.1262	0.1345	0.1322	0.0079					
	Current Hg Samples				0.0667	0.0337	0.0484					
All Hg Samples				0.1039	0.0812	0.0778	0.025–0.254					
²⁰⁵ Tl	1150	0.006	0.006	0.004	0.0053	0.006	0.0009	0.165	0.004–0.006	0.0003–0.0058	0.0002–0.001	0.0002–0.0012
	939	0.0057	0.0055	0.0055	0.0056	0.0055	0.0001					
	Aged Tl Samples				0.0055	0.0056	0.0007					
	41	0.0055	0.0048	0.0052	0.0052	0.0052	0.0003					
	14	0.0036	0.0038	0.0035	0.0036	0.0036	0.0001					
	9	0.005	0.006	0.0063	0.0058	0.006	0.0006					
	Current Tl Samples				0.0049	0.005	0.0010					
All Tl Samples				0.0051	0.0055	0.0009	0.004–0.006					
²⁰⁸ Pb	1150	0.5384	0.5595	0.5663	0.5547	0.5595	0.0119	0.197	0.164–0.566	0.27–4.75	0.22–3.82	0.10–3.71
	939	0.1638	0.1702	0.1641	0.1660	0.1641	0.0029					
	Aged Pb Samples				0.3604	0.3543	0.1945					
	41	0.515	0.5153	0.5154	0.5152	0.5153	0.0002					
	14	0.5508	0.5508	0.541	0.5475	0.5508	0.0046					
	9	0.2379	0.1991	0.2599	0.2323	0.2379	0.0251					
	Current Pb Samples				0.4317	0.5153	0.1424					
All Pb Samples				0.4032	0.5153	0.1689	0.164–0.566					

*: Spearman's correlation is significant at the 0.01 level (2-tailed). **: Spearman's correlation is significant at the 0.05 level (2-tailed).

3. Results and discussion

Sociodemographic characteristics of the subject: Healthcare worker is female, born in 1974 (46 years old at the time of the first sample), has a body mass index (BMI) of 33, smoked 3-5 cigarettes per day until 2019, utilizes ramipril for hypertension, and has engaged in exercise (walking and swimming) since 2019. She drinks bottled spring water and uses tap water for other purposes. She follows a Mediterranean diet, has four mercury amalgam fillings, applies nail polish 1-3 times per year, uses cream 1-2 times daily, and applies perfume 1-2 times daily. She brushes her teeth 2-3 times per day and has been living in Çanakkale, Türkiye, since 2007. The ICP-MS analysis results and reference ranges of metals/metalloids in aged and current fingernails are provided in Table 2.

The characteristics of the samples are presented in Table S1. Triplicate ICP-MS measurements were conducted using European Reference Material (fish muscle, ERM- BB422) for accuracy and precision studies (Table S6). Recovery rates ranged from 80.4% to 108.3%, and relative standard deviations varied from 3.2% to 5.3% for the studied metals and metalloids. Calibration plots of the standards used in ICP-MS analyses are displayed in Fig. S1 and Fig. S2.

The quantities and standard deviations of the elements ^{52}Cr , ^{63}Cu , ^{66}Zn , ^{75}As , ^{78}Se , ^{88}Sr , ^{111}Cd , ^{121}Sb , ^{201}Hg , ^{205}Tl , and ^{208}Pb were simultaneously determined by ICP-MS in the examined fingernails, and Spearman's rho values for the relationship between the element quantities according to the age groups of the samples were calculated (Table 2). The mean of the relative standard deviations was 5.26%, and Kendall's W value was 0.99, indicating that the triplicate measurements strongly agreed. When the samples were grouped as

aged and current, Spearman rho values and p-values of three measurements over time were found to be ^{52}Cr ($r_s=0.884$, $p=0.000$), ^{63}Cu ($r_s=-0.862$, $p=0.000$), ^{66}Zn ($r_s=-0.436$, $p=0.104$), ^{75}As ($r_s=-0.840$, $p=0.000$), ^{78}Se ($r_s=0.524$, $p=0.045$), ^{88}Sr ($r_s=0.022$, $p=0.938$), ^{111}Cd ($r_s=0.273$, $p=0.325$); ^{121}Sb ($r_s=0.822$, $p=0.000$), ^{201}Hg ($r_s=0.316$, $p=0.251$), ^{205}Tl ($r_s=0.165$, $p=0.557$), and ^{208}Pb ($r_s=0.197$, $p=0.483$), respectively (Table 2). Accordingly, when the variability over time of the amounts of the elements was examined, there was a very strong positive correlation for Cr and Sb and a very strong negative correlation for Cu and As (Table 2). These results showed very strong positive correlations for Cr and Sb, moderate positive correlations for Se, and strong negative correlations for Cu and As. The correlations between three consecutive intra-day readings were evaluated for each element using Spearman's rho (Table 3).

As seen in Table 3, no statistically significant correlation was found between the elemental levels of each element determined in three consecutive measurements, only between the Tl1, Tl2, and Tl3 measurements of the Tl levels. However, a moderate positive correlation ($r_s=0.564$) existed between Tl1 and Tl2 and between Tl2 and Tl3. Excellent or very strong correlations ($r_s=1-0.900$, $p<0.01$) between the first and second measurements, first and third measurements, or second and third measurements of elements other than Tl indicate high reproducibility and low measurement error. Therefore, this shows a high level of analytical precision.

When the difference between the elemental means detected in samples taken on different dates and therefore of various ages was compared by the Kruskal-Wallis test, it was determined that there was a significant difference ($p<0.05$) in all elements except Tl (Table S2).

Table 3. Correlation between elemental levels in fingernail samples according to the results of three repeated intraday readings/measurements (Spearman's rho)

Elements	Measurements	Spearman rho	Elements	Measurements	Spearman rho
Cr	Cr1-Cr2	1	Sr	Sr1-Sr2	0.900*
	Cr1-Cr3	1**		Sr1-Sr3	0.800
	Cr2-Cr3	1**		Sr2-Sr3	0.900*
Cu	Cu1-Cu2	1	Cd	Cd1-Cd2	0.900*
	Cu1-Cu3	1**		Cd1-Cd3	1**
	Cu2-Cu3	1**		Cd2-Cd3	0.900*
Zn	Zn1-Zn2	0.800	Sb	Sb1-Sb2	0.921*
	Zn1-Zu3	0.900*		Sb1-Sb3	0.821
	Zu2-Zu3	0.600		Sb2-Sb3	0.975*
As	As1-As2	0.900*	Hg	Hg1-Hg2	1
	As1-As3	1**		Hg1-Hg3	1**
	As2-As3	0.900*		Hg2-Hg3	1**
Se	Se1-Se2	0.600	Tl	Tl1-Tl2	0.564
	Se1-Se3	0.900*		Tl1-Tl3	0.100
	Se2-Se3	0.700		Tl2-Tl3	0.564
			Pb	Pb1-Pb2	0.900*
				Pb1-Pb3	0.900*
				Pb2-Pb3	1**

n= 5, *p< 0.05, **p<0.01

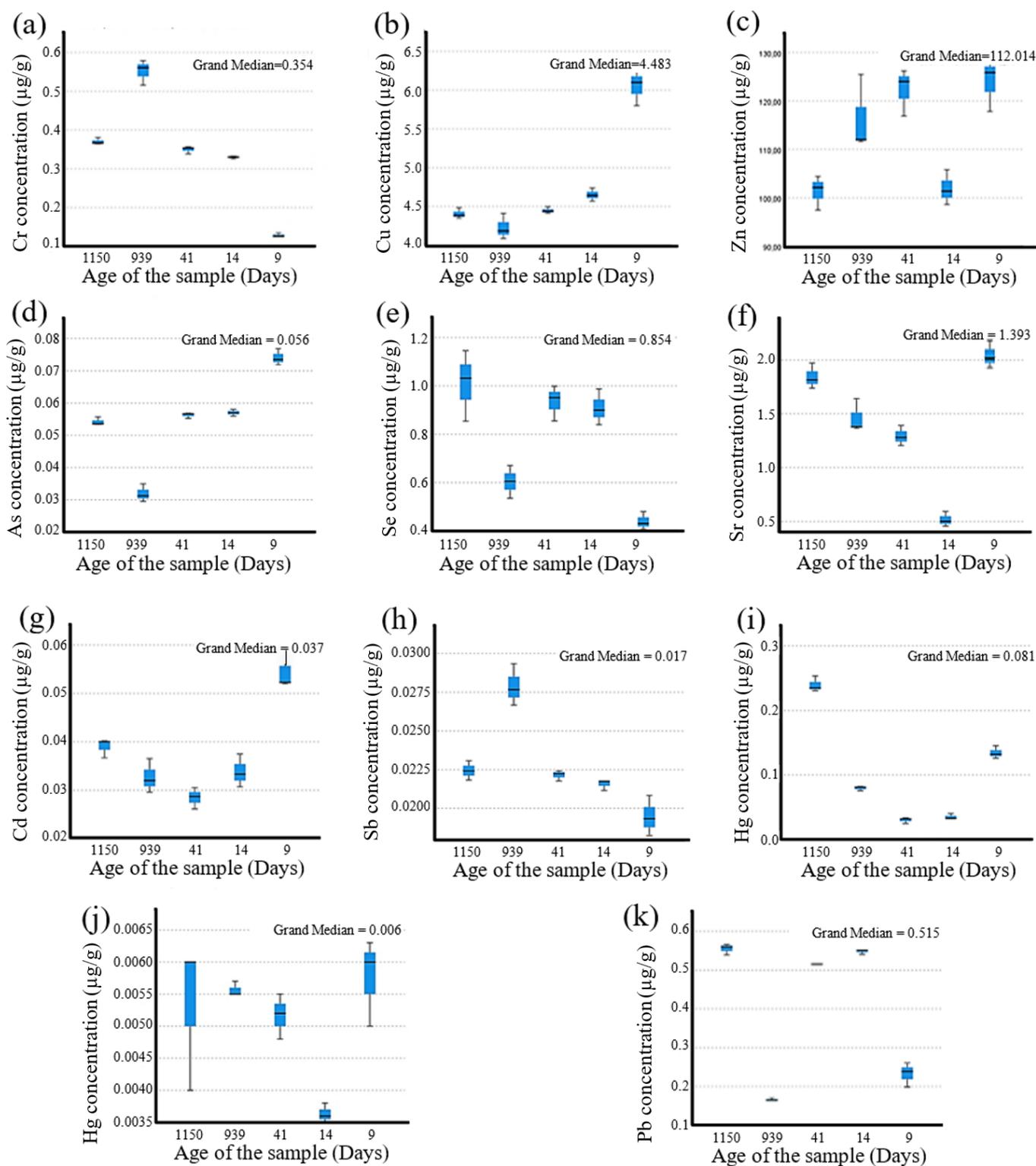


Figure 1. Comparison of ^{52}Cr (a), ^{63}Cu (b), ^{66}Zn (c), ^{75}As (d), ^{78}Se (e), ^{88}Sr (f), ^{111}Cd (g), ^{121}Sb (h), ^{201}Hg (i), ^{205}Tl (j), and ^{208}Pb (k) concentrations ($\mu\text{g/g}$) versus age of fingernail samples by Kruskal-Wallis Test.

Fig. 1 (a-k) shows the intra-individual variation of the metal(loid) amounts detected in these five different ages (1150, 939, 41, 14, and 9 days old) of the fingernail samples over 3 years. The mean intra-individual amounts of the elements do not show a linear change, such as decreasing with increasing sample age or increasing with decreasing sample age.

When the nail samples were divided into two groups as current (41, 14, and 6 days) and aged (1150 and 939

days) nails, the Mann-Whitney U test showed that there was no significant difference ($p > .05$) between the aged and current nail groups in Zn, Se, Sr, Cd, Tl, and Pb elements (Table 4). However, it was determined that there was a significant difference ($p < 0.05$) between the aged and current nail groups in Cr, Cu, As, Sb, and Hg elements. Accordingly, Cr, Sb, and Hg levels were higher in the aged nail group than in the current nail group; Cu and As levels were higher in the current nail group.

Table 4. Comparison of elemental levels found in nail samples according to nail age groups

Elements	Age Group	N	Mean (SD) µg/g	Median (Min. – Max.) µg/g	Mann-Whitney U	p
Cr	Aged	6	0.5 (0.1)	0.5 (0.4-0.6)	0.000	0.001
	Current	9	0.3 (0.1)	0.3 (0.2-0.4)		
Cu	Aged	6	4.3 (0.1)	4.4 (4.1-4.5)	2.000	0.003
	Current	9	5.1 (0.8)	4.6 (4.4-6.3)		
Zn	Aged	6	108 (10)	108 (98-125)	16.000	0.195
	Current	9	116 (11)	118 (99-128)		
As	Aged	6	0.04 (0.01)	0.04 (0.03-0.06)	1.000	0.002
	Current	9	0.06 (0.01)	0.06 (0.06-0.08)		
Se	Aged	6	0.8 (0.2)	0.8 (0.5-1.2)	23.000	0.637
	Current	9	0.8 (0.2)	0.9 (0.4-1.0)		
Sr	Aged	6	1.6 (0.2)	1.7 (1.4-2.0)	19.000	0.346
	Current	9	1.3 (0.7)	1.3 (0.5-2.2)		
Cd	Aged	6	0.036 (0.004)	0.04 (0.03-0.04)	26.000	0.906
	Current	9	0.04 (0.01)	0.03 (0.03-0.06)		
Sb	Aged	6	0.021 (0.004)	0.021 (0.02-0.03)	2.500	0.004
	Current	9	0.016 (0.002)	0.017 (0.01-0.02)		
Hg	Aged	6	0.16 (0.09)	0.16 (0.08-0.25)	9.000	0.034
	Current	9	0.07 (0.05)	0.03 (0.02-0.15)		
Tl	Aged	6	0.006 (0.001)	0.006 (0.004-0.006)	16.000	0.192
	Current	9	0.005 (0.001)	0.005 (0.004-0.006)		
Pb	Aged	6	0.4 (0.2)	0.4 (0.2-0.6)	24.000	0.723
	Current	9	0.4 (0.2)	0.5 (0.2-0.6)		

When the relationship between the metal(loid) amounts detected in the fingernails was analyzed by Spearman's correlation (n: 15), it was found to be statistically significant for different elements in different, positive or negative directions, most of them at very strong or strong levels (Table 5). Correlation of the elements with each other: between Cr and Cu ($r_s = -0.914$, $P < 0.01$), between Cr and As ($r_s = -0.896$, $P < 0.01$), between Cr and Sb ($r_s = 0.952$, $P < 0.01$), between Cu and As ($r_s = 0.957$, $P < 0.01$), between Cu and Sb ($r_s = -0.927$, $P < 0.01$), between Zn and Se ($r_s = -0.532$, $P < 0.05$), between Zn and Pb ($r_s = -0.613$, $P < 0.05$), between As and Sb ($r_s = -0.884$, $P < 0.01$), between Se and Pb ($r_s = 0.708$, $P < 0.01$), between Sr and Cd ($r_s = 0.721$, $P < 0.01$), between Sr and Hg ($r_s = 0.811$, $P < 0.01$), between Sr and Tl ($r_s = 0.594$, $P < 0.05$), between Cd and Hg ($r_s = 0.761$, $P < 0.01$), and between Hg and Tl ($r_s = 0.583$, $P < 0.05$). Correlations between first, second, and third measurements of fingernail samples were also investigated, and the results were in harmony (Tables S3-S5).

This study represents the first instance of the simultaneous determination of Cr, Cu, Zn, As, Se, Sr, Cd,

Sb, Hg, Tl, and Pb metal(loid)s in both aged and current fingernails utilizing the ICP-MS technique. This relates to the repeatability of intraday triplicate readings and the variability observed over three years. In this study, the mean amounts of metal(loid)s in fingernails determined by the ICP-MS method were within the reference ranges specified in the literature [2,5,15]. As one of the most significant findings of the study, a strong correlation (RSD = 5.26% and Kendall's W = 0.99) was observed between the intra-day measurements of the elements, with excellent or very strong correlations between the intra-day measurements of the elements, except for Tl. Another significant result was that different correlation patterns were found for different elements when the time-dependent variation of elemental levels was analysed. When the mean elemental levels in the two nail groups were compared, Cr, Sb, and Hg levels were higher in the nail group aged for a more extended period, while Cu and As levels were higher in the nail group aged for a shorter period. These results demonstrated high reproducibility, low measurement error, and high analytical precision in

Table 5. Correlations (Spearman's rho) of metal(loid)s detected in all measurements carried out over three years in the fingernail samples

	Cr	Cu	Zn	As	Se	Sr	Cd	Sb	Hg	Tl	Pb
Cr	1										
Cu	-0.914**	1									
Zn	-0.250	0.332	1								
As	-0.896**	0.957**	0.329	1							
Se	0.304	-0.307	-0.532*	-0.254	1						
Sr	-0.089	0.125	0.239	0.164	-0.371	1					
Cd	-0.418	0.404	-0.161	0.393	-0.321	0.721**	1				
Sb	0.952**	-0.927**	-0.212	-0.884**	0.271	-0.215	-0.488	1			
Hg	0.100	-0.111	-0.239	-0.118	-0.196	0.811**	0.761**	-0.007	1		
Tl	0.065	-0.223	0.306	-0.209	-0.406	0.594*	0.331	0.119	0.583*	1	
Pb	-0.159	0.170	-0.613*	0.163	0.708**	-0.214	0.070	-0.219	0.061	-0.434	1

n=15, *p<0.05, **p<0.01

three consecutive intraday measurements of the analyzed elements; fluctuations occurred in the intra-individual amounts of the nail elements over time. In other words, the elements did not show a common trend, such as decreasing or increasing, as the time between samples increased. The fluctuations in elemental amounts over time and the different patterns of inter-elemental correlations were thought to be due to the chemical and geochemical properties of the elements and factors that may affect the exposure status. Differences in element levels may be due to fluctuations in environmental pollution.

The concentrations of Cr, Cu, Zn, As, Se, Cd, Sb, Hg, and Pb found in this study are very similar to the results obtained by Rodushkin and Axelsson (2000) from the fingernails of 96 people living in northern Sweden and the results obtained by Goullé et al. [15] from the fingernails of 130 and 50 people living in France [5,15]. However, our Tl values were 3–6 times higher than the reference values in the study of Goullé et al. [15] and were in harmony with the results of Rodushkin and Axelsson [5]. On the other hand, our Tl levels were 3–15 times lower than the Tl levels measured by Mercan et al. [27] in the fingernails of 5 people living in Istanbul/Türkiye and working with archived historical documents [27]. Although the study by Mercan et al. [27] was an occupational exposure study, we wanted to compare it because there were no other Tl data available in the Turkish literature. The amounts of Cr, Cu, Zn, As, Se, Cd, and Pb we obtained in our study were found to be compatible with the results obtained from the fingernails of 63 people living in Zonguldak, northern Türkiye [28]. The strontium levels in our study ranged from 0.4552 to 2.1789 $\mu\text{g/g}$, and the maximum value may have been due to marine aerosols. This maximum value was within a reference range cited by Rodushkin and Axelsson [5]. These observed variations in Tl and strontium levels compared to the values in the literature indicate that geographical differences are essential in terms of the reference values given in the fingernails.

When we wanted to compare our results regarding the time-dependent variability of metal(loid) levels in fingernails and the correlation between measurements with the literature, we compared them with studies conducted on toenails due to the research gap on this subject. For example, Garland et al. [25] found low to moderate correlations (Spearman's rho 0.33, 0.26, 0.58, 0.58, 0.54, 0.54, 0.48, and 0.56, respectively) for the elements Cr, Cu, Zn, As, Se, and Hg between toenail samples over 6 years. Lin et al. [26] found low or moderate correlations between elemental concentrations over 3 years for Cr, Zn, As, and Pb (rho: 0.21, 0.33, 0.29, and 0.33, respectively) and strong correlations for Cu, Se, and Hg (rho: 0.55, 0.52, and 0.59, respectively) among

toenail samples. Wu et al. [29] reported that the correlations of intra-individual toenail metal levels over time were slightly different for different metals; however, the correlations decreased for all metals with increasing time between samples. In addition, the strong agreement between three intraday repeated measurements of the elements found in our study was similar to the study of Lin et al. [26]. The most significant and notable correlation result in our study was the finding of positive correlations for Cr, Sb, and Se, and negative correlations for Cu and As. The correlation's strength supports using the nail sample as a biomarker. However, the correlation in different directions supports our finding that the concentrations of Cu and As elements were higher in the current/less-retained hand nail samples, while the concentrations of Cr, Sb, and Se elements were higher in the older/aged hand nail samples.

Another correlation we analyzed was the inter-elemental correlations over time; accordingly, the correlation of all measurements made in the 3 years with each other was a very strong positive correlation between Cr and Sb, Cu and As, Sr and Hg; a strong positive correlation between Cd [5] and Hg, Sr and Cd, Se and Pb; Sr and Tl, Hg and Tl; a very strong negative correlation between Cr and Cu, Cr and As, Cu and Sb, As and Sb; a strong negative correlation between Zn and Pb; moderate negative correlation between Zn and Se. Rodushkin et al. [5] mentioned inter-elemental correlations for fingernails and stated that these correlations may be due to the similar chemical properties of the elements as well as their occurrence in nature; therefore, they may be significant in terms of not showing familiar exposure sources. However, their study reported that, in addition to essential elements such as Zn, Cu, and Se, potentially toxic elements, including Cd, Pb, As, and Tl, did not show a significant correlation. Although the reason for the correlations between the elements in our study was not entirely apparent, it was thought that the correlated elements originated from common natural sources and shared similar geochemical properties, which could account for this correlation. Retrospective determination of metal(loid)s accumulated in fingernails is essential in terms of environmental exposure studies as well as forensic toxicology [30]. Accordingly, fingernails can also be used in biomonitoring of metal(loid) exposure and in the diagnosis of poisoning in terms of public health and clinical toxicology. When the results of the study are evaluated in terms of forensic toxicology, it can be said that the analyzed fingernails show an exposure of approximately $12/0.1=120$ days (4 months) ago, assuming that the fingernail grows an average of 0.1 mm

per day and the average thumbnail length is 12 mm [10,13].

4. Conclusion

In this study, the concentrations of Cr, Cu, Zn, As, Se, Sr, Cd, Sb, Hg, Tl, and Pb in fingernails were measured simultaneously by inductively coupled plasma-mass spectrometry (ICP-MS), and the intra-day repeatability and time-dependent variability of the measurements were evaluated. From an analytical toxicology perspective, intraday measurements of nail samples using ICP-MS demonstrated high reproducibility and analytical precision. Additionally, it was found that the time-dependent changes in the measured elements were not linear and that different elements exhibited distinct correlation patterns. However, to make sense of these statistically significant results from a clinical and toxicological perspective, a prospective cohort study should be conducted on a larger population. These prospective studies may reveal both time-dependent and regional changes in the amounts of metal(loid) in fingernails.

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Supplementary Information

Table S1. Characteristics of the samples

	No 1	No 2	No 3	No 4	No 5
Date of collection	30.08.2020	27.09.2020	18.03.2023	11.10.2023	07.11.2023
Date of analysis	27.03.2023	22.11.2023	27.03.2023	22.11.2023	22.11.2023
Age (day)	1150	939	41	14	9
Weight (in 25 mL)	64.5 mg	72.9 mg	65.5 mg	70.9 mg	70.0 mg

Table S2. Comparison of element levels of fingernail samples collected on different dates by Kruskal-Wallis test (n: 3 replicates)

Element	Sample Age (Days)	Mean (SD)	Median (Min-Max)	Kruskal Wallis	p	Significant Difference
Cr	A.1150	0.3706(0.00876)	0.3665(0.36-0.38)	13.500	0.009	A>E
	B.939	0.5517(0.03242)	0.5608(0.52-0.58)			B>E
	C.41	0.3495(0.00933)	0.3535(0.34-0.36)			B>D
	D.14	0.3295(0.00378)	0.3304(0.33-0.33)			
	E.9	0.1287(0.00499)	0.1259(0.13-0.13)			
Cu	A.1150	4.4049(0.06933)	4.3817(4.35-4.48)	12.433	0.014	D>B
	B.939	4.2270(0.16622)	4.1848(4.09-4.41)			E>B
	C.41	4.4467(0.04219)	4.4359(4.41-4.49)			E>A
	D.14	4.6493(0.08426)	4.6417(4.57-4.74)			
	E.9	6.0522(0.23115)	6.0998(5.80-6.26)			
Zn	A.1150	101.3611(3.52930)	102.1464(97.51-104.43)	11.167	0.025	C>A
	B.939	116.3668(7.89732)	112.0139(111.60-125.48)			E>A
	C.41	122.3650(4.85127)	123.9958(116.91-126.19)			C>D
	D.14	101.9337(3.61632)	101.3871(98.62-105.79)			E>D
	E.9	124.0168(5.49279)	125.8456(117.84-128.36)			
As	A.1150	0.0542(0.00127)	0.0536(0.05-0.06)	12.700	0.013	D>B
	B.939	0.0320(0.00276)	0.0313(0.03-0.04)			E>B
	C.41	0.0563(0.00085)	0.0566(0.06-0.06)			E>A
	D.14	0.0570(0.00105)	0.0570(0.06-0.06)			
	E.9	0.0755(0.00316)	0.0762(0.07-0.08)			
Se	A.1150	1.0106(0.14720)	1.0318(0.85-1.15)	11.333	0.023	A>E
	B.939	0.6045(0.06746)	0.6059(0.54-0.67)			A>B
	C.41	0.9350(0.07277)	0.9518(0.86-1.00)			C>E
	D.14	0.9093(0.07373)	0.9001(0.84-0.99)			D>E
	E.9	0.4397(0.03787)	0.4312(0.41-0.48)			
Sr	A.1150	1.8431(0.11894)	1.8157(1.74-1.97)	12.767	0.012	A>D
	B.939	1.4634(0.15483)	1.3811(1.37-1.64)			E>D
	C.41	1.2932(0.09419)	1.2801(1.21-1.39)			E>C
	D.14	0.5167(0.07072)	0.5010(0.46-0.59)			
	E.9	2.0760(0.13292)	2.1231(1.93-2.18)			
Cd	A.1150	0.0390(0.00197)	0.0400(0.04-0.04)	12.167	0.016	A>C
	B.939	0.0327(0.00350)	0.0320(0.03-0.04)			E>B
	C.41	0.0284(0.00221)	0.0287(0.03-0.03)			E>C
	D.14	0.0338(0.00343)	0.0333(0.03-0.04)			
	E.9	0.0545(0.00402)	0.0523(0.05-0.06)			
Sb	A.1150	0.0179(0.00075)	0.0179(0.02-0.02)	12.722	0.013	A>E
	B.939	0.0245(0.00162)	0.0242(0.02-0.03)			B>E
	C.41	0.0176(0.00042)	0.0177(0.02-0.02)			B>D
	D.14	0.0169(0.00040)	0.0171(0.02-0.02)			
	E.9	0.0144(0.00156)	0.0142(0.01-0.02)			
Hg	A.1150	0.2396(0.01223)	0.2350(0.23-0.25)	13.033	0.011	C>A
	B.939	0.0797(0.00369)	0.0812(0.08-0.08)			C>E
	C.41	0.0302(0.00472)	0.0320(0.02-0.03)			D>A

	D.14	0.0353(0.00463)	0.0329(0.03-0.04)			
	E.9	0.1345(0.00971)	0.1322(0.13-0.15)			
Tl	A.1150	0.0053(0.00115)	0.0060(0.00-0.01)	8.353	0.079	-----
	B.939	0.0056(0.00012)	0.0055(0.01-0.01)			
	C.41	0.00520(0.00035)	0.0052(0.00-0.01)			
	D.14	0.0036(0.00015)	0.0036(0.00-0.00)			
	E.9	0.0058(0.00068)	0.0060(0.01-0.01)			
Pb	A.1150	0.5547(0.01455)	0.5595(0.54-0.57)	12.923	0.012	D>E A>B A>E
	B.939	0.1660(0.00361)	0.1641(0.16-0.17)			
	C.41	0.5152(0.00021)	0.5153(0.52-0.52)			
	D.14	0.5475(0.00566)	0.5508(0.54-0.55)			
	E.9	0.2323(0.03078)	0.2379(0.20-0.26)			

Table S3. Correlations between metal levels in the **first** measurements of fingernail samples (Spearman's rho)

	Cr	Cu	Zn	As	Se	Sr	Cd	Sb	Hg	Tl	Pb
Cr	1										
Cu	-1**	1									
Zn	-0.500	0.500	1								
As	-1**	1**	0.500	1							
Se	0.300	-0.300	-0.900*	-0.300	1						
Sr	-0.300	0.300	0.400	0.300	-0.300	1					
Cd	-0.500	0.500	0.000	0.500	-0.100	0.600	1				
Sb	0.975**	-0.975**	-0.616	-0.975**	0.359	-0.410	-0.410	1			
Hg	0.100	-0.100	-0.300	-0.100	0.100	0.600	0.800	0.154	1		
Tl	0.800	-0.800	-0.400	-0.800	0.300	0.300	-0.100	0.718	0.500	1	
Pb	-0.300	0.300	-0.600	0.300	0.800	-0.300	0.100	-0.205	-0.100	-0.300	1

n=5, *p<.05, **p<.01

Table S4. Correlations between metal levels in the **second** measurements of fingernail samples (Spearman's rho)

	Cr	Cu	Zn	As	Se	Sr	Cd	Sb	Hg	Tl	Pb
Cr	1										
Cu	-1**	1									
Zn	-0.100	0.100	1								
As	-0.900*	0.900*	0.500	1							
Se	0.100	-0.100	0.000	0.000	1						
Sr	-0.100	0.100	0.300	0.200	-0.800	1					
Cd	-0.200	0.200	-0.100	0.100	-0.900*	0.900*	1				
Sb	0.975**	-0.975**	0.051	-0.821	0.205	-0.205	-0.359	1			
Hg	0.100	-0.100	-0.300	-0.200	-0.700	0.800	0.900*	-0.103	1		
Tl	0.051	-0.051	0.205	0.051	-0.718	0.975**	0.872	-0.079	0.872	1	
Pb	-0.100	0.100	-0.500	0.000	0.500	-0.200	-0.100	-0.205	0.200	-0.051	1

n=5, *p<.05, **p<.01

Table S5. Correlations between metal levels in the third measurements of fingernail samples (Spearman's rho).

	Cr	Cu	Zn	As	Se	Sr	Cd	Sb	Hg	Tl	Pb
Cr	1										
Cu	-1**	1									
Zn	-0.300	0.300	1								
As	-1**	1**	0.300	1							
Se	0.400	-0.400	-0.900*	-0.400	1						
Sr	0.200	-0.200	0.000	-0.200	0.100	1					
Cd	-0.500	0.500	0.100	0.500	-0.300	0.600	1				
Sb	0.900*	-0.900*	-0.100	-0.900*	0.300	-0.100	-0.800	1			
Hg	0.100	-0.100	-0.100	-0.100	0.000	0.900*	0.800	-0.300	1		
Tl	-0.100	0.100	0.900*	0.100	-0.700	0.400	0.200	0.000	0.200	1	
Pb	-0.100	0.100	-0.900*	0.100	0.800	0.100	0.200	-0.300	0.200	-0.800	1

N=5, *p<.05, **p<.01

RAW DATA

Certified Reference Materials, Replicates, Accuracy and Precision

Table S6. ICP-MS results obtained from European Reference Material (fish muscle, ERM- BB422, n=3).

	Certified Amount [mg/kg]	Certified S.D.	Certified R.S.D. (%)	Found Amount [mg/kg]	Found S.D.	Found R.S.D. (%)	Bias (%)	Recovery (%)
55 Mn [He]	0,368	0,028	7,6	0,381	0,015	3,9	3,5	103,5
56 Fe [He]	9,4	1,4	14,9	9,5	0,5	5,3	1,1	101,1
63 Cu [He]	1,67	0,16	9,6	1,68	0,08	4,8	0,6	100,6
66 Zn [He]	16,0	1,1	6,9	15,5	0,5	3,2	3,1	96,9
75 As [He]	12,7	0,7	5,5	13,5	0,5	3,7	6,3	106,3
78 Se [He]	1,33	0,13	9,8	1,44	0,06	4,2	8,3	108,3
111 Cd [He]	0,0075	0,0018	24,0	0,0080	0,0004	5,0	6,7	106,7
202 Hg [He]	0,601	0,03	5,0	0,483	0,021	4,3	19,6	80,4

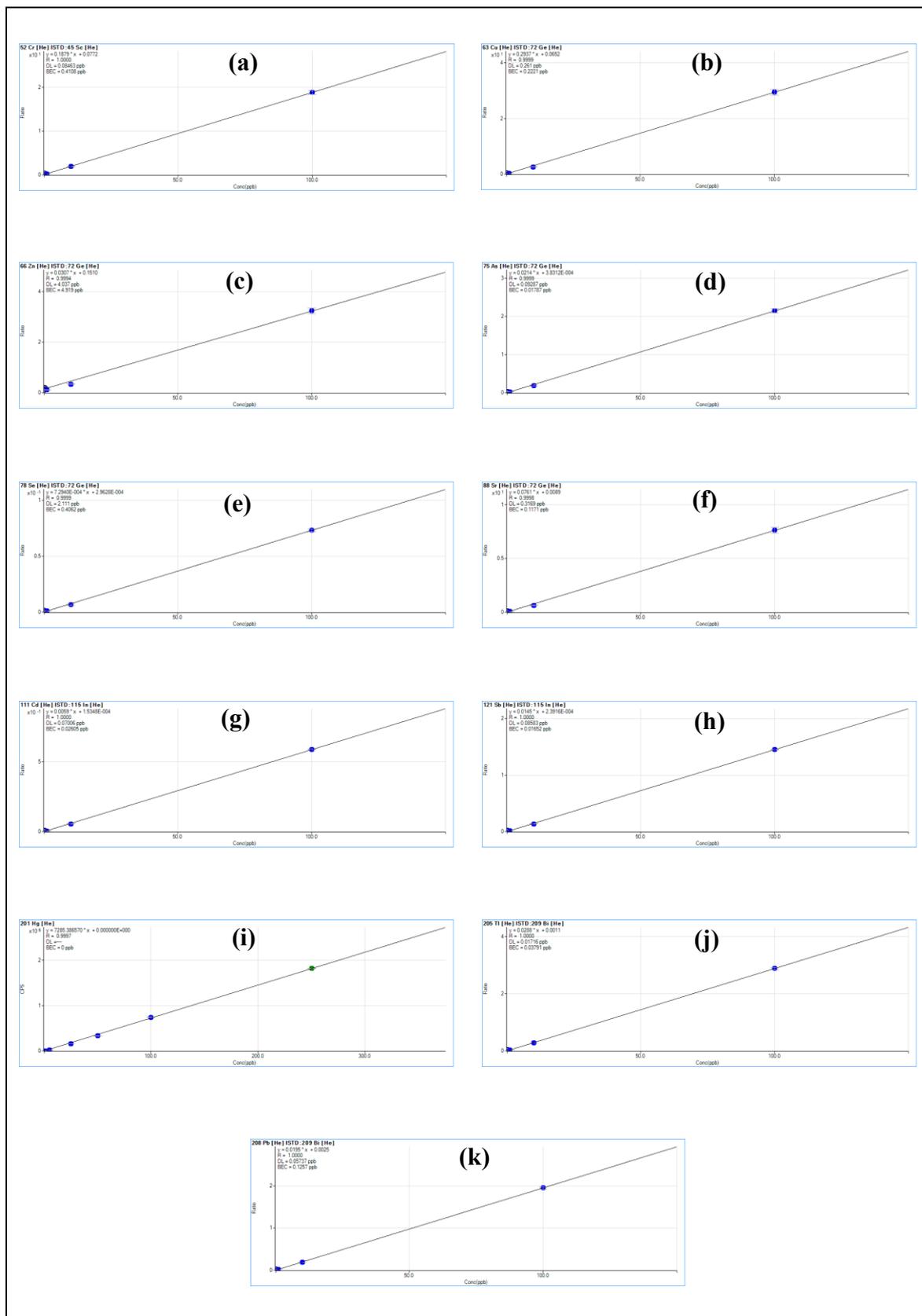


Figure S1. Calibration plots of the standards used in ICP-MS analyses dated March 27, 2023: ^{52}Cr (a), ^{63}Cu (b), ^{66}Zn (c), ^{75}As (d), ^{78}Se (e), ^{88}Sr (f), ^{111}Cd (g), ^{121}Sb (h), ^{201}Hg (i), ^{205}Tl (j), and ^{208}Pb (k).

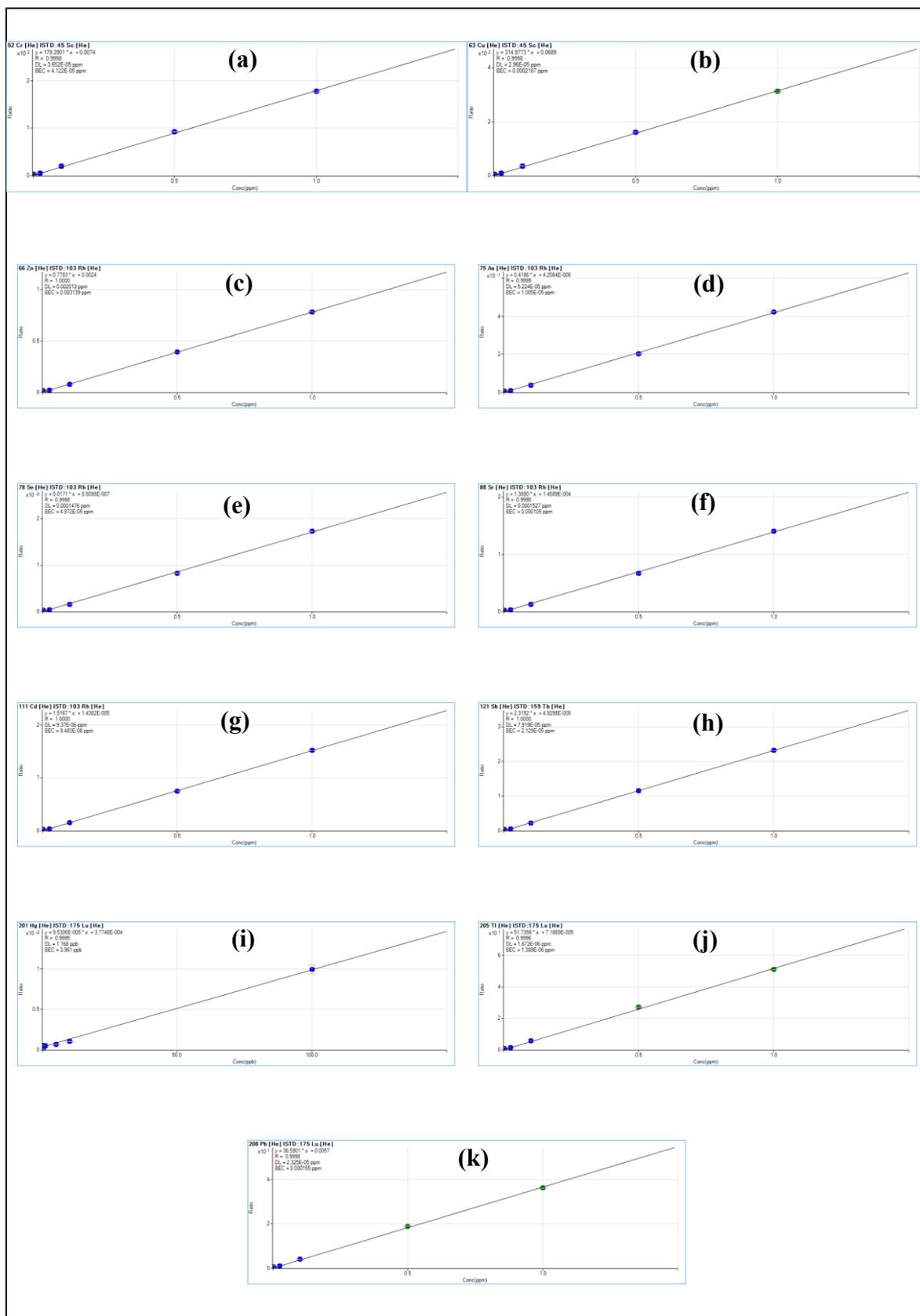


Figure S2. Calibration plots of the standards used in ICP-MS analyses dated November 22, 2023: ^{52}Cr (a), ^{63}Cu (b), ^{66}Zn (c), ^{75}As (d), ^{78}Se (e), ^{88}Sr (f), ^{111}Cd (g), ^{121}Sb (h), ^{201}Hg (i), ^{205}Tl (j), and ^{208}Pb (k).