Aerobic and Anaerobic PCB Biodegradation in the Environment

Daniel A. Abramowicz
Environmental Laboratory, GE Corporate Research and Development, Schenectady, New York

Studies have identified two distinct biological processes capable of biotransforming polychlorinated biphenyls (PCBs): aerobic oxidative processes and anaerobic reductive processes. It is now known that these two complementary activities are occurring naturally in the environment. Anaerobic PCB dechlorination, responsible for the conversion of highly chlorinated PCBs to lightly chlorinated ortho-enriched congeners, has been documented extensively in the Hudson River and has been observed at many other sites throughout the world. The products from this anaerobic process are readily degradable by a wide range of aerobic bacteria, and it has now been shown that this process is occurring in surficial sediments in the Hudson River. The widespread anaerobic dechlorination of PCBs that has been observed in many river and marine sediments results in reduction of both the potential risk from and potential exposure to PCBs. The reductions in potential risk include reduced dioxinlike toxicity and reduced carcinogenicity. The reduced PCB exposure realized upon dechlorination is manifested by reduced bioaccumulation in the food chain and by the increased anaerobic degradability of these products. — Environ Health Perspect 103(Suppl 5):97-99 (1995)

Key words: aerobic PCB biodegradation, anaerobic PCB dechlorination, dioxinlike toxicity, carcinogenicity, PCB biotransformation

Introduction

Polychlorinated biphenyls (PCBs) are a family of 209 related chemical compounds that were manufactured and sold as complex mixtures differing in their average chlorination level. The individual PCB isomers, or PCB congeners, are described according to the position of the chlorine substitution, e.g., 2,3,4,3',4'-pentachlorobiphenyl (the shorthand 234-34-CB will be used in this article).

The desirable physical and chemical properties of PCBs (excellent dielectric and flame resistance properties, chemical and thermal stability) led to their extensive industrial use as heat transfer fluids, hydraulic fluids, solvent extenders, plasticizers, flame retardants, organic diluents, and dielectric fluids (1). Extensive application of these chemically and thermally stable compounds has resulted in widespread contamination (2-4); it is estimated that several hundred million pounds have been released to the environment (5). The high octanol/water partition coefficient (K ow) of some PCB congeners results in their accumulation in fatty tissues and their biomagnification in the food chain (6).

PCB Biodegradation

These compounds have been shown to undergo biodegradation under a variety of conditions in the laboratory and in the environment (7-10). Two distinct biological systems capable of biodegrading PCBs have been identified: aerobic oxidative processes and anaerobic reductive processes.

The aerobic bacterial biodegradation of PCBs is widely known and has been well studied (7-10). Several microorganisms have been isolated that can aerobically degrade PCBs, preferentially degrading the more lightly chlorinated congeners. These organisms attack PCBs via the well-known 2,3-dioxigenase pathway, converting PCB congeners to the corresponding chlorobenzoic acids. These chlorobenzoic acids can then be degraded by indigenous bacteria, resulting in the production of carbon dioxide, water, chloride, and biomass.

Anaerobic bacteria attack more highly chlorinated PCB congeners through reductive dechlorination. In general, this microbial process effects the preferential removal of meta and para chlorines, resulting in a depletion of highly chlorinated PCB congeners with corresponding increases in lower chlorinated, ortho-substituted PCB congeners. The altered congener distribution of residual PCB contamination was the earliest evidence of the anaerobic dechlorination of PCBs (11-13). This same activity has been observed in the laboratory (14-16), where the selective removal of meta and para chlorines was also noted.

The widespread dechlorination of PCBs in aquatic sediments has now been documented for several river systems (17-19). These surveys demonstrate that PCB dechlorination is prevalent in aquatic sediments. Extensive PCB dechlorination has been observed in sediments of the upper Hudson River (Figure 1). This survey of approximately 1000 sampling locations in a 6-mile stretch of the river (mile point 194.5 to 188.5) indicates that microbial dechlorination is widespread throughout these sediments. Extensive changes had occurred in sediments exhibiting a broad range of PCB concentrations, even as low as 5 ppm (17).

A current list of sites where PCB-dechlorinating microorganisms have been found is shown in Table 1. Note that these organisms can be detected in a number of PCB-free (uncontaminated) environments upon the addition of PCBs in the laboratory. This suggests that PCB-dechlorinating activity may be the result of a common reductive pathway present in many different anaerobic microorganisms located throughout the environment. Support for this hypothesis comes from recent efforts demonstrating that several iron and cobalt heme cofactor systems are capable of reductively dechlorinating a wide variety of chlorinated organic compounds (20,21), including PCBs (22). In general, environmental dechlorination is more extensive at higher PCB concentrations, consistent...
with the faster dechlorination rates observed at higher PCB concentrations in the laboratory (23).

**Benefits of Anaerobic PCB Dechlorination**

The benefits of anaerobic PCB dechlorination involve reductions in both the potential risk from and potential exposure to PCBs. These reductions in the potential risk from PCBs include reduced dioxinlike toxicity and reduced carcinogenicity. The preferential loss of *meta* and *para* chlorines catalyzed by anaerobic dechlorination results in dramatic reductions in the levels of coplanar, dioxinlike PCB congeners in the mixture (24). These reductions in concentrations correlate with reductions in ethoxyresorufin-O-deethylase (EROD) induction potency and toxic equivalency factors for the mixture. Most importantly, these same extensive reductions are occurring in the environment (24). The reduced carcinogenicity as a result of dechlorination is supported by the recent reanalysis of the original rat cancer studies (25). In these studies, only the most highly chlorinated PCB mixture (Aroclor 1260, average 6.4 chlorines per biphenyl) resulted in observable cancer potencies. Aroclor 1254 (average 5.1 chlorines per biphenyl) and Clophen A30 did not demonstrate any tumorigenic effect (25). Clophen A30 is similar in composition to Aroclor 1242, with an average 3.3 chlorines per biphenyl. Decreasing PCB chlorination levels and microbial anaerobic PCB dechlorination therefore reduce carcinogenic potential.

Additional reductions in risk associated with PCB-contaminated sediments are realized via reduced PCB exposure upon dechlorination. This reduced exposure is manifested in two ways. First, the lightly chlorinated PCB congeners produced upon dechlorination are more readily degraded by indigenous aerobic bacteria (26). Moreover, new evidence indicates that the aerobic process is occurring naturally in undisturbed Hudson River sediments (27). Second, dechlorination significantly reduces the bioaccumulation potential of the PCB mixture through conversion to congeners that do not significantly bioaccumulate in the food chain. The lightly chlorinated PCB congeners resulting from dechlorination (e.g., 2-2-CB and 2-2-CB)

---

**Table 1.** Known sites containing microorganisms capable of anaerobic PCB dechlorination.

| PCB-contaminated sites                      | Uncontaminated sites       |
|---------------------------------------------|-----------------------------|
| Escambia Bay Florida                        | Adirondack Marsh New York   |
| Fox River/Green Bay Wisconsin              | Center Pond Massachusetts   |
| Grass River New York                        | Hudson River New York       |
| Hoosic River Massachusetts                  | Puget Sound Washington     |
| Housatonic River Massachusetts              | Red Cedar River Michigan   |
| Hudson River New York                       | Saline River Michigan       |
| Kalamazoo River Michigan                    | St. Lawrence River New York|
| Lake Hartwell South Carolina                | Waukegan Harbor Illinois    |
| Lake Ketelmeer The Netherlands              | Woods Pond Massachusetts    |
| Lake Shinji Japan                           |                            |
| Moreau Drag Strip New York                 |                            |
| New Bedford Harbor Massachusetts            |                            |
| Otonabee River/Rice Lake Canada             |                            |
| Rhine River Germany                         |                            |
| Rhine River The Netherlands                 |                            |
| Sheboygan River Wisconsin                  |                            |
| Silver Lake Massachusetts                   |                            |
| St. Lawrence River New York                 |                            |
| Waukegan Harbor Illinois                    |                            |
| Woods Pond Massachusetts                    |                            |

---

**Figure 1.** Locations of sediment PCB accumulations in the upper Hudson River, based on reanalysis of the 1984 New York State survey of the Thompson Island Pool. (+) Samples containing ≥10 ppm PCB; (−) samples displaying extensive dechlorination (peak >10/peak ≤1).
display an approximate 450-fold reduction in their tendency to accumulate in fish, as compared to the more highly chlorinated tri- and tetra-chlorinated PCBs present in the original Aroclor 1242 mixture. Thus, natural anaerobic PCB dechlorination reduces the potential risk associated with PCBs via direct reductions in carcinogenic potency, dioxinlike toxicity, and exposure.

REFERENCES

1. Hutzinger O, Safe S, Zitko V. The Chemistry of PCBs. Cleveland, OH: CRC Press, 1974.
2. Buckel EH. Accumulation of airborne polychlorinated biphenyls in foliage. Science 216:520 (1982).
3. Jensen S. Report of a new chemical hazard. New Scientist 32:612 (1966).
4. Tanabe S, Hidaka H, Tatsukawa R. PCBs and chlorinated hydrocarbon pesticides in Antarctic atmosphere and hydrosphere. Chemosphere 12(2):277–288 (1983).
5. Hutzinger O, Veerkamp W. Xenobiotic chemicals with pollution potential. In: Microbial Degradation of Xenobiotics and Recalcitrant Compounds (Leisinger T, Hutter T, Cook AM, Nuesch J, eds). New York: Academic Press, 1981:3–45.
6. Safe S. Metabolism uptake, storage, and bioaccumulation. In: Halogenated Biphenyls, Naphthalenes, Dibenzodioxins, and Related Products (Kinbrough V, ed). Elsevier/North Holland, 1980:81–107.
7. Abramowicz DA. Aerobic and anaerobic biodegradation of PCBs: a review. In: CRC Critical Reviews in Biotechnology, Vol 10 (Steward GG, Russell I, eds). Boca Raton, FL: CRC Press, 1990:241–251.
8. Bedard DL. Bacterial transformations of polychlorinated biphenyls. In: Biotechnology and Biodegradation, Advances in Applied Technology Series, Vol 4 (Kamely D, Chakraborty A, Omenn GS, eds). The Woodlands, TX: Portfolio Publishing, 1990:369–388.
9. Furukawa K. Microbial degradation of polychlorinated biphenyls (PCBs). In: Biodegradation and Detoxification of Environmental Pollutants (Chakraborty AM, ed). Boca Raton, FL: CRC Press, 1982:33–57.
10. Furukawa K. Modifications of PCBs by bacteria and other microorganisms. In: PCBs and the Environment, Vol 2 (Waid JS, ed). Boca Raton, FL: CRC Press, 1986:89–100.
11. Brown JF, Wagner RE, Bedard DL, Brennan MJ, Carnahan JC, May RJ. PCB transformations in upper Hudson sediments. Northeast Environ Sci 3:167–179 (1984).
12. Brown JF, Bedard DL, Brennan MJ, Carnahan JC, Feng H, Wagner RE. PCB dechlorination in aquatic sediments. Science 236:709–712 (1987).
13. Brown JF, Wagner RE, Feng H, Bedard DL, Brennan MJ, Carnahan JC, May RJ. Environmental dechlorination of PCBs. Environ Toxicol Chem 6:579–593 (1987).
14. Quensen JF, Tiedje JM, Boyd SA. Reductive dechlorination of PCBs by anaerobic microorganisms from sediments. Science 242:752–754 (1988).
15. Quensen JF, Boyd SA, Tiedje JM. Dechlorination of four commercial polychlorinated biphenyl mixtures (Aroclors) by anaerobic microorganisms from sediments. Appl Environ Microbiol 56:2360–2369 (1990).
16. Abramowicz DA, Brennan MJ, Van Dort HM. Anaerobic biodegradation of polychlorinated biphenyls. In: Extended Abstracts of American Chemical Society National Meeting, Div Environ Chem 29(2):377–379 (1989).
17. Abramowicz DA, Brown JF Jr, O’Donnell MK. Anaerobic PCB dechlorination in Hudson River sediments. In: General Electric Company Research and Development Program for the Destruction of PCBs, Tenth Progress Report. Schenectady, NY: General Electric Corporate Research and Development, 1991:17–30.
18. Brown JF Jr, Wagner RE. PCB movement, dechlorination, and detoxication in the Acushnet Estuary. Environ Toxicol Chem 9:1215–1233 (1990).
19. Lake JL, Pruett RJ, Osterman FA. An examination of dechlorination processes and pathways in New Bedford harbor sediments. Mar Environ Res 33:31–47 (1992).
20. Krone UE, Thauer RK, Hogenkamp CH. Reductive dehalogenation of chlorinated C2-hydrocarbons mediated by corrinoids. Biochemistry 28:4908–4914 (1989).
21. Gantzer CJ, Wackett LP. Reductive dechlorination catalyzed by bacterial transition-metal coenzymes. Environ Sci Technol 25:715–722 (1991).
22. Assaf-Anid N, Nies L, Vogel TM. Reductive dechlorination of a polychlorinated biphenyl congener and hexachlorobenzene by vitamin B12. Appl Environ Microbiol 58:1057–1060 (1992).
23. Abramowicz DA, Brennan MJ, Van Dort HM, Gallagher EL. Factors influencing the rate of polychlorinated biphenyl dechlorination in Hudson River sediments. Environ Sci Technol 27(6):1125–1131 (1993).
24. Quensen J, Boyd SA, Tiedje JM, Lopshire RF, Enke CG. Expected dioxinlike toxicity reduction as a result of the dechlorination of Aroclors. In: General Electric Company Research and Development Program for the Destruction of PCBs, Eleventh Progress Report. Schenectady, NY: General Electric Corporate Research and Development, 1992:189–196.
25. Moore JA. Reassessment of Liver Findings in PCB Studies for Rats. Washington: Institute for Evaluating Health Risks, July 1, 1991.
26. Harkness MR, McDermott JB, Abramowicz DA, Salvo JJ, Flanagan WP, Stephens ML, Mondello FJ, May RJ, Lobos JH, Carroll KM, Brennan MJ, Bracco AA, Fish KM, Warner GL, Wilson PR, Dietrich DK, Lin DT, Morgan CB, Gately WL. In situ stimulation of aerobic PCB biodegradation in Hudson River sediments. Science 259:503–507 (1993).
27. Flanagan WP, May RJ. Metabolite detection as evidence for naturally occurring aerobic PCB biodegradation in Hudson River sediments. Environ Sci Technol 27(10):2207–2212 (1993).