Metals & Elements
TOXIC + ESSENTIAL

Metals & Elements – Toxic + Essential (Hair)
Interpretation Guide

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MOSAIC DIAGNOSTICS

Introduction

This interpretation guide provides an overview of all analytes measured on the MosaicDX **Metals & Elements - Toxic + Essential (Hair)** test. The test evaluates concentrations of 19 toxic metals, 21 essential elements, and 7 important ratios utilizing a single, non-invasive hair sample collected from the privacy of the patient's home. The analytes measured are organized into:

Toxic Heavy Metals — elements with established or potential toxicological significance and no known essential biological role in humans

Essential & Other Elements — nutrients with recognized physiological functions, along with elements that lack an established essential role but may still carry biological, medicinal, environmental, or toxicological relevance

It is designed to support clinical interpretation by offering, for each analyte:

- Potential sources of exposure or intake
- Mechanisms of action
- Potential health impacts
- Specimen Type — an overview of the biological specimen types used to assess each element, along with the strengths and limitations of each matrix (e.g., blood, urine, hair)

Disclaimer: The preferred biomonitoring specimen varies by element; however, blood, serum, and urine remain the most extensively validated matrices for assessing exposure to many metals and metalloids, while hair analysis serves as a complementary tool for selected elements and longer-term exposure assessment. Metal results should always be interpreted in the context of clinical history, exposure assessment, and other laboratory findings, and confirmed with validated blood, serum, or urine testing when clinically indicated.

The information provided in this guide is intended solely for educational purposes and should not be construed as treatment recommendations. It is recommended that you consult with your healthcare provider for any necessary treatment.

Toxic Heavy Metals

Aluminum

Aluminum (Al) is the most abundant metal in the earth's crust and has no known biological function in humans. It is widely present in food, drinking water, medications, personal care products, and industrial materials, existing primarily in bound forms but becoming more biologically available as the trivalent Al^{3+} ion under certain environmental conditions. Although gastrointestinal absorption is normally very low, systemic exposure increases with more soluble aluminum (e.g., aluminum citrate) compounds, impaired renal function, iron deficiency, and citrate co-ingestion. Aluminum accumulates primarily in bone and, to a lesser extent, the brain and other tissues, where chronic accumulation has been associated with neurotoxicity, bone disease, various organ dysfunction, and oxidative stress.

Specimen type: Occupational and biomonitoring studies have found both serum/plasma and urine to be acceptable specimens for assessing aluminum exposure, depending on the clinical scenario. Hair has also been used in occupational and environmental biomonitoring studies to help identify aluminum exposures, but is limited in validation.

Antimony

Antimony (Sb) is a non-essential metalloid found in industrial and consumer products including plastics, flame-retardant textiles, and contaminated food and water. Exposure occurs primarily through inhalation and ingestion, with limited dermal absorption. Excess exposure may adversely affect the respiratory, gastrointestinal, cardiovascular, nervous, and renal systems.

Specimen type: Urinary antimony is the biomonitoring matrix used by the National Health and Nutrition Examination Survey (NHANES). Occupational, environmental, and epidemiological studies have used hair to evaluate exposures with variable results.

Arsenic

Arsenic (As) is a naturally occurring metalloid and one of the most abundant elements in the earth's crust, found in rocks, soil, water, air, and food. It exists in two primary forms: inorganic arsenic (iAs), which is the more toxic form and classified as carcinogenic, and organic arsenic (e.g. arsenobetaine), which is relatively nontoxic and excreted largely intact. Chronic arsenic exposure primarily affects the skin, cardiovascular, endocrine, nervous, hepatic, and renal systems and is a well-established risk factor for various cancers.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urinary arsenic for biomonitoring. The American College of Occupational and Environmental Medicine (ACOEM) guidance statement states hair can be an additional method to identifying exposures if arsenic exposure is suspected but not found in urine, however blood is not preferred because arsenic is rapidly cleared from it.

Barium

Barium (Ba) is a non-essential alkaline earth metal naturally found in soil, water, and certain minerals. Exposure occurs primarily through contrast media (barium sulfate), drinking water, dietary sources, and occupational or industrial settings. Soluble barium compounds interfere with potassium and calcium signaling, primarily affecting the cardiovascular, neuromuscular, respiratory, and skeletal systems.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine to evaluate barium exposures. Population studies have utilized hair for barium exposure, though validation is limited.

Beryllium

Beryllium (Be) is a non-essential alkaline earth metal and a known human carcinogen primarily used in aerospace, electronics, nuclear, and defense industries due to its strength, light weight, and heat resistance. Beryllium in the lungs can trigger immune-mediated inflammation leading to chronic beryllium disease, pulmonary fibrosis, and an increased risk of lung cancer.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine to evaluate beryllium exposures. Hair has been evaluated in animal models and some occupational biomonitoring studies, but validation remains a limitation. The beryllium lymphocyte proliferation test (BeLPT) is the preferred test for detecting beryllium sensitization and chronic beryllium disease.

Bismuth

Bismuth (Bi) is a non-essential metal widely used in gastrointestinal medications, including bismuth subsalicylate (Pepto-Bismol®) and colloidal bismuth subcitrate, for dyspepsia, peptic ulcer disease, and Helicobacter pylori treatment. Less than 1% of ingested bismuth is systemically absorbed, with most remaining in the gastrointestinal tract and being excreted in the feces; however, prolonged or excessive use may result in tissue accumulation. Although generally safe at recommended doses, chronic overexposure can potentially lead to neurotoxicity.

Specimen type: Clinical and biomonitoring studies generally utilize urine or blood (whole/plasma) to evaluate bismuth exposure. Hair has been used primarily in analytical method-development studies.

Cadmium

Cadmium (Cd) is a toxic, non-essential metal with no known physiological role and is classified as a Group 1 human carcinogen. Exposure occurs primarily through contaminated food, cigarette smoke, and occupational or industrial sources, where it gradually accumulates in the kidneys and liver over time. Cadmium disrupts essential metal-dependent enzymes, promotes oxidative stress and mitochondrial dysfunction, and primarily affects the kidneys and skeletal system, with additional effects on the respiratory, cardiovascular, reproductive, and metabolic systems.

Specimen type: The National Health and Nutrition Examination Survey (NHANES), The American Heart Association (AHA), The Occupational Safety and Health Administration (OSHA) utilize urine or blood for evaluation of cadmium exposure. Biomonitoring studies have used hair for evaluation of exposure.

Gold

Gold (Au) is a non-essential noble metal that is relatively inert in its elemental (metallic) form but becomes biologically active when ionized (Au(I), Au(III). Exposure most commonly occurs through jewelry, dental restorations, medical devices, and historical therapeutic gold compounds used to treat rheumatoid arthritis. Gold accumulates primarily in the macrophages and immune cells and is one of the most common causes of metal contact allergies.

Specimen type: Blood/plasma and urine have been used in occupational and clinical studies to assess gold exposure. Occupational biomonitoring studies and analytical investigations have utilized hair, but with limited validation.

Lead

Lead (Pb) is a toxic, non-essential heavy metal with no known physiological role, and no level of exposure has been shown to be completely safe. Although environmental exposure has declined, lead remains a significant concern due to its persistence in older infrastructure and contaminated environments. Once absorbed, lead distributes to blood, soft tissues, and bone, where it can remain for decades and be remobilized during periods of increased bone turnover. Chronic lead exposure has been associated with neurodevelopmental impairment, cardiovascular disease, and kidney disease.

Specimen type: The Center of Disease Control (NIOSH and NAHANES), American Heart Association (AHA), The Occupational Safety and Health Administration (OSHA), and The American College of Occupational and Environmental Medicine (ACOEM) all utilize (whole) blood to evaluate lead exposure. Urine has been evaluated in occupational and biomonitoring studies as a complementary exposure matrix. Environmental, occupational, and population biomonitoring studies have shown hair to be an indicator of lead exposure, however if found in either urine or hair, whole blood should be used to confirm.

Mercury

Mercury (Hg) is a toxic, non-essential heavy metal with no known physiological role. It is encountered through seafood, dental amalgams, occupational and industrial exposures, and environmental contamination, and exists in elemental, inorganic, and organic forms that differ in their absorption and distribution within the body. Mercury primarily affects the nervous system and kidneys by disrupting antioxidant defenses, mitochondrial function, and cellular signaling through high-affinity binding to sulfur- and selenium-containing proteins.

Specimen type: The Center of Disease Control, through NHANES and the Agency for Toxic Substances and Disease Registry (ATSDR) utilizes blood to evaluate methylmercury and total mercury and urine for elemental or inorganic mercury. The Environmental Protection Agency (EPA) utilizes blood for methylmercury exposures. The World Health Organization (WHO), Joint FAO/WHO Expert Committee on Food Additives (JECFA) and the European Food Safety Authority (EFSA) recognize hair as a biomarker for methylmercury exposures.

Nickel

Nickel (Ni) is a non-essential ubiquitous transition metal classified as a Group 1 human carcinogen that is found in food, water, and consumer products. It is the leading cause of allergic contact dermatitis worldwide, while chronic occupational inhalation increases the risk of lung and nasal cancer. Nickel exists as soluble and insoluble compounds; soluble forms are more readily absorbed and acutely toxic, whereas insoluble forms are more strongly associated with respiratory carcinogenicity following inhalation.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine to evaluate nickel exposures. Environmental, occupational, and population biomonitoring studies have shown hair to be an additional indicator of nickel exposure, however, correlations with blood and urine can be inconsistent. For suspected nickel allergy, patch testing remains the diagnostic gold standard.

Palladium

Palladium (Pd) is a non-essential platinum group metal widely used in automotive catalytic converters, dental alloys, jewelry, and electronics. Although environmental exposure is generally low, palladium is an emerging contaminant due to increasing catalytic converter emissions and is a recognized cause of allergic contact dermatitis, particularly in individuals with nickel sensitivity. While systemic toxicity is uncommon because oral absorption is limited, palladium can promote oxidative stress and immune activation following inhalation or dermal exposure.

Specimen type: Environmental and occupational biomonitoring studies have demonstrated that urinary palladium can reflect certain exposures. Preliminary studies evaluating measurement feasibility and exposure differences found hair to be supportive in identifying exposures in industrial populations. For suspected palladium allergy, patch testing with sodium tetrachloropalladate (Na_2PdCl_4) provides greater sensitivity than palladium chloride.

Platinum

Platinum (Pt) is a non-essential platinum group metal widely used in jewelry, catalytic converters, industrial manufacturing, laboratory equipment, and platinum-based chemotherapy agents. Exposure occurs primarily through occupational inhalation, environmental emissions, medical therapies, and contact with platinum-containing products. While metallic platinum is largely biologically inert, soluble platinum salts are potent respiratory and skin sensitizers, and platinum-based chemotherapeutics are associated with nephrotoxicity, neurotoxicity, ototoxicity, and bone marrow suppression.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine to evaluate platinum exposures. Environmental and occupational biomonitoring studies have demonstrated hair platinum utility in industrial exposures. Skin prick testing is recommended for suspected platinum salt allergy.

Silver

Silver (Ag) is a non-essential transition metal with broad antimicrobial properties that has been widely used in wound care, medical devices, and topical burn treatments. It is naturally present in trace amounts in food and water, but higher exposures occur through colloidal silver supplements, silver-containing consumer products, occupational settings, and certain medical applications. Less than half of absorbed silver is retained, primarily accumulating in the liver and kidneys, where chronic exposure over months to years can lead to tissue deposition. Although low-level exposure is generally considered safe, excessive accumulation may disrupt selenium-dependent antioxidant systems and is most notably associated with argyria, a permanent blue-gray discoloration of the skin.

Specimen type: Population biomonitoring and exposure studies have evaluated blood and urine as biomarkers of silver exposure, with whole blood having the strongest supporting evidence. Analytical validation and occupational biomonitoring studies have shown hair silver to distinguish exposed populations, although external contamination and standardization impacts interpretation.

Thallium

Thallium (Tl) is a highly toxic heavy metal with no known physiological function in humans. Although environmental exposure is typically low, thallium is used industrially in semiconductor manufacturing, specialty glass, electronics, and as thallium-201 in myocardial perfusion imaging. It is colorless, tasteless, and odorless in its soluble forms, properties that have contributed to accidental and intentional poisonings. Due to its ionic size closely resembling potassium, thallium readily substitutes for potassium in cellular transport systems, disrupting normal cellular function.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine to evaluate thallium exposures. Analytical validation, environmental biomonitoring, and forensic studies have established hair as a complementary long-term matrix for thallium exposure.

Thorium

Thorium (Th) is a naturally occurring radioactive actinide and known human carcinogen with no physiological role in humans. It is present in soil, rocks, and trace amounts in food and is used in aerospace alloys, ceramics, gas lantern mantles, rare earth processing, and nuclear energy applications. Although gastrointestinal absorption is low, inhaled or retained thorium can persist in the body for decades, accumulating primarily in bone and liver where it acts as both a chemical and radiological toxin.

Specimen type: Radiation-protection bioassay programs, occupational monitoring, and analytical validation studies have evaluated urine as a biomonitoring matrix for thorium, although occupational studies have shown limited correlation with airborne exposure. Analytical validation and limited occupational biomonitoring studies have demonstrated that thorium can be measured in hair, however, reflection is inconsistent with exposed from unexposed populations and has limited validation.

Tin

Tin (Sn) is a naturally occurring metal with no established role in humans. It is widely used in food packaging, electronics, plastics, PVC products, pesticides, solder, and consumer goods, making low-level exposure common. Tin exists in organic and inorganic forms that differ in biological activity, with inorganic having relatively low toxicity aside from gastrointestinal irritation, while organic forms (organotins) have been associated with neurological, endocrine, immune, and metabolic effects.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine to evaluate tin exposures. Two environmental biomonitoring studies have demonstrated that hair tin correlates with exposure.

Titanium

Titanium (Ti) is a naturally occurring transition metal with no known physiological role in humans that is chemically similar to iron. It is widely used in medical and dental implants, food additives, cosmetics, pigments, and industrial applications because of its strength, corrosion resistance, and biocompatibility. Although gastrointestinal absorption is minimal and titanium is generally considered to have low systemic toxicity, certain forms, particularly nanoparticles, are more biologically active and have been associated with oxidative stress, inflammation, and tissue injury following chronic or high-level exposure. Titanium dioxide (TiO_2 also known as E171) has been classified as a possible human carcinogen (Group 2B), and its use as a food additive has been banned in the European Union.

Specimen type: Pharmacokinetic modeling, health-based risk assessment, analytical validation, occupational, and implant-related studies support whole blood as a biomonitoring matrix for titanium. Occupational and implant-related studies have shown urinary titanium to increase with exposures. Occupational and implant-related studies have demonstrated that hair titanium can distinguish exposed from unexposed populations.

Uranium

Uranium (U) is a naturally occurring radioactive heavy metal with no known physiological function in humans that is present in rocks, soil, water, and food. Although natural, depleted, and enriched uranium differ in radioactivity, they share similar chemical toxicity because each forms the same uranyl ion (UO_2^{2+}) in the body, making heavy metal toxicity more clinically relevant than radiotoxicity. Once absorbed, uranium accumulates predominantly in the kidneys and skeleton, where it can persist for years, promoting oxidative stress, mitochondrial dysfunction, and renal injury.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine to evaluate uranium exposures. Whole blood is analytically validated, but concentrations are generally low. Environmental biomonitoring studies have shown that hair uranium can reflect chronic exposure over a longer period than urine, and an occupational study alluded to hair being able to distinguish natural from depleted or enriched uranium, however reference values and standardization is limited.

Elevated Toxin Indicator

Potentially toxic elements vary in relative toxicity, and multiple elevated elements can compound risk even when no single result is extreme. Co-exposure to multiple metals has been shown to produce greater organ damage than any single metal alone, even when each individual level is only moderately elevated, and cumulative multi-metal exposure is independently associated with adverse health outcomes beyond what any one metal's level would predict. The Elevated Toxin Indicator flags this risk with a simple green/yellow/red status based on how many elements are elevated and how severe those elevations are - rather than combining results into a single composite score. A single high-toxicity element at an extreme level can trigger the highest alert on its own; a cluster of moderate elevations can do the same.

Essential and Other Elements

Boron

Boron (B) is a naturally occurring trace element found primarily in fruits, vegetables, legumes, nuts, seeds, whole grains, and drinking water, with additional exposure occurring in occupational settings involving borates, fiberglass, ceramics, and flame retardants. Boron supports mineral homeostasis by influencing calcium, magnesium, phosphorus, vitamin D, and steroid hormone metabolism and contributes to normal cellular signaling, cognitive function, immune regulation, and antioxidant defenses. Although a defined boron deficiency syndrome has not been established, inadequate intake has been associated with impaired bone metabolism, altered mineral metabolism, reduced cognitive performance, and diminished immune function, while excessive exposure may cause gastrointestinal, neurologic, dermatologic, and renal effects.

Specimen type: Occupational exposure studies, population biomonitoring surveys, and validated analytical methods support urine for evaluating recent boron exposure. Hair has been utilized in biomonitoring studies to assess boron exposure with established ranges, however standardization and contamination are limitations.

Calcium

Calcium (Ca) is the most abundant mineral in the body, with almost all of it stored in bone and teeth, and is obtained primarily from dairy products, fortified foods, leafy green vegetables (low in oxalates), and dietary supplements. Calcium is essential for skeletal mineralization, muscle contraction, nerve conduction, intracellular signaling, blood coagulation, and vascular function, with concentrations tightly regulated by parathyroid hormone, calcitonin, and vitamin D. Inadequate calcium intake has been associated with impaired bone mineralization, osteoporosis, and increased risk of pregnancy complications, while excessive intake may contribute to hypercalcemia, nephrolithiasis, and other renal, gastrointestinal, and neurologic effects.

Specimen type: Population reference interval studies and clinical practice guidelines from American Association of Clinical Endocrinologists/American College of Endocrinology support urine as a non-invasive matrix for evaluating calcium intake and excretion. The American College of Cardiology states that serum levels are tightly regulated, so serum calcium does not exclude inadequate intake or stores. An observational cross-sectional biomonitoring study determined hair may suggest long term trends, but was unable to demonstrate a consistent relationship with serum.

Chromium

Chromium (Cr) is a transition metal that exists primarily as trivalent chromium (Cr III), found in foods such as meats, whole grains, brewer's yeast, and dietary supplements, and hexavalent chromium (Cr VI), an established human carcinogen encountered primarily through occupational exposures including welding, electroplating, painting, and chromate production. Although Cr(III) has historically been proposed to support insulin action and glucose and lipid metabolism, current evidence does not clearly establish chromium as an essential nutrient for humans. Chromium deficiency has been documented primarily in patients receiving long-term chromium-free parenteral nutrition and is associated with impaired glucose tolerance and insulin resistance, whereas excessive Cr(VI) exposure is associated with oxidative stress, respiratory disease, dermatitis, hepatic and renal injury, and an increased risk of lung cancer.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine and blood to monitor chromium. European biomonitoring initiative research indicates that RBC/Erythrocyte chromium can be a biomarker of Cr(VI) exposure. A cross-sectional observational biomonitoring study found chromium to be measurable in hair but is limited.

Cobalt

Cobalt (Co) is a transition metal whose established biological role in humans is as the central metal component of vitamin B12 (cobalamin), which is obtained from animal-derived food sources and supports DNA synthesis, red blood cell production, and neurologic function. Additional cobalt exposure may occur through occupational settings involving hard-metal manufacturing, cobalt alloys, cement production, and metal processing, as well as from cobalt-containing orthopedic implants. Inorganic cobalt deficiency has not been described in humans, whereas vitamin B12 deficiency results in megaloblastic anemia, peripheral neuropathy, and cognitive impairment. Excess cobalt exposure may cause allergic dermatitis, asthma, hard-metal lung disease, cardiomyopathy, hypothyroidism, polycythemia, and neurologic or sensory impairment, depending on the route and duration of exposure.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes both urine and blood to monitor cobalt. Occupational studies have found cobalt measurable in hair, but correlations with internal levels can be inconsistent.

Copper

Copper (Cu) is an essential trace element obtained primarily from shellfish, organ meats, nuts, seeds, whole grains, and chocolate. Copper serves as a cofactor for numerous enzymes involved in energy production, iron metabolism, antioxidant defense, connective tissue formation, neurotransmitter synthesis, and immune function. Copper deficiency, most commonly associated with malabsorption, bariatric surgery, prolonged parenteral nutrition, or excess zinc intake, may result in anemia, neutropenia, osteoporosis, and potentially irreversible neurologic dysfunction, whereas excess copper can cause oxidative tissue injury and, in disorders such as Wilson disease, progressive hepatic and neurologic toxicity.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes serum to evaluate copper. The American Association for the Study of Liver Diseases (AASLD) recommends 24-hour urinary copper for insights into circulating free copper. A human biomonitoring study and an observational study both found copper measurable in hair, however, correlations with blood or serum can be inconsistent.

Germanium

Germanium (Ge) is a non-essential metalloid that can be found in trace amounts in foods, while substantially greater exposures have primarily resulted from germanium-containing dietary supplements. The antioxidant, immunomodulatory, antiviral, and anticancer effects of organogermanium compounds remains limited to in vitro and animal studies, and no deficiency state has been demonstrated in humans or animals, at this time. Excess germanium is the primary clinical concern, with prolonged supplement use associated with progressive and sometimes irreversible renal injury, particularly with inorganic germanium. Chronic toxicity may also cause muscle weakness and mitochondrial myopathy, peripheral neuropathy, anemia, and, in severe cases, multisystem organ dysfunction and death.

Specimen type: Comparative, epidemiological, and matrix validation studies have found both urine and hair to be supportive for measuring germanium.

Iron

Iron (Fe) is an essential trace element obtained from heme sources such as red meat, poultry, and seafood, and non-heme sources including legumes, leafy greens, and fortified grains. Iron is required for oxygen transport, mitochondrial energy production, DNA synthesis, and neurotransmitter synthesis, with absorption and storage tightly regulated to maintain normal iron homeostasis. Iron deficiency is most commonly caused by blood loss, impaired absorption, inadequate intake, or increased physiological demand, and can cause fatigue, impaired cognitive and physical performance, restless legs syndrome, and microcytic anemia. Iron overload, from either hereditary hemochromatosis or repeated blood transfusion, chronic liver disease or excessive intake, can lead to progressive accumulation in the liver, heart, pancreas, and other tissues, resulting in cirrhosis, cardiomyopathy, diabetes, and other organ dysfunction.

Specimen type: The American Academy of Family Physicians (AAFP) and the American Academy of Pediatrics (AAP) both recommend serum ferritin, in conjunction with a Complete Blood Count (CBC), for assessing iron status. Urine is not generally used for evaluating iron status because iron lacks a regulated renal excretory pathway. A biomonitoring study found iron is measurable in hair and may provide insights into long term trends, but correlations with serum were inconsistent.

Lithium

Lithium (Li) is the lightest alkali metal and is naturally present in grains, vegetables, mushrooms, and drinking water (most common source), with additional exposure occurring through pharmaceutical lithium preparations and industrial applications. Lithium has no established enzymatic role in humans, but influences multiple cellular signaling pathways and is widely used therapeutically to treat bipolar disorder and other mood disorders. A lithium deficiency syndrome has not been identified in humans, however, excessive lithium exposure may cause neurologic, renal, endocrine, and cardiovascular toxicity, with toxicity most commonly occurring during pharmaceutical therapy or impaired renal clearance.

Specimen type: A cross-sectional observational study found lithium identifiable in urine, but is inconsistently correlated with serum or saliva levels. According to systematic reviews and meta-analyses, serum lithium is the standard laboratory test for therapeutic monitoring in patients receiving lithium treatment. A biomonitoring study identified lithium in hair, and found a relationship between body burden, dosage, and exposure or toxicity, however validated against serum is limited.

Magnesium

Magnesium (Mg) is an essential mineral found in green leafy vegetables, nuts, seeds, legumes, whole grains, dairy products, and fish. Magnesium serves as a cofactor for over 600 enzymatic reactions involved in energy production, protein and DNA synthesis, neuromuscular function, cardiac rhythm, bone health, and glucose metabolism. Magnesium deficiency, most commonly resulting from inadequate intake, gastrointestinal losses, renal wasting, transcellular redistribution, or certain medications (e.g. proton pump inhibitors, diuretics, certain antibiotics, etc), may cause muscle cramps, weakness, cardiac arrhythmias, hypocalcemia, hypokalemia, and neurologic dysfunction. Excess magnesium, typically resulting from impaired renal function, or excessive intake of magnesium-containing medications (antacids, laxatives, cathartics) or supplementation, may lead to hypotension, reduced reflexes, respiratory depression, and cardiac conduction abnormalities.

Specimen type: Cohort and meta-analysis, along with expert reviews from the New England Journal of Medicine and Clinical Endocrinology, endorse 24-hour urine as the preferred non-invasive specimen for distinguishing renal magnesium wasting from gastrointestinal or dietary losses. The National Institute of Health (NIH) states serum magnesium should be used for assessing magnesium status, however it is limited because it reflects less than 1% of total body magnesium and normal values do not exclude intracellular depletion. Mechanistic and analytical studies support erythrocyte magnesium being a better reflection of intracellular magnesium status than serum, but remains an adjunctive test because of limited standardization and clinical validation. An observational study hypothesized measuring magnesium in hair may reflect longer-term status, however a different observational cross-sectional study comparing blood and hair found no significant correlation.

Manganese

Manganese (Mn) is an essential trace element found in legumes, nuts, whole grains, leafy vegetables, and drinking water. Manganese functions as a cofactor for enzymes involved in antioxidant defense, energy metabolism, amino acid metabolism, and normal growth, immune function, and neurologic health. Manganese deficiency is uncommon and has no well-defined clinical syndrome in humans. Excessive exposures are more common and most occur through occupational inhalation, contaminated drinking water, parenteral nutrition, or impaired biliary excretion, and may result in neurotoxicity characterized by manganism, a Parkinson-like syndrome with motor and cognitive impairment.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine and serum to evaluate manganese, although these are not generally recommended for routine exposures due to manganese being eliminated predominately via the hepatobiliary route. Systematic reviews and meta-analyses support hair as a non-invasive matrix, particularly for pediatrics, when assessing chronic manganese exposure, however, a critical review noted there can be inconsistencies, potentially due to contamination.

Molybdenum

Molybdenum (Mo) is an essential trace element obtained primarily from legumes, whole grains, nuts, dairy products, and organ meats. It functions as a cofactor for enzymes involved in sulfur amino acid metabolism, purine metabolism, drug metabolism, and cellular detoxification. Molybdenum deficiency is rare and is generally limited to prolonged parenteral nutrition or rare inherited disorders affecting molybdenum cofactor synthesis. Excessive exposure has been associated with abnormal mineral metabolism (e.g. selenium, copper), gastrointestinal disturbances, and potential kidney toxicity.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) and the Canadian Health Measures Survey, both use urine as a matrix for assessing molybdenum exposure because urinary excretion closely reflects recent dietary intake. A population-based study found that molybdenum was measurable in hair, however correlations with other matrices were inconsistent.

Phosphorus

Phosphorus (P) is an essential macromineral found in dairy products, meat, fish, eggs, legumes, nuts, whole grains, and phosphate-containing food additives. It plays a critical role in bone mineralization, energy production (ATP), cell membrane structure, nucleic acid synthesis, acid-base balance, and cellular signaling. Phosphorus deficiency is uncommon and is most often associated with malabsorption, renal phosphate wasting, or intracellular redistribution, leading to muscle weakness, impaired bone mineralization, and, in severe cases, neurologic and cardiac dysfunction. Excess phosphorus, particularly in individuals with chronic kidney disease or high dietary intake of phosphate additives, contributes to secondary hyperparathyroidism, vascular calcification, and impaired bone health.

Specimen type: According to the Kidney Disease Outcomes Quality Initiate (KDOQI/NKF), serum is recommended for evaluating phosphate status. An international expert review in The Lancet Diabetes & Endocrinology supports paired urine and serum measurement for renal phosphate handling. Cross-sectional comparative biomarker and population-based observational studies suggest that hair analysis may provide insights into phosphorus and its relationship with calcium, however, correlations between hair and other matrices remain inconsistent.

Potassium

Potassium (K) is an essential electrolyte found primarily in fruits, vegetables, legumes, dairy products, and potatoes, and is the principal intracellular cation involved in maintaining fluid balance, nerve conduction, muscle contraction, cardiac function, hormone secretion, vascular tone, blood pressure control, GI motility, acid–base homeostasis, and glucose/insulin metabolism. Potassium deficiency most commonly results from gastrointestinal losses, diuretic use, or inadequate intake and may cause muscle weakness, fatigue, cardiac arrhythmias, and impaired glucose metabolism. Excess potassium is typically associated with impaired kidney function, medications that reduce renal potassium excretion, or excessive supplementation and may result in life-threatening cardiac conduction abnormalities and arrhythmias.

Specimen type: The American College of Cardiology and The American Heart Association support serum/plasma for potassium evaluations, however serum only reflects ~2% of total body potassium.

Numerous studies, as well as, a systematic review and meta-analysis, have demonstrated that 24-hour urine is a reference method for potassium intake and renal handling. Potassium has been measurable in hair, however, a pilot cross sectional study found no significant correlation with blood, and to date, no study has specifically evaluated hair potassium against serum or urine.

Rubidium

Rubidium (Rb) is a naturally occurring, nonessential, ultra-trace alkali metal that is widely distributed in soil, water, plants, and foods, with additional exposure from industrial sources and medical use of radioactive rubidium-82 for cardiac PET imaging. Rubidium closely mimics potassium and is transported by the Na+/K+-ATPase and potassium channels, which allows it to enter cells and serves as the basis for its use as a potassium tracer and cardiac perfusion imaging agent. Deficiency has not been demonstrated in humans, although experimental studies have investigated potential influences on nitric oxide and NMDA pathways, however it remains unproven clinically. Excessive rubidium may interfere with potassium homeostasis because of its competition with it for cellular uptake and renal handling and may contribute to electrolyte disturbances, including hypokalemia.

Specimen type: Population-based biomonitoring studies, national reference surveys, and analytical validation studies support urine as a biomonitoring matrix for rubidium. Analytical validation and occupational biomonitoring studies show hair rubidium is reliably measurable and varies with rubidium status, however concentrations appear to be influenced by potassium physiology rather than exposure alone, and standardization is limited.

Selenium

Selenium is an essential trace element found mainly in Brazil nuts, seafood, meats, eggs, and grains, though amounts depend largely on soil content. It is incorporated into 25 selenoproteins involved in antioxidant defense, thyroid hormone metabolism, immune function, and cellular redox regulation. Deficiency is uncommon but classically causes Keshan disease (selenium-responsive cardiomyopathy) and Kashin-Beck disease (endemic osteoarthropathy), while long-term deficiency may impair thyroid, immune, and cardiovascular function. Excess results in selenosis, characterized by brittle hair and nails, alopecia, garlic breath, gastrointestinal symptoms, peripheral neuropathy, and, at higher concentrations, adverse metabolic effects.

Preferred specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes serum or plasma as the primary specimen for assessing selenium status. A national population-based study found urine to be reflective of selenium intake, with other studies confirming association with plasma/ serum levels. Cross-sectional comparative biomarker and population-based observational studies suggest that hair selenium may provide insights into selenium status, with modest correlations observed with erythrocyte selenium.

Sodium

Sodium (Na) is an essential electrolyte and the principal extracellular cation, obtained primarily from processed, packaged, and restaurant foods (mainly in the U.S.), as well as naturally occurring sources such as vegetables, dairy products, and meat. Sodium maintains extracellular fluid volume, osmotic balance, nerve transmission, muscle contraction, and blood pressure regulation. Unlike most essential elements, serum sodium reflects water balance and extracellular tonicity rather than total body sodium stores due to tight regulation by renal sodium handling and vasopressin-mediated water balance. Sodium deficiency (hyponatremia) most commonly results from impaired water regulation, fluid losses, medications, or hormonal disturbances and may cause weakness, headache, cognitive changes, seizures, and severe neurologic complications. Excess sodium intake is common at the population level and is associated with increased blood pressure and risk of cardiovascular, cerebrovascular, and renal disease.

Specimen type: Clinical guidelines from the American Academy of Family Physicians (AFP) support the use of spot urine sodium combined with urine osmolality and creatinine for evaluating hyponatremia. Dietary sodium biomonitoring studies and expert consensus statements identify repeated 24-hour urine collections as the preferred method for estimating dietary sodium intake. Physiological and clinical studies demonstrate that serum or plasma sodium primarily reflects fluid balance and extracellular tonicity rather than total body sodium stores. Cross-sectional and laboratory assessment studies have found that hair sodium does not correlate with blood or dietary sodium.

Strontium

Strontium (Sr) is a naturally occurring alkaline-earth trace element that closely resembles calcium and is found primarily in drinking water, soil, and foods, particularly fruits, vegetables, and nuts. Approximately 99% of body strontium is stored in bone and teeth, where it can substitute for calcium within hydroxyapatite and influence bone remodeling through effects on osteoblast and osteoclast activity. Strontium has no established essential biological requirement in humans, although its calcium-like behavior allows it to interact with calcium absorption, vitamin D metabolism, and skeletal mineralization. Deficiency is not a recognized clinical condition, as no recommended intake or deficiency syndrome has been established. Excess strontium exposure may interfere with calcium metabolism and bone mineralization, potentially contributing to rickets or osteomalacia, and has been associated with cardiovascular and thromboembolic risks.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes urine as the primary specimen for assessing strontium status. Clinical and analytical biomonitoring studies have established serum or plasma for short-term measure and may be useful during kidney disease. Cross-sectional and prospective studies have found no significant correlation between hair and blood strontium, though have found it in serum, and one observational study proposed hair as a long-term indicator of strontium status.

Sulfur

Sulfur (S) is an essential non-metal element and the seventh most abundant element in the human body, obtained primarily from dietary sulfur-containing amino acids, including methionine and cysteine, found in eggs, meat, poultry, fish, dairy, legumes, and cruciferous vegetables. Sulfur is incorporated into key biological molecules including glutathione, taurine, coenzyme A, S-adenosylmethionine, and sulfated compounds involved in antioxidant defense, methylation, detoxification, and connective tissue structure. Deficiency is uncommon, but may occur with inadequate protein intake, malnutrition, or sulfur amino acid depletion and can impair glutathione production, methylation pathways, antioxidant capacity, and lean body mass maintenance. Excess sulfur intake is generally uncommon from diet but may influence sulfur metabolism, gastrointestinal microbial activity, and sulfate accumulation in conditions such as impaired renal function.

Specimen type: Metabolic and dietary biomonitoring studies support urine as a measure of sulfur-containing amino acid (SAA) metabolism. Hair mineral studies demonstrate that sulfur is abundant and measurable in keratin, but there are currently no studies demonstrating a validated relationship between hair sulfur and systemic sulfur metabolism, dietary SAA intake, or urinary sulfate.

Vanadium

Vanadium (V) is an ultratrace transition metal classified as an "occasionally beneficial" element rather than an established essential nutrient, as no human deficiency syndrome, recommended intake, or essential biological requirement has been defined. Dietary sources include shellfish, mushrooms, grains, and spinach, with additional exposure occurring through drinking water, volcanic groundwater, industrial emissions from fuel-oil combustion, occupational settings, and vanadium-containing supplements. Vanadium can mimic phosphate in biological systems and interact with enzymes involved in cellular signaling, including inhibition of protein tyrosine phosphatases that regulate insulin receptor activity, contributing to insulin-mimetic effects observed in experimental studies. Deficiency has not been demonstrated in humans, although animal studies suggest potential impacts on growth, lipid metabolism, and glucose regulation. Excess vanadium exposure, particularly from occupational or inhalational sources, may promote oxidative stress, mitochondrial injury, respiratory irritation, DNA damage, and potential nephrotoxicity.

Specimen type: Occupational, epidemiologic, and pharmacokinetic studies support urine as the preferred matrix for vanadium exposure, with urinary levels reflecting occupational and environmental exposure and vanadium elimination. Comparative biomonitoring studies have demonstrated that vanadium is measurable in hair, but does not reliably correlate with other matrices.

Zinc

Zinc (Zn) is an essential trace element and the second most abundant transition metal in the body, obtained primarily from dietary sources including red meat, shellfish, poultry, eggs, dairy products, nuts, legumes, and fortified grains. Zinc functions as a structural, catalytic, and regulatory component of more than 300 enzymes and transcription factors involved in immune function, protein synthesis, cellular growth, wound healing, antioxidant defense, and DNA regulation. Deficiency may result from inadequate intake, high-phytate diets, malabsorption, chronic illness, or genetic disorders and can cause dermatitis, alopecia, impaired taste, delayed wound healing, growth impairment, and reduced immune function. Excess zinc, typically from prolonged high-dose supplementation, can interfere with copper absorption causing a deficiency, influence anemia, neutropenia, impaired immune function, and neurologic complications.

Specimen type: The National Health and Nutrition Examination Survey (NHANES) utilizes serum as the primary specimen for assessing zinc status. Systematic review, experimental, and population biomonitoring studies support urinary zinc as a responsive, non-invasive measure of zinc excretion and intake, although interpretation is influenced by renal function and metabolic conditions. A systematic review and expert reviews suggest hair zinc may respond to zinc status, but consideration in profound deficiency causing hair loss should be considered.

Zirconium

Zirconium (Zr) is a naturally occurring transition metal with no known physiological role in humans. It is widely used in dental and orthopedic implants, ceramics, refractory materials, antiperspirants, and the nuclear industry because of its strength, corrosion resistance, and biocompatibility. Although zirconium is generally considered to have low systemic toxicity, it can accumulate in bone and other tissues, and newer evidence suggests it can cross the blood-brain and placental barriers. Toxicity appears to depend on the chemical form and particle size, with nanoparticulate zirconium demonstrating greater biological activity than bulk materials.

Specimen type: Controlled human stable-isotope tracer studies, radiation-protection biokinetic modeling, and implant-related clinical studies have evaluated urine and blood as biomonitoring matrices for zirconium. There are currently no studies that have evaluated measuring zirconium exposure in hair.

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