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Precious metals – Determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS or ICP-Q-MS

Biomonitoring Method – Translation of the German version from 2024

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Abstract

The working group "Analyses in Biological Materials" of the German Senate Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area (MAK Commission) developed and verified the presented biomonitoring method for the determination of urinary concentrations of gold, silver, platinum, rhodium, and iridium using high-resolution inductively coupled plasma–sector-field mass spectrometry (ICP-SF-MS) or inductively coupled plasma-single quadrupole mass spectrometry (ICP-Q-MS). The aim of this work was to establish a reliable, selective and sensitive method which is suitable for routine analysis in laboratories with high sample throughput. The method is characterised by diluting the urine samples 1 : 5 (v/v) with 10% *aqua regia*, addition of terbium as internal standard, and determination of the concentrations of the respective precious metals by ICP-SF-MS or ICP-Q-MS. The procedure has been comprehensively validated by ICP-SF-MS, and the reliability data have been confirmed by replication and verification of the procedure in a second, independent laboratory using ICP-Q-MS. Quantitative evaluation is carried out via external calibration using precious-metal standards diluted with 10% *aqua regia*. The good precision and accuracy data show that the method provides reliable and accurate analytical results. The method is both selective and sensitive, and the limits of quantitation of 12.3–18.5 ng/l

urine (ICP-SF-MS) or of 12.5 ng/l urine (ICP-Q-MS) are sufficient to determine occupational exposure to gold, silver, platinum, rhodium, and iridium and, in individual cases, exposure in the general population as well.

1 Characteristics of the method

Matrix	Urine
Analytical principle	Inductively coupled plasma-sector-field mass spectrometry (ICP-SF-MS) or inductively coupled plasma-single quadrupole mass spectrometry (ICP-Q-MS)

Parameters and corresponding hazardous substances

Hazardous substance	CAS No.	Parameter	CAS No.
Gold and its compounds	7440-57-5	Gold	7440-57-5
Silver and its compounds	7440-22-4	Silver	7440-22-4
Platinum and its compounds	7440-06-4	Platinum	7440-06-4
Rhodium and its compounds	7440-16-6	Rhodium	7440-16-6
Iridium and its compounds	7439-88-5	Iridium	7439-88-5

Reliability criteria

Gold (^{197}Au) by ICP-SF-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng gold per litre of urine and n = 9 or n = 10 determinations	s_w = 14.1% or 3.32% u = 32.5% or 7.51%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng gold per litre of urine and n = 10 determinations	s_w = 17.1% or 8.35% u = 38.7% or 18.9%
Accuracy:	Recovery (rel.) at a spiked concentration of 125 ng or 500 ng gold per litre of urine and n = 10 determinations	r = 84.2% or 89.0%
Limit of detection:	4.72 ng gold per litre of urine	
Limit of quantitation:	15.6 ng gold per litre of urine	

Silver (^{107}Ag) by ICP-SF-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng silver per litre of urine and n = 10 determinations	s_w = 9.21% or 6.09% u = 20.8% or 13.8%

Day-to-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng silver per litre of urine and n = 10 determinations	s_w = 13.3% or 12.0% u = 30.1% or 27.1%
Accuracy:	Recovery (rel.) at a spiked concentration of 125 ng or 500 ng silver per litre of urine and n = 10 determinations	r = 67.5% or 70.0%
Limit of detection:	3.75 ng silver per litre of urine	
Limit of quantitation:	12.4 ng silver per litre of urine	

Silver (^{109}Ag) by ICP-SF-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng silver per litre of urine and n = 10 determinations	s_w = 5.53% or 6.44% u = 12.5% or 14.6%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng silver per litre of urine and n = 10 determinations	s_w = 12.1% or 10.9% u = 27.4% or 24.7%
Accuracy:	Recovery (rel.) at a spiked concentration of 125 ng or 500 ng silver per litre of urine and n = 10 determinations	r = 68.8% or 69.7%
Limit of detection:	4.57 ng silver per litre of urine	
Limit of quantitation:	15.1 ng silver per litre of urine	

Platinum (^{194}Pt) by ICP-SF-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng platinum per litre of urine and n = 10 determinations	s_w = 6.62% or 2.76% u = 15.0% or 6.24%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng platinum per litre of urine and n = 10 determinations	s_w = 7.51% or 7.49% u = 17.0% or 16.9%
Accuracy:	Recovery (rel.) at a spiked concentration of 125 ng or 500 ng platinum per litre of urine and n = 10 determinations	r = 88.2% or 87.9%
Limit of detection:	5.43 ng platinum per litre of urine	
Limit of quantitation:	17.9 ng platinum per litre of urine	

Platinum (^{195}Pt) by ICP-SF-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng platinum per litre of urine and n = 10 determinations	s_w = 7.49% or 4.78% u = 16.9% or 10.8%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng platinum per litre of urine and n = 10 determinations	s_w = 4.37% or 6.60% u = 9.88% or 14.9%
Accuracy:	Recovery (rel.) at a spiked concentration of 125 ng or 500 ng platinum per litre of urine and n = 10 determinations	r = 88.8% or 87.7%
Limit of detection:	5.60 ng platinum per litre of urine	
Limit of quantitation:	18.5 ng platinum per litre of urine	

Rhodium (^{103}Rh) by ICP-SF-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng rhodium per litre of urine and n = 10 determinations	s_w = 7.99% or 1.54% u = 18.1% or 3.48%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng rhodium per litre of urine and n = 10 determinations	s_w = 10.5% or 12.5% u = 23.8% or 28.3%
Accuracy:	Recovery (rel.) at a spiked concentration of 125 ng or 500 ng rhodium per litre of urine and n = 10 determinations	r = 81.8% or 75.1%
Limit of detection:	4.28 ng rhodium per litre of urine	
Limit of quantitation:	14.1 ng rhodium per litre of urine	

Iridium (^{193}Ir) by ICP-SF-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng iridium per litre of urine and n = 9 or n = 10 determinations	s_w = 3.68% or 0.908% u = 8.49% or 2.06%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a spiked concentration of 125 ng or 500 ng iridium per litre of urine and n = 10 determinations	s_w = 5.43% or 6.99% u = 12.3% or 15.8%
Accuracy:	Recovery (rel.) at a spiked concentration of 125 ng or 500 ng iridium per litre of urine and n = 10 determinations	r = 89.1% or 92.4%
Limit of detection:	3.73 ng iridium per litre of urine	
Limit of quantitation:	12.3 ng iridium per litre of urine	

Gold (^{197}Au) by ICP-Q-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng gold per litre of artificial urine and n = 5 determinations	s_w = 2.40%, 1.31%, 1.52%, or 1.46% u = 6.66%, 3.64%, 4.22%, or 4.05%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng gold per litre of artificial urine and n = 3 determinations	s_w = 5.3%, 3.9%, 2.0%, or 2.1% u = 22.8%, 16.8%, 8.6%, or 9.0%
Accuracy:	Recovery (rel.) at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng gold per litre of artificial urine and n = 3 determinations	r = 101%, 101%, 101%, or 101%
Limit of quantitation:	12.5 ng gold per litre of urine	

Silver (^{107}Ag) by ICP-Q-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng silver per litre of artificial urine and n = 5 determinations	s_w = 1.65%, 2.47%, 0.625%, or 0.705% u = 4.58%, 6.86%, 1.74%, or 1.96%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng silver per litre of artificial urine and n = 3 determinations	s_w = 2.3%, 2.6%, 1.2%, or 1.9% u = 9.9%, 11.2%, 5.2%, or 8.2%
Accuracy:	Recovery (rel.) at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng silver per litre of artificial urine and n = 3 determinations	r = 101%, 102%, 101%, or 102%
Limit of quantitation:	12.5 ng silver per litre of urine	

Platinum (^{195}Pt) by ICP-Q-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng platinum per litre of artificial urine and n = 5 determinations	s_w = 3.05%, 2.03%, 0.768%, or 1.09% u = 8.47%, 5.64%, 2.13%, or 3.03%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng platinum per litre of artificial urine and n = 3 determinations	s_w = 3.6%, 2.5%, 1.5%, or 1.4% u = 15.5%, 10.8%, 6.5%, or 6.0%
Accuracy:	Recovery (rel.) at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng platinum per litre of artificial urine and n = 3 determinations	r = 100%, 100%, 98.9%, or 98.8%
Limit of quantitation:	12.5 ng platinum per litre of urine	

Rhodium (^{103}Rh) by ICP-Q-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng rhodium per litre of artificial urine and n = 5 determinations	s_w = 2.70%, 2.00%, 0.702%, or 0.800% u = 7.50%, 5.55%, 1.95%, or 2.22%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng rhodium per litre of artificial urine and n = 3 determinations	s_w = 3.3%, 2.3%, 0.9%, or 1.1% u = 14.2%, 9.9%, 3.9%, or 4.7%
Accuracy:	Recovery (rel.) at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng rhodium per litre of artificial urine and n = 3 determinations	r = 95.5%, 98.9%, 102%, or 103%
Limit of quantitation:	12.5 ng rhodium per litre of urine	

Iridium (^{193}Ir) by ICP-Q-MS

Within-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng iridium per litre of artificial urine and n = 5 determinations	s_w = 2.57%, 0.861%, 0.784% or 1.04% u = 7.13%, 2.39%, 2.18%, or 2.89%
Day-to-day precision:	Standard deviation (rel.) Prognostic range at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng iridium per litre of artificial urine and n = 3 determinations	s_w = 2.7%, 1.0%, 1.5%, or 1.7% u = 11.6%, 4.3%, 6.5%, or 7.3%
Accuracy:	Recovery (rel.) at a concentration of 40 ng, 75 ng, 375 ng or 1000 ng iridium per litre of artificial urine and n = 3 determinations	r = 101%, 100%, 98.6%, or 98.3%
Limit of quantitation:	12.5 ng iridium per litre of urine	

2 General information on gold, silver, platinum, rhodium, and iridium

The precious metals gold and silver, as well as the platinum-group metals platinum, rhodium, and iridium, are some of the rarest elements in the Earth's crust and are often characterised as ultra-trace elements. They exhibit similar chemical and physical properties; among other characteristics, they form coloured compounds, can exist in many oxidation states, can form complexes, and—with the exception of gold—are good catalysts (Renner et al. 2018). Moreover, they have high melting and boiling points (Sitzmann 2013). Due to the increasing use of precious metals in modern electronics and automotive catalysts as well as in the field of medicine, increased exposure in affected workplaces can be assumed as well as an increased release into the environment. Due to expectedly low concentrations, the determination of precious metals in biological matrices, such as urine, presents a considerable analytical challenge.

Gold (Au, atomic number: 79, rel. atomic mass: 197.0) is a yellow, shiny, highly ductile, and stable precious metal with a melting point of 1064 °C. At 4 µg/kg in the Earth's crust, gold is one of the rarest elements and primarily occurs native and, in most cases, as an alloy with silver. The only naturally occurring isotope of gold has the relative atomic mass of 197 and takes the oxidation states –I, 0, +I, +II, +III, and +V, whereby 0, +I, and +III are the most stable and most frequent (Sitzmann 2011). Gold is either produced in or imported into the European Economic Area in amounts of ≥ 100 to < 1000 t/a (ECHA 2023 a). From a technical standpoint, the most important gold compound is tetrachloroauric(III) acid (CAS No. 16903-35-8), from which almost all other gold compounds are produced (Greim 2006). Since pure gold is not very hard, it is often alloyed with silver, copper, nickel, cadmium, indium, tin, zinc, platinum, or palladium. Gold

is primarily used in the production of jewellery and coins (Begerow et al. 2001) as well as in alloys for dental prostheses in combination with silver, copper, platinum, palladium, gallium, indium, and zinc (Sitzmann 2011). Furthermore, certain gold compounds (aurothioglucose, aurothiomalate, and auranofin) are also employed as therapeutic agents in the treatment of rheumatoid arthritis (Benemann et al. 2004).

It can be assumed that bioavailable gold ions are released only in very small amounts from gold and its alloys. Both intraperitoneally and intramuscularly applied gold compounds as well as orally ingested, soluble gold compounds are absorbed and transported through the blood stream primarily to the kidneys, the liver, the spleen, and the lungs, whereby the main target organs for toxicological effects are the kidneys (Greim 2006). In an environmental survey from the year 1998, a clear correlation could be found between the presence of gold-containing dentures and the gold concentration in the urine, whereby it was shown that the 99th percentiles of the gold concentrations, depending on the number of teeth with a gold-containing filling, lied between 665 and 872 ng gold/l urine (Benemann et al. 2004). Environmental gold concentrations in urine samples of adults (n = 21) lied between 10 and 310 ng/l and for children (n = 262) and adolescents (n = 17) they ranged from 20–880 ng/l (Begerow et al. 1999 a) and from 10–39 ng/l (Begerow et al. 1999 b). Soluble, inorganic gold compounds are considered to be skin-sensitising substances (Greim 2006) and were therefore designated with an "Sh" by the Commission (DFG 2023). To date, there are no suitable data for the establishment of a MAK or BAT value for gold and its compounds.

Representative levels of gold in the urine of occupationally exposed persons are shown in Table 1. Table 2 provides examples of gold concentrations in the urine of the non-exposed general population.

Tab. 1 Gold concentrations in urine samples from occupationally exposed persons

Occupational group (number of persons; country)	Gold [ng/l]		References
	Mean	Range	
Dental technicians (27; Germany)	195.3	12.3–1106.1	Begerow et al. 1999 b
Road-construction workers (17; Germany)	33.6	14.3–108.9	

Tab. 2 Gold concentrations in urine samples from the general population

Study collective (number of persons; country)	Gold [ng/l]		References
	Mean	Range	
Adults (1080; Germany)	81.6	13.2[a)]–2120	Becker et al. 2002
Adults with more than 8 teeth containing dental precious metals (140; Germany)	115	18.2[a)]–916	
Adults (87, of which 80 < LOQ; Germany)	27[b)]	LOQ (24)–340	Heitland and Köster 2006
Adults (102, of which 90 < LOQ; Germany)	< LOQ (13)[b)]	< LOQ (13)–300	Heitland and Köster 2021

LOQ: limit of quantitation
[a)] 10th percentile
[b)] Concentrations below the LOQ were included in the calculation as LOQ/2.

Silver (Ag, atomic number: 47, relative atomic mass: 107.9) is a soft, shimmery-white transition metal which melts at 961 °C. Silver occurs primarily in ores such as acanthite (Ag_2S) but also in its solid form. In addition to natural silver with the stable isotopes ^{107}Ag (51.8%) and ^{109}Ag (48.2%), there are numerous known artificial isotopes with relative atomic masses between 102 and 117 (Brumby et al. 2008).

Silver is produced in or imported into the European Economic Area in amounts of ≥ 10 000 to < 100 000 t/a (ECHA 2023 b). Industrially, silver is used for surface coatings, as a catalyst, or as an alloy additive. It is also used in the electronics industry, in the manufacture of coins and medals, in jewellery production, and in dental alloys (Sitzmann 2007 b).

In the workplace, silver is mainly absorbed into the body via the inhalation of dusts as well as via gastrointestinal absorption; it may, however, also penetrate directly into the skin in the form of small metal particles (Henschler 1973). Excretion takes place almost completely with the faeces, while excretion with the urine is only of secondary importance (ATSDR 1990; Mertens et al. 2023). Larger amounts of silver are observed in the body bound as silver albuminate and are distributed via the bloodstream or lymphatic system before being deposited as silver sulfide in the tissue, primarily in the reticuloendothelial system (Gammill et al. 1950). This local or systemic deposition of silver in the skin, mucous membranes (especially of the eyes), and in the internal organs ("argyrosis") is irreversible and cannot be treated. Since argyrosis, however, does not lead to detectable, specific organ changes or any pathological findings, it is not actually a form of poisoning, but rather a merely cosmetically disadvantageous effect (Henschler 1973). It can generally be assumed that background exposure to silver has increased in recent years, mostly due to the use of silver nanoparticles to which an antibacterial effect is attributed. With a size of 1–100 nm, these silver particles are used as antibacterial coatings in food storage, e.g. in refrigerators and freezers, but can also be found in foot and shoe sprays, in T-shirts, and in bandaging, throat, and hair sprays (Bachler et al. 2013) and can thereby be taken up orally and dermally as well as by inhalation. The Commission has established a MAK value for silver of 0.1 mg/m^3 for the inhalable fraction (peak limitation category II; excursion factor of 8) (DFG 2023).

Exemplary levels of silver in the urine of occupationally exposed persons are shown in Table 3. Table 4 provides an overview of silver concentrations in the urine of the non-exposed general population.

Tab. 3 Silver concentrations in urine samples from occupationally exposed persons

Occupational group (number of persons/ controls; country)	Silver [ng/l]		References
	Mean ± standard deviation	Range	
Workers in indium-ingot production (57; China)	140 ± 50	40–250	Liu et al. 2021
Controls (63; China)	100 ± 30	40–200	
Workers in precious metal-powder production (27; USA)	11 300	500–52 000	Rosenman et al. 1987

Tab. 4 Silver concentrations in urine samples from the general population

Study collective (number of persons; country)	Silver concentration [ng/l]		References
	Mean	Range	
Adults (55, of which 33 < LOQ; Italy)	0.08[a)]	0.05–0.16	Chellini et al. 2017
Adults (87, of which 80 < LOQ; Germany)	< LOQ (8)[b)]	LOQ (8)–80	Heitland and Köster 2006
Adults (102, of which 97 < LOQ; Germany)	< LOQ (14)[b)]	< LOQ (14)–22	Heitland and Köster 2021

LOQ: limit of quantitation
[a)] geometric mean
[b)] Concentrations below the LOQ were included in the calculation as LOQ/2.

Platinum (Pt, atomic number: 78, relative atomic mass: 195.1) is a grey or shimmery-silver metal which is not very hard, but tough, and has a melting point of 3827 °C. With a concentration of 5 µg/kg in the Earth's uppermost crust, platinum ranks 76th in frequency, close to palladium and gold. The natural isotopes of platinum possess the following relative atomic masses (prevalence): ^{190}Pt (0.01%), ^{192}Pt (0.79%), ^{194}Pt (32.9%), ^{195}Pt (33.8%), ^{196}Pt (25.3%), and ^{198}Pt (7.2%). Platinum usually occurs in association with other platinum-group metals, either as solid platinum or as a mineral such as sperrylite ($PtAs_2$), geversite ($PtSb_2$), cooperite (PtS), or iridium platinum (Sitzmann 2006 b). In its compounds, platinum is present in oxidation states 0 to +VI, whereby +II and +IV are the most frequent. Platinum has a strong tendency to form coordination compounds (platinates) and occurs in solutions exclusively in this form (Begerow et al. 2001).

Platinum is produced in or imported into the European Economic Area in amounts of ≥ 100 to < 1000 t/a (ECHA 2022 a). Chloro complexes of platinum, especially hexachloroplatinic(IV) acid and its ammonium and alkaline salts, which are relatively stable in aqueous solutions, are of special importance in the manufacture and further processing of platinum (Alt et al. 1994). Among other applications, finely dispersed platinum is used, due to its good catalytic properties, in numerous industrial processes, such as nitric acid production and ammonia synthesis (Rüdel and Reher 2004), as well as in petrochemical procedures and is also used in automotive catalysts (Sitzmann 2006 b). Due to its high melting point and corrosion resistance, platinum is also used in the production of electrical switching contacts, heat conductors, and thermocouples as well as in medical and technical devices and in the production of jewellery (Rüdel and Reher 2004). Certain platinum compounds such as cisplatin (*cis*-[$PtCl_2(NH_3)_2$]), carboplatin, spiroplatin, or iproplatin are used as cytostatic drugs in the treatment of tumours (Alt et al. 1994). Moreover, according to manufacturer specifications, some dental alloys contain up to 20% platinum (Begerow et al. 1997 b).

In the workplace, platinum and its compounds are usually taken up by inhalation or, to a much lesser extent, via oral or dermal routes. Soluble platinum compounds are thereby easily absorbed and excreted with the urine within 24 hours after absorption (20–45%). In the workplace, inhalation and dermal exposure to halogen-containing platinum-complex compounds, such as hexa- and tetrachloroplatinates, may have sensitising effects on airways and skin (Schramel et al. 1999). For this reason, the chloroplatinates were designated with "Sah" by the Commission and a peak concentration of 2 µg/m³ (as platinum) should not be exceeded (DFG 2023).

Table 5 shows the urinary platinum concentrations of occupationally exposed persons from various areas of operation. Table 6 provides an overview of platinum concentrations in the urine of the non-exposed general population.

Tab. 5 Platinum concentrations in urine samples from occupationally exposed persons

Occupational group (number of persons/ controls; country)	Platinum [ng/l], unless otherwise specified		References
	Mean ± standard deviation	Range	
Workers in catalyst production (19; Germany)	950	23–9200	Angerer and Schaller 1993
Workers in platinum-catalyst production (34; Germany)	–	16–6270 ng/g creatinine	Schierl et al. 1998
Workers in platinum-catalyst recycling (5; Germany)	320	20–630	Angerer and Schaller 1993
Workers in the processing of platinum nozzles (16; Germany)	214	10–2900	Angerer and Schaller 1993
Hospital personnel (21; Germany)	–	< 1.8–34.4	Ensslin et al. 1994
Dental technicians (27; Germany)	25.7	0.8–167.8	Begerow et al. 1999 b
Road-construction workers (17; Germany)	0.9	0.2–4.4	Begerow et al. 1999 b
Bus drivers (29; Germany)	2.8	1.0–40	Schierl et al. 1994
TÜV testers (13; Germany)	2.2	0.5–21.0	Schierl et al. 1994
Motorway-maintenance workers (18; Germany)	–	< 1.0–6.6	Schaller et al. 1996
Motorway-maintenance workers (10; United Kingdom)	58 ng/g creatinine	22–135 ng/g creatinine	Farago et al. 1998
Taxi drivers (10; Germany)	1.3	1.0–28	Schierl et al. 1994
Streetcar operators (67; Italy)	3.55 ± 5.42 ng/g creatinine	0.22–27.61 ng/g creatinine	Iavicoli et al. 2007
Precious-metal refinery workers (118; South Africa)	0.28[a)]	0.22–0.36	Linde et al. 2018 a
Precious-metal refinery workers with direct exposure via skin/respiratory tract (89; South Africa)	285 ng/g creatinine	220–369 ng/g creatinine	Linde et al. 2018 b

Tab. 5 *(continued)*

Occupational group (number of persons/ controls; country)	Platinum [ng/l], unless otherwise specified		References
	Mean ± standard deviation	Range	
Precious-metal refinery workers (7; United Kingdom)	47 ng/g creatinine	21–118 ng/g creatinine	Farago et al. 1998
Waste-incineration plant workers (26; Italy)	7.21[b)]	–	Bena et al. 2020
Controls (9; Italy)	2.84[b)]	–	

TÜV: Technischer Überwachungsverein (technical inspection association)
[a)] geometric mean
[b)] median

Tab. 6 Platinum concentrations in urine samples from the general population

Study collective (number of persons; country)	Platinum [ng/l], unless otherwise specified		References
	Mean ± standard deviation	Range	
Adults (14; Germany)	1.1	0.5–14.3	Messerschmidt et al. 1992
Adults (16; Germany)	1.7	0.5–7.7	Begerow et al. 1996
Adults (21; Germany)	1.8 ng/g creatinine	0.5–7.7 ng/g creatinine	Begerow et al. 1997 a
Adults (10; Germany)	5.4	1.2–35	Schramel et al. 1995
Adults (12; Germany)	6.3	2.1–17.4	Begerow et al. 1999 b
Adults (12; Germany)	–	1–12 ng/g creatinine	Schierl et al. 1998
Adults without gold dental fillings (20; Germany)	1.2	0.9–6.6	Phillipeit and Angerer 1998
Adults with gold dental fillings (26; Germany)	23.1	0.9–151.2	Phillipeit and Angerer 1998
Adults (63; China)	0.10 ± 0.03	0.04–0.20	Liu et al. 2021
Adults (49; Italy)	4.64 ± 3.28	0.53–10.79	Iavicoli et al. 2004
Adults (218; Germany)	2.42 ng/g creatinine[a)]	0.08–188 ng/g creatinine	Munker et al. 2016
Adults (1080, of which 25 < LOQ; Germany)	5.58	0.50[b)]–185.3	Benemann et al. 2004
Adults with more than 8 teeth containing dental precious metals (136; Germany)	11.45	0.80[b)]–98.10	
Adults (55, of which 33 < LOQ; Italy	0.019[c)]	0.01–0.04	Chellini et al. 2017
Adults (87, of which 81 < LOQ; Germany)	11[d)]	LOQ (9)–120	Heitland and Köster 2006
Adults (63, of which 59 < LOQ; Germany)	6[d)]	LOQ (10.5)–26	Heitland and Köster 2004
Adults (102, of which 97 < LOQ; Germany)	< LOQ (15)[d)]	< LOQ (15)–87	Heitland and Köster 2021

LOQ: limit of quantitation
[a)] median
[b)] 10th percentile
[c)] geometric mean
[d)] Concentrations below the LOQ were included in the calculation as LOQ/2.

Rhodium (Rh, atomic number: 45, relative atomic mass: 102.9), a platinum-group metal, is a silvery-white, tough and malleable metal with a melting point of 1963 °C. ^{103}Rh is the only natural isotope of rhodium and occurs mainly in the oxidation state +III, but also in all oxidation states from –I to +VI (Sitzmann 2007 a). Alongside iridium, rhodium is the most chemically resistant platinum metal (IFA 2024). Rhodium occurs in nature in its solid form and can form numerous coordination compounds. In addition to rhodium(III) chloride, which is applied as a catalyst in reduction

reactions, polymerisations, isomerisations, and other chemical syntheses, primarily organic rhodium complexes, such as chlorotris(triphenylphosphine)rhodium(I) ($RhCl[P(C_6H_5)_3]_3$), are known to be excellent catalysts. For this reason, rhodium is widely used in catalytic converters, whereby a certain amount of rhodium is assumed to be released into the environment (Alt et al. 2001). Furthermore, rhodium is used as an alloy additive to platinum and palladium for shells of high-temperature laboratory furnaces or for welding electrodes in space technology, among other applications. Other uses for rhodium alloys include jewellery manufacture and the production of electrical contacts and switches. Rhodium is also employed for the galvanisation of mirrors for optical devices (Rinkovec 2019).

Rhodium is produced in or imported into the European Economic Area in amounts of ≥ 10 to < 100 t/a (ECHA 2022 b).

Rhodium is primarily taken up by ingestion or inhalation of rhodium-containing dust. It is known that rhodium trichloride is genotoxic and possibly also carcinogenic. For this reason, the Commission designated rhodium trichloride and, by analogy, rhodium and its inorganic compounds as Category 3 carcinogens in the List of MAK and BAT Values (DFG 2023). Another finding which contributed to this classification is the fact that rhodium complexes possess a cytostatic effect similar to those of platinum complexes. The Commission currently has no suitable data on the toxicokinetics and metabolism in humans or for the establishment of a MAK or BAT value for rhodium and its compounds (Greim 2007).

Representative levels of rhodium in the urine of occupationally exposed persons from various areas of operation are shown in Table 7. Table 8 provides rhodium concentrations in the urine of the non-exposed general population.

Tab. 7 Rhodium concentrations in urine samples from occupationally exposed persons

Occupational group (number of persons/ controls; country)	Rhodium [ng/l], unless otherwise specified		References
	Mean ± standard deviation	Range	
Streetcar operators (61; Italy)	21.73 ± 10.73 ng/g creatinine	2.54–48.81 ng/g creatinine	Iavicoli et al. 2007
Waste-incineration plant workers (26; Italy)	20.26[a)]	–	Bena et al. 2020
Controls (9; Italy)	12.55[a)]	–	

a) median

Tab. 8 Rhodium concentrations in urine samples from the general population

Study collective (number of persons; country)	Rhodium [ng/l], unless otherwise specified		References
	Mean	Range	
Adults (217; Germany)	7.27 ng/g creatinine[a)]	2.54–19.4 ng/g creatinine	Munker et al. 2016
Adults (102, all < LOQ; Germany)	< LOQ (13)	< LOQ (13)	Heitland and Köster 2021

LOQ: limit of quantitation
a) median

Iridium (Ir, atomic number: 77, relative atomic mass: 192.2), a platinum-group element, is a silvery-white precious metal which is very hard, though brittle, and has a melting point of 2446 °C. ^{191}Ir (37.3%) and ^{193}Ir (62.7%) are the only naturally occurring isotopes and are mostly present in the oxidation states 0, +III, and +IV, whereby all states between 0 and +VI have been observed (Sitzmann 2006 a). Due to its high corrosion resistance, iridium is frequently used in the electronics industry and is further used together with platinum, palladium, and rhodium in automotive catalysts (Iavicoli and Leso 2022). Furthermore, iridium alloys are employed, for example, in the production of jewellery, injection needles, instrument parts, electrical contacts, and dental alloys. In the chemical industry, iridium also serves as a catalyst, and in the medical field, it is applied as ^{192}Ir for cancer treatment (Begerow et al. 2008).

Iridium is produced in or imported into the European Economic Area in amounts of ≥ 1 to < 10 t/a (ECHA 2021).

At this time, there is only limited knowledge on exposure in the general population (Iavicoli and Leso 2022). To date, there are no suitable data for the establishment of a MAK or BAT value for iridium and its compounds.

Table 9 shows urinary iridium concentrations in occupationally exposed persons from various areas of operation. Table 10 shows representative urinary iridium concentrations in the non-exposed general population.

Tab. 9 Iridium concentrations in urine samples from occupationally exposed persons

Occupational group (number of persons/ controls; country)	Iridium [ng/l]		References
	Mean ± standard deviation	Range	
Waste-incineration plant workers (26; Italy)	1.13[a)]	–	Bena et al. 2020
Controls (9; Italy)	1.00[a)]	–	
Streetcar operators (64; Italy)	13.8 ± 15.7	1.14–53.2	Iavicoli et al. 2008
Controls (58; Italy)	13.4 ± 10.8	2.00–38.6	

[a)] median

Tab. 10 Iridium concentrations in urine samples from the general population

Study collective (number of persons; country)	Iridium [ng/l]		References
	Mean	Range	
Adults (1080, of which 257 < LOQ; Germany)	0.41	0.1[a)]–16.5	Benemann et al. 2004
Adults (102, all < BG; Germany)	< LOQ (9)	< LOQ (9)	Heitland and Köster 2021

LOQ: limit of quantitation
[a)] 10th percentile

3 General principles

The method described herein is used to determine the urinary concentrations of gold, silver, platinum, rhodium, and iridium with high-resolution ICP-SF-MS or on an ICP-MS/MS device operated in single quadrupole mode (ICP-Q-MS). Sample preparation consists of diluting urine samples 1 : 5 (v/v) with 10% *aqua regia*. The urine samples thus diluted are then mixed with terbium, which serves as internal standard (ISTD), and the analyte concentration is determined by ICP-SF-MS or ICP-Q-MS. External calibration is carried out using single-element standards diluted in 10% *aqua regia*, whereby ultra-pure water (ICP-SF-MS) or artificial urine (ICP-Q-MS) is used.

4 Equipment, chemicals, and solutions

4.1 Equipment

- ICP-SF mass spectrometer (e.g. ELEMENT-2, Thermo Fisher Scientific GmbH, Dreieich, Germany)
- ICP-MS/MS device, operated in single quadrupole mode (e.g. iCAP™ TQ, Thermo Fisher Scientific GmbH, Dreieich, Germany)
- ICP mass spectrometer (e.g. iCAP™ Q, Thermo Fisher Scientific GmbH, Dreieich, Germany)
- Piston-stroke pipettes with variably adjustable volumes of 10–100 µl, 100–1000 µl, or 1000–10 000 µl with matching pipette tips (e.g. Eppendorf AG, Hamburg, Germany)
- 125-ml PTFE or FEP-Nalgene® bottles (e.g. No. 2103-0004 or 2100-0004, Thermo Fisher Scientific GmbH, Dreieich, Germany)
- 10-ml and 40-ml quartz-glass tubes (e.g. Gaßner Glastechnik GmbH, Oberhaching, Germany)

- 15-ml and 50-ml polypropylene tubes (e.g. No. 91017 and 91056, TPP Techno Plastic Products AG, Trasadingen, Switzerland)
- 250-ml urine-collection bottles made of high-density polyethylene (HD-PE) with threaded tops (e.g. No. 77.577, Sarstedt AG & Co. KG, Nümbrecht, Germany)

4.2 Chemicals

Unless otherwise specified, all chemicals must be a minimum of *pro analysi* grade.

Chemicals used for method development by ICP-SF-MS:

- Hydrochloric acid TraceSELECT®, fuming, ≥ 37% (e.g. No. 84415, Honeywell Deutschland Holding GmbH, Offenbach, Germany)
- Nitric acid, 70%, sub-boiling distilled (e.g. No. 225711, Merck KGaA, Darmstadt, Germany)
- Gold standard, 1000 mg/l in 10% HCl, certified (e.g. No. N9304231, PerkinElmer LAS (Germany) GmbH, Rodgau, Germany)
- Silver standard, 1000 mg/l in 2% HNO_3, certified (e.g. No. N9303725, PerkinElmer LAS (Germany) GmbH, Rodgau, Germany)
- Platinum standard, 1000 mg/l in 2% HCl, certified (e.g. No. N9304255, PerkinElmer LAS (Germany) GmbH, Rodgau, Germany)
- Rhodium standard, 1000 mg/l in 2% HCl, certified (e.g. No. N9304259, PerkinElmer LAS (Germany) GmbH, Rodgau, Germany)
- Iridium standard, 1000 mg/l in 2% HCl, certified (e.g. No. N9304235, PerkinElmer LAS (Germany) GmbH, Rodgau, Germany)
- Terbium standard, 1000 mg/l in 2% HNO_3, certified (e.g. No. N9300157, PerkinElmer LAS (Germany) GmbH, Rodgau, Germany)
- Ultra-pure water (e.g. Milli-Q® Synergy® water-purification system, Merck KGaA, Darmstadt, Germany)
- Argon, 5.0 (AIR LIQUIDE Deutschland GmbH, Gröbenzell, Germany)

Chemicals used for method verification by ICP-Q-MS:

- Hydrochloric acid, 35%, ROTIPURAN® Supra (e.g. No. HN53.3, Carl Roth GmbH + Co. KG, Karlsruhe, Germany)
- Nitric acid, 69%, ROTIPURAN® Supra (e.g. No. HN50.1, Carl Roth GmbH + Co. KG, Karlsruhe, Germany)
- Gold ICP standard solution, 1000 mg/l in 2–5% HCl, certified, ROTI®Star (e.g. No. 2420.1, Carl Roth GmbH + Co. KG, Karlsruhe, Germany)
- Silver ICP standard solution, 1000 mg/l in 2–4% HNO_3, certified, ROTI®Star (e.g. No. 2468.1, Carl Roth GmbH + Co. KG, Karlsruhe, Germany)
- Platinum ICP standard solution, 1000 mg/l in 10% HCl, certified, ROTI®Star (e.g. No. 2448.1, Carl Roth GmbH + Co. KG, Karlsruhe, Germany)
- Rhodium ICP standard, 1000 mg/l in 2–3% HNO_3, certified, Certipur® (e.g. No. 1.70345, Merck KGaA, Darmstadt, Germany)
- Iridium ICP standard solution, 1000 mg/l in 10% HCl, ROTI®Star (e.g. No. 2424.1, Carl Roth GmbH + Co. KG, Karlsruhe, Germany)
- Terbium ICP Standard, 1000 mg/l in 2–3% HNO_3, certified, Certipur® (e.g. No. 1.70358, Merck KGaA, Darmstadt, Germany)
- Artificial urine (z. B. No. 1000-D, Synthetic Urine e.K., Eberdingen-Nussdorf, Germany)

- Ultra-pure water (e.g. Milli-Q® Synergy® water-purification system, Merck KGaA, Darmstadt, Germany)
- Argon, 4.8 (Linde GmbH, Pullach, Germany)
- Helium, 4.8 or 5.0 (Linde GmbH, Pullach, Germany)

4.3 Solutions

- 10% *Aqua regia*
  In a 125-ml PTFE or FEP-Nalgene® bottle, 80 ml of ultra-pure water are placed and 7.5 ml of fuming hydrochloric acid are carefully added as well as 2.5 ml of concentrated nitric acid. After cooling, 10 ml of ultra-pure water are added.

The 10% *aqua regia* must be freshly prepared each workday.

4.4 Internal standard (ISTD)

- ISTD working solution (10 mg/l)
  In a 10-ml quartz-glass tube or a 15-ml PP tube, 100 µl of the terbium standard (1000 mg/l) are placed and mixed with 9900 µl of 10% *aqua regia* to a final volume of 10 ml.
- ISTD spiking solution (100 µg/l)
  In a 10-ml quartz-glass tube or a 15-ml PP tube, 100 µl of ISTD working solution are placed and mixed with 9900 µl of 10% *aqua regia* to a final volume of 10 ml.

The working and spiking solutions of the ISTD are prepared freshly each workday.

4.5 Calibration standards

- Working solution (10 mg/l)
  In a 10-ml quartz-glass tube or a 15-ml PP tube, 100 µl of each precious-metal standard (1000 mg/l) are placed and mixed with 9500 µl of 10% *aqua regia* to a final volume of 10 ml.
- Spiking solution I (100 µg/l)
  In a 10-ml quartz-glass tube or a 15-ml PP tube, 100 µl of the working solution are placed and mixed with 9900 µl of 10% *aqua regia* to a final volume of 10 ml.
- Spiking solution II (10 µg/l)
  In a 10-ml quartz-glass tube or a 15-ml PP tube, 1000 µl of spiking solution I are placed and mixed with 9000 µl of 10% *aqua regia* to a final volume of 10 ml.

The working and spiking solutions of the precious metals are prepared freshly each workday.

For the determination of precious metals by ICP-SF-MS, the calibration standards were prepared in 10% *aqua regia* in 40-ml quartz-glass tubes according to the pipetting scheme given in Table 11. The calibration standards were then diluted 1 : 5 (v/v) with 10% *aqua regia*, spiked with terbium as ISTD at a concentration of 1 µg/l (analogously to the urine samples as described in Section 5.2), and analysed as described in Sections 6 and 7.

Tab. 11 Spiking scheme for the preparation of calibration standards for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS

Calibration standard	Spiking solution II [µl]	10% *aqua regia* [µl]	Final volume [µl]	Precious-metal concentration [ng/l]
0	0	30000	30000	0
1	150	29850	30000	50
2	300	29700	30000	100
3	750	29250	30000	250
4	1500	28500	30000	500

For the determination of precious metals by ICP-Q-MS, the calibration standards were prepared in 50-ml PP tubes, according to the pipetting scheme given in Table 12, using artificial urine in 10% *aqua regia*. These calibration standards already represent the ready-to-measure solutions with added terbium as ISTD at a concentration of 0.1 µg/l; further workup according to Section 5 is not necessary. These calibration standards were analysed analogously to the urine samples as described in Sections 6 and 7.

Tab. 12 Spiking scheme for the preparation of calibration standards for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-Q-MS

Calibration standard	Artificial urine [µl]	Spiking solution I [µl]	Spiking solution II [µl]	ISTD-spiking solution [µl]	HCl [µl]	HNO_3 [µl]	Water [µl]	Precious-metal concentration [ng/l]
0	10000	0	0	50	3750	1250	34950	0
1	10000	0	12.5	50	3750	1250	34938	2.5
2	10000	0	25	50	3750	1250	34925	5
3	10000	0	50	50	3750	1250	34900	10
4	10000	0	125	50	3750	1250	34825	25
5	10000	25	0	50	3750	1250	34925	50
6	10000	50	0	50	3750	1250	34900	100
7	10000	125	0	50	3750	1250	34825	250

5 Specimen collection and sample preparation

5.1 Specimen collection

The urine samples should be collected in polyethylene containers which have been pre-rinsed with 1% nitric acid. Urine collected over 24 hours is best-suited for the determination of background exposure to the precious metals considered in this method, although spot or first-morning urine samples may be used as well. In cases of occupational exposure, it is advisable to perform sampling at the end of the shift.

The collected urine can be kept in the refrigerator at 4 °C. For long-term storage over a period of weeks or months, the urine should be frozen at –20 °C.

5.2 Sample preparation

The urine samples are brought to room temperature and thoroughly mixed. For sample preparation, urine is diluted 1 : 5 (v/v) with 10% *aqua regia*. Terbium is added to the samples as ISTD. The developer of the method (ICP-SF-MS) used a terbium concentration of 1 µg/l in the measurement solution; the verifiers of the method (ICP-Q-MS) worked with a terbium concentration of 0.1 µg/l in the measurement solution.

6 Operational parameters

Analytical determination during method development was carried out by ICP-SF-MS and during external method validation with ICP-Q-MS.

The adjustments described in this section are instrument-specific and must be tested and adapted by the user as needed. The information given here is therefore only intended as a point of reference. It may be necessary to make further adjustments on devices from other manufacturers.

The analytical instrumentation must generally follow the daily optimisation routine described in the manufacturer's specifications and reach the given specification values (optimisation routines and specifications vary by manufacturer). In principle, a different nebuliser can be used for sample introduction.

6.1 Instrument-specific parameters for ICP-SF-MS

Plasma power:	1.2 kW
Nebuliser gas:	0.96 l Argon/min, optimised daily
Middle gas:	0.6 l Argon/min
Outer gas:	15 l Argon/min
Torch:	1.8 mm inner diameter
Sample introduction:	Peristaltic pump with a flow rate of 0.8 ml/min
Nebuliser:	SeaSpray nebuliser
Spray chamber:	Cyclone type
Selected isotopes:	^{197}Au, ^{107}Ag, ^{109}Ag, ^{194}Pt, ^{195}Pt, ^{103}Rh, ^{193}Ir, ^{159}Tb

These measurements were carried out at normal resolution ("low", about 300) for gold, silver, rhodium, and iridium and at high resolution ("high", ≥ 9500) for platinum.

6.2 Instrument-specific parameters for ICP-Q-MS

Plasma power:	1.55 kW
Plasma gas:	Argon
Nebuliser gas:	Argon
Sample introduction:	Peristaltic pump
Nebuliser:	PFA-ST MicroFlow
Spray chamber:	Cyclone type
Dwell time per *m/z*:	100 ms
Number of sweeps:	10

Number of main runs: 5

Selected isotopes: ^{197}Au, ^{107}Ag, ^{195}Pt, ^{103}Rh, ^{193}Ir, ^{159}Tb

The measurements were performed for all analytes in KED-high-matrix mode and single quadrupole mode.

7 Analytical determination

For analytical determination, the urine samples prepared as described in Section 5.2 are directly measured. Quantification during method development was performed by ICP-SF-MS, whereby the analytes were quantified on the mass traces ^{197}Au, ^{107}Ag, ^{109}Ag, ^{194}Pt, ^{195}Pt, ^{103}Rh, and ^{193}Ir. During external method verification, quantification was performed on the mass traces ^{197}Au, ^{107}Ag, ^{195}Pt, ^{103}Rh, and ^{193}Ir.

8 Calibration

The calibration solutions prepared according to Section 4.5 are used for calibration. The measurement signal of the analyte is divided by the measurement signal of the ISTD. A linear calibration curve is obtained by plotting the signal ratio (analyte/^{159}Tb) against the respective analyte concentration. The linearity is similarly observed up to higher concentration ranges (10 000 ng/l). Figure 1 shows representative calibration curves for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS.

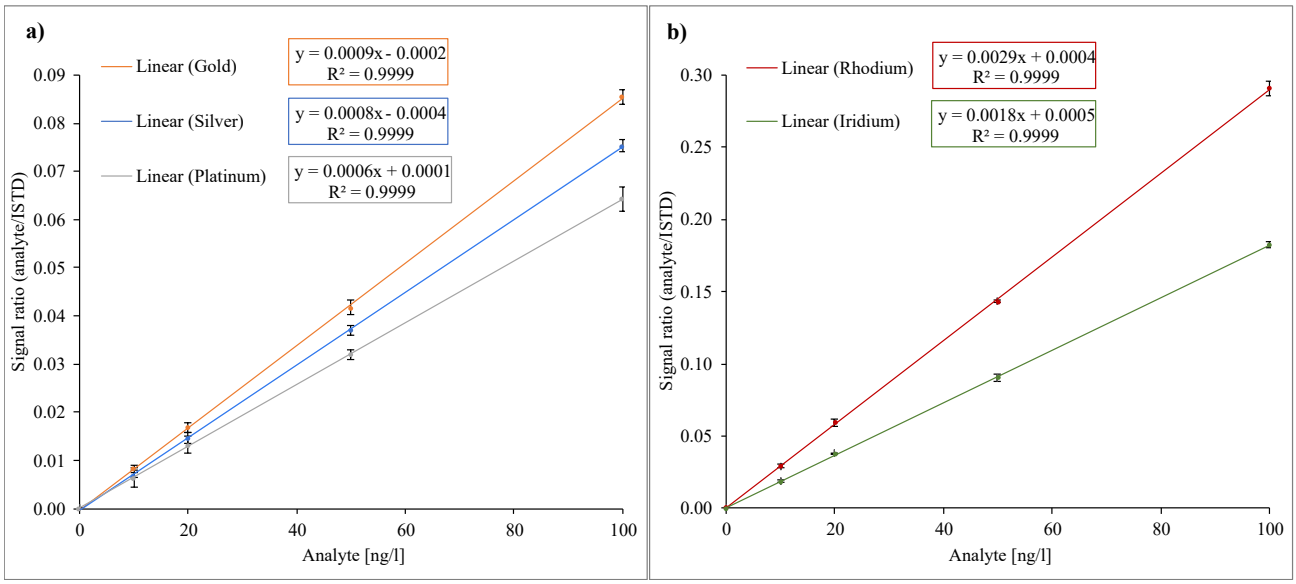

Fig. 1 Calibration curves for the determination of a) gold, silver, and platinum as well as b) rhodium and iridium in urine by ICP-SF-MS

9 Calculation of analytical results

Urinary precious-metal concentrations are calculated using the calibration function for the analytical run in question (Section 8), taking the 1 : 5 dilution of the samples into account. The calculated analyte/ISTD signal ratio is inserted into the corresponding calibration-curve function, yielding the analyte concentration in ng/l, which must then be multiplied by a factor of 5 to obtain the respective precious-metal concentration in undiluted urine.

10 Standardisation and quality control

Quality assurance of the analytical results is carried out as stipulated in the guidelines of the *Bundesärztekammer* (German Medical Association) and in a general chapter published by the Commission (Bader et al. 2010; Bundesärztekammer 2014).

At least one control sample is included in each analytical run for quality-control purposes. Since control material is not commercially available, it must be prepared in the in-house laboratory. For this purpose, the concentration of the control samples must lie within the concentration range relevant for assessment. The nominal value and tolerance ranges of the quality-control material is ascertained as part of a pre-analytical period (Bader et al. 2010).

11 Evaluation of the method

The reliability of this ICP-SF-MS method was confirmed by comprehensive validation as well as by replication and verification in a second, independent laboratory on an ICP-MS/MS device operated in single quadrupole mode. Additional validation data were collected by the verifiers of the method on a single quadrupole ICP-MS device.

11.1 Precision

Within-day precision

To determine within-day precision, the developer of the method processed a native 24-hour urine sample unspiked, as well as spiked with the analytes in concentrations of 125 ng/l and 500 ng/l, and performed analysis by ICP-SF-MS. The precision data thus obtained are given in Table 13. During method verification, ready-to-measure solutions were prepared in 10% *aqua regia* using artificial urine and were measured using ICP-Q-MS. The precision data thereby obtained are presented in Table 14.

Tab. 13 Within-day precision for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS (n = 9 or 10)

Analyte	Spiked concentration [ng/l]	Concentration in the measuring solution [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
	0	0	< LOQ	10	–	–
^{197}Au	125	25	26.8	9	14.1	32.5
	500	100	105	10	3.32	7.51
	0	0	3.60[a)]	10	–	–
^{107}Ag	125	25	21.7	10	9.21	20.8
	500	100	85.6	10	6.09	13.8
	0	0	3.04[b)]	10	–	–
^{109}Ag	125	25	21.2	10	5.53	12.5
	500	100	83.4	10	6.44	14.6

Tab. 13 *(continued)*

Analyte	Spiked concentration [ng/l]	Concentration in the measuring solution [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
	0	0	< LOQ	10	–	–
^{194}Pt	125	25	26.0	10	6.62	15.0
	500	100	96.1	10	2.76	6.24
	0	0	< LOQ	10	–	–
^{195}Pt	125	25	25.9	10	7.49	16.9
	500	100	99.6	10	4.78	10.8
	0	0	< LOQ	10	–	–
^{103}Rh	125	25	19.5	10	7.99	18.1
	500	100	85.3	10	1.54	3.48
	0	0	< LOQ	10	–	––
^{193}Ir	125	25	25.6	9	3.68	8.49
	500	100	104	10	0.908	2.06

LOQ: limit of quantitation
[a] 6 of 10 values < LOQ (2.49 ng/l); values < LOQ included in the calculation as LOQ/2.
[b] 5 of 10 values < LOQ (3.02 ng/l); values < LOQ included in the calculation as LOQ/2.

Tab. 14 Within-day precision for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-Q-MS (n = 5)

Analyte	Concentration in the measuring solution[a] [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
	8	8.32	5	2.40	6.66
^{197}Au	15	15.3	5	1.31	3.64
	75	75.6	5	1.52	4.22
	200	203	5	1.46	4.05
	8	7.9	5	1.65	4.58
^{107}Ag	15	15.0	5	2.47	6.86
	75	75.2	5	0.625	1.74
	200	200	5	0.705	1,96
	8	8.21	5	3.05	8.47
^{195}Pt	15	15.3	5	2.03	5.64
	75	75.5	5	0.768	2.13
	200	199	5	1.09	3.03
	8	7.41	5	2.70	7.50
^{103}Rh	15	14.5	5	2.00	5.55
	75	76.9	5	0.702	1.95
	200	205	5	0.800	2.22
	8	8.16	5	2.57	7.13
^{193}Ir	15	15.1	5	0.861	2.39
	75	75.3	5	0.784	2.18
	200	200	5	1.04	2.89

[a] The theoretical spiked concentration in the undiluted urine is equal to five times the concentration in the measuring solution.

Day-to-day precision

To determine day-to-day precision, the developer of the method used the same materials as for determining within-day precision. They were processed on ten different days and analysed by ICP-SF-MS. The precision data thus obtained are given in Table 15. The method verifiers used the same material as was used for the determination of within-day precision, which was analysed on three different days by ICP-Q-MS. The precision data thus obtained are presented in Table 16.

Tab. 15 Day-to-day precision for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS (n = 10)

Analyte	Spiked concentration [ng/l]	Concentration in the measuring solution [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
	0	0	< LOQ	10	–	–
^{197}Au	125	25	22.1	10	17.1	38.7
	500	100	90.0	10	8.35	18.9
	0	0	< LOQ	10	–	–
^{107}Ag	125	25	18.6	10	13.3	30.1
	500	100	71.7	10	12.0	27.1
	0	0	< LOQ	10	–	–
^{109}Ag	125	25	19.5	10	12.1	27.4
	500	100	72.0	10	10.9	24.7
	0	0	< LOQ	10	–	–
^{194}Pt	125	25	23.9	10	7.51	17.0
	500	100	89.8	10	7.49	16.9
	0	0	< LOQ	10	–	–
^{195}Pt	125	25	24.3	10	4.37	9.88
	500	100	89.8	10	6.60	14.9
	0	0	< LOQ	10	–	–
^{103}Rh	125	25	22.5	10	10.5	23.8
	500	100	77.1	10	12.5	28.3
	0	0	< LOQ	10	–	–
^{193}Ir	125	25	22.7	10	5.43	12.3
	500	100	92.8	10	6.99	15.8

LOQ: limit of quantitation

Tab. 16 Day-to-day precision for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-Q-MS (n = 3)

Analyte	Concentration in the measuring solution[a)] [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
	8	8.07	3	5.3	22.8
^{197}Au	15	15.1	3	3.9	16.8
	75	75.4	3	2.0	8.6
	200	202	3	2.1	9.0

Tab. 16 *(continued)*

Analyte	Concentration in the measuring solution[a)] [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
^{107}Ag	8	8.06	3	2.3	9.9
	15	15.2	3	2.6	11.2
	75	76.1	3	1.2	5.2
	200	204	3	1.9	8.2
^{195}Pt	8	8.01	3	3.6	15.5
	15	15.0	3	2.5	10.8
	75	74.2	3	1.5	6.5
	200	197	3	1.4	6.0
^{103}Rh	8	7.64	3	3.3	14.2
	15	14.8	3	2.3	9.9
	75	76.5	3	0.9	3.9
	200	206	3	1.1	4.7
^{193}Ir	8	8.05	3	2.7	11.6
	15	15.0	3	1.0	4.3
	75	74.0	3	1.5	6.5
	200	197	3	1.7	7.3

[a)] The theoretical spiked concentration in the undiluted urine is equal to five times the concentration in the measuring solution.

11.2 Accuracy

Recovery

The accuracy of the method was calculated from the day-to-day precision data. The mean relative recoveries calculated by the method developer are given, after subtraction of any blank values, in Table 17. Table 18 provides the mean relative recoveries calculated by the method verifiers from the day-to-day precision data.

Tab. 17 Relative recovery for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS (n = 10)

Analyte	Concentration in the measuring solution[a)] [ng/l]	Recovery (rel.) r [%]
^{197}Au	25	84.2
	100	89.0
^{107}Ag	25	67.5
	100	70.0
^{109}Ag	25	68.8
	100	69.7
^{194}Pt	25	88.2
	100	87.9
^{195}Pt	25	88.8
	100	87.7

Tab. 17 *(continued)*

Analyte	Concentration in the measuring solution[a)] [ng/l]	Recovery (rel.) *r* [%]
^{103}Rh	25	81.8
	100	75.1
^{193}Ir	25	89.1
	100	92.4

[a)] The theoretical spiked concentration in the undiluted urine is equal to five times the concentration in the measuring solution.

Tab. 18 Relative recovery for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-Q-MS (n = 3)

Analyte	Concentration in the measuring solution[a)] [ng/l]	Recovery (rel.) *r* [%]
^{197}Au	8	101
	15	101
	75	101
	200	101
^{107}Ag	8	101
	15	102
	75	101
	200	102
^{195}Pt	8	100
	15	100
	75	98.9
	200	98.8
^{103}Rh	8	95.5
	15	98.9
	75	102
	200	103
^{193}Ir	8	101
	15	100
	75	98.6
	200	98.3

[a)] The theoretical spiked concentration in the undiluted urine is equal to five times the concentration in the measuring solution.

Interlaboratory comparison

The accuracy of the method was also tested in the context of an interlaboratory comparison. The six participating laboratories each received aliquots of six urine samples spiked with various concentrations of gold, silver, platinum, rhodium, and iridium. Five of the participating laboratories determined the precious metals by ICP-MS but used various dilutions of the urine samples as well as different ISTDs (Table 19). The sixth laboratory participated in the interlaboratory comparison in order to test the accuracy of the method hereby described using an alternative procedure. In Laboratory 6, the urine samples from the interlaboratory comparison were analysed by instrumental neutron-activation analysis (INAA). However, only gold and iridium could be analysed because the spiked concentrations of the remaining elements were below the detection limit for INAA. The samples were freeze-dried and continuously irradiated for 10 hours, with a thermal neutron flux of 5×10^{16} $s^{-1}m^{-2}$, in the pneumatic irradiation facility BP3 of the

2.3-MW research reactor of the Delft Reactor Institute (Delft University of Technology, Netherlands) (TU Delft Reactor Institute 2024). The neutron flux in each sample was measured during irradiation, whereby a multi-element standard prepared in the in-house laboratory was used as a reference material for internal quality control. An internally developed INAA software was used for the analysis and interpretation of the gamma-ray spectra (further details on the INAA method can be found in the Section "Annex").

The results of the interlaboratory comparison are depicted in Figure 2. The participating laboratories achieved very similar results for platinum, rhodium, and iridium (deviations from the mean of 9.7–17.1%), and the measured concentrations largely corresponded to the spiked concentrations (nominal values), whereby, for all participants, rhodium tended towards values which were slightly too high. A considerably larger range of variations was shown among participants' results for gold and silver. For gold, Laboratory 5 (ICP-MS) measured concentrations which were clearly too low, compared with the nominal value, in all six urine samples. This could have been caused by prolonged sample storage, as it is difficult to keep gold in solution over a long period of time. The results of the remaining participants were largely similar; for higher spiked urine samples, concentrations tended to vary from the nominal value to a greater extent. For the determination of silver, the results of almost all participating laboratories were below the nominal values, and Laboratories 4 (ICP-SF-MS) and 5 (ICP-MS) reported concentrations which were clearly too low.

Tab. 19 Participants and measurement methods of the interlaboratory comparison for the determination of gold, silver, platinum, rhodium, and iridium in urine

Participant	Measurement of	Analytical technique (instrument)	Dilution	ISTD
Lab. 1	^{197}Au, ^{107}Ag, ^{195}Pt, ^{103}Rh, ^{193}Ir	ICP-MS (iCAP^{TM} Q, Thermo Fischer Scientific GmbH, Dreieich, Germany)	1 : 5 or 1 : 10	^{159}Tb
Lab. 2	^{197}Au, ^{107}Ag, ^{196}Pt, ^{103}Rh, ^{193}Ir	ICP-MS/MS in single quadrupole mode (iCAP^{TM} TQ, Thermo Fischer Scientific GmbH, Dreieich, Germany)	1 : 40	^{159}Tb
Lab. 3	^{197}Au, ^{107}Ag, ^{195}Pt, ^{103}Rh, ^{193}Ir	ICP-MS (Agilent 7900, Agilent Technologies GmbH, Waldbronn, Germany)	1 : 5	^{115}In
Lab. 4	^{197}Au, $^{107/109}$Ag, $^{194/195}$Pt, ^{103}Rh, ^{193}Ir	ICP-SF-MS (ELEMENT-2, Thermo Fischer Scientific GmbH, Dreieich, Germany)	1 : 5	^{159}Tb
Lab. 5	^{197}Au	ICP-MS (iCAP^{TM} RQ, Thermo Fisher Scientific GmbH, Hemel Hempstead, United Kingdom)	1 : 20	^{165}Ho
	^{107}Ag, ^{103}Rh		1 : 20	^{169}Tm
	^{195}Pt, ^{193}Ir	ICP-MS/MS (Agilent 8900, Agilent Technologies GmbH, Cheadle, United Kingdom)	1 : 10	^{169}Tm
Lab. 6	Gold, iridium	INAA	–	Multi-element standard

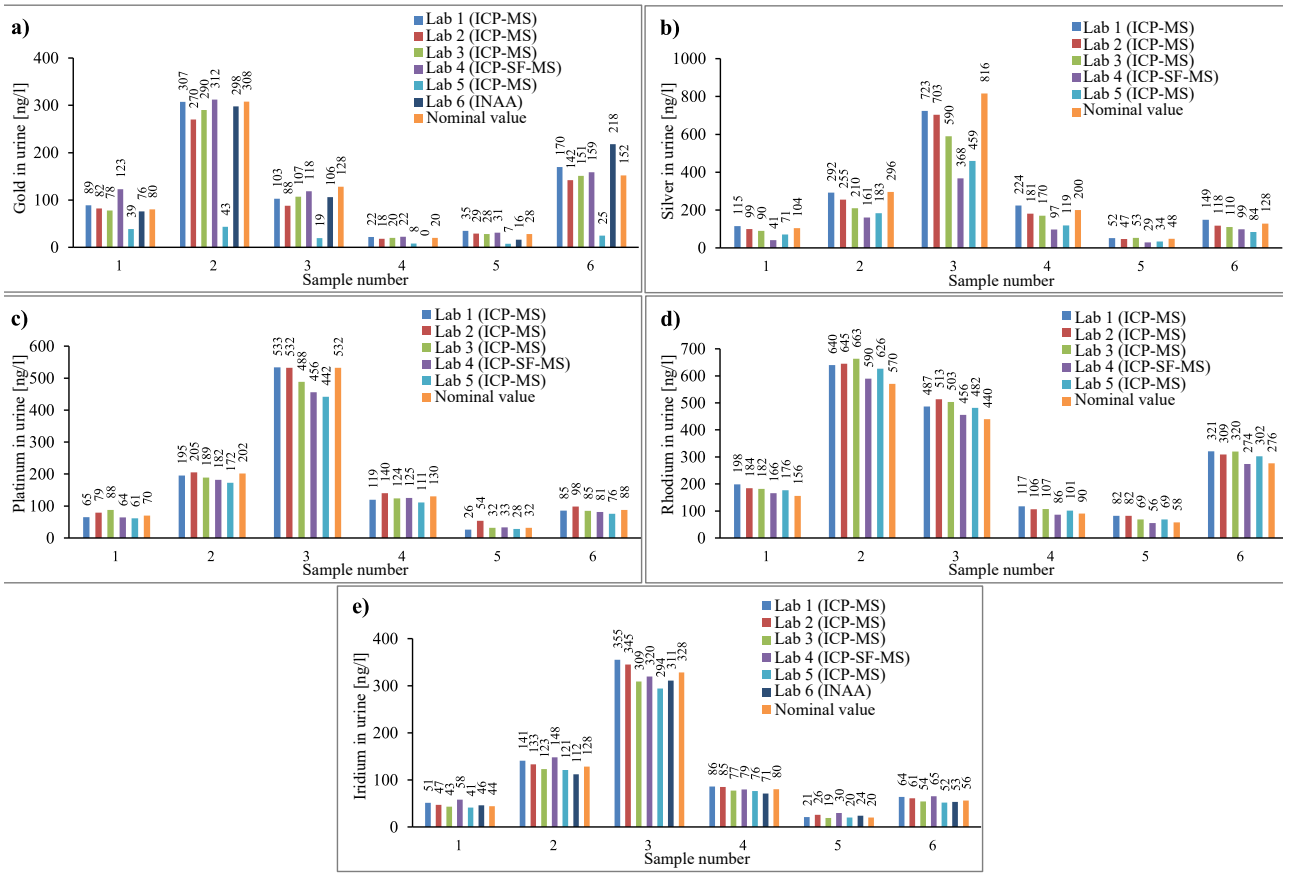

Fig. 2 Results of the interlaboratory comparison for the determination of a) gold, b) silver, c) platinum, d) rhodium, and e) iridium in urine

11.3 Limits of detection and quantitation

The detection limits were determined by the developer of the method from the standard deviation of the spectral underground intensities per the 3s criterion. The quantitation limits were likewise calculated from the tenfold standard deviation of the spectral underground intensities. The values thus obtained for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS are given in Table 20.

The method verifiers used the precision data to establish the concentration of the smallest calibration standard (2.5 ng/l in the measuring solution) as quantitation limit for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-Q-MS. This corresponds to a concentration of 12.5 ng/l in undiluted urine, which is in the same range as the values determined by ICP-SF-MS.

Tab. 20 Limits of detection and quantitation for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS

Analyte	Detection limit [ng/l]	Quantitation limit [ng/l]
^{197}Au	4.72	15.6
^{107}Ag	3.75	12.4
^{109}Ag	4.57	15.1
^{194}Pt	5.43	17.9

Tab. 20 *(continued)*

Analyte	Detection limit [ng/l]	Quantitation limit [ng/l]
^{195}Pt	5.60	18.5
^{103}Rh	4.28	14.1
^{193}Ir	3.73	12.3

11.4 Sources of error

Interferences may especially arise for highly concentrated urine samples measured with a dilution of less than 1 : 5. Higher urinary sodium chloride concentrations play a role (Na plasma with a possibly altered ionisation and thereby erroneous quantification in cases of external calibration) as well as other, increasingly occurring matrix effects. No interferences arose when using the 1 : 5 dilution selected here, such that it presents a reasonable compromise between the minimisation of interferences and the achievement of sufficiently low detection limits.

For the determination of gold, urine should be diluted exclusively with 10% *aqua regia*. Urine dilution using HNO_3 did yield better precision data for all other analytes, but led to the issue that gold would not remain in solution, thereby leading to non-reproducible validation data and extremely poor recoveries.

For the determination of platinum, it must be noted that, due to interfered signals of the platinum isotopes, significant overestimations of the concentration may arise in low-resolution mode. For this reason, it might be important to measure platinum in the high-resolution mode.

Clean-room conditions as well as sufficient purity of all chemicals used are important prerequisites to achieve the low detection limits of this method.

Table 21 and Figure 3 provide an overview of the hypothetical interferences posed for the isotopes used in the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS. The interferences are shown with the same relative intensity, whereby it must be noted that the occurrence or intensity of the individual interfering peaks when measuring real samples depends on the concentration of the interfering polyatomic clusters in the urine sample to be analysed.

Tab. 21 Spectral interferences in the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-SF-MS

Analyte	*m/z*	Frequent interferences	*m/z*	Infrequent interferences	*m/z*
^{197}Au	196.96656	^{181}Ta^{16}O	196.94292	^{180}Hf^{17}O	196.94569
		^{157}Gd^{40}Ar	196.88635	^{179}Hf^{18}O	196.94499
				^{161}Dy^{36}Ar	196.89449
				^{159}Tb^{38}Ar	196.88808
^{107}Ag	106.90510	^{67}Zn^{40}Ar	106.88951	^{69}Ga^{38}Ar	106.88831
		^{71}Ga^{36}Ar	106.89225	^{90}Zr^{17}O	106.90384
		^{91}Zr^{16}O	106.9055		
		^{89}Y^{18}O	106.90502		
^{109}Ag	108.90475	^{69}Ga^{40}Ar	108.88796	^{71}Ga^{38}Ar	108.88743
		^{93}Nb^{16}O	108.90129	^{73}Ge^{36}Ar	108.89101
				^{91}Zr^{18}O	108.90480

Tab. 21 *(continued)*

Analyte	*m/z*	Frequent interferences	*m/z*	Infrequent interferences	*m/z*
^{194}Pt	193.96268	$^{154}Gd^{40}Ar$	193.88326	$^{156}Gd^{38}Ar$	193.88486
		$^{154}Sm^{40}Ar$	193.88460	$^{158}Gd^{36}Ar$	193.89166
		$^{178}Hf^{16}O$	193.93862	$^{176}Hf^{16}O$	193.94058
				$^{176}Y^{16}O$	193.94174
^{195}Pt	194.96479	$^{155}Gd^{40}Ar$	194.88501	$^{157}Gd^{38}Ar$	194.88670
		$^{159}Tb^{36}Ar$	194.89290	$^{177}Hf^{18}O$	194.94239
		$^{179}Hf^{16}O$	194.90074	$^{178}Hf^{17}O$	194.94284
^{196}Pt	195.96495	$^{156}Gd^{40}Ar$	195.88451	$^{156}Dy^{40}Ar$	195.88667
		$^{180}Hf^{16}O$	195.94147	$^{158}Gd^{38}Ar$	195.88684
		$^{180}W^{16}O$	195.94164	$^{160}Dy^{36}Ar$	195.89275
		^{196}Hg	195.96581	$^{160}Gd^{36}Ar$	195.89461
				$^{178}Hf^{18}O$	195.94287
^{103}Rh	102.90550	$^{205}Tl^{2+}$	102.48721	$^{65}Cu^{38}Ar$	102.89052
		$^{63}Cu^{40}Ar$	102.89198	$^{67}Zn^{36}Ar$	102.89468
		$^{87}Sr^{16}O$	102.90380		
		$^{87}Rb^{16}O$	102.90409		
		$^{85}Rb^{18}O$	102.91096		
		$^{206}Pb^{2+}$	102.98723		
		$^{207}Pb^{2+}$	103.48794		
^{191}Ir	190.96060	$^{151}Eu^{40}Ar$	190.88224	$^{153}Eu^{38}Ar$	190.88397
		$^{175}Lu^{40}Ar$	190.93570	$^{155}Gd^{36}Ar$	190.89018
				$^{173}Yb^{18}O$	190.93738
				$^{174}Yb^{17}O$	190.93800

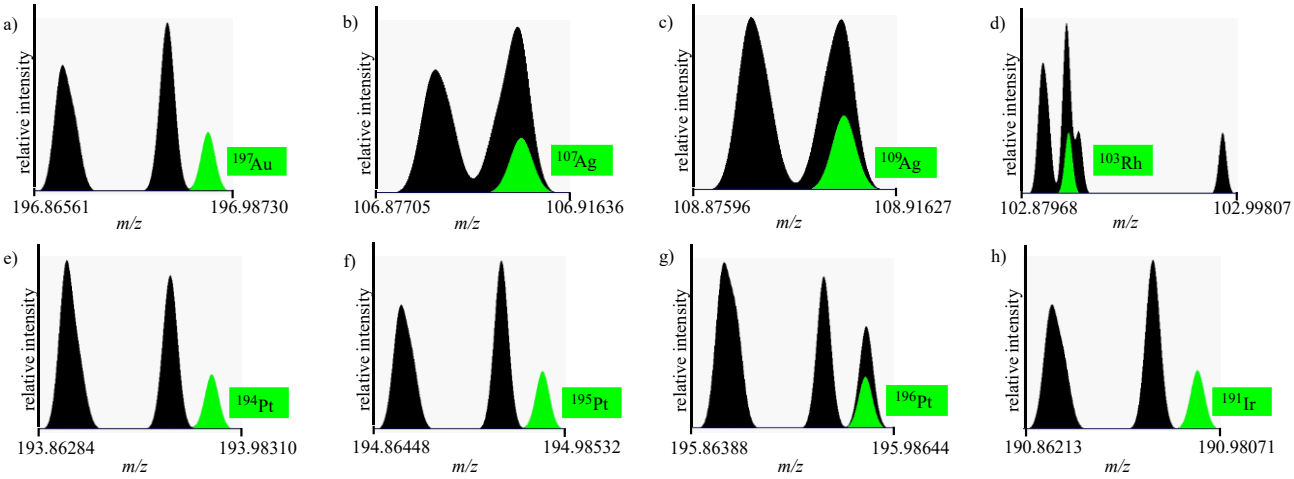

Fig. 3 Possible interference peaks (in black) that can occur on almost the same mass traces as the analyte peaks (in green) when determined using ICP-SF-MS: ^{197}Au (a), ^{107}Ag (b), ^{109}Ag (c), ^{103}Rh (d), ^{194}Pt (e), ^{195}Pt (f), ^{196}Pt (g), and ^{191}Ir (h)

12 Discussion of the method

The method hereby presented was developed to cover the concentration range relevant for occupational medicine and, if possible, for environmental medicine, for the determination of gold, silver, platinum, rhodium, and iridium in urine. Moreover, this method was developed to present a simple, quick, and reliable procedure for high sample throughput. Other methods on the determination of precious metals in urine, such as the measurement of iridium in urine by ICP-SF-MS (Begerow et al. 2008), use laborious and time-consuming standard-addition and digestion procedures (e.g. using UV light) which do not appear to be practical for the routine analysis of large numbers of samples. The method herein described uses only sample dilution to sufficiently minimise matrix influences and to allow a simple and reliable determination of gold, silver, platinum, rhodium, and iridium in urine with high sample throughput.

With this method, all precious metals measured with ICP-SF-MS yielded detection limits in the single-digit ng/l-range as well as quantitation limits of 12.3–18.5 ng/l, which allow the detection of higher background urine levels in the general population. The recoveries of about 70% (Ag) to about 90% (e.g. Pt) are acceptable, as the range of within-day variation remains mostly in the single-digit percentage range for each analyte.

The verifiers of the method were able to show that gold, silver, platinum, rhodium, and iridium in diluted urine could also be determined, both easily and reliably, using ICP-Q-MS. Quantitation limits of 12.5 ng/l were achieved for all precious metals hereby measured. The good precision data and recoveries between 95.5 and 102% also enable reliable measurements down into the range relevant for environmental medicine. Determinations on a single quadrupole device (ICP-MS) also resulted in a limit of quantification of 12.5 ng/l, whereby the relative recoveries for gold and platinum in the lower calibration range were just under 70% (Au) or 80% (Pt) in some analytical runs, such that the triple quadrupole device operated in single quadrupole mode is preferable for measurements in the lower concentration range. The validation data ascertained by the verifiers of the method for determination with the single quadrupole device are given in the Section "Annex".

Instruments used ICP-SF mass spectrometer (ELEMENT-2, Thermo Fischer Scientific GmbH, Dreieich, Germany); ICP-Q mass spectrometer (iCAP™ TQ, Thermo Fisher Scientific GmbH, Dreieich, Germany)

Notes

Competing interests

The established rules and measures of the Commission to avoid conflicts of interest (www.dfg.de/mak/conflicts_interest) ensure that the content and conclusions of the publication are strictly science-based.

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Annex

Determination of gold and iridium by INAA

As part of the interlaboratory method comparison, gold and iridium were determined by one laboratory using INAA, besides the procedures described in the manuscript above. The concentrations of the remaining elements lied below the detection limit of this method. For INAA, 5 ml of urine were filled into pouches made of 0.007-mm HDPE film (HDPE plastic film, Art. 6.056.10, Superprof B.V., Vught, Netherlands), transferred to a tube, and frozen for five days at –50 °C. The frozen urine samples were then freeze-dried under vacuum (Vacuum freeze-dryer EZ550Q, Kinetic, with vacuum pump GVD 5, Atlas Copco Holding GmbH, Essen, Germany). Analogously prepared blind samples (an HDPE plastic-film pouch with 5 ml of lyophilised Milli-Q® water and an empty HDPE plastic-film pouch) served the purpose of blank-value correction. The freeze-dried urine material in the HDPE plastic-film pouches was transferred into cylindrical HPDE sample capsules (diameter of 9 mm, height of 10 mm, Posthumus Plastics, Beverwijk, Netherlands). The sample capsules were inserted between HDPE capsules with dried zinc standards, which served to monitor the neutron flux in order to ensure an exact thermal neutron flux during the irradiation of each sample. These zinc standards were prepared from a traceable zinc standard solution (NIST® SRM® 3168a) by gravimetric pipetting of about 0.05 ml onto filter paper with a diameter of 5 mm in an HDPE capsule and subsequently dried in an oven.

The laboratory that carried out sample irradiation and the subsequent INAA is part of the Reactor Institute Delft in the Netherlands. The samples were continuously irradiated for 10 hours, with a thermal neutron flux of about 5×10^{16} $s^{-1}m^{-2}$, in the pneumatic irradiation facility BP3 of the 2.3-MW research reactor (Hoger Onderwijs Reactor) at TU Reactor Institute Delft. A multi-element standard developed in-house was used as a reference material for internal quality control.

After a 10-day decay period, the gamma-ray spectra of the irradiated samples were each measured for one hour with an Ortec® Ge(Li) detector (model GWL-220-15-S, Ametek, Oak Ridge, TN, USA). The absolute photopeak efficiency was 1.1×10^{-1} for the 1332 keV photopeak of ^{60}Co. The dead time during measurement was corrected using the Pulser method, whereby a 25-Hz Pulser peak was used to introduce an artificial peak into the high-energy end of the spectrum; dead time was found to be under 9% for all samples. The neutron-flux monitors (zinc standards) were each measured for 15 minutes with the same detector with dead times of 12% or less. An INAA software developed by the Reactor Institute Delft was used for the analysis and interpretation of gamma-ray spectra.

Validation data for the determination of gold, silver, platinum, rhodium, and iridium in urine on a single quadrupole device (ICP-MS)

In addition to the determination on the triple quadrupole system, which was operated in single quadrupole mode, the verifiers of the method collected additional validation data on a single quadrupole device (iCAP™ Q, Thermo Fisher Scientific GmbH, Dreieich, Germany). The following tables present the data thus obtained for within-day precision (Table 22), day-to-day precision (Table 23), and accuracy (Table 24). The accuracy of the method was thereby calculated from the day-to-day precision data.

Tab. 22 Within-day precision for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-MS (n = 5)

Analyte	Concentration in the measuring solution[a)] [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
^{197}Au	8	8.20	5	2.07	5.75
	15	14.2	5	1.55	4.30
	75	71.2	5	1.84	5.12
	200	191	5	0.639	1.77
^{107}Ag	8	7.71	5	4.93	13.7
	15	14.9	5	2.95	8.19
	75	73.6	5	2.65	7.36
	200	198	5	0.842	2.34
^{195}Pt	8	6.78	5	5.31	14.7
	15	12.6	5	4.84	13.4
	75	70.9	5	1.06	2.94
	200	189	5	0.646	1.79
^{103}Rh	8	8.12	5	2.34	6.50
	15	15.0	5	0.600	1.67
	75	74.9	5	1.55	4.30
	200	200	5	0.355	0.985
^{193}Ir	8	7.95	5	3.02	8.38
	15	14.4	5	0.972	2.70
	75	71.6	5	0.936	2.60
	200	193	5	1.34	3.72

[a)] The theoretical spiked concentration in the undiluted urine is equal to five times the concentration in the measuring solution.

Tab. 23 Day-to-day precision for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-MS (n = 3)

Analyte	Concentration in the measuring solution [a)] [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
^{197}Au	8	7.21	3	15.1	65.0
	15	14.0	3	8.2	35.3
	75	73.3	3	2.7	11.6
	200	198	3	2.8	12.0

Tab. 23 *(continued)*

Analyte	Concentration in the measuring solution [a] [ng/l]	Measured concentration [ng/l]	Number of repeated measurements n	Standard deviation (rel.) s_w [%]	Prognostic range u [%]
^{107}Ag	8	7.94	3	4.2	18.1
	15	15.1	3	3.2	13.8
	75	74.6	3	2.0	8.6
	200	199	3	1.1	4.7
^{195}Pt	8	7.22	3	7.5	32.3
	15	14.1	3	8.9	38.3
	75	73.3	3	2.9	12.5
	200	196	3	3.0	12.9
^{103}Rh	8	8.06	3	4.6	19.8
	15	15.2	3	1.6	6.9
	75	75.7	3	1.4	6.0
	200	202	3	1.1	4.7
^{193}Ir	8	7.96	3	2.6	11.2
	15	14.9	3	2.9	12.5
	75	73.9	3	2.5	10.8
	200	199	3	2.5	10.8

[a] The theoretical spiked concentration in the undiluted urine is equal to five times the concentration in the measuring solution.

Tab. 24 Relative recovery for the determination of gold, silver, platinum, rhodium, and iridium in urine by ICP-MS (n = 3)

Analyte	Concentration in the measuring solution [a] [ng/l]	Recovery (rel.) r [%]
^{197}Au	8	88.6
	15	93.3
	75	97.7
	200	98.6
^{107}Ag	8	99.3
	15	100
	75	99.4
	200	99.4
^{195}Pt	8	90.2
	15	93.7
	75	97.8
	200	98.1
^{103}Rh	8	101
	15	101
	75	101
	200	101

Tab. 24 *(continued)*

Analyte	Concentration in the measuring solution[a)] [ng/l]	Recovery (rel.) *r* [%]
^{193}Ir	8	99.5
	15	99.0
	75	98.6
	200	99.5

[a)] The theoretical spiked concentration in the undiluted urine is equal to five times the concentration in the measuring solution.