Thallium

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Thallium, as a pharmaceutical cosmetic product, is applied for facial hair removal and fungal infections of the scalp. Thallium acetate is currently used as a catalyst in organic synthesis in the oxidation of olefins and hydrocarbons, and in epoxidation and polymerization reactions. Detection of Tl is a challenging task because its concentration in environmental samples may be at a nanogram per gram level or lower.

Keywords: thallium ; toxic metal ; phytoremediation ; scintigraphy ; detoxification therapy

1. Introduction

Thallium (Tl) is a rare earth bluish-white heavy metal (81 atomic number, 204.38 atomic mass, 11.85 g/cm 3), and is soft, malleable, and exists in two oxidation states (I and III). The name thallium derives from Greek thallos, a young olive-green shoot. Although thallium is present in the natural environment in low concentration, it is widely distributed in water environments [1]. The European COST Action TD1407 included Tl in the list of technology-critical elements, with associated environmental impacts and potential human health threats [2]. This element is a non-essential metal present in low concentration in human tissues but is endowed with high potential toxicity. Indeed, it has been considered one of the most toxic among the heavy metals, more toxic to humans than mercury, cadmium, lead, copper, or zinc [3][4]. Acute Tl poisoning in humans induces pathological changes in organs such as the stomach, liver, kidneys, brain, intestine, cardiovascular and nervous systems, along with chronic effects such as mental disorders or polyneuritis, and may even result in death [5]. The lethal dose of Tl for an adult human is only 8–10 mg/kg. Monovalent thallium is similar to potassium in ionic radius and electrical charge, and these factors contribute to its toxic nature. Thallium acts on several organs, interfering with cellular metabolism, affecting vital potassium-dependent processes and mitochondrial metabolism, affecting uncoupling mitochondrial oxidative phosphorylation. In addition, thallium increases reactive oxygen species (ROS) formation and phospholipid peroxidation, alters the mitochondrial membrane potential (MMP), causing mitochondrial depolarization and swelling with a release of cytochrome C from the inner mitochondrial membrane. These processes are likely to account for the neurotoxic effects of the metal [6]. Long-term, low-dose prenatal Tl exposure may cause dysfunction in the mother [7], whereas absorbed Tl can affect the developing fetus because it can cross the placental barrier [8]. Several treatment modalities have been used for thallium toxicity, but no single antidote has been shown to be effective in severe toxicity. However, combinations of different treatments have been proven to be beneficial in several cases. Prussian blue (PB) has been the most prescribed antidote to treat thallium poisoning. This chelator agent is administered by the oral route, decreasing the absorption of Tl to the enterohepatic circulation, and therefore increasing the elimination of Tl into feces [9]. Despite its effectiveness as an antidote, in severe cases of human thallotoxicosis, its administration is still ineffective. Other chelating agents have been administered alone or in combination with PB, such as sodium diethyldithiocarbamate and D-penicillamine [10][11]. The combined treatment of PB and metallothionein has proven to be a good antidotal option against thallotoxicosis [12]. Blood purification treatments are also a beneficial treatment option, especially for patients with severe thallium poisoning [13]. Despite its toxicity, known since the 1970s [14][15], this metal is applied in cardiovascular scintigraphy and as a tool for imaging malignant tumors such as lung cancer, breast cancer and osteosarcoma bone cancer [16]. Thallium-201 chloride (201Tl-thallous chloride) was the first radiopharmaceutical clinically used for cardiac imaging technique in the evaluation of ischemic heath disease. Short-lived radioactive thallium (emitting X-rays and gamma-rays) is administered by the intravenous route in the human body. It is obtained from metal mining, ore processing or smelting operations and is discarded as a by-product in the environment [17]. In recent years, Tl contamination incidences have been reported in many countries, mostly due to industrial activities such as the mining and smelting of Tl-rich sulfide ores, metallurgical production, coal combustion, and cement production [18]. Recent studies have shown that elevated Tl levels often occur in soils, waters, sediments, and agricultural products in the vicinity of industrial sites using Tl-bearing mineral resources [19]. Thallium can be released into the environment as waste from the production of cadmium, lead and zinc, and cement factories, and by the combustion of coal in coal-fired power plants. There is an increasing contemporary demand for this metal in the advanced technology field, in infrared spectrometers and other optical systems, electronic devices, alloys, semiconductors, and the laser industry [20][21]. High

levels of thallium have been found in drinking water, vegetables, fruits and food due to anthropogenic activities [19][22]. Human beings are subjected to thallium exposure through the intake of contaminated fruits, vegetables, and other food, water, through the inhalation of polluted air, and living near industrial facilities such as cement and coal-fired power plants, mines and ore smelting. Aprea et al. reported a study which represents the most extensive human biomonitoring campaign for the evaluation of thallium exposure available at international level [22]. Staff et al. showed that urinary thallium concentrations were higher in thallium workers than in non-occupationally exposed people and general workers [23]. Therefore, the removal of this element from soil and water is vital to eradicate its health impacts. Phytoremediation is a green technology that uses plants to remove toxic and radioactive metals, and organic compounds such as pesticides and detergents from soil and water, and it is used for its cost-effectiveness and environmental friendliness [24]. Some plants are ideal for the phytoremediation process, especially when they grow fast and have a high biomass [25]. Solanum nigrum L., Brassica oleracea acephala L., Brassica napus , Brassica juncea , Iberis intermedia and Callitriche cophocarpa have been identified as good species for the phytoremediation of soil and waters contaminated by thallium [26][27][28].

2. Thallium Toxicity

Although being a highly toxic element, thallium has been studied to a much lesser degree than other toxic elements such as lead, cadmium, or mercury [29][30]. This happens mainly because Tl is often undetected by classical analytical methods which tend to have poorer sensitivity for Tl than for other elements. All forms of thallium are soluble enough to be toxic to living organisms [1]. Tl is a colorless, water-soluble, tasteless, and affordable element; therefore, it may cause isolated and massive human poisoning. The first symptoms (**Table 1**) of poisoning can be different and non-specific, making differential diagnosis difficult. The effects of Tl toxicity in human beings arise after a couple of weeks from its administration, with alopecia being the main symptom, firstly with hair loss, then complete baldness, followed by axillary and pubic hair loss. Thallium poisoning becomes troubling when other symptoms occur such as gastrointestinal problems (nausea, vomiting and diarrhea), peripheral and central nervous system disorders (dysesthesia, ataxia, tremors, convulsions, paralysis, sleeplessness, hallucinations, and delirium), and cardiac problems, such as tachycardia and hypotension, lethargy, and coma) [31][32].

Table 1. Symptoms of thallium exposure.

	References
Cardiac symptoms	[31][32]
Coma	
Hypotension	
Lethargy	
Tachycardia	
Dermatological symptoms	[32]
Alopecia (after about 3 weeks)	
Anhidrosis	
Hypohidrosis	
Mees lines on the nails (after about 1 month)	
Gastrointestinal symptoms	[32]
Diarrhea or constipation	
Nausea and vomiting	
Stool containing blood	
Hematologic symptoms	[32]
Anemia	
Eosinophilia	
Leukocytosis	
Neutrophilia	

	References
Thrombocytopenia	
Neurologic symptoms (after 3–5 days)	[31][32]
Ataxia	
Convulsion	
Death	
Distal muscle weakness of the hands or feet	
Hallucination	
Headache	
Insomnia	
Paresthesia	
Tremor	
Ocular symptoms	[32]
Atrophy of the optic nerve	
Cranial nerve 7th palsy	
Nystagmus	
Lens opacity	
Optic neuropathy	
Ptosis	

Thallium poisoning can even lead to death. Thallous sulfate is odorless and tasteless and was once successfully used as a household rodenticide and insecticide, but many countries in the Western word have banned such use due to numerous cases of unintentional or criminal poisonings of humans. After numerous cases of unintentional poisonings, the commercial use of thallium salts as household poison for rats, squirrels and ants was banned in the West [33]. Tl has been described as an infamous adulterant added to opioids, heroin, and cocaine [34][35]. In mammals, Tl is more toxic than mercury, lead, zinc, cadmium, and copper. Thallium is absorbed by the ingestion of polluted food of animal and vegetable origin, and the inhalation of contaminated air, through skin contact and mucous membranes; it is distributed throughout the body by the blood and can cross the encephalic and placental barriers. Thallium is accumulated in the liver, bones, brain, kidney, testes, stomach, lungs, spleen, and skin of the scalp; it has also been detected in hair, nails, tears, and breast milk. Concentrations of Tl in human organs follow this order: brain (0.42–1.5 ng/g), liver (1.5 ng/g), kidney (6.1 ng/g), hair (150–650 ng/g), bone (600 ng/g), and nail (1200 ng/g) [36]. The major route of elimination of this metal is mainly in urine and feces. The urine test is the most reliable and accurate way to determine Tl concentrations in the human body. Under normal conditions, thallium in urine does not have to exceed 1 mg/g creatinine and can be detected after 1 h for up to 2 months after exposure [1]. The measurement is usually carried out for spectrophotometric determination. The method is focused on the oxidation of 3-methyl-2-benzothiazolinone hydrazone hydrochloride by Tl^{3+} to diazonium cation, in the presence of imipramine hydrochloride in phosphoric acid medium to obtain a blue-colored solution with a maximum absorption length of 635 nm [37]. A possible mechanism of Tl toxicity is its ability to affect glutathione (GSH) activity. Indeed, glutathione binds heavy metals, including thallium, through its –SH group, inhibiting their toxicity. In addition, glutathione blocks the formation of ROS while maintaining the oxidant homeostasis of the plasma. Eskandari and collaborators studied the effects of Tl on rat liver mitochondria [38]. Tl^{+} in different concentrations induced a significant increase in mitochondrial ROS formation, ATP depletion, glutathione oxidation, mitochondrial membrane potential (MMP) collapse and mitochondrial outer membrane rupture with cytochrome C release, and peroxidation of membrane phospholipids, especially binding to anionic head groups (**Figure 1**). This suggests that Tl^{+} may alter the fluidity of the mitochondrial membranes, acting on phospholipid packing and affecting the activities of membrane-associated transport systems and enzymes, and disrupting receptor functions. Tl does not have biological functions; however, Tl^{+} can enter cells through potassium uptake channels due to its similarity in charge and ionic radius to potassium (K^{+}). The estimated absorption of this metal through the respiratory apparatus in unpolluted environments is below 0.005 µg/day [39]. Tl follows potassium distribution pathways and, in this way, alters many of potassium-dependent processes. For example, Tl may inhibit the enzymatic activity of Na^{+}/K^{+}-ATPase [40]. Thallium can substitute K^{+} in Na^{+}/K^{+}-ATPase and shows a tenfold

greater affinity for Na^+/K^+-ATPase by inhibiting the activity of this enzyme. This enzyme with an antiport mechanism across the cellular and mitochondrial membranes makes three sodium ions move against two potassium ions. This difference in charge provides the driving force to import with symport mechanism glucose, amino acids, and nutrients (**Figure 1**). In addition, in mitochondria Tl alters the balance of Bax/Bad/Bcl-2 proteins, activating caspase-9, caspase-8 and caspase-3, thus leading to apoptotic death [5]. Tl compromises mitochondrial energy production by inhibiting pyruvate dehydrogenase, succinate dehydrogenase, complexes I, II and IV of the electron transport chain (ETC), and uncoupling oxidative phosphorylation with decreasing ATP synthesis (**Figure 1**). In addition, thallium takes the place of potassium in the stabilization of ribosomes, as well as in physiological muscle contraction. Other possible mechanisms of Tl poisoning include cell mitosis, cell metabolic disorders, interference with DNA synthesis and the induction of chromosomal abnormalities. This metal interferes with the mechanisms of energy production especially in glycolysis, the Krebs cycle and oxidative phosphorylation [41]. Other mechanisms of Tl toxicity include the interference of Tl with the active sites of several enzymes as it interacts with amino-sulfhydryl groups. Thallium may inhibit the function of enzymes, such as pyruvate kinase, ATPase, and aldehyde dehydrogenase, by binding to the sulfhydryl groups (–SH) of cysteines [42]. In addition, thallium takes the place of potassium in the stabilization of ribosomes, as well as in physiological muscle contraction [43].

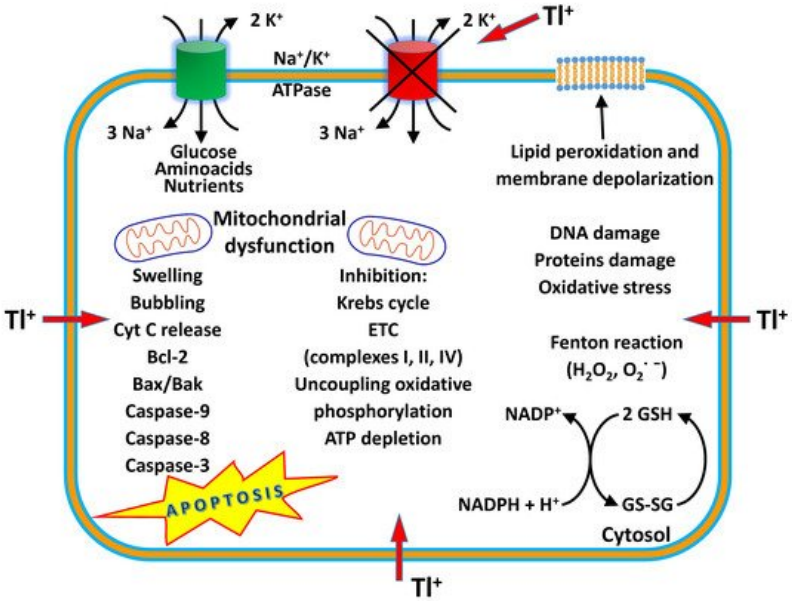

Figure 1. Mechanism of thallium action.

Thallium acts on cells and mitochondria by inducing oxidative stress and generating ROS, activating apoptosis, inhibiting the electron transport chain, reducing ATP synthesis, altering membrane permeability, and damaging DNA and proteins.

3. Uses of Thallium

The US Geological Survey estimates that the annual worldwide production of this metal is about 10 metric tons as a by-product from the smelting of copper, zinc and lead ores. About 17 million kilograms of global thallium resources are contained in zinc ores in Canada, the United States and Europe, whereas 630 million kilograms are in the world's coal mines [17]. In the 1930s, thallium was used to treat venereal diseases (e.g., syphilis and gonorrhea), malaria, and ringworm as a depilatory agent. Thallium salts were first used as pesticides in Germany in the 1920s, and because of their severe toxicity eventually became used as rodenticides. However, after several poisonings, thallium use as rodenticide was banned in the United States in 1965 [44]. The odorless thallium sulfate and acetate have been used to kill rats, squirrels, and ants; however, after many cases of unintentional poisoning, it was banned in Western countries. Unfortunately, cases of thallium poisoning are still reported in countries where it is still illegally used as a rodenticide and ant killer. There is an increasing contemporary demand for thallium in advanced industrial technology. It is used in the manufacture of electronic equipment, camera lenses, semiconductor materials (Tl selenite), scintillator counters, laser equipment, low-temperature thermometers in alloys with mercury, and photoelectric cells. Special glass with a high index of refraction is prepared from thallium oxide. It is also used in imitation jewels and artificial diamonds, green fireworks, yellow-greenish glass (Tl sesquioxide), in the production of pesticides, phosphate fertilizers and in the impregnation of woods and leather against fungi and bacteria [17][29][39]. In medicine, the most important use of ^{201}Tl (TlCl) is as radiological contrast agent in scintigraphy imaging of the heart, liver and testes, and in tumor visualization. Thallium, as a pharmaceutical cosmetic product, is applied for facial hair removal and fungal infections of the scalp [45]. Thallium acetate is currently used as a catalyst in organic synthesis in the oxidation of olefins and hydrocarbons, and in epoxidation and

polymerization reactions [46]. Detection of Tl is a challenging task because its concentration in environmental samples may be at a nanogram per gram level or lower. Most studies for the determination of Tl are conducted in water matrices. Mass spectrometry, atomic absorption spectrometry and voltammetry are key analytical techniques used for the determination and monitoring of Tl in environmental samples [47][48][49].

References

1. Karbowska, B. Presence of thallium in the environment: Sources of contaminations, distribution and monitoring methods. Environ. Monit. Assess. 2016, 188, 640.
2. Cobelo-García, A.; Filella, M.; Croot, P.; Frazzoli, C.; Du Laing, G.; Ospina-Alvarez, N.; Rauch, S.; Salaun, P.; Schäfer, J.; Zimmermann, S. COST action TD1407: Network on technology-critical elements (NOTICE)—from environmental processes to human health threats. Environ. Sci. Pollut. Res. 2015, 22, 15188–15194.
3. Sinicropi, M.S.; Caruso, A.; Capasso, A.; Palladino, C.; Panno, A.; Saturnino, C. Heavy metals: Toxicity and carcinogenicity. Pharmacologyonline 2010, 2, 329–333.
4. Carocci, A.; Rovito, N.; Sinicropi, M.S.; Genchi, G. Mercury toxicity and neurodegenerative effects. Rev. Environ. Contam. Toxicol. 2014, 229, 1–18.
5. Osorio-Rico, L.; Santamaria, A.; Galván-Arzate, S. Thallium Toxicity: General Issues, Neurological Symptoms, and Neurotoxic Mechanisms. Adv. Neurobiol. 2017, 18, 345–353.
6. Osorio-Rico, L.; Villeda-Hernández, J.; Santamaría, A.; Königsberg, M.; Galván-Arzate, S. The N-methyl-d-aspartate receptor antagonist MK-801 prevents thallium-induced behavioral and biochemical alterations in the rat brain. Int. J. Toxicol. 2015, 34, 505–513.
7. Zhu, B.; Liang, C.; Yan, S.; Li, Z.; Huang, K.; Xia, X.; Hao, J.; Zhu, P.; Tao, F. Association between serum thallium in early pregnancy and risk of gestational diabetes mellitus: The Ma'anshan birth cohort study. J. Trace Elem. Med. Biol. 2019, 52, 151–156.
8. Wu, M.; Shu, Y.; Song, L.; Liu, B.; Zhang, L.; Wang, L.; Liu, Y.; Bi, J.; Xiong, C.; Cao, Z.; et al. Prenatal exposure to thallium is associated with decreased mitochondrial DNA copy number in newborns: Evidence from a birth cohort study. Environ. Int. 2019, 129, 470–477.
9. Altagracia-Martínez, M.; Kravzov-Jinich, J.; Martínez-Núñez, J.M.; Ríos-Castañeda, C.; López-Naranjo, F. Prussian blue as an antidote for radioactive thallium and cesium poisoning. Orphan Drugs Res. Rev. 2012, 2, 13–21.
10. Kamerbeek, H.H.; Rauws, A.G.; Ten Ham, M.; Van Heijst, A.N.P. Dangerous redistribution of thallium by treatment with sodium diethyldithiocarbamate. Acta Med. Scandinav. 1971, 189, 149–154.
11. Montes, S.; Pérez-Barrón, G.; Rubio-Osornio, M.; Ríos, C.; Diaz-Ruíz, A.; Altagracia-Martínez, M.; Monroy-Noyola, A. Additive effect of DL-penicillamine plus Prussian blue for the antidotal treatment of thallotoxicosis in rats. Environ. Toxicol. Pharmacol. 2011, 32, 349–355.
12. Anaya-Ramos, L.; Díaz-Ruíz, A.; Ríos, C.; Montes, S.; Aguirre-Vidal, Y.; García-Jiménez, S.; Baron-Flores, V.; Monroy-Noyola, A. Metallothionein alone or in combination with Prussian blue attenuates acute thallium systemic toxicity in rats. Res. Sq. 2020.
13. Ghannoum, M.; Nolin, T.D.; Goldfarb, D.S.; Darren, M.R.; Mactier, R.; Mowry, J.B.; Dargan, P.I.; MacLaren, R.; Hoegberg, L.C.; Laliberté, M.; et al. Extracorporeal treatment for thallium poisoning: Recommendations from the EXTRIP Workgroup. Clin. J. Am. Soc. Nephrol. 2012, 7, 1682–1690.
14. Lebowitz, E.; Greene, M.V.; Fairchild, R.; Bradley-Moore, P.R.; Atkins, H.L.; Ansari, A.N.; Richards, P.; Belgrave, E. Thallium-201 for medical use. I. J. Nucl. Med. 1975, 16, 151–155.
15. Ritchie, J.L.; Trobaugh, G.B.; Hamilton, G.W.; Gould, K.L.; Naraharn, K.A.; Williams, D.L. Myocardial imaging with thallium-201 at rest and during exercise: Comparison with coronary arteriography and resting and stress electrocardiography. Circulation 1977, 56, 66–71.
16. Poudyal, B.; Shrestha, P.; Chowdhury, Y.S. Thallium-201. StatPearls . 21 July 2020. Available online: https://www.ncbi.nlm.nih.gov/books/NBK560586/ (accessed on 11 August 2021).
17. U.S. Geological Survey (U.S. GS). Thallium Statistics and Information. Available online: http://minerals.usgs.gov/minerals/pubs/commodity/thallium/ (accessed on 29 June 2021).
18. Wang, J.; Zhou, Y.; Dong, X.; Yin, M.; Tsang, D.C.; Sun, J.; Liu, J.; Song, G.; Liu, Y. Temporal sedimentary record of thallium pollution in an urban lake: An emerging thallium pollution source from copper metallurgy. Chemosphere 2020, 242, 125172.

19. Liu, J.; Wei, X.; Zhou, Y.; Tsang, D.C.W.; Bao, Z.; Yin, M.; Lippold, H.; Yuan, W.; Wang, J.; Feng, Y.; et al. Thallium contamination, health risk assessment and source apportionment in common vegetables. Sci. Total Environ. 2020, 703, 135547.
20. Sander, S.; Kappenstein, O.; Ebner, I.; Fritsch, K.A.; Schmidt, R.; Ptaff, K.; Luch, A. Release of aluminium and thallium ions from uncoated food contact materials made of aluminium alloys into food and food simulant. PLoS ONE 2018, 13, e0200778.
21. Datta, A.; Fiala, J.; Becla, P.; Motakef, S. Stable room-temperature thallium bromide semiconductor radiation detectors. APL Mater. 2017, 5, 106109.
22. Aprea, M.C.; Nuvolone, D.; Petri, D.; Voller, F.; Bertelloni, S.; Aragona, I. Human biomonitoring to assess exposure to thallium following the contamination of drinking water. PLoS ONE 2020, 15, e0241223.
23. Staff, J.F.; Cotton, R.J.; Warren, N.D.; Morton, J. Comparison of urinary thallium levels in non-occupationally ex-posed people and workers. Int. Arch. Occup. Environ. Health 2014, 87, 275–284.
24. Farooqi, Z.U.R. Phytoremediation of inorganic pollutants: An eco-friendly approach, its types and mechanisms. Plant Environ. 2012, 1, 110–129.
25. Rai, G.K.; Bhat, B.A.; Mushtaq, M.; Tariq, L.; Rai, P.K.; Basu, U.; Dar, A.A.; Islam, S.T.; Dar, T.U.H.; Bhat, J.A. Insights into decontamination of soils by phytoremediation: A detailed account on heavy metal toxicity and mitigation strategies. Physiol. Plant. 2021, 173, 287–304.
26. Al-Najar, H.; Schulz, R.; Römheld, V. Phytoremediation of thallium contaminated soils by brassicaceae. In Environmental Chemistry; Springer: Berlin/Heidelberg, Germany, 2005; pp. 187–196.
27. Rader, S.T.; Maier, R.M.; Barton, M.D.; Mazdab, F.K. Uptake and fractionation of thallium by Brassica juncea in a geogenic thallium-amended substrate. Environ. Sci. Technol. 2019, 53, 2441–2449.
28. Wu, Q.; Leung, J.Y.S.; Huang, X.; Yao, B.; Yuan, X.; Ma, J.; Guo, S. Evaluation of the ability of black nightshade Solanum nigrum L. for phytoremediation of thallium-contaminated soil. Environ. Sci. Pollut. Res. 2015, 22, 11478–11487.
29. Carocci, A.; Catalano, A.; Lauria, G.; Sinicropi, M.S.; Genchi, G. Lead toxicity, antioxidant defense andenvironment. Rev. Environ. Contam. Toxicol. 2016, 238, 45–67.
30. Genchi, G.; Sinicropi, M.S.; Carocci, A.; Lauria, G.; Catalano, A. Mercury exposure and heart diseases. Int. J. Environ. Res. Public Health 2017, 14, 74.
31. Zavaliy, L.B.; Petrikov, S.S.; Simonova, A.Y.; Potskhveriya, M.M.; Zaker, F.; Ostapenko, Y.N.; Ilyashenko, K.K.; Dikaya, T.I.; Shakhova, O.B.; Evseev, A.K.; et al. Diagnosis and treatment of persons with acute thallium poisoning. Toxicol. Rep. 2021, 8, 277–281.
32. Kemnic, T.R.; Coleman, M. Thallium Toxicity; StatPearls Publishing: Treasure Island, NV, USA, 2021.
33. Yumoto, T.; Tsukahara, K.; Naito, H.; Iida, A.; Nakao, A. A successfully treated case of criminal thallium poisoning. J. Clin. Diagn. Res. 2017, 11, OD01–OD02.
34. Ghaderi, A.; Vahdati-Mashhadian, N.; Oghabian, Z.; Moradi, V.; Afshari, R.; Mehrpour, O. Thallium exists in opioid poisoned patients. DARU J. Pharm. Sci. 2015, 23, 1–4.
35. Molavi, N.; Ghaderi, A.; Banafshe, H.R. Determination of thallium in urine, blood, and hair in illicit opioid users in Iran. Hum. Exp. Toxicol. 2020, 39, 808–815.
36. Tyagi, R.; Rana, P.; Khan, A.R.; Bhatnagar, D.; Devi, M.M.; Chaturvedi, S.; Tripathi, R.P.; Khushu, S. Study of acute biochemical effects of thallium toxicity in mouse urine by NMR spectroscopy. J. Appl. Toxicol. 2011, 31, 663–670.
37. Nagaraja, P.; Ghllab Saeed Al-Tayar, N.; Shivakumar, A.; Shresta, A.K.; Gowda, A.K. Spectrophotometric determination of the trace amount of thallium in water and urine samples by novel oxidative coupling reaction. E-J. Chem. 2009, 6, 1153–1163.
38. Eskandari, M.R.; Mashayekhi, V.; Aslani, M.; Hosseini, M.J. Toxicity of thallium on isolated rat liver mitochondria: The role of oxidative stress and MPT pore opening. Environ. Toxicol. 2005, 30, 232–241.
39. International Programme on Chemical Safety (IPCS). Thallium. Environmental Health Criteria; World Health Organization: Geneva, Switzerland, 1996; Volume 182.
40. Cvjetko, P.; Cvjetko, I.; Pavlica, M. Thallium Toxicity in Humans. Arh. Hig. Rada Toksikol. 2010, 61, 111–119.
41. Hoffman, R.S. Thallium toxicity and the role of Prussian blue in therapy. Toxicol. Rev. 2003, 22, 29–40.
42. Rodríguez-Mercado, J.J.; Altamirano-Lozano, M.A. Genetic toxicology of thallium: A review. Drug Chem. Toxicol. 2013, 36, 369–383.

43. Douglas, K.T.; Bunni, M.A.; Baindur, S.R. Thallium in biochemistry. Int. J. Biochem. 1990, 22, 429–438.
44. Riyaz, R.; Pandalai, S.L.; Schwartz, M.; Kazzi, Z.N. A fatal case of thallium toxicity: Challenges in management. J. Med. Toxicol. 2013, 9, 75–78.
45. Stockinger, H.E. Thallium. In Patty's Industrial Hygiene and Toxicology: Vol. 2A: Toxicology, 3rd ed.; John Wiley and Sons Publishing: New York, NY, USA; Chichester: Brisbane, Australia; Toronto, ON, Canada, 1987; pp. 1914–1931.
46. Blain, F.; Kazantzis, G. Thallium. In Handbook on the Toxicology of Metals, 4th ed.; Nordberg, G.F., Fowler, B.A., Nordberg, M., Eds.; Academic Press: Cambridge, MA, USA, 2015; pp. 1129–1240. ISBN 9780123973399.
47. Lei, C.; Xu, X. Determination of Thallium in Drinking Water and Source Water by Using Inductively Coupled Plasma-mass Spectrometry. Fujian Anal. Test. 2012, 3, 27–29.
48. Asadoulahi, T.; Dadfarnia, S.; Shabani, A.M.H. Determination of thallium traces by ETAAS after on-line matrix separation and preconcentration in a flow injection system. J. Braz. Chem. Soc. 2007, 18, 1353–1359.
49. Lukaszewski, Z.; Jakubowska, M.; Zembrzuski, W.; Karbowska, B.; Pasieczna, A. Flow-injection differential-pulse anodic stripping voltammetry as a tool for thallium monitoring in the environment. Electroanalysis 2010, 22, 1963–1966.