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AQUATIC ENVIRONMENTAL MERCURY CONTAMINATION

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Summary

The effect that man has had on the mass balance of mercury in the marine environment is relatively insignificant. Recent attention has been focused on the problem of local mercury-contaminated areas caused by man. Many forms of mercury are introduced into the aquatic environment. As mercury has a strong affinity with organic compounds, a large portion of the introduced mercury will eventually be absorbed by the organic particles and settle on the bottom of the waterways. It also appears that any form of mercury will be methylated by the interaction of microbial action and chemical reaction in the sediment.

Some soluble portions of methylmercury will be released from the sediment and readily taken up by the living organisms. Plants accumulate methylmercury by passive absorption. In contrast, fish can concentrate methylmercury through their food as well as through their gills. Since the uptake rate of methylmercury is much faster than the normal elimination rate and the methylmercury has a metabolizable character, it is retained in the organism and mercury concentration amplified along the food chain. Methylmercury is more dangerous than other kinds of mercury compounds.

Over the years mercury and its compounds have become useful to society in a host of applications. They have also developed a notorious reputation as toxic substances in workplace, home and the environment, with a long record of disabling sickness and fatality. For instance, mercury posed a serious problem in Minamata Bay, Japan, where mercury reached a level sufficiently high to kill fish, shellfish, and persons who consume those contaminated organisms. The problems of aquatic environmental mercury contamination will be more serious in the future if man still utilizes natural resources indiscriminately. Therefore, it is deemed necessary to investigate and evaluate the following aspects of mercury contamination:

1. Sources and aquatic environmental dynamics of mercury.
2. Uptake, accumulation, and elimination of mercury by aquatic organisms.
3. Biological effects of mercury contamination.

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Sources and aquatic environmental dynamics of mercury

There are two sources discharging mercury into the environment: man-made and natural. The principal man-made discharges are through the application of pesticides, chlor-alkali production, fuel burning, catalytic process, ore refining, sewage treatment waste, incineration, phosphate rock processing, paint manufacture and use, and breakage of mercury-containing devices[1]. The principal natural discharges are through leaching and volatilization of the geological formations containing significant quantities of mercury such as the volcanic fumaroles [2, 3]. However, the local incidence of mercury pollution caused by natural sources is very rare. The effect that man has had on the mass balance of mercury in the marine environment is relatively insignificant[4]. In addition, analyses of mercury concentration in the muscle of preserved marine fish caught 90 years ago are similar to values obtained from fish caught recently[5, 6]. Recent concern has locally focused on pesticide applications and water discharges from chlor-alkali plans because these sources contribute significant amounts of mercury and have been closely associated with contamination of the food chain. D'Itri[7] estimated that in 1968 agriculture in the United States consumed 260,000 pounds of mercury for the manufacture of fungicides. (Fungicides are needed in agriculture because great crop losses are caused by a wide variety of plant pathogenic fungi.) A large portion of this mercury entered the aquatic system by surface and ground water runoff. He also estimated that in more than 990,000 pounds of mercury was discharged into the United States aquatic system by chlor-alkali plants. (The chlor-alkali industry uses continous flow mercury cathode cells to produce chlorine and caustic soda.)

Mercury is usually discharged into the river environment in one of the following forms[8]:

1) as inorganic divalent mercury, Hg^{2+}
2) as metallic mercury, Hg^0
3) as phenylmercury, $C_6H_5Hg^+$
4) as methylmercury, CH_3Hg^+
5) as alkoxyalkylmercury, e.g., $CH_3O{-}CH_2{-}CH_2Hg^+$

Once the mercury enters the aquatic system it will be partly sorbed by the particulate organic matter. Bothner and Carpenter[9] reported that between 50 and 75 percent of the mercury ions in the Columbia River was associated with river particulates within 10 to 60 hours after introduction. Hannerz[10] found that suspended solids in pond water act as scavengers of mercury carrying the absorbed mercury to the bottom. The ability of mercury to become absorbed is shown by the fact that water solution at a pH of 5 to 8, and containing less than 500 ppb mercury, loses mercury to the walls of glass or polyethylene containers to the extent of about 70 percent after 5 to 10 days[11]. According to Jonasson[11], mercury will probably be very tightly bound and concentrated by sediments containing high concentrations of metal oxides. Jeanne[12] states that the available evidence indicates that stream sediments and related fine materials remove a high percentage of slugs of mercury introduced into streams for a distance ranging from several yards to several miles. Schell and Barnes[13] found that since 1916 the concentrations of mercury in sediment profiles of Lake Washington have increased tenfold. The concentrations reached a maximum during the late 1940's and do not appear to be increasing further.

It is necessary to understand the transformation reactions between the different compounds of mercury in nature if the ecological effects of the different kinds of discharges and risks involved are to be evaluated. Jernelov[8] presented a diagram (Fig. 1) showing some of the steps by which mercury and its compounds are converted to methylmercury.

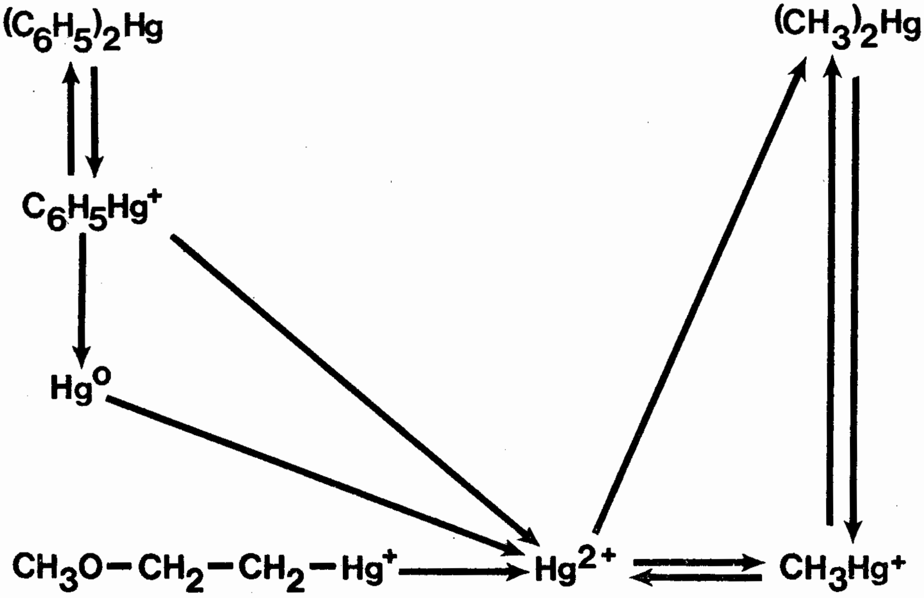

Fig. 1

Mild reducing conditions, which occur in many lake and stream sediments, can cause mercury to precipitate as sulfide cinnabar, which has an extremely low solubility; however, very strong reducing conditions may increase the solubility somewhat by converting the mercuric ion to free metal[14]. Cinnabar can be slowly oxidized in ferric-ion-charged water derived from pyrite freeing the mercury into solution[11]. Oxygen deficient river bottoms are often rich in hydrogen suphide; under such conditions hydrogen sulphide reacts with inorganic mercury ions to form mercuric sulphide[2]. Jernelov[8] found that when mercury was added to mud as a sulphide it was methylated under permanent anaerobic condition. Gillespie[14] used guppies as a measure of mobilization of mercury from sediments to which many forms of mercury has been added. Total mercury concentration rose rapidly in fish exposed to sediments containing metallic mercury. The proportion of methylmercury in fish reached a maximum of 30 percent for metallic mercury, 40 percent for mercuric chloride, and 45 percent for mercuric sulphide. Matsumura *et al.*[16] stated that three factors contribute to the methylation and release of mercury into water: alkaline pH, organic content of the sediment, and micro-organisms.

Jensen and Jernelov[17] found that the divalent form of inorganic mercury in organic mud could be biologically methylated in the bottom sediments, both under natural and aquarium conditions. Jernelov[8] stated that in Sweden investigation had been made of sediments in a large number of lakes and rivers to determine the occurrence and rate of methylation of mercury. In all cases, micro-organisms capable of methylating mercury were found to be present in the sediments. Wood *et al.*[18] showed that methyl mercury could be produced from divalent mercury by enzymatic and non-enzymatic reactions of methanogenic bacteria. The methylation through biological acitivity produced both mono- and dimethylmercury[17, 18]. Monomethylmercury has a strong tendency to remain in water solution, whereas dimethylmercury has a strong tendency to evaporate into the atmosphere[19].

The pH of the water affects the methylation process. A higher pH will favor a higher production of the more volatile dimethylmercury and a much faster discharge of the mercury into the atmosphere[19]. This effect may be due to organisms favoring high pH that produced more dimethylmercury or the transformation of monomethylmercury into dimethylmercury [19]. A lower pH will result in the production of a high proportion of the less volatile monomethylmercury[2]. Also, dimethylmercury decomposes to monomethylmercury at a low pH. Thus, under acid conditions, the total amount of mercury, as monomethylmercury, dissolved in water should be greater[19].

In summary, it appears that regardless of the form in which mercury is introduced into the aquatic environment, it eventually can be converted to methylmercury.

Uptake, accumulation, and elimination of mercury by aquatic organisms

Plants concentrate mercury directly from the surrounding media by adsorption and absorption[20]. The concentration factors for freshwater plants range from 200 to several thousand, depending on the kinds of mercury compounds[20, 21, 22]. Glooschenko[23] reported that the accumulation of ^{203}Hg by the marine diatom (*Chaetoceros costatum*) is not dependent on photosynthesis. Accumulation of mercury by alga (*Cladophora fracta*) could be described by a saturation curve[24]. Zero to 67 percent of the mercury in the phytoplankton is inorganic[22]. Phytoplankton also cannot methylate the mercury[20].

Once mercury is introduced into the food chain it becomes available to all organisms of the chain. The reports on high mercury concentration in tuna and swordfish and the high trophic level in freshwater fishes suggest that mercury may be concentrated in the same manner as such organic compounds as chlorinated hydrocarbon, i.e., passed through and amplified by the food chain[25]. This concept appears correct when considering the data presented by Johnels *et al.*[26], Johnels and Westermark[27], Dustman *et al.*[28], Jernelov[29], and Scott and Armstrong[30]. However, Knauer and Martin[22] concluded from their investigation that there was no biological amplification of mercury in the three lower throphic levels (phytoplankton, zooplankton, and anchovy) in the uncontaminated Central Pacific region. Their conclusion may be inaccurate, since only the total mercury (inorganic + organic) amplification is taken into consideration. If the organic mercury is considered, biological amplification may be found, because 33–100 percent of the total mercury in phytoplankton is inorganic, compared with 0–24 percent in anchovy. According to Matida *et al.*[20], less than 2 percent of inorganic mercury, but 33–48 percent of organic mercury can be taken up by fish.

Fish accumulate mercury directly from the water as well as from food. The rates of accumulation depend on different kinds of mercury compounds as well as on environmental factors[20,31] MacLeod and Pessah[32] found that the rate of mercury uptake increases as the temperature of the water increases. Hannerz[10] found that the uptake of methylmercury by pike is less in brackish water than in freshwater; however, he found that cod concentrate methylmercury faster in salt water than in brackish water. According to Larsson[19], cod accumulate mercury to higher levels in seawater than in brackish water, presumably because cod swallow more water in 100 percent seawater than they do in brackish water.

The importance of the gastrointestinal tract in mercury uptake has been demonstrated by Miettinen *et al.*[33,34] and Matida *et al.*[20], among others. Although orally administered in the experiments, the mercury was often regurgitated and the general consensus was that between33 and 90 percent of methylmercury in food was absorbed by the gastrointestinal tract. Jernelov[29] considered the growth efficiency (10 percent or 10 kg of prey producing 1 kg of predator) as the percentage of mercury uptake from the total food intake, and concluded that the higher trophic level derived a higher percentage of mercury from food than did the lower trophic level. He estimated that of the total mercury in northern pike, about 50 percent was derived from food and the remaining 90 percent from the water. This estimation may be inaccurate, since the growth efficiency between trophic levels is not a constant value for all levels. Because it is a carnivorous fish, northern pike may have higher growth efficiency than 10 percent.

Olson *et al.*[31] compared the mercury uptake rates of gill and skin of rainbow trout and found that the uptake occurred primarily through the gills. They also found that methylmercury demonstrated high affinity with red blood cells (up to 90 percent was bound to red cells in 40 minutes), and only 9 percent of inorganic mercury was taken up by red cells.

A positive linear relation between age and mercury content of fish is well-documented[13, 30, 35–39]. However, Johnels and Westermark[27] found that for low levels of mercury in fish (below 0.2 ppm) no increase, or a very moderate increase, in mercury content was found to occur as fish weight increased. As the mean level of mercury increased, they found that the mercury level in relation to the weight increased noticeably. At extremely high levels of mercury, caused by manifest contamination, they found no relation to age or weight. Greeson[40] and Wallace *et al.*[41] interpret this to indicate that there is a threshold level of mercury in the environment, above which fish cannot eliminate mercury from their muscular tissues faster than it is incorporated and accumulation thus occurs. Lofroth[42] states that this relationship is an indication that fish are adapted to a mercury concentration of less than 0.2 ppm. According to him, all data that have been collected indicated that the maximum natural concentration in fish is 0.2 ppm. or less, fresh weight. According to Matida *et al.*[20], the mercury accumulation rate in warmblooded animals is very much faster than in cold-blooded animals.

Recently, various researchers have attempted to determine how much of the mercury present in fish is in the methyl form. Matida *et al.*[20] found that rainbow trout accumulated methylmercury to a level of 70 percent of their total mercury. Kamps[43] found that the proportion of methylmercury to total mercury ranged from 67 to 125 percent in tuna and sordfish. Bache *et al.*[36], found methylmercury in a range of 30 to 102 percent of the total mercury in lake trout. They also found that the proportion of methylmercury to total mercury increased with age. Contrary to this finding, Westoo[44] found that the mercury present in the flesh of salmon is essentially all methylmercury, regardless of the age of the fish. Rivers *et al.*[45] found a considerably lower proportion of methylmercury (20 percent of the total mercury) in Pacific blue marlin, and the proportion decreased as the weight of the fish increased. The fact that practically all mercury in fish is methylmercury is also substantiated by Noren and Westoo[46], Johnels and Westermark[27], and Westoo[47]. This is not surprising in light of the fact that all forms of mercury introduced into the aquatic environment can be converted to methylmercury.

Hannerz[10] found that by exposing pike to methylmercury for 70 to 90 days, the concentration factor was the greatest in the kidneys, followed by the liver, spleen, stomach, heart, gill, brain, fins, gonads, muscle, scales, eyes, and bone. According to Matida *et al.*[20], the concentrations of total mercury in the organs of fish that were orally administered mercury compounds show highest values in kidney and liver, regardless of the forms of the mercury compounds. The percentage of the amount of total mercury accumulated in the muscle against that in the total fish bodies was highest in the fish administered methylmercuric chloride. On the contrary, the largest part of the total mercury in total fish bodies was found in the composite of skin, gills, bones, fins and alimentary canals in fish administered mercuric chloride[20, 48, 49]. Westoo[44] found that methylmercruy contributed 26 to 67 percent of the total visceral mercury.

The loss rate of mercuric chloride in rainbow trout is faster than that of methylmrcuric chloride[20]. Loss of methylmercury from fish changes from fast to slow. The fast loss occurs early and lasts only a few weeks while the mercury is being redistributed throughout the body. The subsequent loss from the established binding sites follows slowly; indeed, the half-life estimated for this component is of the order of two years[2, 23]. The investigators also have shown extremely low rates of loss from aquatic molluscs and crayfish, and they have noted distinct species differences. Seymour[50] found a similar pattern of loss of mercuric chloride from Pacific oysters. Jarvenpaa *et at.*[51] and Lockhart *et al.*[52] found that the biological half-life of mercury in pike is approximately 2 years. Amend[53] found that juvenile sockeye salmon, treated repeatedly with mercurials, accumulated and retained high levels of mercury in their tissues for several months, but after 4 years at sea all the fish examined had normal levels of mercury in their tissue. The concentration in ppm had an exponential decrease. According to Rucker and Amend[54], legal-size hatchery fish treated with mercury, or wild fish that have eaten mercury-contaminated fingerlings, may be a public health hazard.

Biological effects of mercury contamination

The forms of mercury vary in their relative toxicity to man and animals. The alkyl (methyl and ethyl) compounds are believed to be the most toxic, followed by metal mercury vapor, which is more toxic than the inorganic salts, and organic compounds, other than alkyl[1]. Harris *et al.*[55] reported a significant reduction in photosynthesis and growth of marine and freshwater phytoplankton exposed to 1 ppb methylmercury compounds. At levels of 50 ppb, photosynthesis ceased. Martida *et al.*[20] found that methylmercuric chloride retarded the growth of green algae (*Seenedesmus dimorphus*) at a level of 10 ppb. They also found that the growth of the same green algae was retarded by mercuric chloride at a level higher than 50 ppb.

Weir and Hine[56] found that of all metal ions, mercury was the most toxic to conditioned goldfish, producing measurable effects at 0.003 ppm. According to McIntyre[57] methylmercury at levels of 1.0 ppm, and greater reduced rainbow trout sperm viability.

The toxicity of mercury compounds also varies with the environmental conditions. The toxicity of mercury to rainbow trout increased as the water temperature increased[32, 58]. The concentrations of mercuric chloride corresponding to 96 TL_m of rainbow trout were 0.40, 0.18 and 0.22 ppm at 5, 10 and 20° C respectively [32]. According to the observations of Matida *et al.*[20] the contaminated fish (10 ppm of mercury in their bodies) showed dark color, ate only a little food, swam by rolling from side to side, kept their body position vertically on the bottom by bending their bodies, and lost the ability to turn in front of the glass walls of the aquaria. They also reported that the abnormal fish seemed a little larger than the normal fish and that histological examination revealed neurological changes. Takeuchi *et al.*[59] reported that cataracts were very often observed in the highly mercury-contaminated fish. Since the outbreak of Minimata disease in 1953, there have been investigations on the effect of mercury compounds on man. Many of them are reported in Hartung and Dinman[60].

May[61] intensively reviewed the enzyme reactions caused by mercury. Basically, there are two reactions: (1) inhibition and (2) stimulation. Jackim, *et al.*[62] found that *in vivo* mercury increased the alkaline phosphatase activity but inhibited the acid phosphatase activity in *Fundulus heteroclitus.* Though mercury inhibits most of the enzymes, there are some that can be stimulated and, consequently, it increases the ability of an organism to adapt to, and to tolerate and resist mercury poisoning[63].

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บทคัดย่อ

ในปัจจุบัน สารปรอทที่ถูกปล่อยลงไปยังสิ่งแวดล้อมของทะเลและมหาสมุทรของโลก ยังไม่ได้ก่อให้เกิดปัญหาในการเปลี่ยนแปลงความสมดุลย์ของสารปรอทที่มีอยู่แล้วในธรรมชาติแต่อย่างใด ปัญหาส่วนใหญ่มักเกิดขึ้นเฉพาะแห่ง เช่น ในบริเวณอ่าวมินามาตะของญี่ปุ่น หรืออ่าวบางอ่าวในประเทศต่าง ๆ ที่มีการอุตสาหกรรมผลิตโซดาและคลอรีน สารปรอทที่ถูกปล่อยลงสู่แหล่งน้ำนั้น มีอยู่หลายรูปด้วยกัน สารปรอทมีความสามารถที่จะเข้าไปเกี่ยวเชื่อมกับสารอินทรีย์ได้ดี ฉะนั้น เมื่อมีสารปรอทจำนวนหนึ่งถูกปล่อยลงสู่แหล่งน้ำ ส่วนใหญ่ของสารปรอทจำพวกนี้ จะถูกดูดซึมเข้าไปอยู่ในตะกอนที่เป็นพวกสารอินทรีย์ และตกตะกอนลงสู่พื้นท้องน้ำในเวลาต่อมา ได้มีการพิสูจน์แล้วว่า

สารปรอทสามารถถูก methylated โดยปฏิกิริยาทางเคมีและชีวะเคมี ในตะกอนของพื้นท้องน้ำ

ส่วนของ methylmercury ที่ละลายน้ำได้ จะถูกปล่อยขึ้นจากตะกอนที่พื้นท้องน้ำ และพร้อมกันนี้ มันก็จะถูกรับเข้าไว้ในสิ่งมีชีวิต พืชสามารถสะสม methylmercury โดยวิธี passive absorption ซึ่งแตกต่างกับพวกสัตว์ เช่น ปลาที่สามารถสะสม methylmercury โดยวิธี active absorption (กินและดูดซึมเข้าไปทางเหงือก) ด้วยเหตุที่ว่าอัตราการดูดซับ methylmercury เข้าสู่ร่างกายนั้น เร็วกว่าอัตราการขับถ่าย methylmercury ออกจากร่างกาย จึงทำให้เกิดการสะสมในร่างกายได้ตามระยะเวลา และนอกจากนี้ยังทำให้เกิดการสะสมเพิ่มขึ้นไปตามลูกโซ่ของอาหารอีกด้วย methylmercury มีอันตรายมากกว่าสารปรอทในรูปอื่น ๆ