Table 7. Effects of minerals on the metabolism and distribution of methyl mercury: minerals.

Nutrient	MeHg exposure	Nutrient dose	Animal model	Duration of experiment	Effects	Ref.
Protective effects						
Calcium ion	1×10^{-4} to 5×10^{-3} mg MeHg/L water	20–30 mg calcium/L	Algae	15 d	Inhibits MeHg toxicity; plays a more important role than Mg in the amelioration of MeHg toxicity	(*195*)
Chloride	MeHg–GSH 1 mmol MeHg/L centrifuged erythrocytes	Cl^-, dose NA	*In vitro*, rat erythrocytes	30 min	Cl^- inhibits MeHg uptake; uptake might use the Cl^- transport system	(*93*)
Copper	Hg, dose NA	Cu, dose NA	Rat	NA	Cu decreased whole-body retention of Hg by 50%; Cu decreased Hg:MT in the kidney	(*133*)
Magnesium ions	1×10^{-4} to 5×10^{-3} mg MeHg/L in water	20–30 mg/L magnesium in water	Algae	15 d	Had only a minor effect on severity of MeHg toxicity	(*195*)
Phosphate	1/3 of LD_{50} MeHgCl (single i.p. injection)	Pi buffer (i.p. injection, pretreatment)	Mouse	NA	Decreased severity of inhibition of protein synthesis and ATP synthesis	(*196*)
Phosphate	1×10^{-4} to 5×10^{-3} mg MeHg/L in water	20–30 mg/L phosphate	Algae	15 d	Ameliorated effect of MeHg, possibly due to effect on bioavailability; suggested that alkaline and hard eutropic waters might help protect fresh water organisms against heavy metal toxicity	(*195*)
Selenium	20 ppm MeHgCl in diet	8 ppm Se as selenite in diet	Chick	28 d	Decreased liver Hg; enhanced Hg depression of weight gain	(*197*)
Selenium	30 ppm MeHgCl in diet	Se, 0.4 ppm (type not mentioned) in diet	Cotournix quail	7 d	Se decreased elevated barbituate-induced sleeping time	(*198*)
Selenium	50 µmol MeHgCl/kg bw, p.o.	50 µmol selenite/kg bw, p.o.	Guinea pig	13 d	Se decreased concentration of Hg in major organs except brain; brain Hg was only lower after 7 d; organ and subcelluar distribution of Se was also altered to increase binding to insoluble nonhistone proteins	(*199*)
Selenium	15–30 ppm MeHgCl in diet	0.6 ppm selenite in diet	Hen	NA	At lower levels of Hg, less Hg is accumulated in liver and kidney	(*156*)
Selenium	4 µM MeHgCl	1, 3, 5 µM selenite	*In vitro* embryonic chicken neural retinal cells	24 hr	Provided protective effect on cell aggregation compared to MeHgCl alone	(*200*)
Selenium	3×10^{-6} M MeHgCl	1×10^{-7} to 3×10^{-5} M selenite	*In vitro* human blood	72 hr	Prevented the induction of sister chromatid exchange dose dependently when added simultaneously to Hg	(*117*)
Selenium	18 µg Hg/g/d in fish diet	115 µg Se/g/d in fish diet	Human	NA	Decreased bleeding time	(*36*)
Selenium	5 nM MeHgCl	5 nM selenite	*In vitro* human blood	2 hr	Released MeHg from blood proteins	(*201*)
Selenium	1×10^{-5} M MeHgCl	0.8×10^{-5} M selenate or 0.2×10^{-5} M selenite	*In vitro* rat (cerebellar tissues)	4 d	Both types of Se showed protection against toxicity	(*202*)
Selenium	5–15 ppm MeHgCl in diet, 7 d	1 ppm selenite in diet, 7 d	Japanese quail	9 d	Alleviated depression in weight gain and feed consumption; Se concentration in blood increased, but GSH–peroxidase activity in blood was not altered, suggesting that the Se remained unavailable	(203)
Selenium	20 ppm MeHgCl in corn oil	5 ppm selenite in water	Japanese quail	9 wk	Decreased percent mortality close to control; brain contained up to 40 ppm MeHg, but no symptoms of mortality occurred; increased Hg retention in liver, kidney, brain, eggs	(119)
Selenium	30 ppm MeHgC in diet	0.6 ppm selenite in diet	Japanese quail	28–34 d	Protected toxicity (altered hematocrit, decreased bond calcification, survival rate)	(*204*)
Selenium	5–30 ppm MeHgCl in diet	0.35–6 ppm selenite in diet	Japanese quail	20 wk	Survival increased with increasing Se in diet; lessened effects on egg hatchability, fertility, and production; Se alone resulted in toxic effects	(*205*)
Selenium	20 ppm MeHg in water	0.35–6 ppm selenite in diet	Japanese quail	67 d	Increased survival rate from 0 to 33% with 3 ppm Se	(*206*)
Selenium	25 ppm MeHgCl in diet	1 ppm selenite in diet	Japanese quail	15 d	Protected mortality	(*84*)
Selenium	32 ppm MeHgCl in diet	0.6 ppm Se in diet, 5 wk	Japanese quail	24 d	Prevented decrease SGOT levels in severe Hg toxicity; did not affect SGPT levels	(*207*)
Selenium	10 ppm MeHg in diet	0.6 ppm selenite in diet	Japanese quail	18 wk	Protected survival; effect was dose-dependent; protection extended from parents to offspring	(*208*)
Selenium	0.075–20 ppm MeHg from tuna or 0.075–20 ppm MeHgOH in diet	0.23–0.67 ppm Se from 17% tuna in diet	Japanese quail	6 wk	Decreased Hg intoxication; increased retention of Hg and Se	(*55*)
Selenium	10 ppm MeHgCl in diet	6 ppm selenium in diet	Japanese quail	16 wk	Prolonged survival time, improved egg production, improved fertility	(*71*)

(*Continued*)

Table 7. *Continued*.

Nutrient	MeHg exposure	Nutrient dose	Animal model	Duration of experiment	Effects	Ref.
Selenium	15, 30 ppm MeHg in diet	Selenite, 0.6 ppm in diet	Leghorn hen	35 d	Prevented rapid weight loss, improved egg laying and incidence of shell defects; prevented increased kidney weight by Hg; prevented change in SGOT; prevented increase in transaminase levels	(*177*)
Selenium	10 ppm MeHgCl in diet	Se, 10 ppm in diet	Mallard	10 wk	Combined treatment alleviated Hg-induced decreased activity for liver GSH peroxidase, brain G-6-PDH and liver GSSG. Plasma glucose was slightly increased and hematocrit was slightly decreased; increased Se retention in brain but decreased Hg retention in brain; increased Se uptake in liver	(*209*)
Selenium	10 ppm MeHgCl in diet	Sel-Met,10 ppm or 10 ppm Se in diet	Mallard	73 d	Prevented paralysis of the legs, but combination of Se and MeHG decreased reproductive stress over either alone, increased teratogenicity, and increased Se in tissues	(*210*)
Selenium	20 nmol MeHgCl/g bw, single injection on 6 consecutive d	10 nmol selenite,/g bw, simultaneous with or 30 min prior to MeHg, single injection (control dietary Se = 0.5 µg/g)	Mouse (Se deficient)	7 d	Reduced the MeHg-induced decrease in glutathione-*S*-transferase	(*120*)
Selenium	8 µC MeHg in lake water/vessel, dose NA	1–100 µg Se/L as selenite	Northern Pike	3–12 d	Reduced Hg contamination at low Se concentrations	(*211*)
Selenium	102 ng MeHg/d dry weight sediment	Se, 1.45 vs 0.28 mg/kg dry weight sediment or 0.5–50 mg Se/kg dry sediment as sodium selenite	Oligochaete worm	14 d	Higher doses of Se decreased MeHg uptake (25–86% reduction)	(*212*)
Selenium	7 mg MeHg/kg bw, single oral dose at 5 wk	0.03–5 ppm selenite (6–7 wk in diet	Pig	7 wk	Protected histologic signs of toxicity; decreased Hg in muscle, cerebrum, heart, liver,kidney, and blood; MeHg decreased Se in blood, liver, kidney, and muscle; clinical Se deficiency developed	(*213*)
Selenium	MeHg, dose NA	7.5 µM selenite or selenate (perfusion medium)	Rainbow trout		Increased uptake of MeHg across the gills	(*214*)
Selenium	15–25 ppm MeHgCl	Selenite, 0.6 ppm in diet *ad libitum*	Rat	6–10 wk	Improved weight gain and survival; slightly decreased kidney Hg	(*70*)
Selenium	1 µmol MeHgCl/kg bw, i.v. injection	5 µmol sodium selenite/kg bw, i.v. injection	Rat	5–60 min	Increased cerebral MeHg, decreased kidney MeHg (up to 60 min after treatment); lowered blood methyl mercury; did not alter binding of MeHg to GSH	(*215*)
Selenium	MeHg as panogen-42 (MeHg dicyandiamide) 25 ppm in diet	3 ppm selenite, in diet	Rat	4 wk	Enhanced liver and kidney organ accumulation of both Hg and Se when diets contain both but decreased Se retention; had beneficial effect on body weight and food consumption	(*216*)
Selenium	20 ppm MeHgCl in diet	3 ppm selenite in water	Rat	61 d	Protective effect was observed for growth and morbidity; Hg increased the accumulation of Se in organs (8-fold in kidneys)	(*157*)
Selenium	20 ppm MeHgCl in diet	0.5–1.5 ppm selenite or Se from tuna in diet	Rat	70 d	Both types of Se showed protection of survival rate, morbidity, and growth rate; tuna was half as effective as selenite in preventing neurologic manifestations; no correlation between Hg in brain and neurologic manifestations in groups with Se	(*72*)
Selenium	2.0 mg MeHgCl/kg bw/d, i.p. injection	2.0 mg sodium selenite/kg bw/d, i.p. injection	Rat	8 wk	Prevented crossing reflex of hind limbs, ataxicgait, weight loss, and reduction in glutathione peroxidase activity after 6 wk	(*217*)
Selenium	0.01 mmol MeHgCl/kg bw, s.c. injection	0.01 mol sodium selenite/kg bw, s.c. injection, 30 min before injection of Hg	Rat	1 hr	Increased Hg in blood, testes, brain; decreased Hg in kidney; did not affect liver, spleen, heart, or plasma	(*122*)
Selenium	10 mg MeHgCl/kg bw/d orally (for 8–10 d)	0.5 mg selenite/kg bw, s.c. injection daily at same time as Hg	Rat	15–17 d	Delayed weight loss and delayed onset of signs of neurotoxicity; accelerated accumulation of Hg in brain but shortened its retention	(*218*)
Selenium	20 µmol MeHgCl/kg, bw, i.p. injection	20 µmol selenite/kg bw (1 hr before or after Hg)	Rat	2 hr	Decreased Hg in liver and kidney and increased it in brain; increased benzene extractable Hg, which was present as bis(methylmercuric) selenide	(*219*)
Selenium	MeHgCl in diet, dose NA	Selenite	Rat		Showed protection against neurotoxicity	(*220*)

(*Continued*)

Table 7. *Continued*.

Nutrient	MeHg exposure	Nutrient dose	Animal model	Duration of experiment	Effects	Ref.
Selenium	0–40 ppm MeHgCl in diet	5 ppm selenite in diet	Rat	74 d	Protected weight gain at high MeHg, increased Hg in liver but decreased Hg-induced reduction in liver size and enlargement of kidney	(*221*)
Selenium	Bis(methylmercuric) selenide, dose NA	Se, dose NA			Less inhibition of glucose-6-phosphate dehydrogenase, catalase, and trypsin	(*222*)
Selenium	8 µC MeHg in lake water/vessel, dose NA	1–100 µg Se/L as selenite	White sucker	3–12 d	Reduced Hg contamination at low Se concentrations	(*211*)
Selenium	8 µC MeHg in lake water/vessel, dose NA	1–100 µg Se/L as selenite	Yellow Perch	3–12 d	Reduced Hg contamination at low Se concentrations	(*211*)
Selenium	10 nmol MeHg/g feed	8–50 nmol selenite/mL drinking water	Mouse	1–2 wk	Restored decrease in membrane fragility	(*223*)
Selenium	10–1,000 ppm MeHgCl, in diet	2–8 ppm sodium selenite in diet	Mouse	45 d	Protected damage at all doses; induced enzymes at high levels (100 ppm MeHg, 2–8 ppm Se) in liver and kidney; modified enzymes of GSH metabolism; suggests observations are a mixture of toxicity and repair	(*224*)
Selenium	1–100 µM MeHgCl	10–80 µM selenium	*In vitro* cerebral mouse neurons	1–24 hr	Blocked toxicity	(*145*)
Selenium	25 ppm MeHg in diet	0.6 ppm selenite	Rat	10 wk	Prevented increase in SGPT and SGOT levels	(*177*)
Zinc	10 µM MeHgI	100 µM $ZnSO_4$, 24-hr pretreatment	*In vitro* (rat astrocytes)		Increased MT protein levels and mRNA levels; provided resistance to MeHg-induced swelling; attenuated increased Na^+ uptake and K^+ release due to MeHg	(*225*)
Enhanced toxicity						
Halogens (Cl, nitrate, sulfate, phosphate, carbonate), sodium bromide, sodium iodide	100 µg Hg/L in water as MeHgCl	10^{-2} to 10^5 µM halogens	Fish (*Oryzias latipes*)	1–4 d	Cl^- significantly decreased hatchability of fish eggs; calcium chloride enhanced MeHg toxicity when present simultaneously; halides decreased survival time; chlorides reduced Hg content of whole embryos	(*226*)
Selenium	3 mg MeHgCl/kg bw, p.o., every 2nd d for 3 wk (10 doses)	Equimolar selenite	Guinea pig	28 d	Se decreased excretion of Hg in feces (2-fold) and in urine (7-fold); Se made a two-compartment model the best fit with half-lives for Hg of 8.7 and 40.8 d	(*227*)
Selenium	1×10^{-5} M MeHgCl	Selenate, 4×10^{-5} M and selenite, 1×10^{-5} M	*In vitro* rat (cerebellar tissues)	4 d	Enhanced toxicity	(*202*)
Selenium	20 ppm MeHgCl in diet	8 ppm Se in diet as selenite	Japanese quail	25 d	Increased liver Hg; no effect on weight gain	(*197*)
Selenium	10 µg MeHgCl/g in diet	2.5–10 µg sodium selenite/g diet	Japanese quail	21 d	Increased hepatic Hg levels; no change in hepatic GSH and GSSG; GSH transferase isozyme activities were modified; thiol-transferase and GSH–peroxidase activity were stimulated	(*228*)
Selenium	15, 25, 35 µmol MeHgCl/kg bw/d on d 13, 14, and 15 of pregnancy (s.c. dose)	0.1, 0.2, 0.4 mg Se/kg diet as selenite, 5–7 wk	Mouse	8–10 wk	0.1 ppm Se in diet was enough to protect against fetolethality at 25 µmol/kg/d MeHgCl; GSH–peroxidase activity in mother was not affected; GSH–peroxidase activity in fetal liver was decreased and Se was increased, suggesting a decrease in Se bioavailability; Se supplementation increased Se in fetal liver	(*229*)
Other effects						
Calcium ion	1 mmol MeHg/L as MeHg–GSH	Ca^{2+}, dose NA	*In vitro* rat erythrocytes	30 min	No effect of Ca^{2+}-free buffer on MeHg uptake; Ca^{++} role may be via ATPase or signal transduction	(*93*)
Chloride ion	.5 µM MeHgCl in buffer	1–500 mM NaCl	*In vitro*	NA	Alters permeability of Hg across lipid membranes; suggests that Hg crosses the membrane in a neutral form	(*190*)
Magnesium ions	1 mmol MeHg/L as MeHg–GSH	Mg^{2+} (dose NA)	Rat erythrocytes	30 min	Mg^{2+}-free buffer had no effect on MeHg uptake; Mg^{2+} does not likely play an important role	(*93*)
Phosphate	1/3 of LD_{50} MeHgCl, single i.p. injection	Pi buffer, i.p. injection posttreatment	Mouse		Pi treatment was less effective in correcting already induced metabolic disorders	(*196*)
Potassium ions	0–1,000 µM MeHgCl	K^+	*In vitro,* rat astrocytes	30 min	MeHg inhibited uptake of Rb, a tracer for K^+	(*230*)
Selenium	Environmental, ocean	Se, environmental	Bowhead whale	NA	Positive correlation between Hg and Se; Hg:Se ratio was 1:40	(*231*)

(*Continued*)

Table 7. *Continued*.

Nutrient	MeHg exposure	Nutrient dose	Animal model	Duration of experiment	Effects	Ref.
Selenium	13 ppm phenyl Hg in seed	Se, dose NA	Chicken eggs	2 mo	MeHg was identified in the eggs, I-Hg was predominant in the yolk; Se level was higher than in normal eggs	(*232*)
Selenium	MeHg, dose NA	Selenite, dose NA	Fetus		MeHg increased the toxicity of selenite	(*233*)
Selenium	MeHg, dose NA	Selenite, selenomethionine, dose NA	Goldfish		NA	(*234*)
Selenium	0.3–0.9 nmol Hg/g wet weight	8.8–15.8 nmol Se/g	Human kidney	NA	Hg:Se in kidney is consistent with 1:1 ratio	(*235*)
Selenium	Hg, dose NA	Se and selenoprotein P, dose NA	*In vitro*		Hg–Se complex binds Seleno-protein P, but not Hg^{2+}	(*236*)
Selenium	10 nM MeHgCl	10 nM selenite	*In vitro* rabbit blood	30 min	Formation of bis(MeHg) selenide with the participation of GSH; MeHg transferred to the benzene fraction with molar ratio of 2:1	(*237*)
Selenium	10 µM MeHgCl	2.5 µM selenite	*In vitro* rat organs	30 min	Shows sulfhydryl groups of proteins and non-proteins are involved in interaction between protein-bound MeHg and selenite (GSH in liver and brain), Cys (in kidney); Cys in kidney may just be a breakdown product of GSH	(*238*)
Selenium	50 nM MeHgCl	50 nM selenite	*In vitro* rat blood	2 hr	Dereased Hg binding to egg albumin and to erythrocytes	(*201*)
Selenium	5–15 ppm MeHgCl, 7 d in diet	1 ppm selenite in diet, 7 d	Japanese quail	7 d	Se had no effect on Hg in kidney or brain but increased Hg in liver; Hg did not affect the level of Se in kidney, liver, or brain, but increased Se in the blood	(*239*)
Selenium	10 ppm MeHgCl in diet	0.3% selenite	Japanese quail	16 wk	No affect on survival of MeHg-fed quail	(*71*)
Selenium	0–1.0 mM MeHgCl, intraduodenal dose	0.01 mM Se as Se–Met, intraduodenal dose	Leghorn cockerels	3 wk	Lack of interaction between Se and Hg; note Hg level is manyfold excess of Se; suggests effect not of great nutritional importance	(*98*)
Selenium	0–1.0 mM MeHgCl, intraduodenal dose	0.01 mM selenite, intraduodenal dose	Leghorn cockerel	3 wk	No affect on selenite absorption; lack of interaction between Se and Hg; since Hg level is many fold excess of Se effect not of great nutritional importance	(*98*)
Selenium	10 nmol MeHg/g feed	0, 8, 20, 50 nmol selenite/mL drinking water	Mice		Selenite increased Hg in brain and liver, but decreased it in blood, kidneys, and spleen	(*223*)
Selenium	100 µg MeHgCl, s.c.	69 µg selenite, i.v. injection 1 wk after Hg	Mice	1 wk	Increased free MeHg in blood, liver and kidney, but not brain	(*201*)
Selenium	15, 25, 35 µM MeHgCl/kg bw/d, s.c. injection, to dams on d 13,14, and 15 of pregnancy	Se deficiency	Mouse	8–10 wk toxicity	Se deficiency exacerbated MeHg fetal lethal	(*229*)
Selenium	Bis(methylmercuric) selenide, i.v. injection, dose NA	Se, dose NA	Mouse		Decreased Hg retention in brain	(*240*)
Selenium	MeHg, dose NA	Se, dose NA	Mouse		Decreased Hg retention in brain	(*240*)
Selenium	1 nmol MeHgCl/mL in drinking water during pregnancy	3 µg Se–Met/mL in drinking water	Mouse (pregnant)	60 d	Increased Hg in offspring, decreased kidney Hg deposition in offspring	(*97*)
Selenium	20 mg MeHgCl/L in drinking water every second d	2 mg selenite/L in drinking water every second d	Rat	95 d	Increased mercury staining in cerebral cortex, thalamus, hypothalamus, brain stem nuclei, Purkinje cells, and white matter; increased Hg in nuclei of neurons; delayed functional toxicity (crossing of hind limbs, ataxia); did not delay malnourishment	(*241*)
Selenium	0.5 µmol MeHgCl, 0.2 mL, s.c. injection, or 1.25–5 µmol, injected by gastric gavage, 5 mL/kg bw	0.5 µmol, 0.2 mL, s.c. injection, selenite alone or in combination with MeHgCl	Rat	48 hr	Increased retention of Se but did not affect blood levels; retention was time dependent	(*157*)
Selenium	1–38 µmol MeHgCl/kg bw, i.p. injection	0.25–10 µmol selenite/kg bw i.p. injection	Rat	72 hr	Concurrent, equimolar injections protected slight decrease in GSH–peroxidase activity in brain; increased brain Hg uptake but did not alter Hg distribution	(*242*)
Selenium	0.01 mmol MeHgCl/kg bw	0.01 mmol selenite/kg bw	Rat		NA	(*122*)
Selenium	9 µmol MeHg/kg bw, oral intubation	Selenite 3–9 µmol/kg bw	Rat	16 hr	Hg was increased in all organs except kidney where Hg was decreased; effectiveness was Se–Met > Se–Cys > selenate > selenite	(*243*)

(*Continued*)

Table 7. *Continued*.

Nutrient	MeHg exposure	Nutrient dose	Animal model	Duration of experiment	Effects	Ref.
Selenium	Organic, inorganic Hg, dose NA	Se, dose NA	Rat	NA	NA	(*244*)
Selenium	MeHgCl injection, dose NA	Selenite injection, simultaneous, dose NA	Rat	NA	Gel chromatography of plasma showed that proteins derived from a pronase E digestion did not contain Hg and only low Se; the Hg–Se-rich fraction did not contain protein, but gel chromatography of serum showed that proteins derived from a pronase E digestion contained high Hg and Se; properties suggest a mercuric selenide colloid	(*245*)
Selenium	0.5 µmol MeHg, 5 mL	0.5 µmol selenite, 5 mL	Rat	7 d	Temporarily increases the concentration of MeHg in the brain; temporal separation of Hg and Se exposure alters MeHg distribution	(*246*)
Selenium	MeHg, dose NA	Selenite, dose NA	Rat		No significant effect on GSH–peroxidase activity in liver	(*247*)
Selenium	Hg in pike or trout 1:6 Hg:Se	3.4 mg Se–Met/kg fish meal	Rat		Se–Met increased both Hg^{2+} and MeHg in the blood	(*248*)
Selenium	Hg in Northern Pike or rainbow trout 1:6 Hg:Se	3.4 mg selenium dioxide/kg fish meal	Rat		Se decreased both inorganic Hg and MeHg in the blood and liver in rats fed Northern Pike	(*248*)
Selenium	16.6 µM MeHgCl	8.3 µM selenite	NA	10 min	Formation of bis(MeHg) selenide in benzene-soluble fraction	(*249*)
Sodium ions	MeHg-GSH 1 mmol MeHg/L centrifuged erythrocytes	Na^+, dose NA	Rat erythrocytes	30 min	Na^+-free buffer stimulated MeHg uptake; suggests a Na^+-dependent transport system exists for MeHg uptake	(*93*)
Zinc	Organic, inorganic Hg, dose NA	Zn, dose NA	Rat			(*244*)
Zinc	Hg, dose NA	Zn, dose NA	Rat		Zn slightly decreased whole-body retention of Hg; decreased Hg:MT in the kidney	(*135*)
Zinc	1×10^{-4} to 5×10^{-3} mg MeHg/L water	Zn, dose NA	Algae	15 d	NA	(*195*)

Abbreviations: GSSG, oxidized GSH; MeHgCl, methyl mercury chloride; MeHgOH, methyl mercury hydroxide; Se–Met, seleno-L-methionine.