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INTESTINAL ABSORPTION AND BIOMAGNIFICATION OF ORGANOCHLORINES

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Abstract—Dietary uptake rates of several organochlorines from diets with different lipid contents were measured in goldfish (*Carassius auratus*) to investigate the mechanism of intestinal absorption and biomagnification of organic chemicals. The results suggest that intestinal absorption is predominantly controlled by chemical diffusion rather than lipid cotransport. Data for chemical uptake in human infants are presented to illustrate that biomagnification is caused by the digestion of food in the gastrointestinal tract. The findings are discussed in the context of two conflicting theories for the mechanism of biomagnification, and a mechanistic model is presented for the dietary uptake and biomagnification of organic chemicals in fish and mammals.

Keywords—Bioaccumulation Fish Humans PCBs Food chain

INTRODUCTION

Various studies have demonstrated that inert organochlorines with high octanol/water partition coefficients (K_{ow}), (log $K_{ow} > 6$) can biomagnify, that is, the fugacity of the chemical in the organism reaches a level that exceeds that in the diet of the organism. This can result in food-chain accumulation, in which the chemical fugacity in organisms increases with every step in the food chain [1–3]. These observations violate equilibrium partitioning and level I fugacity models, which assume equal fugacities for all organisms of a food chain. Although equilibrium partitioning is a well-understood mechanism for chemical distribution, the mechanism of biomagnification is largely unknown.

Two models have been proposed to explain the biomagnification phenomenon of hydrophobic organic substances. The first model assumes that intestinal absorption of hydrophobic organic substances from the gastrointestinal tract (GIT) into the organism's tissues is predominantly through passive diffusion. Thus, to achieve a fugacity (in units of pascals) in the organism (f_B) that exceeds that in its diet (f_D)—i.e., biomagnification—a fugacity gradient has to be established in which the fugacity in the gut (f_G) exceeds that in the organism, resulting in a net uptake of chemical across the GIT. This implies that in the GIT, f_D is elevated to f_G. The factors that have been proposed to contribute to this process are, first, the reduction of the volume of food in the GIT as a result of food digestion and absorption and, second, the change of the composition of the food phase during digestion, resulting in a reduction of the chemical's fugacity capacity of the food [1,4].

The second model assumes that biomagnification occurs in the organism's tissues and not in the GIT. The increase in chemical fugacity is due to transformation of lipids into energy, causing the absorbed and nonmetabolizable chemicals to be "left behind" but at a higher concentration and fugacity. Passive diffusion can no longer be the main dietary absorption route because, due to the biomagnification in the organism, f_B is higher than f_D and f_G, causing a net diffusion of chemical from the organism to the GIT. Chemical uptake across the GIT is thus believed to be due to lipid coassimilation, which is a "piggy-backing" process in which the chemical moves across the GIT in association with dietary lipids. Several observations support the role of lipid cotransport in dietary uptake of hydrophobic organic molecules in fish and mammals [5].

Although both models can explain biomagnification of persistent organochlorines, the hypothesized mechanisms differ in the mode of intestinal absorption (i.e., diffusion vs. coassimilation) and the site of biomagnification (i.e., GIT vs. organism's tissues). Consequently, there are different methods to estimate or predict biomagnification and food-chain transfer in aquatic and terrestrial

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food chains under natural conditions, ranging from chemical exchange models [6,7] to bioenergetic models [8]. To test these biomagnification models and improve the ability to manage and control the distribution of contaminants in food chains, we present experimental data regarding the mechanisms of intestinal transport of organochlorines and the location of the biomagnification process. In our study design we assume that in essence (but not necessarily in detail) dietary uptake and biomagnification in fish and mammals are similar. There are many examples of the similarities in the digestive processes of fish and mammals that provide a basis for comparing dietary uptake and biomagnification of hydrophobic organic substances in fish and mammals [9].

THEORY

To test the mechanism of intestinal absorption of organochlorines, an experiment was conducted in which fish were exposed to diets that contained identical concentrations of a series of organochlorines but which varied in their lipid contents from virtually 0 to 13.5%. To illustrate the theoretical basis for this experiment, we briefly outline the two models for dietary uptake and bioaccumulation. The models are presented in fugacity format [10], and they are simplified to reflect the experimental conditions of our studies in which chemical exposure was through the diet only.

Chemical uptake from food can be viewed as the combined result of chemical transport through the GIT and between the GIT and the organism (Fig. 1), shown respectively in Equations 1 and 2:

$$\begin{aligned} V_G \cdot dC_G/dt &= V_G \cdot Z_G \cdot df_G/dt \\ &= D_D \cdot f_D + D_{GO} \cdot f_B \\ &\quad - D_F \cdot f_G - D_{GI} \cdot f_G \end{aligned} \quad (1)$$

$$\begin{aligned} V_B \cdot dC_B/dt &= V_B \cdot Z_B \cdot df_B/dt \\ &= D_{GI} \cdot f_G - D_{GO} \cdot f_B - D_E \cdot f_B \end{aligned} \quad (2)$$

where V_G and V_B are the volumes (cubic meters) of, respectively, the GIT and the organism and Z_G, Z_B, and Z_D are the chemical's fugacity capacities (moles per cubic meter per Pascal) in, respectively, the GIT, the organism, and the diet. The Ds are transport parameters (moles per Pascal per day): D_D for dietary consumption, that is, the product of the feeding rate F_D (cubic meters per day) and Z_D; D_F for chemical elimination by fecal egestion, that is, the product of the fecal egestion rate F_F (cubic meters per day) and Z_G; D_{GI} for chemical transfer from the GIT into the organism; D_{GO} for chemical transfer from the organism to the GIT. D_E is a combined transport and transformation parameter for gill elimination and metabolic transformation. D_E is related to the elimination rate constant k_E (day^{-1}) by $V_B \cdot k_E \cdot Z_B$. C_G and C_B are the chemical concentrations (moles per cubic meter) in, respectively, the GIT and the organism. They are directly related to f_G and f_B, because C_G equals $f_G \cdot Z_G$ and C_B is $f_B \cdot Z_B$. Equations 1 and 2 contain the implicit assumption that the GIT contents are well mixed, that is, fecal matter and GIT contents have the same composition.

Assuming a steady-state mass balance for the GIT, it follows from Equation 1 that f_G adopts a value of

$$f_G = (D_D \cdot f_D + D_{GO} \cdot f_B)/(D_{GI} + D_F). \quad (3)$$

Substitution of Equation 3 into 2 gives the net dietary flux N_D (moles per day):

$$\begin{aligned} N_D &= V_B \cdot dC_B/dt \\ &= [D_D \cdot D_{GI}/(D_F + D_{GI})] \cdot f_D \\ &\quad - [D_F \cdot D_{GO}/(D_F + D_{GI})] \cdot f_B - D_E \cdot f_B. \end{aligned} \quad (4)$$

The first term in Equation 4, $f_D \cdot D_D \cdot D_{GI}/(D_F + D_{GI})$, is the total dietary chemical flux into the organism and can be rewritten as the familiar product $F_D \cdot E_D \cdot C_D$ or $V_B \cdot k_D \cdot C_D$, in which F_D is the feeding rate (cubic meters per day), E_D is the dietary uptake efficiency $[D_{GI}/(D_F + D_{GI})]$, C_D is the chemical concentration (moles per cubic meter) in the food, and k_D is the dietary uptake rate constant (day^{-1}), that is, $F_D \cdot E_D/V_B$ [4]. The second term, $f_B \cdot D_F \cdot D_{GO}/(D_F + D_{GI})$, represents chemical elimination through fecal egestion and can be rewritten as $F_F \cdot E_F \cdot C_B$ or $V_B \cdot k_F \cdot C_B$, where F_F is the rate of fecal egestion (cubic meters per day), E_F is the fecal elimination efficiency $[(Z_G/Z_B) \cdot D_{GO}/(D_F + D_{GI})]$, and k_F is the fecal egestion rate constant (day^{-1}), that is, $F_F \cdot E_F/V_B$. The ratio Z_G/Z_B is the chemical's partition coefficient K_{GB} between the gastrointestinal contents and the organism. The third term, $D_E \cdot f_B$, represents chemical elimination through all routes other than fecal egestion and equals $V_B \cdot k_E \cdot C_B$. t is time (day). Equation 4 is thus equivalent to

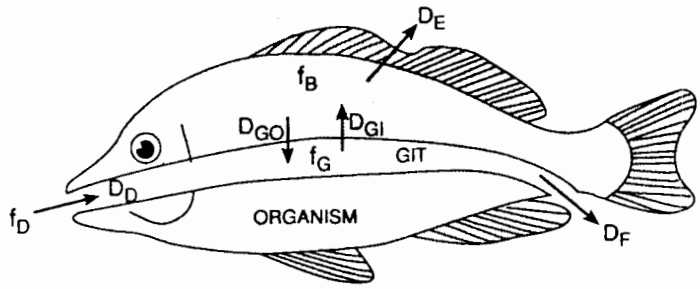

Fig. 1. Schematic diagram of dietary uptake of organic chemicals, illustrating the role of dietary consumption (D_D), intestinal absorption (D_{GI}), intestinal elimination (D_{GO}), fecal egestion (D_F), and chemical elimination via the gills and metabolic transformation (D_E).

$$N_D = V_B \cdot dC_B/dt$$
$$= F_D \cdot E_D \cdot C_D - F_F \cdot E_F \cdot C_B - V_B \cdot k_E \cdot C_B$$
$$= k_D \cdot C_D - (k_F + k_E) \cdot C_B. \quad (5)$$

At steady state ($N_D = 0$), we can define the biomagnification factor (BMF), C_B/C_D, as

$$BMF = C_B/C_D = F_D \cdot E_D/(F_F \cdot E_F + V_B \cdot k_E)$$
$$= k_D/(k_F + k_E) \quad (6)$$

Because during the initial phase of a dietary uptake experiment of hydrophobic chemicals in fish the loss terms in Equations 4 and 5 can often be ignored [11], Equations 4 and 5 can be integrated to give

$$C_B = [D_D \cdot D_{GI}/(D_F + D_{GI})] \cdot f_D \cdot t/V_B$$
$$= (F_D \cdot E_D \cdot C_D/V_B) \cdot t. \quad (7)$$

Diffusion

If simple passive diffusion is the dominant and rate-determining transport mechanism for intestinal absorption [12], then D_{GI} and D_{GO} are equal and can be represented by $k \cdot A \cdot Z_G$, where k is the chemical's mass transfer coefficient (meters per day) for diffusion across the GIT and A is the diffusion area in square meters. E_D is then $k \cdot A/(F_F + k \cdot A)$ and Equation 7 is

$$C_B = (F_D \cdot C_D/V_B) \cdot [k \cdot A/(F_F + k \cdot A)] \cdot t. \quad (8)$$

Coassimilation

If hydrophobic substances are absorbed predominantly across the GIT in association with or solubilized in a lipid vehicle [5,13,14], D_{GI} is the product of the lipid absorption rate G_L (in cubic meters lipid per day) and the fugacity capacity of the lipids Z_L, that is, $G_L \cdot Z_L$. E_D is then $G_L \cdot Z_L/(F_F \cdot Z_G + G_L \cdot Z_L)$, which after substitution in Equation 7 gives

$$C_B = (F_D \cdot C_D/V_B)$$
$$\cdot [G_L \cdot Z_L/(F_F \cdot Z_G + G_L \cdot Z_L)] \cdot t. \quad (9)$$

Equations 8 and 9 illustrate that it is possible to distinguish between the two proposed intestinal absorption mechanisms by varying the lipid content of the food and thus G_L, but keeping F_D, V_B, and C_D constant. If intestinal absorption is predominantly through diffusion, then a large (approximately 100-fold) increase in lipid content should result in a small drop of the dietary uptake efficiency and the uptake rate N_D as only the fecal egestion rate F_F is likely to increase somewhat. If intestinal absorption is through lipid coassimilation, then a low- or no-lipid diet should result in a low dietary uptake efficiency and a large increase in the food's lipid content should result in a large increase of the dietary uptake efficiency. Hypothetically, the only exception to this would occur if in all treatments chemical egestion in feces, $F_F \cdot Z_G$, is insignificant compared to lipid coassimilation, $G_L \cdot Z_L$, in which case E_D is 1.0.

STUDIES IN FISH

Materials

1,2,4,5-Tetra-, penta-, and hexachlorobenzene were obtained from Aldrich Chemical Co. (Milwaukee, WI). 2,2′,5,5′-Tetra-, 2,2′,4,4′,6,6′-hexa-, 2,2′,3,3′,4,4′,5,5′-octa, and decachlorobiphenyl, and octachlorostyrene were obtained from ANA Labs (Gaillard, France). Analytical-grade *n*-hexane and

petroleum ether were obtained from Caledon Ltd., Ontario. Florisil 60/100-μm mesh and silica gel 100/200-μm mesh were obtained from Supelco Canada Ltd. Anhydrous sodium sulfate, from J.T. Baker Chemical Co., was heated to 650°C overnight and stored at 130°C before use.

Experiment

The experiment was carried out in a thermostatted (21 ± 1°C) 300-L glass fish tank, which was divided in three equal compartments by aluminum screen windows. Throughout the experiment, with exception of the 10- to 15-min feeding periods, the water was continuously aerated (O_2 concentration was 8.0 ppm) and carbon filtered at a rate of 11 L/min. To each compartment, 50 goldfish (*Carassius auratus*) were added (Table 1). The fish were allowed to stabilize for 21 d, feeding on dried fish food, TetraMin® (TetraWerke, Germany) (6% lipid, 45% proteins, 31% carbohydrate, 7% fiber, 8% moisture, 3% sodium), at a rate of 0.013 grams food per fish per day. Then, the fish in each of the three compartments were fed a daily diet of a high-, a medium-, and a low-lipid food, respectively, each containing an equal concentration of the test chemicals (Table 1). After 1, 2, 3, 5, 7, 9, 12, 14, 16, 19, and 21 d, samples of three to four fish were collected. The fish were killed in liquid nitrogen, then degutted, frozen, and analyzed independently.

Low-lipid food was prepared by column extraction of 64 g dried fish food (TetraMin) with 750 ml petroleum ether. The lipid extract was added to 32 g TetraMin and the petroleum ether evaporated to make the high-lipid food. Medium-lipid food was unaltered TetraMin. Test chemicals were applied to the foods by adding the food to a solution of the test chemicals in petroleum ether, which was then evaporated to dryness.

Fecal egestion rates and food digestibility were measured in independent experiments by feeding fish low-, medium-, and high-lipid food at the same feeding rates as those in the dietary uptake experiment. Feces were collected daily by filtration of the water before the fish were fed. The feces were then dried in an oven at 90°C and weighed. Food digestibility was measured as the ratio of the weights of consumed (i.e., administered food − dried fecal matter) and administered food.

Chemical analysis in fish and food

Fish were thawed, measured, and weighed independently then ground to a paste in a mortar with 20 ml anhydrous sodium sulfate. This paste was added to a 0.025- × 0.60-m glass column containing 10 ml anhydrous sodium sulfate and 70 ml (1:1) dichloromethane:petroleum ether. After 1 h, the column was eluted with 250 ml petroleum ether. The extract was then concentrated by evaporation to approximately 2 ml. Sample cleanup was by passing the concentrate through a 0.01- × 0.55-m glass column, containing, from bottom to top, 8 ml silica, 8 ml acidified silica (40% [w/w] sulfuric acid), and 3 ml anhydrous sodium sulfate. This co' was eluted with 50 ml petroleum ether. The ex was concentrated to 1 ml then diluted to 10 ml in hexane and analyzed by GC. Food analysis was

Table 1. Summary of the experimental conditions of the dietary uptake studies in fish

	Low	Medium	High
Average fish weight (g)[a]	1.28 (±0.51)	1.28 (±0.52)	1.30 (±0.62)
Lipid content fish (%)[a]	1.00 (±0.45)	1.01 (±0.43)	1.00 (±0.40)
Feeding rate per fish (mg food/day)	13.0	12.8	13.0
Lipid content food (%)	<0.2	6.3	13.5
Caloric intake (cal/day)	54	59	62
Fecal egestion rate (mg feces/day) per fish	3.1 (±0.3)	3.9 (±0.4)	5.2 (±0.5)
Food digestibility (%)	76 (±7)	70 (±6)	60 (±6)
Food concentrations (μg/g)			
Tetrachlorobenzene	38.6	40.6	43.7
Pentachlorobenzene	40.2	37.2	39.1
Hexachlorobenzene	29.0	27.4	27.5
Octachlorostyrene	21.2	21.2	20.3
Tetrachlorobiphenyl	8.64	8.64	7.69
Hexachlorobiphenyl	27.0	26.8	26.3
Octachlorobiphenyl	16.4	15.2	16.4
Decachlorobiphenyl	11.3	10.7	10.9

[a] $n = 30$.

done in a similar manner. The recovery of the entire fish and food extraction procedure ranged from 85% (±5%) for trichlorobenzene to 98% (±4%) ($n = 3$) for octachlorobiphenyl.

GC analysis was performed on a Varian 3500, equipped with a 30-m DB-5 capillary column (J & W Scientific, Rancho Cordova, CA), a ^{63}Ni electron-capture detector, and an integrator. Injector temperature was 250°C, detector temperature was 300°C, and column temperature was programed from 50 to 300°C. The carrier gas was ultra-high-pure-grade helium at 1.5 ml/min. The makeup gas was ultra-high-pure-grade 5% methane-95% argon at 60 ml/min. The injection mode was splitless, with an injection volume of 1 μl. Standards were prepared from the pure chemicals.

Lipid content analysis of fish and food

After extraction, but before cleanup, food and fish extracts were evaporated to dryness and then further dried in an oven at 60°C for 1 h. The lipids were then determined by weight.

Statistics

Standard deviations are reported in parentheses. Confidence intervals (C.I.) are reported in square brackets and have a 95% probability.

RESULTS AND DISCUSSION

Typical results of the experiment are shown in Figure 2 for pentachlorobenzene and octachlorobiphenyl. During the experiment, lipid levels and weights of the fish did not show significant changes over time ($P < 0.05$). Due to the low elimination rates, C_F increased linearly with t during the initial 15 d of the experiment for tetra- and pentachlorobenzene, and throughout the entire 21-d uptake period for the other test chemicals. The dietary uptake efficiency E_D could thus be determined from the slope of the C_F vs. t relationship (Table 2). For the lower K_{ow} substances, no significant differences in E_D were observed between the treatments (Table 2). However, for octachlorostyrene and hexa-, octa-, and decachlorobiphenyl, E_D from the low-fat food was found to be significantly higher than E_D from the high-fat food ($P < 0.05$). These results are in agreement with a diffusion-controlled uptake rate. The higher dietary uptake efficiencies from low-fat foods are likely to be due to greater digestibility of the low-fat food, resulting in a lower fecal egestion rate F_F and thus a higher E_D. The measurements of the food digestibility (Table 1), which are in good agreement with similar observations for other fish species [15], tend to confirm this hypothesis because F_F in fish with the low-fat diet was 3.1 mg (±0.3 mg) dried feces per day, a food digestibility of 76% (±7%), whereas F_F in fish exposed to the high-fat food was 5.2 mg (±0.5 mg) dried feces per day, a digestibility of 60% (±6%). Because the lower food digestibility for the higher fat food applies to all chemicals, differences in E_D should have been observed for all chemicals. However, the variability in the observed concentrations of the lower K_{ow} chemical was too large to detect possible differences in E_D.

In an experiment similar to our experiment in fish, it was shown that a 10-fold variation in the mass of lipid carrier (triglyceride oil) in the food had no effect on the dietary uptake of benzo[*a*]pyrene (log K_{ow} 6.5) in rats and that portal, not lymphatic, transport was the major dietary uptake route [13]. Similar findings were reported for 3-methylchol-

Table 2. Octanol/water partition coefficients and observed dietary uptake efficiencies and their 95% C.I.s for various organochlorines in low-, medium-, and high-lipid foods

	Log K_{ow}	Low	Medium	High
Tetrachlorobenzene	4.51[a]	46 [±10]	50 [±8]	50 [±9]
Pentachlorobenzene	5.03[a]	48 [±7]	51 [±8]	46 [±10]
Hexachlorobenzene	5.47[a]	50 [±5]	46 [±5]	46 [±6]
Tetrachlorobiphenyl	6.10[b]	47 [±6]	47 [±6]	44 [±4]
Octachlorostyrene	6.29[c]	66 [±8]	62 [±4]	48 [±6]
Hexachlorobiphenyl	7.0[b]	42 [±4]	36 [±6]	33 [±5]
Octachlorobiphenyl	7.8[b]	53 [±3]	48 [±2]	35 [±4]
Decachlorobiphenyl	8.26[b]	34 [±3]	30 [±2]	26 [±4]

[a]From [25].
[b]From [26].
[c]From [27].

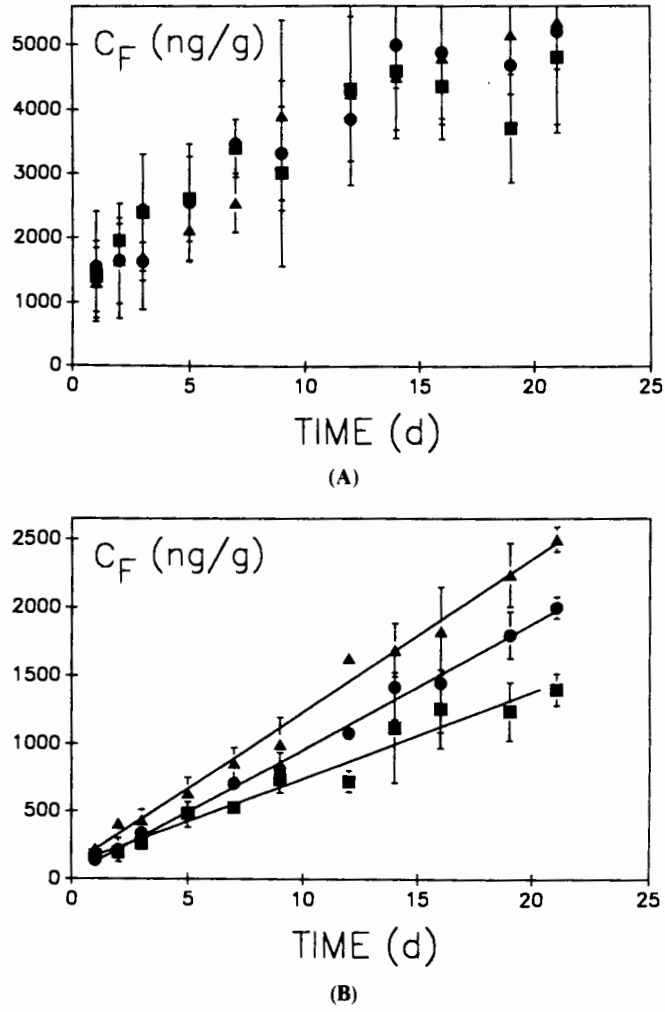

Fig. 2. Wet-weight-based concentrations of pentachlorobenzene (**A**) and octachlorobiphenyl (**B**) in fish (ng/g fish) and their standard deviations during dietary exposure to equimolar diets containing <0.2%-fat (▲), 6.3%-fat (●), and 13.5%-fat (■) food as a function of time (in days).

anthrene and aminostilbene derivatives [16]. For DDT, observations are contradictory, and both lymphatic transport and gut absorption were identified to be major routes of dietary uptake in rats, but metabolic transformation of DDT caused complications for the analysis [14]. Based on the results of these and other studies, there is sufficient evidence that lipid coassimilation and diffusion play a role in the dietary absorption of hydrophobic substances in fish and mammals [5,12]. In effect, following Friedman and Nylund [17] and Thomson and Dietschy [18], it can be proposed that hydrophobic substances are transported to the intestinal wall in association with lipid molecules. Then the chemical separates from the lipid to diffuse as a single molecule through the intestinal wall, as only single molecules (including fatty acids) permeate the intestinal wall. At the other side of the intestinal wall, the chemical is reassociated and "packaged" with lipoproteins and resynthesized triglycerides [5], a process driven by the resynthesis of triglycerides and thus the availability of fat in the GIT. This process is illustrated in more detail in Figure 3. Our results conform to this theory and indicate that for the dietary uptake of chlorinated benzenes and PCBs in fish, diffusion rather than coassimilation appears to be the rate-determining process for dietary uptake because increased lipid absorption did

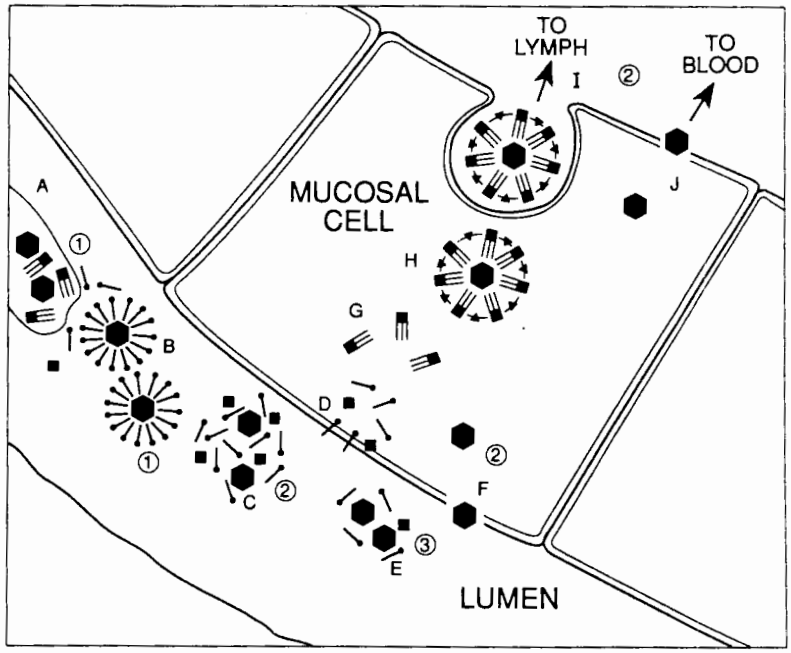

Fig. 3. Schematic representation of dietary chemical absorption and magnification: (A) Chemical enters the GIT in association with food. (B) Triglycerides are hydrolyzed and fatty acids are released in the presence of enzymes and bile acids to form micelles that contain hydrophobic substances. The micelles with the chemical then diffuse through the unstirred water layers to the mucosal surface. (C) Fatty acids diffuse out the micelles and (D) diffuse as individual molecules through the unstirred aqueous diffusion layers and the mucosal membrane, causing (E) an increase in the chemical fugacity and concentration in the GIT, which provides the driving force for (F) a net diffusion of the chemical across the unstirred aqueous layers and mucosal membrane. (G) Within the cell the triglycerides are reconstituted and (H) packaged into lipoproteins, which can be released by (I) exocytosis. Chemical transport may occur in association with these "lipid particles" and/or (J) by diffusion into the blood. The numbers exemplify the differences in chemical fugacities that may occur at steady state.

not increase the dietary uptake rate of the test chemicals. The direct consequence of this crucial role of diffusion is that biomagnification has to occur in the GIT because net uptake through diffusion can occur only if the fugacity in the GIT exceeds that in the organism.

STUDIES IN HUMANS

To provide evidence for the location of the biomagnification process, we reanalyzed data of a study by Kodama and Ota [19], who measured polychlorinated biphenyl (PCB) concentrations in maternal blood and milk and in the baby's blood for mother-baby couples before and during breast fe-ding. The reported PCB concentrations were expressed on a lipid-weight basis in Table 3 and Figure 4. The data show that, at birth, the PCB concentration in the blood of the mother is approximately four times higher than that in the cord blood, which represents the blood of the baby. However, on a lipid-weight basis, the PCB concentrations in the mother and the baby are approximately equal because lipid levels in cord blood are three to four times lower than that in maternal blood [23,24]. The PCB concentration in the breast milk fat collected immediately after birth is also approximately equal to that in the blood on a lipid-weight basis. These findings are supported by an independent study by Masuda et al. [22] showing that PCB concentrations in maternal blood (2.5 ± 0.14 ppb, $n = 30$) and cord blood (0.61 ± 0.05, $n = 60$) are approximately equal if expressed on a lipid-weight basis, that is, respectively, 438 and 381 ppb. PCB concentrations in milk fat (350 ± 25 ppb, $n = 52$) and blood fat (245 ppb) are also approximately equal [22]. After birth and during breast feeding, the PCB concentration in maternal blood and milk falls approximately two- to threefold, whereas the PCB concentration in the blood of the baby increases six to sevenfold over a two-year period, approaching a level at the end of

Table 3. Observed PCB concentrations (in ppb) in blood, blood fat, milk, and milk fat of a mother and in the blood and blood fat of the mother's baby at different times (in months) after birth

Time	Blood, mother[a]	Blood fat, mother[b]	Milk, mother[a]	Milk fat, mother[c]	Blood, infant[a]	Blood fat, infant[d]
0	12	2,100			3.1	1,940
3	5.7	1,000	64.2	1,780	11.5	2,020
12					17.5	3,070
15	4.7	820				
16			28.8	800	19	3,330
24	3.7	640			20	3,510

[a]Original data from [20].
[b]Calculated from the PCB concentration in blood using an average blood lipid content of 0.57% [28].
[c]Calculated from the PCB concentration in milk using the reported lipid content of 3.6% [19].
[d]Calculated from the PCB concentration in infant blood by using a blood lipid content of 0.16% for cord blood ($t = 0$), that is, 3.5 times lower than maternal blood [20], and 0.57% for infant blood levels at and after three months.

the breast feeding period that is approximately five to six times higher than that in the mother's blood. This increase in concentration is achieved while the baby is growing, which is known to have a "diluting" effect on the PCB concentration. Part of the increase of the PCB concentration in the infant's blood can be attributed to an increase of blood triglyceride levels, which typically triple within the first 3 d after birth [20] and reach a constant value comparable to adult concentrations within three months after birth [23]. Estimates of lipid-based PCB concentrations (Table 3) thus increase from an initial level of approximately 1,940 to 3,510 ppb, which is approximately five times higher than lipid-based PCB concentrations in maternal blood and the milk the infant consumes at the end of the breast feeding period.

These results illustrate that while contaminant transfer is via the blood (i.e., via the placenta), lipid-weight-based PCB concentrations in the mother and in the fetus achieve a similar level. Because lipid-weight-based concentrations are, in effect, surrogates for chemical fugacities, the mother and baby appear to be at a "chemical equilibrium" (i.e., equal fugacities) at birth, and no biomagnification ha curred. But when the baby is exposed to the s or actually a lower PCB fugacity by consuming milk (i.e., uptake via the GIT), the PCB lipid-based concentration and fugacity in the infant rise to exceed that in the milk (biomagnification), even while the

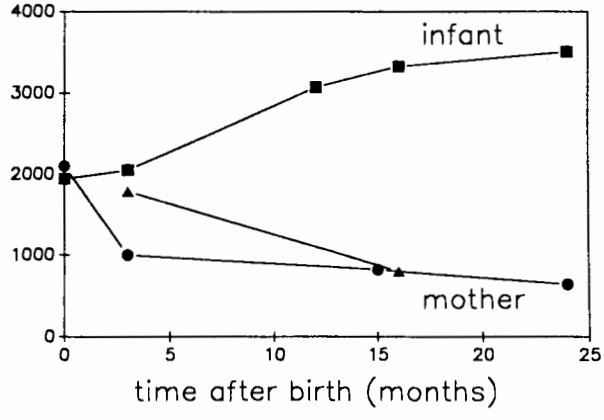

Fig. 4. PCB concentrations (ppb) in blood lipids (●) and milkfat (▲) of a mother and in the blood fat of the mother's baby (■) vs. time (in months) during a 2-year period of breast feeding following birth ($t = 0$).

infant is growing. This indicates that during pregnancy, the internal metabolism of the fetus does not cause a magnification of the PCB concentration and fugacity. The biomagnification of PCB appears to occur only as a result of food digestion in the GIT.

CONCLUSIONS

The results that are presented provide support for two important aspects of the "digestion" hypothesis for chemical biomagnification, namely, that passive diffusion is the predominant driving force for gastrointestinal uptake of hydrophobic organic substances, and that magnification occurs in the GIT as a result of food digestion.

If our interpretation is correct and biomagnification is due largely to food digestion in the GIT, then chemical biomagnification factors in organisms can be determined from (a) the feeding and fecal egestion rates of the organism, (b) the chemical's partition coefficient K_{GB} between the gastrointestinal contents and the organism, and (c) the rate of chemical elimination through routes other than fecal egestion (e.g., via gills and metabolic transformation) relative to the rate of chemical elimination in the feces.

For example, for very hydrophobic (e.g., $\log K_{ow} > 6$) nonmetabolizable chemicals, for which gill elimination is insignificant ($V_B \cdot k_E \ll F_F \cdot E_F$ or $k_E \ll k_F$), the biomagnification factor is $F_D/(F_F \cdot K_{GB})$, resulting in typical values for fish of approximately three to five, depending on the digestibility of the food in the fish. However, if elimination through metabolic transformation and/or gill excretion is much faster than fecal elimination ($V_B \cdot k_E \gg F_F \cdot E_F$ or $k_E \gg k_F$), then the biomagnification factor (BMF) C_B/C_D is $F_D \cdot E_D/V_B \cdot k_E$. This is often the case in fish for chemicals with a log K_{ow} less than approximately 6 [24]. For example, 2,5-dichlorobiphenyl has a log K_{ow} of 5.0, an E_D of 0.5, and a k_E of 0.066 d^{-1} in a 5-g goldfish [11]. Thus, assuming a typical feeding rate F_D of 0.05 grams food per day, 2,5-dichlorobiphenyl will have a BMF C_B/C_D of approximately 0.076, which is in agreement with the observed value of 0.08 [11] and suggests no significant biomagnification in the fish.

This relatively simple model is believed to provide a more correct and simpler alternative to quantify chemical biomagnification in organisms and food chains than whole-organism energy balance models, which are considerably more complicated and data intensive.

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