

### Ⅲ. 研究成果の刊行に関する一覧表

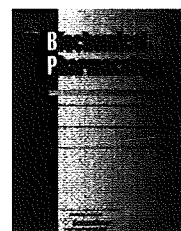
研究成果の刊行に関する一覧表

雑 誌

発表者氏名	論文タイトル名	発表誌名	巻号	ページ	出版年
Hirabayashi Y, and Inoue T.	Aryl hydrocarbon receptor biology and xenobiotic responses in hematopoietic progenitor cells.	Biochem Pharmacol	77(4)	521-535	2009
Kawasaki Y, Hirabayashi Y, Kaneko T, Kanno J, Kodama Y, Matsushima Y, Ogawa Y, Saitoh M, Sekita K, Uchida O, Umemura T, Yoon B I, Inoue T.	Benzene-Induced Hematopoietic Neoplasms Including Myeloid Leukemia in <i>Trp 53</i> -Deficient C57BL/6 and C3H/He Mice.	Toxicol Sci	110(2)	293-306	2009
Yi J Y, Hirabayashi Y, Choi Y K, Kodama Y, Kanno J, Han J H, Inoue T, and Yoon B I.	Benzene activates caspase-4 and -12 at the transcription level, without an association with apoptosis, in mouse bone marrow cells lacking the p53 gene.	Arch Toxicol	83(8)	795-803	2009
Inoue, T., Hirabayashi, Y.	Hematopoietic neoplastic diseases develop in C3H/He and C57BL/6 mice after benzene exposure: Strain differences in bone marrow tissue responses observed using microarrays.	Chem Biol Interact	Doi:10.1016/j.cbi.2009.12.005	1-6	2009
井上 達	内分泌攪乱化学物質の低用量作用と毒性学のあたらしい課題.	科学 (Science Journal KAGAKU)	79(9)	1022-1028	2009
Kim H, Hayashi S, Chambon P, Watanabe H, Iguchi T, Sato T.	Effects of diethylstilbestrol on ovarian follicle development in neonatal mice.	Reprod Toxicol	27(1)	55-62	2009
Lange A, Paull GC, Coe TS, Katsu Y, Urushitani H, Iguchi T and Tyler CR.	Sexual Reprogramming and Estrogenic Sensitization in Wild Fish Exposed to Ethinylestradiol.	Environ Sci Technol	43(4)	1219-25	2009
Tyler CR, Filby AL, Bickley LK, Cumming RI, Gibson R, Labadie P, Katsu Y, Liney KE, Shears JA, Silva-Castros V, Urushitani H, Lange A, Winter MJ, Iguchi T and Hill EM.	Environmental Health Impacts of Equine Estrogens Derived from Hormone Replacement Therapy.	Environ Sci Technol.	43(10)	3897-904	2009
Miyagawa S, Satoh Y, Haraguchi R, Suzuki K, Iguchi T, Taketo MM, Nakagata N, Matsumoto T, Takeyama K, Kato S and Yamada	Genetic Integrations of the Androgen and Wnt/ $\beta$ -catenin Pathways for the Masculinization of External Genitalia.	Mol Endocrinol	23(6)	871-80	2009
Oka T, Miyahara M, Yamamoto J, Mitsui N, Fujii T, Tooi O, Kashiwagi K, Takase M, Kashiwagi A, Iguchi T.	Application of metamorphosis assay to a native Japanese amphibian species, <i>Rana rugosa</i> , for assessing effects of thyroid system affecting chemicals.	Ecotoxicol Environ Safety	72(5)	1400-5	2009
Miyagawa S, Moon A, Haraguchi R, Inoue C, Harada M, Nakahara C, Suzuki K, Matsumaru D, Kaneko T, Matsuo I, Yang L, Taketo MM, Iguchi T, Evans SM and Yamada G.	Dosage-dependent hedgehog signals integrated with Wnt/ $\beta$ -catenin signaling regulate external genitalia formation as an appendicular program.	Development	136(23)	3969-78	2009
Kim H, Nakajima T, Hayashi S, Chambon P, Watanabe H, Iguchi T, Sato T.	Effects of Diethylstilbestrol on Programmed Oocyte Death and Induction of Polyovular Follicles in Neonatal Mouse Ovaries.	Biol Reprod	81(5)	1002-9	2009
Moore BC, Milnes MR, Kohno S, Katsu Y, Iguchi T, Guillette LJ.	Influences of Sex, Incubation Temperature, and Environmental Quality on Gonadal Estrogen and Androgen Receptor Messenger RNA Expression in Juvenile American Alligators ( <i>Alligator mississippiensis</i> ).	Biol Reprod	82(1)	194-201	2010

Miyagawa S, Katsu Y, Ohta Y, Sudo T, Lubahn DB, <u>Iguchi T</u> .	Estrogen Receptor ESR1 Is Indispensable for the Induction of Persistent Vaginal Change by Neonatal 5alpha-Dihydrotestosterone Exposure in Mice.	Biol Reprod	82(3)	497-503	2010
Myers JP, vom Saal FS, Akingbemi BT, Arizono K, Belcher S, Colborn T, Chahoud I, Crain DA, Farabollini F, Guillette LJ Jr, Hassold T, Ho S-M, Hunt PA, <u>Iguchi T</u> , Jobling S, <u>Kanno J</u> , Laufer H, Marcus M, McLachlan JA, Nadal A, Oehlmann J, Olea N, Palanza P, Parmigiani S, Rubin BS, Schoenfelder G, Sonnenschein C, Soto AM, Talsness CE, Taylor JA, Vandenberg LN, Vandenberg JG, Vogel S, Watson CS, Welshons WV. and Zoeller RT,	Why Public Health Agencies Cannot Depend upon Good Laboratory Practices as a Criterion for Selecting Data: The Case of Bisphenol A.	Environ Health Perspect	117(3)	309-15	2009
Kouzu-Fujita M, Mezaki Y, Sawatsubashi S, Mtsumoto T, Yamaoka I, Yano T, Taketani Y, Kitagawa H, and <u>Kato S</u> .	Coactivation of Estrogen Receptor $\beta$ by Gonadotropin-Induced Cofactor GIOT-4.	Mol Cell Biol	29(1)	83-92	2009
Ohtake F, Fujii-Kuriyama Y, <u>Kato S</u> .	AhR acts as an E3 ubiquitin ligase to modulate steroid receptor functions.	Biochem Pharmacol	77(4)	474-84	2009
Kawajiri K, Kobayashi Y, Ohtake F, Ikuta T, Matsushima Y, Mimura J, Pettersson S, Pollenz RS, Sakaki T, Hirokawa T, Akiyama T, Kurosumi M, Poellinger L, <u>Kato S</u> , Fujii-Kuriyama Y.	Aryl hydrocarbon receptor suppresses intestinal carcinogenesis in <i>Apc</i> <sup>Min/+</sup> mice with natural ligands.	Proc Natl Acad Sci USA	106(32)	13481-6	2009
Miki Y, Suzuki T, Nagasaki S, Hata S, Akahira J, <u>Sasano H</u> .	Comparative effects of raloxifene, tamoxifen and estradiol on human osteoblasts <i>in vitro</i> : Estrogen receptor dependent or independent pathways of raloxifene.	J Steroid Biochem Mol Biol	113(3-5)	281-9	2009
Nagasaki S, Suzuki T, Miki Y, Akahira J, Kitada K, Ishida T, Handa H, Ohuchi N, and <u>Sasano H</u> .	17 $\beta$ -hydroxysteroid dehydrogenase type 12 in human breast carcinoma: a prognostic factor via potential regulation of fatty acid synthesis.	Cancer Res	69(4)	1392-9	2009
Nagasaki S, Suzuki T, Miki Y, Akahira JI, Shibata H, Ishida T, Ohuchi N, and <u>Sasano H</u> .	Chicken ovalbumin upstream promoter transcription factor II in human breast carcinoma: Possible regulator of lymphangiogenesis via vascular endothelial growth factor-C expression.	Cancer Sci	100(4)	639-45	2009
Tamaki K, Moriya T, Sato Y, Ishida T, Maruo Y, Yoshinaga K, Ohuchi N, <u>Sasano H</u> .	Vasohibin-1 in human breast carcinoma: A potential negative feedback regulator of angiogenesis.	Cancer Sci	100(1)	88-94	2009
<u>Sasano H</u> , Nagasaki S, Miki Y, and Suzuki T.	New Developments in Intracrinology of Human Breast Cancer: Estrogen Sulfatase and Sulfotransferase.	Ann N. Y. Acad Sci	1155(-)	76-9	2009
Nakamura Y, Hornsby PJ, Casson P, Morimoto R, Satoh F, Xing Y, Kennedy MR, <u>Sasano H</u> , Rainey WE.	Type 5 17 $\beta$ -Hydroxysteroid Dehydrogenase (AKR1C3) Contributes to Testosterone Production in the Adrenal reticularis.	J Clin Endocrinol Metab	94(6)	2192-8	2009
Nakamura Y, Suzuki T, Sugawara A, Arai Y, and Sasano H.	Peroxisome proliferator-activated receptor gamma in human prostate carcinoma.	Pathol Int	59(5)	288-93	2009
Nakamura Y, Suzuki T, Arai Y, and <u>Sasano H</u> .	17 $\beta$ -hydroxysteroid dehydrogenase type 11 (Pan1b) expression in human prostate cancer.	Neoplasma	56(4)	317-20	2009
Nakamura Y, Xing Y, <u>Sasano H</u> , and Rainey WE	The Mediator Complex Subunit 1 Enhances Transcription of Genes Needed for Adrenal Androgen	Endocrinology	150(9)	4145-53	2009

Nagasaki S, Miki Y, Akahira J, Suzuki T, <u>Sasano H.</u>	Transcriptional regulation of 17 $\beta$ - hydroxysteroid dehydrogenase type 12 by SREBP-1.	Mol Cell Endocrinol	307(1-2)	163-8	2009
Loo WT, Chow LW, Suzuki T, Ono K, Ishida T, Hirakawa H, Ohuchi N, <u>Sasano H.</u>	Expression of Thymidine Phosphorylase and Dihydropyrimidine Dehydrogenase in Human Breast Carcinoma Cells and Tissues.	Anticancer Res	29(7)	2525-30	2009
Takeyama D, Miki Y, Fujishima F, Suzuki T, Akahira JI, Hata S, Miyata G, Satomi S and <u>Sasano H.</u>	Steroid and xenobiotic receptor in human esophageal squamous cell carcinoma: A potent prognostic factor.	Cancer Sci	Doi:10.1111/1/j.1349-7006.2009.01380	1-7	2009
Munetsuna E, Hojo Y, Hattori M, Ishii H, <u>Kawato S</u> , Ishida A, Kominami S and Yamazaki T.	Retinoic Acid Stimulates 17 $\beta$ -Estradiol and Testosterone Synthesis in Rat Hippocampal Slice Cultures.	Endocrinology	150(9)	4260-9	2009
Hojo Y, Higo S, Ishii H, Ooishi Y, Mukai H, Murakami G, Kominami T, Kimoto T, Honma S, Poirier D, <u>Kawato S.</u>	Comparison between hippocampus-synthesized and circulation-derived sex steroids in the hippocampus.	Endocrinology	150(11)	5106-12	2009
Hatanaka Y, Mukai H, Mitsuhashi K, Hojo Y, Murakami G, Komatsuzaki Y, Sato R, <u>Kawato S.</u>	Androgen rapidly increases dendritic thorns of CA3 neurons in male rat hippocampus.	Biochem Biophys Res Commun	381(4)	728-32	2009

available at [www.sciencedirect.com](http://www.sciencedirect.com)journal homepage: [www.elsevier.com/locate/biochempharm](http://www.elsevier.com/locate/biochempharm)

## Review

# Aryl hydrocarbon receptor biology and xenobiotic responses in hematopoietic progenitor cells

Yoko Hirabayashi<sup>a</sup>, Tohru Inoue<sup>b,\*</sup><sup>a</sup> Cellular and Molecular Toxicology Division, Center for Biological Safety and Research, National Institute of Health Sciences, Tokyo 158-8501, Japan<sup>b</sup> Center for Biological Safety and Research, National Institute of Health Sciences, 1-18-1 Kamiyohga, Setagayaku, Tokyo 158-8501, Japan

## ARTICLE INFO

## Article history:

Received 31 July 2008

Accepted 19 September 2008

## Keywords:

Aryl hydrocarbon receptor

Hematopoietic stem/progenitor cells

Thioredoxin

Benzene

Gompertzian expressions

## ABSTRACT

Studying the biological functions of the aryl hydrocarbon receptor (AhR) other than its function in xenobiotic drug metabolism may answer the questions as to why AhR orthologues have long been conserved phylogenically widely in the animal kingdom, and why homologues have diverged from nonvertebrate species such as nematodes and drosophila to all the vertebrate species. In this review, we focused on the mechanism of longevity possibly derived from evolution of AhRs and compared the functional difference of hematopoietic progenitors between wild-type (AhR<sup>+/+</sup>) mice and AhR-deficiencies (AhR<sup>+/-</sup>, AhR<sup>-/-</sup>). Particular advantages found in wild-type mice compared with AhR-deficiencies were as follows: first, higher antioxidative function in the hematopoietic microenvironment with low oxidative tension seemed to have developed with the evolution of AhR; second, primitive hematopoietic progenitor-cell-specific deceleration and dormancy of cell-cycle regulation may have developed also with AhR evolution, which keeps hematopoietic progenitor cell compartment dormant without extinction by continuous differentiation; third, the consequent evolution of genomic stabilization with a longer lifespan in wild-type mice developed with the evolution of AhR. Experimentally, mice showed a significant extension of lifespan in a gene-dosage-dependent manner with a delayed onset of leukemogenicity. Another possible additional advantage observed in wild-type mice, the mechanism of which is not yet clarified, is an improved efficiency of fertilization in wild-type mice as compared with AhR-deficiencies, which seems to have developed with the evolution of AhR. Four advantages altogether, including the anti-aging feature mentioned above may have induced the AhR molecule to diverge various of species in the animal kingdom.

© 2008 Elsevier Inc. All rights reserved.

\* Corresponding author. Tel.: +81 3 3700 1564; fax: +81 3 3700 1622.

E-mail address: [tohru@nihs.go.jp](mailto:tohru@nihs.go.jp) (T. Inoue).

Abbreviations: AhRs, aryl hydrocarbon receptors; ARNT, aryl hydrocarbon receptor nuclear translocator; BM, bone marrow; BrdUrd, 5-bromo-2'-deoxyuridine (RN: 59-14-3); CFU, colony forming unit; CFU-E, colony forming unit-erythroid; CFU-GM, colony forming unit-granulocyte macrophage; CFU-S, colony forming unit in spleen; CYP, cytochrome P450; DCFH-DA, 2',7'-dichlorodihydrofluorescein diacetate; Hif, hypoxia-inducing factor; KO, knockout; LKS fraction, a hematopoietic progenitor fraction with stem cell antigen (Sca1) and c-kit, without surface lineage-restricted antigen; MNU, 1-methyl-1-nitrosourea (RN: 684-93-5); PAS, the *Drosophila* period clock protein (PER), vertebrate ARNT, and *Drosophila* single-minded protein (SIM); PLTs, platelets; RBCs, red blood cells; ROS, reactive oxygen species; TCDD, 2,3,7,8-tetrachlorodibenzo-p-dioxin (RN: 1746-01-6); UV, ultraviolet; WBCs, white blood cells; XRE, xenobiotic responsive element. 0006-2952/\$ – see front matter © 2008 Elsevier Inc. All rights reserved. doi:10.1016/j.bcp.2008.09.030

## Contents

1. Introduction—The hematopoietic stem cells and aging as a xenobiotic tissue model . . . . .	522
2. Aryl hydrocarbon receptor and its evolutionary driving forces . . . . .	523
2.1. Aryl hydrocarbon receptor and phylogenic development. . . . .	523
2.2. Physiological function of aryl hydrocarbon receptor: Advantages in fertility? . . . . .	523
2.3. AhR <sup>-/-</sup> mice show earlier onset of spontaneous neoplasms—Gompertzian accelerated aging . . . . .	524
2.4. Longevity as essential driving force for evolution of AhR . . . . .	526
3. Hematopoietic progenitor cells and their cell-cycle regulation . . . . .	527
3.1. Aryl hydrocarbon receptor regulates hematopoietic progenitors . . . . .	527
3.2. Aryl hydrocarbon receptors and cell cycle . . . . .	528
3.2.1. Aryl hydrocarbon receptor and B cell progenitors . . . . .	528
3.2.2. AhR <sup>-/-</sup> mouse shows significant enhancement of hematopoiesis . . . . .	528
3.2.3. AhR promotes cell cycling in hemopoietic progenitors . . . . .	529
3.3. Cell kinetics of CFU-GM receives negative feedback in steady state . . . . .	529
4. Hematopoietic progenitor cells and xenobiotic responses . . . . .	530
4.1. Aryl-hydrocarbon-receptor-mediated hematopoietic alteration by xenobiotic substances . . . . .	530
4.2. Aryl-hydrocarbon-receptor-mediated benzene hematotoxicities . . . . .	530
5. Summary . . . . .	532
Acknowledgements . . . . .	532
References . . . . .	533

### 1. Introduction—The hematopoietic stem cells and aging as a xenobiotic tissue model

The aryl hydrocarbon receptor (AhR) is a xenobiotic receptor, which plays a role as a transcriptional master molecule for drug-metabolizing enzyme genes and protooncogenes after binding to their xenobiotic responsive element (XRE) [1–3]. An orthologue of the gene was identified not only in vertebrates but also in invertebrates; however, xenobiotic ligands such as 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) are not bound in invertebrates [4]. Although the functions of AhR in invertebrates are considered to be different from those in vertebrates, the function of AhR in vertebrates is considered to have biological commonalities other than xenobiotic responses, which is focused on in this review article.

To elucidate the biological functions of AhR, it may be strategically worthwhile to analyze tissue stem cells as a model because the expression level of AhR tends to show a graded decrease along the course of stem cell differentiation [5]. Tissue-specific responses to oxidative stress via AhR [6] are consequently attenuated along the course of stem cell differentiation. Specifically, hematopoietic stem cells are the focus of many studies such as the induction of genomic instability along a graded increase in oxidative stress due to xenobiotic metabolism, and the consequent deletion of telomere length, increase or decrease in telomerase activity, along with the cascading changes of shortening of cellular senescence, development of cancers, broadening of the noncarcinogenic disease spectrum, and consequent shortening of life [7].

In this introduction, an overview on hematopoietic stem cell physiology and alteration of senescence is discussed because physiological and xenobiotic functions of AhR are discussed in this chapter focusing on the hematopoietic system.

Hematopoietic stem cells were discovered half a century ago when development of hematopoietic spleen colonies derived from shielded bone marrow was discovered after whole-body radiation exposure of mice to a lethal dose [8].

In 1961, Till and McCulloch observed spleen colonies in recipient mice a week after lethal-dose radiation exposure followed by injection of intact bone marrow cells [9]. The progenitors of these spleen colonies were named spleen colony forming units (CFU-S), whose progeny and clonal growth were subsequently discovered [10]. Five years after the discovery of CFU-S, *in vitro* formation of colonies that are also derived from relatively matured hematopoietic progenitor cells was discovered by Pluznik and Sachs [11], and Bradley and Metcalf [12], simultaneously in 1965, which are called CFUs in culture. Continuous bone marrow transplantation with biological markers led to the idea that the progenitors of these CFUs are nearly infinite at that time [13]. The hierarchical generation-age structure from these hematopoietic progenitor cells to differentiated red blood cells (RBCs), polymorphic white blood cells (WBCs) via intermittent committed progenitor cells was developed by later series of studies along with development of biological differentiation cellular markers [14,15]; currently, the lineage-negative, c-kit-positive, stem cell antigen (Sca)-1-positive (LKS) cellular compartment is used in experiments as practically most primitive hematopoietic progenitor cells [16,17].

The senescence of hematopoietic progenitor cells was studied in the early 70 using W(c-kit) mutant mice as recipients focusing on the long-term sustainability of recipients as well as on the long-term repopulation after continuous marrow transplantation. Continuous bone marrow transplantation showed continuous clonal survivors of the first generation of bone marrow cells for up to one hundred months [13]. However, the correct number of generation times during that time was not countable, implying that progenitor

cells are capable of infinite growth but show decreased growth rate with age, probably because there is only a slight decrease in the telomere length of the hematopoietic stem cell compartment. The telomerase-deficient mice established by DePinho et al., which lack the essential RNA component for telomerase haloenzyme, interestingly showed a decreased life span as continuously observed for six generations [18], which provides another piece of evidence that hematopoietic progenitor cells possess a nearly infinite growth potential.

Concerning the role of hematopoietic stem cells during aging in an individual, an early onset of spontaneous as well as induced leukemias are observed in p53-deficient mice owing to impaired cyclin-dependent kinase inhibitors after chemical- and radiation-induced injuries. Hematopoietic “niches” are thought to contain genes, such as N-cadherin [19–21], Jagged1/Notch [22], Ang1/Tie-2 [23], osteopontin [24], and SDF1(CXCL12)/CXCR4 genes [25,26]. Cellular senescence of hematopoietic progenitor cells in vivo is also related to stem cell settlements of the hematopoietic microenvironment called niches where primitive hematopoietic progenitor cells locate beneath the epiphyseal bone matrix of the bone marrow. In addition, although it is still speculative, connexin (Cx) 32 molecules were firstly found to be localized solely in primitive hematopoietic stem cells. Thus, they are supposed to be an important component of niches; however, interestingly, methyl nitrosourea (MNU)-induced leukemias develop more preferentially when the Cx32 molecules are deficient [17,27]. It is of interest to clarify the mechanism underlying genomic instability possibly available in Cx32-impaired hematopoietic niche.

Hematopoietic stem cells can be a target of xenobiotic effects; this possibility is not hypothetical but remains limited [28]. Ionizing radiation of p53-deficient mice induces leukemias, which are characterized by stem cell leukemia [29]. The mechanism underlying the development of stem cell leukemia following ionizing radiation is considered to be based on the function of p53, which is required for stem cell differentiation [30].

Concerning the development of lymphoid stem cell lineages, lymphopoiesis also depends on hematopoietic progenitor cell function [31]. Similarly to steady-state hematopoiesis, supported by hematopoietic niches and stromal cells as the source for hematopoietic regulatory cytokine expression, hematopoiesis cannot occur without hematopoietic stromal elements [32]. Hematopoietic stromal cells support hematopoiesis by at least two pathways: one for cell-to-cell interaction [33] and the other for positive and negative cytokine regulations. In the case of B lymphocyte progenitor cells, it was found in stromal-cell-impaired mutant mice, SAM/P1, that B lymphopoiesis is impaired during senescence owing to the simultaneous decrease in the expression levels of positive regulator IL-7 and the negative regulator TGF- $\beta$ , which Tsuboi [34] called vicious suppressive homeostasis during senescence.

## 2. Aryl hydrocarbon receptor and its evolutionary driving forces

AhR was found to be a ligand-activated transcriptional factor with halogenated ligands such as TCDD; however, the ligand-specific activation was found only in vertebrates. Never-

theless, conservation of diverse homologues across vertebrate species suggests common physiological functions across species [4,35]. What was its original function? In this section, mechanisms underlying phylogenetic development of AhR, i.e., possibly based on physiological advantages of AhR, are reviewed.

### 2.1. Aryl hydrocarbon receptor and phylogenetic development

AhR is a member of the basic helix-loop-helix/PER-aryl hydrocarbon receptor nuclear translocator (ARNT)-SIM (bHLH-PAS) family, which consists of transcriptional regulatory proteins [1,2] whose cDNA was cloned by Erna et al. [36] and Burbach et al. [37], and the gene was characterized by Schmidt et al. in 1993 [38]. Since then, a number of homologues of AhR in mammalian species; such the human species (*Homo Sapiens*) [39], various mice (*Mus musculus*) [36,37,40,41], rats (*Rattus norvegicus*; Sprague–Dawley [42], Han-Wistar [43]), hamster (*Mesocricetus auratus*) [44], Atlantic white-sided dolphin (*Lagenorhynchus acutus*) [4], and Baikal seal (*Phoca sibirica*) [45], were cloned. Moreover, nonmammalian vertebrates, such as birds [4,46,47], amphibians [47], bony fishes [4,48–52], cartilaginous fishes [35,53], lampreys (*Petromyzon marinus*) [4,53], and invertebrates such as soft-shell clam (*Mya arenaria*) [54], zebra mussel (*Dreissena polymorpha*) [4], nematode (*Caenorhabditis elegans*) [53], and fruitflies (*Drosophila melanogaster*) [55], were cloned.

According to Hahn in 2002 [4], the ability of AhR to bind halogenated ligands and mediate an adaptive response involving induction of xenobiotic metabolizing enzymes may have been a vertebrate's innovation because invertebrate AhRs were reported to not bind to those ligands. Therefore, the physiological functions of AhR may be initiated from invertebrate species. Those functions mediated by an AhR orthologue in invertebrates are, reported to not bind to TCDD and other synthetic AhR ligands; thus, they are distinguished from those in vertebrates. Furthermore, their functions are found to be necessary for development of distal segments of the antennae and legs [55,56], and further for the specification of photoreceptor identity in the retina [57] in a *Drosophila* AhR homologue, spineless, and for the expression of *C. elegans* ahr-1 in sensory neurons in regulation of neuronal differentiation [58,59]. However, our knowledge on invertebrates may be insufficient to draw general conclusions between AhRs expressed in vertebrates and in invertebrates, but those functions are seemingly not comparable to each other because while those expressed in vertebrates are largely in cycling cells, the others expressed in invertebrates are not in cycling cells but in postmitotic cells. In the case of the PAS domain, it is far more widely distributed from animals to plants, fungi, bacteria, and Archea, its functional evolution does not seem to parallel its molecular evolution. Is there any common functional evolution across vertebrate species?

### 2.2. Physiological function of aryl hydrocarbon receptor: Advantages in fertility?

It may not be the right answer to the question; however, we found that our knockout mice, both homozygous and

Table 1 – Reproductive toxicology in AhR-deficiencies.

Genotype of parents		No. of pups (sets <sup>a</sup> )	Sex		Genotype		
Mother	Father		Male	Female	+/+	+/-	-/-
		(Genotype: AhR <sup>+/+</sup> , +/-, -/-)		(Sex: male, female)			
AhR <sup>+/+</sup>	AhR <sup>+/-</sup>	154 (18)	71 (46, 25, -)	83 (50, 33, -)	96 (46, 50)	58 (25, 33)	- (-, -)
AhR <sup>+/-</sup>	AhR <sup>+/-</sup>	206 (27)	100 (36, 48, 16)	106 (32, 53, 21)	68 (36, 32)	101 (48, 53)	37 (16, 22)

<sup>a</sup> Sets for mating: each set consists of 2 females and 1 male.

hemizygous males, show a greater dysfunction in fertilization than wild-type male mice. For example, during reproduction in the current generation, crossbreeding between hemizygous AhR-knockout (KO) male mice and wild-type female mice produced 71 males and 83 females (Table 1). Among these, 96 mice were of the wild type and 58 mice were hemizygous AhR-KO. Although the number of puppies of wild-type mice and that of hemizygous AhR-KO mice were supposed to be equal in accordance with the Mendelian law, the number of puppies of hemizygous AhR-KO mice (58) was 60.4% lower than that of wild-type mice (96). Interestingly, this low incidence seemed to be largely based on the hemizygous AhR-KO males, because, among the 71 male puppies mentioned above, 25 were hemizygous AhR-KO mice, and 46 were of the wild type, which showed a statistically significant difference ( $p < 0.028$ ). Among the 83 puppies mentioned above, 33 puppies were female hemizygous AhR-KO mice and 50 female puppies were of the wild type, which showed a statistically insignificant difference ( $p > 0.064$ ). Furthermore, the mating study disclosed a more detailed underlying mechanistic background of reproductive dysfunction in male AhR-KO mice. When hemizygous AhR-KO males and their corresponding females were crossbred, the numbers of puppies observed were 100 males and 106 females (Table 1). Among them, the numbers of puppies were 37 homozygous AhR-KO mice, 101 hemizygous AhR-KO mice, and 68 wild-type mice. Because the average number of puppies of C57BL/6 mice at the animal colony was 6-7 mice per litter, the number of puppies observed in the present study was slightly larger than this average (132%), that is, 51.5 puppies, calculated from the total number of puppies (206) divided by 4 (25%) on the basis of the Mendelian law. These results imply that the incidence of homozygous AhR-KO mice was 45.6% lower than the incidence expected from the Mendelian law. Furthermore, this lower incidence is not supposed to be due to the death of AhR-KO puppies; but rather, AhR-KO puppies were supposed to have shifted to the wild type, because the cross-breeding was between hemizygous AhR-KO mice, in which sperms derived from the testicular glands of AhR-KO and wild-type may have competed during fertilization for fertilizing function. Indeed, when homozygous AhR-KO mice were crossbred, neither their litter size nor the ratio of the number of males to that of females was statistically significantly different from that of the wild type, because the competitive disadvantages observed in the hemizygous AhR-KO mice may have been negated by the same testicular dysfunctions in the homozygous AhR-KO mice. The underlying mechanism of the testicular dysfunction is remained to be undetermined. Weight of the testes in AhR-KO mice is generally smaller than those in wild-type mice ( $75.2 \pm 4.2$ ,  $84.9 \pm 8.1$ ,  $105.5 \pm 1.4$  mg; homozygous AhR-KO,

hemizygous AhR-KO, and wild-type mice, respectively). Possible fictional differences of their testicular glands may be more evident in AhR-KO mice treated with MNU (50 mg/kg body weight) than in nontreated mice. The testicular body ratio after MNU treatment in wild-type mice show a 91.0% decrease in wild-type mice compared with the control without MNU treatment, whereas the ratio after MNU treatment in AhR-KO mice show a 71.4% decrease compared with the same control wild-type mice without MNU treatment. These results indicate that the testicular tissue of AhR-KO mice shows a dysfunction in cellular proliferation and regeneration during the course of the development and the recovery after tissue injury.

Nebert et al. also found a low fertility in the D2-linked DBA strain, which seems to be linked to AhR affinity [60]. Thus, AhR seems to contribute to the stabilization of fertilization, which might be one of the reasons its gene has diversified across species during the course of its evolution. Because the focus of this section is the hematopoietic system, further description on the functional contribution of AhR to fertilization may be discussed elsewhere.

### 2.3. AhR<sup>-/-</sup> mice show earlier onset of spontaneous neoplasms—Gompertzian accelerated aging

Fig. 1 shows the incidence of spontaneous malignant lymphomas in each genotype group for AhR plotted along the ordinate axis vs. age in days plotted along the horizontal axis. The development of lymphomas in the AhR<sup>-/-</sup> group (darkly shaded columns) starts earlier than that in the AhR<sup>+/-</sup> (lightly shaded columns) and wild-type (open columns) groups. The incidence

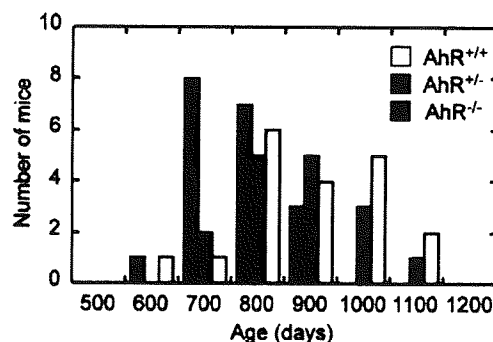


Fig. 1 – Incidences of spontaneous malignant lymphomas at unit time intervals for wild-type (AhR<sup>+/+</sup>) mice and AhR-deficient (AhR<sup>-/-</sup>, AhR<sup>+/-</sup>) mice. (Open columns, AhR<sup>+/+</sup>; lightly shaded columns, AhR<sup>+/-</sup>; darkly shaded columns, AhR<sup>-/-</sup> groups.)



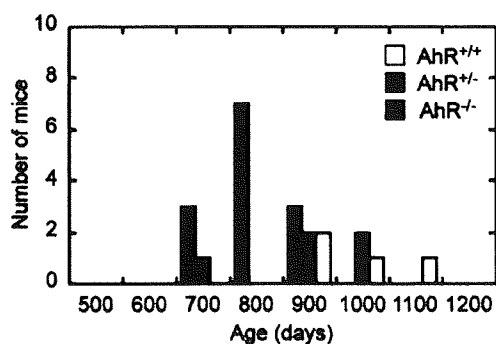


Fig. 2 – Incidences of spontaneous hepatomas at unit time intervals in wild-type (AhR<sup>+/+</sup>) mice and AhR-deficient (AhR<sup>-/-</sup>, AhR<sup>+/-</sup>) mice. (Open columns, AhR<sup>+/+</sup>; lightly shaded columns, AhR<sup>+/-</sup>; darkly shaded columns, AhR<sup>-/-</sup> groups.)

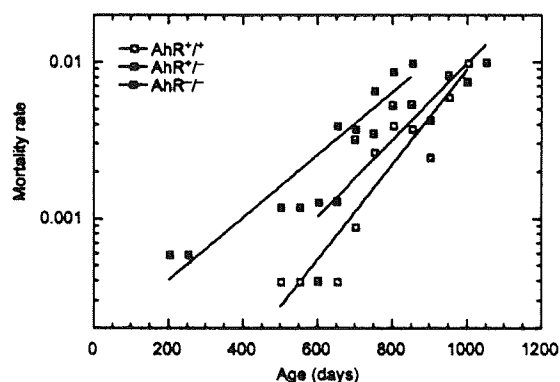


Fig. 3 – Gompertzian expressions [61] of mortality rates of mice of different genotypes: wild-type (AhR<sup>+/+</sup>) mice and AhR-deficient (AhR<sup>-/-</sup>, AhR<sup>+/-</sup>). (Open squares, AhR<sup>+/+</sup>; half-closed squares, AhR<sup>+/-</sup>; closed squares, AhR<sup>-/-</sup> groups.)

of lymphomas in the AhR<sup>-/-</sup> group peaked at 700 days old, whereas those in the AhR<sup>+/-</sup> and wild-type groups peaked at 850 and 1000 days old, respectively. Similarly, the incidences of spontaneous hepatomas in each genotype group are plotted in Fig. 2. In this figure, spontaneous hepatomas in the AhR<sup>-/-</sup> group appear at 700 days old and those in the wild-type group appear much later (900 days) at significantly lower incidences. In Fig. 3, the mortality rate/unit time interval for each genotype group is plotted. Mortality rate/unit time interval is shown in the ordinate on a logarithmic scale and age in days is plotted along the horizontal scale (Gompertzian expression [61]). In this figure, the line for closed squares for the AhR<sup>-/-</sup> mice shows a much early onset curve with a lower and flatter slope than the line for open square for the wild-type group. Thus, the mortality rate of the AhR<sup>-/-</sup> group can be concluded to indicate “accelerated aging”. The shortened lifespan observed in the AhR-KO mice may be due to the impairment of a possible suppression gene in the KO mice. However, some mice for each survival curve are non-tumor-bearing mice. The mechanism of this accelerated aging may not be as simple as that involving a tumor suppressor and remains to be elucidated.

AhR is an orphan receptor whose original physiological function remains unclarified. Since AhR-KO mice were found to show an earlier onset of spontaneous neoplasms than wild-type mice, AhR was assumed to play a suppressor gene function [62]. However, because not all AhR-KO (AhR<sup>-/-</sup>) mice or wild-type mice die of spontaneous neoplasms, the function of wild-type AhR may also be associated with a possible genomic stabilization, consequently extending the lifespan of mice simultaneously. What are the underlying mechanisms that contribute to the extended longevity? Evaluation of reactive oxygen species (ROS) using the 2',7'-dichlorodihydrofluorescein diacetate (DCFH-DA) dye (Fig. 4) showed a prominent increase in oxidative stress in unfractionated bone marrow cells as well as in hematopoietic progenitor cells in AhR-KO mice [63] (Fig. 5). Hematopoietic progenitor cells are quiescent in anoxic environment, and are regulated by a weak oxidative stimulation as redox homeostatic regulation [64]. Thus, the reactivity of the fraction to the DCFH-DA dye was higher in AhR-KO mice than in wild-type mice, which is in good agreement with the mechanism underlying genomic stabilization under a

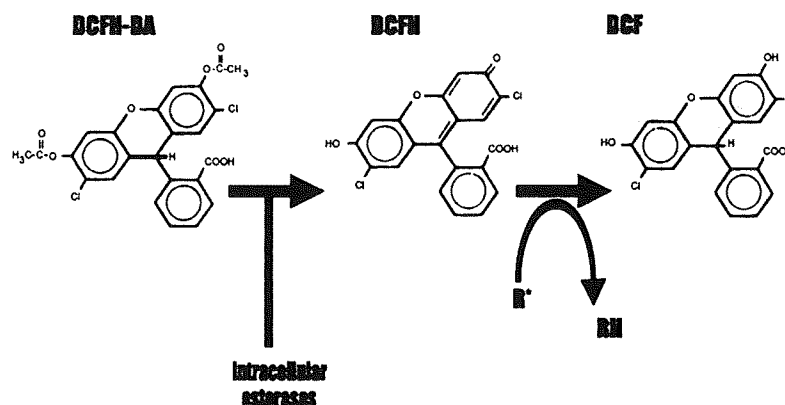


Fig. 4 – 2',7'-Dichlorodihydrofluorescein diacetate (DCFH-DA) as ROS indicator [92] (DCFH: 2',7'-dichlorodihydrofluorescein, DCF, 2',7'-dichlorofluorescein).

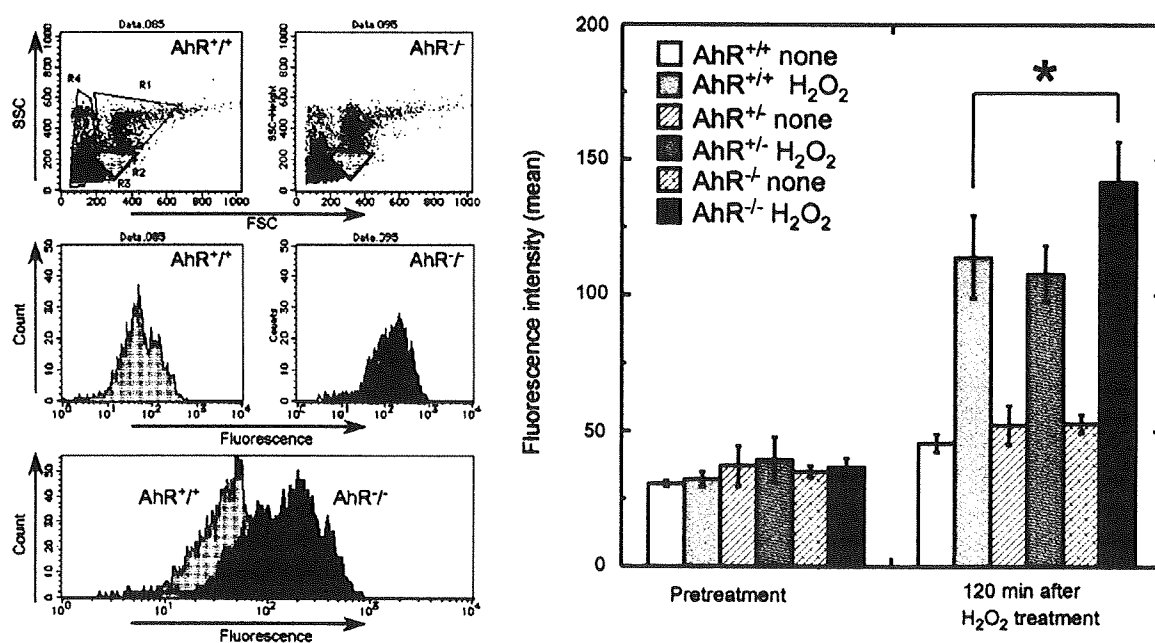


Fig. 5 – Fluorescence intensities of DCF dye in primitive bone-marrow cell fraction between the steady state (none) and the H<sub>2</sub>O<sub>2</sub> treatment. Left panel, top row: primitive progenitor cell compartment (R2) were sorted out from bone marrow (BM) cells of wild-type (AhR<sup>+/+</sup>) mice (left) and AhR-KO (AhR<sup>-/-</sup>) mice (right) using a cell sorter as displayed between the forward scatter (horizontal axis) and the side scatter (ordinate axis). Left panel, middle and bottom rows: Relative cellular counts of the hematopoietic progenitor cells, ordinate axis vs. DCF dye-fluorescence intensity, horizontal axis, are compared between AhR<sup>+/+</sup> mice (middle left) and AhR<sup>-/-</sup> mice (middle right). Both profiles are compared in the bottom. Right panel: Fluorescence intensity of DCF dye of primitive hematopoietic progenitor fractions (R2 area) before (pre) and after (H<sub>2</sub>O<sub>2</sub>) treatment. Fluorescence intensity of DCF dye in R2: Groups for H<sub>2</sub>O<sub>2</sub> treatment at 0 min on the left bars (AhR<sup>+/+</sup>, none and H<sub>2</sub>O<sub>2</sub>; AhR<sup>+/-</sup>, none and H<sub>2</sub>O<sub>2</sub>; AhR<sup>-/-</sup>, none and H<sub>2</sub>O<sub>2</sub>, respectively), and Groups for H<sub>2</sub>O<sub>2</sub> treatment at 120 min on the right bars (AhR<sup>+/+</sup>, none and H<sub>2</sub>O<sub>2</sub>; AhR<sup>+/-</sup>, none and H<sub>2</sub>O<sub>2</sub>; AhR<sup>-/-</sup>, none and H<sub>2</sub>O<sub>2</sub>, respectively).

low oxidative tension in combination with the suppressor gene function and the consequent longevity observed in wild-type mice.

#### 2.4. Longevity as essential driving force for evolution of AhR

Different mouse strains in terms of aryl hydrocarbon receptor function, receptor concentrations, and lifespans are com-

pared. Because mice of different strains show different spontaneous neoplastic propensities, sometimes possess different AhR structures, and have different lifespans, available databases for such AhR-related functional parameters were compared. The results obtained are shown in Table 2.

In this table, two strains, namely, C3H/He and DBA/2, showed a low affinity or a low enzyme activity for constitutively activated cytochrome P450 (CYP) 1A2, whereas C57BL/6J, showed a high affinity or a high enzymatic activity for CYP1A2

Table 2 – AhR binding affinities and receptor activities, cell cycles, and life spans among murine species.

Strain	AhR affinity <sup>a</sup>	CYP1A2 enzyme activity <sup>b</sup>	Receptor concentration <sup>c</sup>	Cell cycle <sup>d</sup>	Lifespan <sup>e</sup> (days)	Notes
C3H/He	High	Low to mid	86 ± 23	High	500	Low signal induction
DBA/2J	Low	Low	-	High	710	708.7 days in other litter. <sup>e</sup>
C57BL/6J	High	High	151 ± 26	Low	789	860.8 days in other litter. <sup>e</sup>

<sup>a</sup> Murine Ah receptor specified by the Ah<sup>d</sup> and Ah<sup>b-3</sup> alleles is compared.

<sup>b</sup> Activities for methoxyresorufin *o*-demethylation (MOD) and pentoxyresorufin *o*-dealkylation, and metabolic activation of IQ for phenobarbital were tested. For activity in DBA/2J, high in male, but low in female for CYP1A2. Activity for MOD was significantly low for both genders [65].

<sup>c</sup> Murine Ah locus (mg/protein) [66].

<sup>d</sup> Scored using hematopoietic cobblestone area-forming cell assay [67].

<sup>e</sup> Data cited from Van Zant and de Haan [67] and Forster MJ et al. [68].

[65]. Although C3H/He mice showed a high affinity, the receptor concentration (mg/protein) measured was low [66]; thus, the total activity reported in the literature is low. It is interesting to determine correlations between AhR activity and the stage of cell cycle or lifespan, because mice with a high AhR activity, i.e., C57BL/6J, seem to show a suppressed cell cycle and longer lifespan, whereas mice with a low AhR activity, i.e., C3H/He, seem to show an accelerated cell cycle with a shortened lifespan [67,68]. No comparable data on genomic stability (or instability) fully supports the above-mentioned AhR activity are available. However, the correlations between AhR activity and the stage of cell cycle or lifespan seem to be plausible and compatible with the results of our present study of experimental induction of AhR-deficiencies.

We also found that AhR-KO mice show an earlier onset of spontaneous neoplasms than wild-type mice [62]. Thus, it is plausible that AhR functions as a tumor suppressor gene in the steady state. Furthermore, because not all of these mice die of malignant neoplasms, AhR may also extend the lifespan of these mice, i.e., it has "longevity" function (Fig. 6). Such biological plausible functions are possible reasons for the molecular evolution of AhR from homologues in invertebrates, such as nematodes, equivalent to those in vertebrates. However, one question remains: Why do AhR-KO mice show early onset of spontaneous neoplasms? Supposedly these mice should exhibit unfavorable xenobiotic responses when AhR is knocked out [69]. Furthermore, the mechanisms of the possible suppressive function of wild-type AhR remain to be elucidated.

Successful fertilization, tumor suppression, and longevity seem to be essential driving forces of phylogenetic evolution of AhR in vertebrate species or, if not all, at least in mammalian species. Not many similar reports are available in the literature but some of them are strongly linked to the present issue. According to Abbott [70], the concentrations of AhR after birth increased rapidly and plateaued from 2 to 21 days and then rapidly decreased in the liver and lungs. Nebert et al. also discussed about the possible AhR-mediated longevity but the lifespan of experimental mice is too short to speculate on longevity [60]. This was supported by a study by Spindler et al. in 1989, which showed distinct differences in the maximum lifespan among different mouse strains with different induction levels of cytochrome p450s [71]. These previous studies suggest the functional advantages of AhR expression, but the mechanism underlying these functional advantages are poorly described. These are much strongly related to the

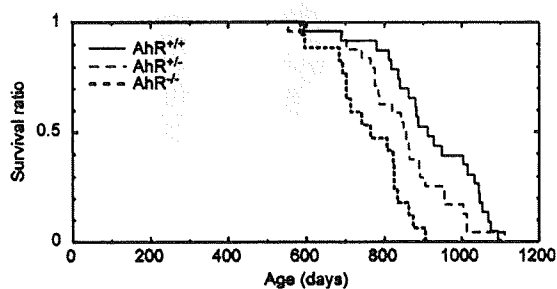


Fig. 6 – Survival curves for wild-type (AhR<sup>+/+</sup>) mice and AhR-deficient (AhR<sup>-/-</sup>, AhR<sup>+/-</sup>) mice. (Solid line, AhR<sup>+/+</sup>; long dotted line, AhR<sup>+/-</sup>; short dotted line, AhR<sup>-/-</sup> groups.)

localization of AhR expression in the tissue and AhR-mediated cell-cycle regulation. Findings possibly related to these issues will be described later.

### 3. Hematopoietic progenitor cells and their cell-cycle regulation

As discussed in the previous section, although we know that AhR functions in maintaining lifespan, we do not know its underlying mechanism. In this particular section, we focus on the biological function of AhR in hematopoietic progenitor cells and in their cell-cycle regulation to elucidate the relevant mechanism that may explain such advantages of the function of AhR.

The hematopoietic microenvironment is hypoxic [72,73], which is located beneath the periosteal region and forms niches. The niches are thought to consist of genes, such as N-cadherin [19–21], Jagged1/Notch [22], Ang1/Tie-2 [23], osteopontin [24], and SDF1(CXCL12)/CXCR4 [25,26] genes, and possibly also the connexin 32 [17,27] gene, which maintains dormancy of hematopoietic stem/progenitor cells, because of the hypoxic state located distant from the vascular network. Stromal cells and endosteal cells in the hypoxic state may express hypoxia inducible factor (Hif)-1alpha [74], and also in some cases, HIF-2alpha [75] is expressed by hematopoietic stem/progenitor cells themselves, which may interact with ARNT molecules leading to steady-state hematopoiesis.

Regarding xenobiotic responses induced by AhR, hematopoiesis is often suppressed probably because of a possible recruitment of ARNT molecules to activate AhR. The monumental study by Luster in 1985 [76] showed a decrease in CFUs following the exposure of mice to TCDD, which may be based on this mechanism. AhR signaling also induces cell-cycle suppression, the mechanism of which has not been elucidated. Nevertheless, such deceleration of cell cycle in hematopoietic stem/progenitor cells contributes to longer stem cell survival, which may be the reason for the extension of animal lifespan.

#### 3.1. Aryl hydrocarbon receptor regulates hematopoietic progenitors

When AhR is activated by xenobiotic ligands, ligand-specific transcription induces the production of drug-metabolizing enzymes, Cyp1A1 and 1B1, as the major products [1,2], which in turn induce oxidative stresses [6,77] and the consequent hematopoietic impairment by the up-regulation of cyclin-dependent kinase inhibitors [78,79]. Such hematopoietic impairment in stem-cell-specific cell cycling can be evaluated by the BUUV method [27,80], which is described in Section 3.3. Under xenobiotic stimulation with AhR ligands, a slight inhibition of transportation of ARNT required by Hif-1alpha and Hif-2alpha in the hypoxic hematopoietic microenvironment induces a possible inhibition of primitive hematopoiesis. On the other hand, steady-state expression of AhR makes ARNT available for Hif-1alpha and Hif-2alpha, the up-regulation of which is maintained by the relatively hypoxic hematopoietic microenvironment. Thus, AhR is important because ARNT released from AhR functions in transcription of

various hematopoietic factors, such as erythropoietin, CXCR4 [81], SDF-1 [73], vascular endothelial growth factor (VEGF) [82], and VE-cadherin [83]. According to the study by Adelman et al. on ARNT-KO mice, production of various CFUs derived from hematopoietic progenitors from embryonic stem (ES) cells markedly decreases in a ARNT-gene-dosage-dependent manner [84]. ARNT is, thus, important to maintain such primitive hematopoiesis.

### 3.2. Aryl hydrocarbon receptors and cell cycle

Whether AhR physiologically suppresses cell growth through relevant signals via a possible endogenous ligand [85] or facilitates cell-cycle progression from  $G_1$  with *Fos* and *Jun* signaling, remains controversial [86]. In the authors' previous study, authors attempted to elucidate a possible hidden function of AhR in hematopoiesis using AhR-knockout mice [87].

#### 3.2.1. Aryl hydrocarbon receptor and B cell progenitors

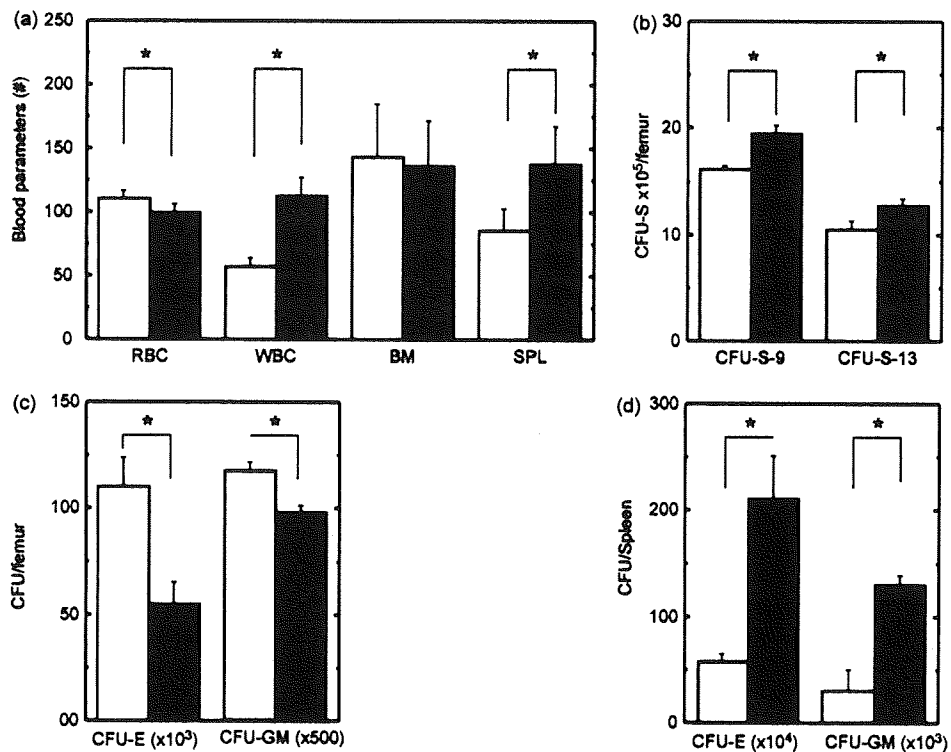
As the authors focused on B cell suppression during B lymphopoiesis [5], the effects of TCDD exposure on hemopoiesis were extensively investigated, since the inhibitory effects of TCDD on bone marrow and immunological parameters, including granulocyte-macrophage (GM) colony forming unit

(CFU) and other progenitors, were first recognized by Luster and coworkers in the early 1980s [76,88]. The down-regulation of AhR expression attenuates myelosuppression in thioredoxin (Trx)-overexpressing mice, as determined by hemopoietic colonization assay, which elucidated the linkage of AhR signals to the antioxidant cascade induced by reactive oxygen species, ROS, after TCDD exposure [89,90].

In studies of Trx-overexpressing mice, attention was focused on the function of AhR in the hemopoietic system, specifically in hemopoietic stem cells/progenitor cells, and the controversial dual function of AhR was found to be consistent because AhR seems to stimulate the cell cycle as an early response to cytokines, whereas simultaneously, suppresses hematopoiesis during the steady state. The Janus-like dual function of AhR found in our present study may contribute to a better understanding of individual health effect that can be induced by an interaction between AhR and its environmental ligands.

#### 3.2.2. AhR<sup>-/-</sup> mouse shows significant enhancement of hematopoiesis

The number of WBCs increases in AhR<sup>-/-</sup> mice (Fig. 7(a)). This is the first observation in AhR<sup>-/-</sup> mice [91] that is consistent with the hypothetical description by Adachi et al. [85] in which a possible physiological ligand is speculated to suppress hema-



**Fig. 7** – Comparison of various blood parameters between wild-type mice (open columns) and AhR-KO (AhR<sup>-/-</sup>) mice (shaded columns); (a) peripheral blood, bone marrow (BM) and spleen weight. #: Vertical axis “Parameters” indicate the counts of peripheral red blood cells (RBCs, ×10<sup>6</sup>/ml) and white blood cells (WBCs, ×10<sup>6</sup>/ml), BM cellularity (×10<sup>5</sup>/femur), and weight of the spleen (SPL, mg). (b) Number of colony forming units in spleen (CFU-S, ×10<sup>5</sup>/femur) observed on days 9 (CFU-S-9) and 13 (CFU-S-13). (c) Numbers of in vitro granulocyte-macrophage CFUs (CFU-GM, ×500/femur) and erythroid CFU (CFU-E, ×10<sup>3</sup>/femur) in femoral BM. (d) Numbers of CFU-GM (×10<sup>3</sup>/spleen) and CFU-E (×10<sup>4</sup>/spleen) in spleen.

\*: Significant difference between wild-type and AhR-KO mice determined by t-test at  $p < 0.05$ .

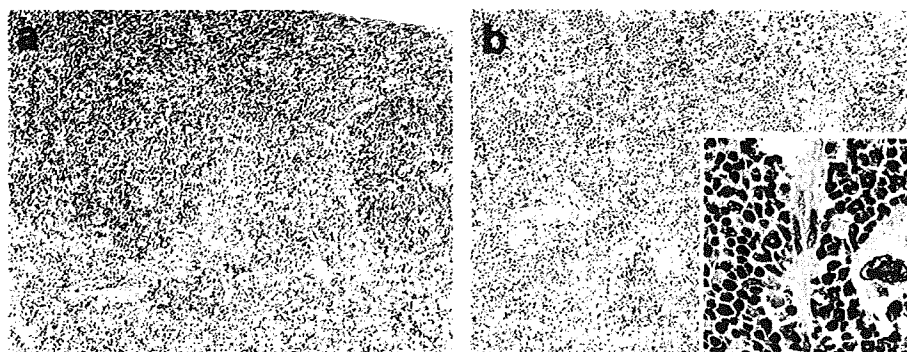


Fig. 8 – Histopathological findings in spleen from wild-type mice (a) and AhR-KO (AhR<sup>-/-</sup>) mice (b). Note, a prominent enhancement of hemopoiesis in the spleen can be observed in AhR<sup>-/-</sup> mice (b). (HE staining. Magnification: a and b  $\times 20$ , inset of b  $\times 80$ .)

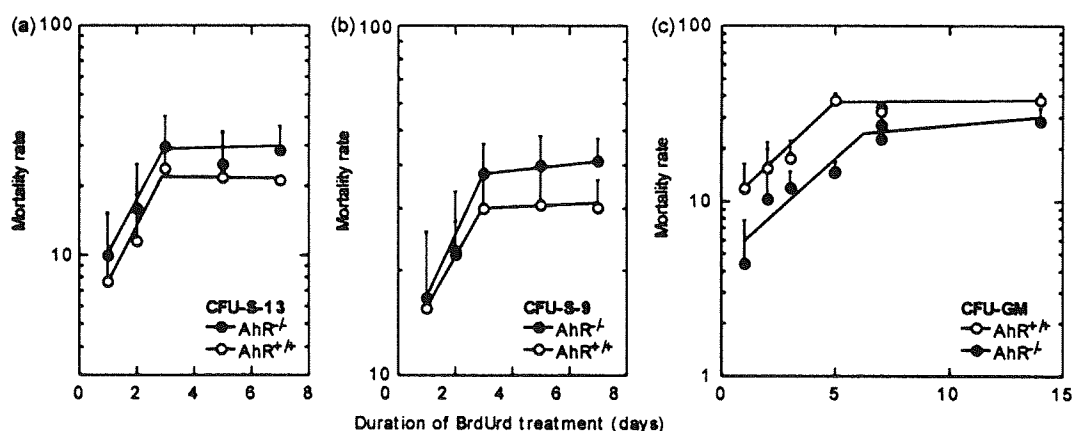


Fig. 9 – Hemopoietic progenitor cell kinetics of each hemopoietic progenitor compartment from wild-type mice (AhR<sup>+/+</sup>) (open symbols) and AhR-KO (AhR<sup>-/-</sup>) (closed symbols), measured by BUUV method [32,80]; numbers of colony forming units in spleen observed on days 13 (CFU-S-13) (a) and 9 (CFU-S-9) (b), and numbers of granulocyte-macrophage CFU (CFU-GM) (c). CFU-S-13 and CFU-GM are significantly different as determined by a paired t-test between AhR<sup>+/+</sup> and AhR<sup>-/-</sup> mice ( $p < 0.05$ ). The plateau level (between day 3 and day 7 of BrdUrd treatment) of CFU-S-9 is also significantly different, as determined by the t-test between AhR<sup>+/+</sup> and AhR<sup>-/-</sup> mice ( $p < 0.05$ ).

topoiesis in AhR<sup>+/+</sup> mice. This is also consistent with the higher numbers of myeloid progenitor cells, i.e., CFU-S-9 and CFU-S-13, observed in AhR<sup>-/-</sup> mice (Fig. 7(b)). Thus, steady-state hematoipoiesis is presumed to be suppressed via AhR signaling by a possible physiological ligand, which is as yet not identified in AhR<sup>+/+</sup> mice. In response to such an AhR-null effect, AhR<sup>-/-</sup> mice reversely show extensive hematopoiesis in the spleen (Fig. 8(b)) as compared with wild-type mice (Fig. 8(a)), although this hemopoietic enhancement is also reflected in another negative hemopoietic regulation in the bone marrow.

### 3.2.3. AhR promotes cell cycling in hemopoietic progenitors

Interestingly, when bone marrow cells are removed from AhR<sup>-/-</sup> mice and AhR<sup>+/+</sup> mice, and are grown in *in vitro* colony assay, the numbers of CFU-GM and CFU-E are both significantly lower in AhR<sup>-/-</sup> mice (Fig. 7(c)), implying that AhR signaling promotes the acute phase response to cytokines during colony growth. The decrease in the number of CFU-E, as shown in Fig. 7(c), possibly affects the number of RBCs in the peripheral blood of AhR<sup>-/-</sup> mice (Fig. 7(a)). These observations

are consistent with those for other hemopoietic progenitors (data not shown). Interestingly, in response to such an AhR-null effect, AhR-KO mice in contrast show extensive hematoipoiesis in the spleen (Fig. 7(d)), which results in a significant increase in spleen weight (Fig. 7(a); rightmost) [28,91].

### 3.3. Cell kinetics of CFU-GM receives negative feedback in steady state

The BUUV method<sup>1</sup> shows a clear enhancement of the cell cycle in primitive progenitor cells, CFU-S-13 (Fig. 9(a)), and in

<sup>1</sup> BUUV method is to evaluate hematopoietic stem/progenitor cell-specific kinetics by continuous perfusion of 5-bromo-2'-deoxyuridine (BrdUrd) through an osmotic pump (Alza Corp., Palo Alto, CA) followed by ultraviolet (UV) – A exposure and hematopoietic colonization assay, which permits to obtain a variety of parameters in the cell kinetics of the hemopoietic progenitor cell compartment, such as a doubling time, a size of cycling- or quiescent fraction, and also the size of cycling fraction during the unit time interval.

relatively mature progenitor cells, CFU-S-9 (Fig. 9(b)) in AhR<sup>-/-</sup> mice. Although the precise mechanism underlying this phenomenon is not clarified yet, the cell kinetics of CFU-GM becomes suppressed in terms of percent cycling fraction per unit time, i.e., less than 5% (Fig. 9(c)), which may be due to a possible negative feedback to an up-regulated cell kinetics of primitive progenitors (Fig. 9(a) and (b)).

The lack of AhR and the complex compensation of bone marrow hematopoiesis might still be insufficient in AhR<sup>+/+</sup> mice, because a compensatory increase in splenic weight in AhR<sup>-/-</sup> mice is evident (Figs. 7(a) and 8). As reported by Puga et al. [86], AhR functions as a cell-cycle regulator rather than as a drug-metabolizing enzyme inducer; thus, possible phenotypes transmitted via AhR may be diversified.

#### 4. Hematopoietic progenitor cells and xenobiotic responses

By analyzing antioxidative responses to thioredoxin concerns, we have recently found that benzene-induced xenobiotic responses are associated with antioxidative signaling [92]. Thus, the increased incidence of spontaneous neoplasms and accelerated aging observed in AhR-KO mice can be hypothesized as consequences of genomic instability possibly due to the absence of xenobiotic or antioxidative responses. ROSs in hematopoietic tissues in both AhR-KO and wild-type mice were evaluated using the DCFH-DA dye by flow cytometry, followed by the fractionation of hematopoietic progenitor cells. Hematopoietic tissues from AhR<sup>-/-</sup> mice showed a high reactivity to DCFH-DA, as shown in Fig. 5. Because the AhR expression level is high on primitive hematopoietic progenitor cells [91] fractionated primitive hematopoietic progenitor cells were also evaluated for their reactivity to DCFH-DA, which was found to be higher than the reactivity of other unfractionated bone marrow cells. Hematopoietic progenitor cells, i.e., the LKS fraction, are quiescent in an anoxic environment; furthermore, its activity is regulated by weak oxidative tension. Thus, the higher reactivity of the hematopoietic progenitor cell fraction in AhR<sup>-/-</sup> mice to the DCFH-DA dye is considered to be in good agreement with the underlying mechanism of genomic stability of wild-type AhR<sup>+/+</sup> mice, which may be linked to the suppressive function of AhR and the consequent longevity.

##### 4.1. Aryl-hydrocarbon-receptor-mediated hematopoietic alteration by xenobiotic substances

When xenobiotic ligands such as TCDD and/or benzo[a]pyrene are applied to AhRs, transcription of drug-metabolizing enzymes such as Cyp1A1 and 1B1 are induced [1,2]. The consequent induction of oxidative stress by these induced Cyp1A1 and 1B1 is known precisely [6,77]. The function of AhR in relation to the hematopoietic system involves two possible factors for hematopoiesis. First, induction of Cyp1A1 and 1B1 by xenobiotic responses consequently induces up-regulation of a cyclin-dependent kinase inhibitor, p27<sup>kip1</sup> or p21<sup>waf1</sup>, which readily suppresses the cell cycle [78,79]. Benzene is a unique newly found chemical whose toxicity is mediated by AhR [69], which suppresses the

hematopoietic stem-cell-specific cell cycle [93], which will be introduced as a model of hematopoietic stem cell modulation in the next section.

Second, what happens in the primitive hematopoietic stem cell system when AhR is stimulated by ligand-dependent up-regulation? In this situation, ARNT required by Hif-1alpha and Hif-2alpha in the hypoxic hematopoietic microenvironment is considered to inhibit primitive hematopoiesis [78]. Because of this suppression of primitive hematopoiesis, various hematopoietic progenitor cell compartments are decreased in number, as observed by Luster et al. in a variety of CFUs after exposure of mice to TCDD [76,88].

The above-mentioned hematopoietic impairment is based on the impaired function of the long-term reconstitution activity of the LKS fraction, i.e., primitive hematopoietic progenitor compartment. The long-term reconstitution activity of the LKS fraction repopulated in lethal-dose-irradiated recipients was heavily impaired after TCDD exposure. When repopulation of the LKS fraction is applied following TCDD exposure, while the nontreated LKS fraction successfully reaches a chimeric ratio of 80% with respect to the competitive donor fraction by 140 days after transplantation, the chimeric ratio is limited only to 15% with peak at 80 days after transplantation and the LKS fraction exposed to TCDD disappears by 140 days after transplantation [94].

Similar lymphopoietic alterations are observed after exposure to TCDD such as inhibition of thymic cell development [95], dysregulation of regulatory T and pro-inflammatory T cell differentiation [96], alteration of B cell maturation and CD34-positive human hematopoietic progenitor cells [97]. These alterations are also observed for ligands other than TCDD [96,98].

##### 4.2. Aryl-hydrocarbon-receptor-mediated benzene hematoxicities

Recent studies have shown that AhR in primitive cells transmits negative signals for the proliferation of such cells [91]. As we previously reported, primitive hemopoietic progenitor cells increases in number in AhR-KO mice; on the other hand, relatively mature progenitor cells, decreases in number in a homeostatic manner [91].

We have reported that benzene-induced hemopoietic toxicity is transmitted by AhR [69]. We also found that CYP2E1 related to benzene metabolism is also up-regulated in the bone marrow following benzene exposure [99]. Therefore, it is of interest to hypothesize a greater role of bone marrow cells in hemopoietic toxicity than in hepatic metabolism. Accordingly, in our present study, benzene-induced hemopoietic toxicity was evaluated in wild-type mice after a lethal dose of whole-body irradiation followed by repopulation with bone marrow cells that lack AhR or, *vice versa*, in AhR-KO mice after repopulation with wild-type bone marrow cells. As a result, benzene-induced hemopoietic toxicity seems to have been transmitted through AhR, and benzene was transformed by *de novo* metabolism with CYP2E1 in the bone marrow.

Six weeks after the repopulation, the steady-state hematopoietic parameters for repopulated mice were obtained and are shown in Fig. 10. The results were essentially the same between the mice repopulated with wild-type bone marrow

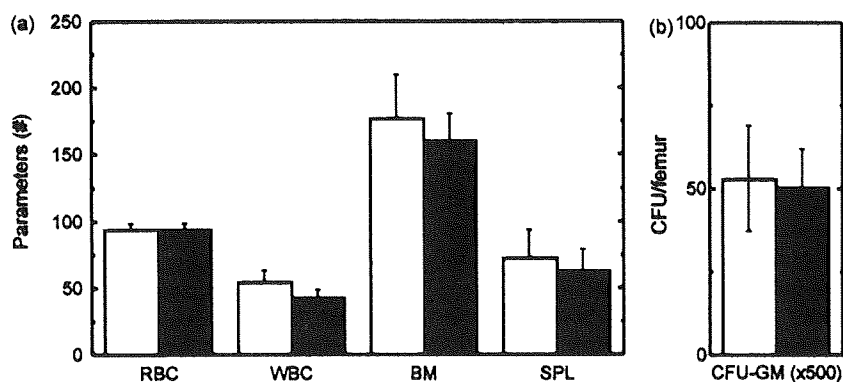


Fig. 10 – Comparison of various blood parameters between mice repopulated with wild-type BM (open columns) and AhR-KO (AhR<sup>-/-</sup>) BM (shaded columns) cells; (a) peripheral blood, BM and spleen weight. #: Vertical axis “Parameters” indicates the counts of peripheral RBCs ( $\times 10^9/\text{ml}$ ) and WBCs ( $\times 10^6/\text{ml}$ ), BM cellularity ( $\times 10^5/\text{femur}$ ), and weight of spleen (SPL, mg). (b) Numbers of CFU-GM ( $5 \times 10^2/\text{femur}$ ) per femur.

cells (open columns) and those repopulated with AhR-KO bone marrow cells (shaded columns).

Fig. 11(a) and (b) show the percentages of RBCs (a) and WBCs (b) with respect to that of the control in the peripheral blood after the repopulation with bone marrow cells. In the wild-type mice repopulated with wild-type bone marrow cells and those with AhR-KO bone marrow cells (open and closed symbols, respectively), benzene exposure induced a slight but statistically significant decrease in RBC count compared with the sham exposure except on day 5 in the wild-type group (100% with standard deviation of the mean indicated by

horizontal lines: Fig. 11(a)). The dose used in our present study was sufficiently high, and the decrease in RBC count was readily observed within two weeks of exposure.

The decreases in WBC count shown in Fig. 11(b) are more significant than those in RBC count throughout the exposure period except on day 5 in the AhR-KO group (the data were significantly different between wild-type mice ( $50.8 \pm 11.2\%$ ) and AhR-KO mice ( $70.6 \pm 17.6\%$ ;  $p = 0.024$ )).

As shown in Fig. 11(c), the decrease in the number of bone marrow cells after benzene exposure is significant in the mice repopulated with wild-type bone marrow cells specifically on

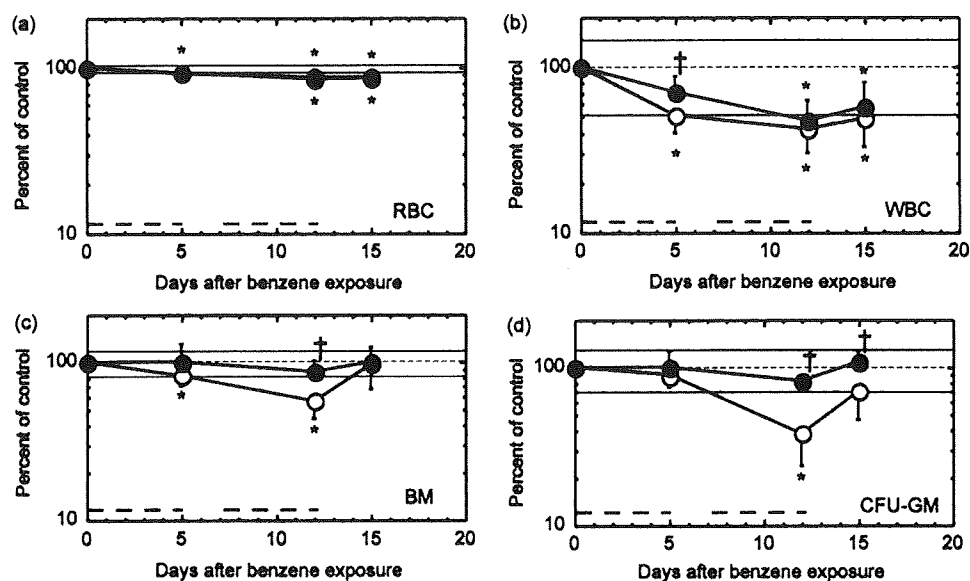


Fig. 11 – Changes in percentage of RBCs (a), WBCs (b), BM cells (c) and CFU-GM (d) of mice repopulated with wild-type BM (open symbols) and AhR-KO (AhR<sup>-/-</sup>) BM (closed symbols) cells during and after benzene exposure, with respect to those in each sham-exposure group. Vertical bars indicate the standard deviation of the mean. Horizontal dashed line indicates the mean (100%) and the solid lines indicate the standard deviation of the mean (100%) from the sham-exposure control wild-type group. The dashed line at the bottom indicates benzene exposure duration.

\*: Significant difference between sham-exposure group and benzene-exposed group determined by t-test at  $p < 0.05$ .

‡: Significant difference between wild-type mice and AhR-KO mice.

days 5 and 12 ( $82.2 \pm 12.0\%$ ,  $p = 0.035$  and  $65.4 \pm 20.3\%$ ,  $p = 0.007$ , respectively; number of cells obtained on day 12, significantly different between the wild-type mice and the AhR-KO mice ( $75.4 \pm 19.7\%$ ;  $p = 0.014$ )), which returned to the normal range by day 15, that is, 3 days after cessation of benzene treatment. In contrast to the peripheral blood parameters (Fig. 11(a) and (b)), the number of bone marrow cells in the mice repopulated with AhR-KO bone marrow cells did not show any decrease, but the mice showed a clear nullification of benzene-induced decrease in the number of bone marrow cells ( $86.7 \pm 14.9\%$ ;  $p = 0.057$ ). Concerning the weight of the spleen, there are no significant differences among the groups regardless of the duration of benzene treatment and AhR expression level (not shown).

In Fig. 11(d), the number of CFU-GM in the bone marrow of mice repopulated with wild-type bone marrow cells much more significantly decreased on day 12 (open symbols,  $37.8 \pm 14.2\%$ ,  $p = 0.019$ ; number of cells, significantly different between wild-type mice and AhR-KO mice ( $82.0 \pm 7.0\%$ ;  $p = 0.001$ )), which rapidly returned to the normal range by day 15, 3 days after cessation of benzene treatment. As shown in this figure, interestingly, the benzene-induced decrease in the number of CFU-GM in the bone marrow of mice repopulated with the AhR-KO bone marrow cells (closed symbols) is clearly nullified for the wild-type bone marrow cells (open symbols), and the number remains within the range found for the sham exposure. The reason for this very prominent decrease in the number of CFU-GM observed in the case of benzene exposure may be due, in part, to the expression of AhR, whose level is significantly high in primitive hematopoietic progenitor cells [5,100]. The KO of AhR nullified the decrease in the number of CFU-GM much more significantly than the decrease in peripheral blood parameters.

## 5. Summary

Oxidative stress induced by AhR-mediated benzene metabolites induces xenobiotic hematological malignancies in C57BL/6 mice. The encounter of AhR with benzene may not be the original biological relevance of historic and phylogenetic evolution of the AhR molecule in a wide range of animals from invertebrates to vertebrates including humans. Would not this be an ironical encounter?

In experimental mice, the existence of AhR apparently extends their lifespan as compared with AhR-KO mice (mean life spans, 756 days in AhR-homozygous KO and 890 days in wild-type C57BL/6). The major reasons for this extension of lifespan by AhRs seem to be the suppression of epigenetic tumorigenicity and age-related gerontological diseases, possibly owing to the advantages derived in reducing oxidative stresses through the AhR function. No precise mechanism has been reported, but the onset of spontaneous neoplasms and non-neoplastic senescent diseases is delayed in wild-type mice as compared with that in AhR-deficient mice. Furthermore, when AhR is knocked out, in the case of the hematopoietic system, the capacity to maintain the hematopoietic stem cell compartment is clearly diminished and the major fraction tends to differentiate into descendant blood cell

classes. The hematopoietic stem cell compartment shows the following. First, the compartment shows a diminished capacity to maintain the LKS fraction, the stem cell compartment, as observed by cell sorting analysis. Second, it shows a decrease in the fraction of the dormant stem cell/progenitor compartment, as measured by the BUUV method for evaluating kinetics of hematopoietic progenitor cells, by continuous *in vivo* treatment with BrdUrd and BrdUrd-labeled cell-purging with ultraviolet (UV) light. Thus, the possible regulation of hematopoietic stem cells maintaining the fraction of dormant hematopoietic stem cells may have mechanistic relevance in terms of a possible genomic stabilization by AhR, which should be elucidated.

The hematopoietic microenvironment is hypoxic during the steady state. This hypoxic state induces AhR to release (unbound) ARNT to Hif-1 $\alpha$  as well as Hif-2 $\alpha$ ; thus, the function of slight changes in regulating oxidative stress for a hematopoietic trigger in the hematopoietic microenvironment in wild-type mice may not be markedly different from that in the AhR-KO mice. However, when a change induces a much higher extent of oxidative stress induced by substances such as hydrogen peroxide in AhR-KO mice, the increased amount of ROSs is readily detected in AhR-KO mice, whereas wild-type mice show active removal of oxidative stress by ROS-scavenging molecules, resulting in notable differences in the amount of ROSs between wild-type and AhR-KO mice (Fig. 5).

Evidence was found in the liver that the expression of antioxidative stress genes such as superoxide dismutase 1 (Cu/Zn-SOD) and SOD2 (Mn-SOD) genes, as well as the Trx gene, which is located downstream of AhR and carrying XRE, are more highly expressed in wild-type mice than in AhR-KO mice [63].

In contrast to the above-mentioned beneficial biological function of AhR, in the case of benzene exposure, benzene exposure induces hematopoietic disturbances and the consequent leukemias. This seems to be induced by oxidative stress in AhR wild-type mice because Trx-overexpressing mice in contrast show nullification of hematopoietic disturbances owing to oxidative stress removal. Here is an enigma of benzene-induced hematotoxicity, that is, oxidative stress induced by as low as one part per million of benzene, which cannot be removed by antioxidative molecules associated with AhR as compared with those induced by hydrogen peroxide. On the other hand, the benzene exposure of AhR-KO mice is supposed to show none of the benzene-mediated oxidative-stress-induced hematopoietic disturbances or myeloid leukemias, simply owing to nullification of benzene metabolism in these mice lacking AhR.

## Acknowledgments

We thank Ms. E. Tachihara, Ms. Y. Kondo, Ms. C. Aoyagi, Ms. Y. Usami, Ms. Y. Shinzawa, and Ms. M. Uchiyama for excellent technical assistance, and Ms. N. Kikuchi, M. Yoshizawa, and Ms. M. Hojo for secretarial assistance. Encouragement of the study and the review of the manuscript by Prof. Fumio Matsumura is also appreciated.

This work was supported in part by a Grant-in-Aid for Scientific Research C, 15510064, 18510066 and also by the



MHLW-Research Fund (H19-Chemistry 003), National Institute of Health Sciences.

## REFERENCES

- [1] de Oliveira SK, Hoffmeister M, Gambaryan S, Muller-Esterl W, Guimaraes JA, Smolenski AP. Phosphodiesterase 2A forms a complex with the co-chaperone XAP2 and regulates nuclear translocation of the aryl hydrocarbon receptor. *J Biol Chem* 2007;282:13656–63.
- [2] Gu YZ, Hogenesch JB, Bradfield CA. The PAS superfamily: sensors of environmental and developmental signals. *Annu Rev Pharmacol Toxicol* 2000;40:519–61.
- [3] Duan R, Porter W, Samudio I, Vyhlidal C, Kladde M, Safe S. Transcriptional activation of c-fos protooncogene by 17beta-estradiol: mechanism of aryl hydrocarbon receptor-mediated inhibition. *Mol Endocrinol* 1999;13:1511–21.
- [4] Hahn ME. Aryl hydrocarbon receptors: diversity and evolution. *Chem Biol Interact* 2002;141:131–60.
- [5] Hirabayashi Y, Miyajima A, Yokota T, Arai K, Li G, Yoon B, et al. Effect of 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) on B cell differentiation in mouse pre-B colonization model regulated by artificially introduced human IL-3 receptors. *Organohalogen Compd* 2002;53:332–5.
- [6] Dalton TP, Puga A, Shertzer HG. Induction of cellular oxidative stress by aryl hydrocarbon receptor activation. *Chem Biol Interact* 2002;141:77–95.
- [7] Trosko JE, Inoue T. Oxidative stress, signal transduction, and intercellular communication in radiation carcinogenesis. *Stem Cells* 1997;15(Suppl. 2):59–67.
- [8] Gershon-Cohen J, Hermel MB, Griffith Jr JQ. The value of small lead shields against the injurious effect of total-body irradiation. *Science* 1951;114:157–8.
- [9] Till JE, McCulloch EA. A direct measurement of the radiation sensitivity of normal mouse bone marrow cells. *Radiat Res* 1961;14:213–22.
- [10] Lewis JP, Trobaugh Jr FE. Haematopoietic stem cells. *Nature* 1964;204:589–90.
- [11] Pluznik DH, Sachs L. The cloning of normal “mast” cells in tissue culture. *J Cell Physiol* 1965;66:319–24.
- [12] Bradley TR, Metcalf D. The growth of mouse bone marrow cells in vitro. *Aust J Exp Biol Med Sci* 1966;44:287–99.
- [13] Harrison DE. Mouse erythropoietic stem cell lines function normally 100 months: loss related to number of transplantations. *Mech Ageing Dev* 1979;9:427–33.
- [14] Cronkite EP. Regulation and structure of hemopoiesis: its application in toxicology. In: Irons RD, editor. *Toxicology of the blood and bone marrow*. New York: Raven Press; 1985.
- [15] Rosendaal M, Hodgson GS, Bradley TR. Organization of haemopoietic stem cells: the generation-age hypothesis. *Cell Tissue Kinet* 1979;12:17–29.
- [16] Okada S, Nakauchi H, Nagayoshi K, Nishikawa S, Miura Y, Suda T. In vivo and in vitro stem cell function of c-kit- and Sca-1-positive murine hematopoietic cells. *Blood* 1992;80:3044–50.
- [17] Hirabayashi Y, Yoon BI, Tsuboi I, Huo Y, Kodama Y, Kanno J, et al. Membrane channel connexin 32 maintains Lin(-)/c-kit (+) hematopoietic progenitor cell compartment: analysis of the cell cycle. *J Membr Biol* 2007;217:105–13.
- [18] Rudolph KL, Chang S, Lee HW, Blasco M, Gottlieb GJ, Greider C, et al. Longevity, stress response, and cancer in aging telomerase-deficient mice. *Cell* 1999;96:701–12.
- [19] Zhang J, Niu C, Ye L, Huang H, He X, Tong WG, et al. Identification of the haematopoietic stem cell niche and control of the niche size. *Nature* 2003;425:836–41.
- [20] Puch S, Armeanu S, Kibler C, Johnson KR, Muller CA, Wheelock MJ, et al. N-cadherin is developmentally regulated and functionally involved in early hematopoietic cell differentiation. *J Cell Sci* 2001;114:1567–77.
- [21] Calvi LM, Adams GB, Weibrecht KW, Weber JM, Olson DP, Knight MC, et al. Osteoblastic cells regulate the haematopoietic stem cell niche. *Nature* 2003;425:841–6.
- [22] Mancini SJ, Mantei N, Dumortier A, Suter U, MacDonald HR, Radtke F. Jagged1-dependent Notch signaling is dispensable for hematopoietic stem cell self-renewal and differentiation. *Blood* 2005;105:2340–2.
- [23] Arai F, Hirao A, Ohmura M, Sato H, Matsuoka S, Takubo K, et al. Tie2/angiopoietin-1 signaling regulates hematopoietic stem cell quiescence in the bone marrow niche. *Cell* 2004;118:149–61.
- [24] Nilsson SK, Johnston HM, Whitty GA, Williams B, Webb RJ, Denhardt DT, et al. Osteopontin, a key component of the hematopoietic stem cell niche and regulator of primitive hematopoietic progenitor cells. *Blood* 2005;106:1232–9.
- [25] Nagasawa T, Hirota S, Tachibana K, Takakura N, Nishikawa S, Kitamura Y, et al. Defects of B-cell lymphopoiesis and bone-marrow myelopoiesis in mice lacking the CXC chemokine PBSF/SDF-1. *Nature* 1996;382:635–8.
- [26] Zou YR, Kottmann AH, Kuroda M, Taniuchi I, Littman DR. Function of the chemokine receptor CXCR4 in haematopoiesis and in cerebellar development. *Nature* 1998;393:595–9.
- [27] Hirabayashi Y, Yoon BI, Tsuboi I, Huo Y, Kodama Y, Kanno J, et al. Protective role of connexin 32 in steady-state hematopoiesis, regeneration state, and leukemogenesis. *Exp Biol Med (Maywood)* 2007;232:700–12.
- [28] Hirabayashi Y, Yoon BI, Li GX, Fujii-Kuriyama Y, Kaneko T, Kanno J, et al. Benzene-induced hematopoietic toxicity transmitted by AhR in the wild-type mouse was negated by repopulation of AhR deficient bone marrow cells. *Organohalogen Compd* 2005;67:2280–3.
- [29] Yoshida K, Aizawa S, Watanabe K, Hirabayashi Y, Inoue T. Stem-cell leukemia: p53 deficiency mediated suppression of leukemic differentiation in C3H/He myeloid leukemia. *Leuk Res* 2002;26:1085–92.
- [30] Yoshida K, Hirabayashi Y, Wada S, Watanabe F, Watanabe K, Aizawa S, et al. p53 (TRP53) deficiency-mediated antiapoptosis escape after 5 Gy X irradiation still induces stem cell leukemia in C3H/He mice: comparison between whole-body assay and bone marrow transplantation (BMT) assay. *Radiat Res* 2007;167:703–10.
- [31] Kondo M, Weissman IL, Akashi K. Identification of clonogenic common lymphoid progenitors in mouse bone marrow. *Cell* 1997;91:661–72.
- [32] Wolf NS, Trentin JJ. Hemopoietic colony studies. V. Effect of hemopoietic organ stroma on differentiation of pluripotent stem cells. *J Exp Med* 1968;127:205–14.
- [33] Ploemacher RE, Mayen AE, De Koning AE, Krenacs T, Rosendaal M. Hematopoiesis: gap junction intercellular communication is likely to be involved in regulation of stroma-dependent proliferation of hemopoietic stem cells. *Hematology* 2000;5:133–47.
- [34] Minami A, Tsuboi I, Harada T, Fukumoto T, Hiramoto M, Koshinaga M, et al. Inflammatory biomarker, neopterin, suppresses B lymphopoiesis for possible facilitation of granulocyte responses, which is severely altered in age-related stromal-cell-impaired mice, SCL/SAM. *Exp Biol Med (Maywood)* 2007;232:134–45.
- [35] Hahn ME. The aryl hydrocarbon receptor: a comparative perspective. *Comp Biochem Physiol C Pharmacol Toxicol Endocrinol* 1998;121:23–53.

- [36] Ema M, Sogawa K, Watanabe N, Chujoh Y, Matsushita N, Gotoh O, et al. cDNA cloning and structure of mouse putative Ah receptor. *Biochem Biophys Res Commun* 1992;184:246-53.
- [37] Burbach KM, Poland A, Bradfield CA. Cloning of the Ah-receptor cDNA reveals a distinctive ligand-activated transcription factor. *Proc Natl Acad Sci USA* 1992;89:1815-9.
- [38] Schmidt JV, Carver LA, Bradfield CA. Molecular characterization of the murine Ahr gene. Organization, promoter analysis, and chromosomal assignment. *J Biol Chem* 1993;268:22203-9.
- [39] Dolwick KM, Schmidt JV, Carver LA, Swanson HI, Bradfield CA. Cloning and expression of a human Ah receptor cDNA. *Mol Pharmacol* 1993;44:911-7.
- [40] Poland A, Palen D, Glover E. Analysis of the four alleles of the murine aryl hydrocarbon receptor. *Mol Pharmacol* 1994;46:915-21.
- [41] Chang C, Smith DR, Prasad VS, Sidman CL, Nebert DW, Puga A. Ten nucleotide differences, five of which cause amino acid changes, are associated with the Ah receptor locus polymorphism of C57BL/6 and DBA/2 mice. *Pharmacogenetics* 1993;3:312-21.
- [42] Carver LA, Hogenesch JB, Bradfield CA. Tissue specific expression of the rat Ah-receptor and ARNT mRNAs. *Nucleic Acids Res* 1994;22:3038-44.
- [43] Pohjanvirta R, Wong JM, Li W, Harper PA, Tuomisto J, Okey AB. Point mutation in intron sequence causes altered carboxyl-terminal structure in the aryl hydrocarbon receptor of the most 2,3,7,8-tetrachlorodibenzo-p-dioxin-resistant rat strain. *Mol Pharmacol* 1998;54:86-93.
- [44] Korkalainen M, Tuomisto J, Pohjanvirta R. Restructured transactivation domain in hamster AH receptor. *Biochem Biophys Res Commun* 2000;273:272-81.
- [45] Kim EY, Hahn ME, Iwata H, Tanabe S, Miyazaki N. cDNA cloning of an aryl hydrocarbon receptor from Baikal seals (*Phoca sibirica*). *Mar Environ Res* 2002;54:285-9.
- [46] Walker MK, Heid SE, Smith SM, Swanson HI. Molecular characterization and developmental expression of the aryl hydrocarbon receptor from the chick embryo. *Comp Biochem Physiol C Toxicol Pharmacol* 2000;126:305-19.
- [47] Karchner SI, Kennedy SW, Trudeau S, Hahn ME. Towards molecular understanding of species differences in dioxin sensitivity: initial characterization of Ah receptor cDNAs in birds and an amphibian. *Mar Environ Res* 2000;50:51-6.
- [48] Karchner SI, Powell WH, Hahn ME. Identification and functional characterization of two highly divergent aryl hydrocarbon receptors (AHR1 and AHR2) in the teleost *Fundulus heteroclitus*. Evidence for a novel subfamily of ligand-binding basic helix loop helix-Per-ARNT-Sim (bHLH-PAS) factors. *J Biol Chem* 1999;274:33814-2.
- [49] Tanguay RL, Abnet CC, Heideman W, Peterson RE. Cloning and characterization of the zebrafish (*Danio rerio*) aryl hydrocarbon receptor. *Biochim Biophys Acta* 1999;1444:35-48.
- [50] Besselink HT, Denison MS, Hahn ME, Karchner SI, Vethaak AD, Koeman JH, et al. Low inducibility of CYP1A activity by polychlorinated biphenyls (PCBs) in flounder (*Platichthys flesus*): characterization of the Ah receptor and the role of CYP1A inhibition. *Toxicol Sci* 1998;43:161-71.
- [51] Abnet CC, Tanguay RL, Hahn ME, Heideman W, Peterson RE. Two forms of aryl hydrocarbon receptor type 2 in rainbow trout (*Oncorhynchus mykiss*). Evidence for differential expression and enhancer specificity. *J Biol Chem* 1999;274:15159-66.
- [52] Karchner SI, Franks DG, Powell WH, Hahn ME. Regulatory interactions among three members of the vertebrate aryl hydrocarbon receptor family: AHR repressor, AHR1, and AHR2. *J Biol Chem* 2002;277:6949-59.
- [53] Hahn ME, Karchner SI, Shapiro MA, Perera SA. Molecular evolution of two vertebrate aryl hydrocarbon (dioxin) receptors (AHR1 and AHR2) and the PAS family. *Proc Natl Acad Sci USA* 1997;94:13743-8.
- [54] Butler RA, Kelley ML, Powell WH, Hahn ME, Van Beneden RJ. An aryl hydrocarbon receptor (AHR) homologue from the soft-shell clam, *Mya arenaria*: evidence that invertebrate AHR homologues lack 2,3,7,8-tetrachlorodibenzo-p-dioxin and beta-naphthoflavone binding. *Gene* 2001;278:223-34.
- [55] Duncan DM, Burgess EA, Duncan I. Control of distal antennal identity and tarsal development in *Drosophila* by spineless-aristopedia, a homolog of the mammalian dioxin receptor. *Genes Dev* 1998;12:1290-303.
- [56] Emmons RB, Duncan D, Estes PA, Kiefel P, Mosher JT, Sonnenfeld M, et al. The spineless-aristopedia and tango bHLH-PAS proteins interact to control antennal and tarsal development in *Drosophila*. *Development* 1999;126:3937-45.
- [57] Wernet MF, Mazzoni EO, Celik A, Duncan DM, Duncan I, Desplan C. Stochastic spineless expression creates the retinal mosaic for colour vision. *Nature* 2006;440:174-80.
- [58] Huang X, Powell-Coffman JA, Jin Y. The AHR-1 aryl hydrocarbon receptor and its co-factor the AHA-1 aryl hydrocarbon receptor nuclear translocator specify GABAergic neuron cell fate in *C. elegans*. *Development* 2004;131:819-28.
- [59] Qin H, Powell-Coffman JA. The *Caenorhabditis elegans* aryl hydrocarbon receptor, AHR-1, regulates neuronal development. *Dev Biol* 2004;270:64-75.
- [60] Nebert DW, Brown DD, Towne DW, Eisen HJ. Association of fertility, fitness and longevity with the murine Ah locus among (C57BL/6N) (C3H/HeN) recombinant inbred lines. *Biol Reprod* 1984;30:363-73.
- [61] Gompertz B. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. *Philos Trans Royal Soc (London)* 1825;115:513-85.
- [62] Hirabayashi Y, Yoon BI, Li GX, Fujii-Kuriyama Y, Kaneko T, Kanno J, et al. Tumor suppressor function of aryl hydrocarbon receptor (AHR): early onsets of spontaneous lymphoma and hepatoma, and resulting shortened life span observed in Ahr deficient mice. *Organohalogen Compd* 2006;68:556-9.
- [63] Hirabayashi Y, Yoon BI, Li GX, Kanno J, Fujii-Kuriyama Y, Inoue T. Aryl hydrocarbon receptor suppresses spontaneous neoplasms and extends life span: possible mechanism implied by hematopoietic stem cell kinetics. *Organohalogen Compd* 2007;69:357-61.
- [64] Zou GM, Luo MH, Reed A, Kelley MR, Yoder MC. Ape1 regulates hematopoietic differentiation of embryonic stem cells through its redox functional domain. *Blood* 2007;109:1917-22.
- [65] Sakuma T, Ohtake M, Katsurayama Y, Jarukamjorn K, Nemoto N. Induction of CYP1A2 by phenobarbital in the livers of aryl hydrocarbon-responsive and -nonresponsive mice. *Drug Metab Dispos* 1999;27:379-84.
- [66] Poland A, Glover E, Taylor BA. The murine Ah locus: a new allele and mapping to chromosome 12. *Mol Pharmacol* 1987;32:471-8.
- [67] Van Zant G, de Haan G. Genetic control of lifespan: studies from animal models. *Expert Rev Mol Med* 1999;1999:1-12.
- [68] Forster MJ, Morris P, Sohal RS. Genotype and age influence the effect of caloric intake on mortality in mice. *FASEB J* 2003;17:690-2.
- [69] Yoon BI, Hirabayashi Y, Kawasaki Y, Kodama Y, Kaneko T, Kanno J, et al. Aryl hydrocarbon receptor mediates benzene-induced hematotoxicity. *Toxicol Sci* 2002;70:150-6.

- [70] Abbott BD, Birnbaum LS, Perdew GH. Developmental expression of two members of a new class of transcription factors: I. Expression of aryl hydrocarbon receptor in the C57BL/6N mouse embryo. *Dev Dyn* 1995;204:133–43.
- [71] Spindler SR, Koizumi A, Walford RL, Mote PL. P1-450 and P3-450 gene expression and maximum life span in mice. *Mutat Res* 1989;219:89–94.
- [72] Inoue T, Hirabayashi Y, Mitsui H, Sasaki H, Cronkite EP, Bullis Jr JE, et al. Survival of spleen colony-forming units (CFU-S) of irradiated bone marrow cells in mice: evidence for the existence of a radioresistant subfraction. *Exp Hematol* 1995;23:1296–300.
- [73] Ceradini DJ, Kulkarni AR, Callaghan MJ, Tepper OM, Bastidas N, Kleinman ME, et al. Progenitor cell trafficking is regulated by hypoxic gradients through HIF-1 induction of SDF-1. *Nat Med* 2004;10:858–64.
- [74] Levesque JP, Winkler IG, Hendy J, Williams B, Helwani F, Barbier V, et al. Hematopoietic progenitor cell mobilization results in hypoxia with increased hypoxia-inducible transcription factor-1 alpha and vascular endothelial growth factor A in bone marrow. *Stem Cells* 2007;25:1954–65.
- [75] Tian H, McKnight SL, Russell DW. Endothelial PAS domain protein 1 (EPAS1), a transcription factor selectively expressed in endothelial cells. *Genes Dev* 1997;11:72–82.
- [76] Luster MI, Hong LH, Boorman GA, Clark G, Hayes HT, Greenlee WF, et al. Acute myelotoxic responses in mice exposed to 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). *Toxicol Appl Pharmacol* 1985;81:156–65.
- [77] Chen ZH, Hurh YJ, Na HK, Kim JH, Chun YJ, Kim DH, et al. Resveratrol inhibits TCDD-induced expression of CYP1A1 and CYP1B1 and catechol estrogen-mediated oxidative DNA damage in cultured human mammary epithelial cells. *Carcinogenesis* 2004;25:2005–13.
- [78] Wang G, Reisdorph R, Clark Jr RE, Miskimins R, Lindahl R, Miskimins WK. Cyclin dependent kinase inhibitor p27(Kip1) is upregulated by hypoxia via an ARNT dependent pathway. *J Cell Biochem* 2003;90:548–60.
- [79] Pang PH, Lin YH, Lee YH, Hou HH, Hsu SP, Juan SH. Molecular mechanisms of p21 and p27 induction by 3-methylcholanthrene, an aryl-hydrocarbon receptor agonist, involved in antiproliferation of human umbilical vascular endothelial cells. *J Cell Physiol* 2008;215:161–71.
- [80] Hirabayashi Y, Matsumura T, Matsuda M, Kuramoto K, Motoyoshi K, Yoshida K, et al. Cell kinetics of hemopoietic colony-forming units in spleen (CFU-S) in young and old mice. *Mech Ageing Dev* 1998;101:221–31.
- [81] Staller P, Sulitkova J, Lisztswan J, Moch H, Oakeley EJ, Krek W. Chemokine receptor CXCR4 downregulated by von Hippel-Lindau tumour suppressor pVHL. *Nature* 2003;425:307–11.
- [82] Ramirez-Bergeron DL, Runge A, Adelman DM, Gohil M, Simon MC. HIF-dependent hematopoietic factors regulate the development of the embryonic vasculature. *Dev Cell* 2006;11:81–92.
- [83] Le Bras A, Lionneton F, Mattot V, Lelievre E, Caetano B, Spruyt N, et al. HIF-2alpha specifically activates the VE-cadherin promoter independently of hypoxia and in synergy with Ets-1 through two essential ETS-binding sites. *Oncogene* 2007;26:7480–9.
- [84] Adelman DM, Maltepe E, Simon MC. Multilineage embryonic hematopoiesis requires hypoxic ARNT activity. *Genes Dev* 1999;13:2478–83.
- [85] Adachi J, Mori Y, Matsui S, Takigami H, Fujino J, Kitagawa H, et al. Indirubin and indigo are potent aryl hydrocarbon receptor ligands present in human urine. *J Biol Chem* 2001;276:31475–8.
- [86] Puga A, Xia Y, Elferink C. Role of the aryl hydrocarbon receptor in cell cycle regulation. *Chem Biol Interact* 2002;141:117–30.
- [87] Mimura J, Yamashita K, Nakamura K, Morita M, Takagi TN, Nakao K, et al. Loss of teratogenic response to 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) in mice lacking the Ah (dioxin) receptor. *Genes Cells* 1997;2:645–54.
- [88] Luster MI, Boorman GA, Dean JH, Harris MW, Luebke RW, Padarathsingh ML, et al. Examination of bone marrow, immunologic parameters and host susceptibility following pre- and postnatal exposure to 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). *Int J Immunopharmacol* 1980;2:301–10.
- [89] Yoon BI, Hirabayashi Y, Kaneko T, Kodama Y, Kanno J, Yodoi J, et al. Transgene expression of thioredoxin (trx/ adf) protects against 2,3,7,8-tetrachlorodibenzo-p-dioxin (tcdd)-induced hematotoxicity. *Arch Environ Contam Toxicol* 2001;41:232–6.
- [90] Yoon BI, Hirabayashi Y, Kaneko T, Kodama Y, Kanno J, Yodoi J, et al. Transgene expression of thioredoxin (TRX/ ADF) protects against 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)-induced hematotoxicity. *Organohalogen Compd* 2001;53:332–5.
- [91] Hirabayashi Y, Li GX, Yoon BI, Fujii-Kuriyama Y, Kaneko T, Kanno J, et al. AhR suppresses hemopoiesis during steady state but accelerates cell cycle as an early response: a study of AhR-knockout mice. *Organohalogen Compd* 2003;64:270–3.
- [92] Li GX, Hirabayashi Y, Yoon BI, Kawasaki Y, Tsuboi I, Kodama Y, et al. Thioredoxin overexpression in mice, model of attenuation of oxidative stress, prevents benzene-induced hemato-lymphoid toxicity and thymic lymphoma. *Exp Hematol* 2006;34:1687–97.
- [93] Yoon BI, Hirabayashi Y, Kawasaki Y, Kodama Y, Kaneko T, Kim DY, et al. Mechanism of action of benzene toxicity: cell cycle suppression in hemopoietic progenitor cells (CFU-GM). *Exp Hematol* 2001;29:278–85.
- [94] Sakai R, Kajiume T, Inoue H, Kanno R, Miyazaki M, Ninomiya Y, et al. TCDD treatment eliminates the long-term reconstitution activity of hematopoietic stem cells. *Toxicol Sci* 2003;72:84–91.
- [95] Svensson C, Silverstone AE, Lai ZW, Lundberg K. Dioxin-induced adseverin expression in the mouse thymus is strictly regulated and dependent on the aryl hydrocarbon receptor. *Biochem Biophys Res Commun* 2002;291:1194–200.
- [96] Quintana FJ, Basso AS, Iglesias AH, Korn T, Farez MF, Bettelli E, et al. Control of T(reg) and T(H)17 cell differentiation by the aryl hydrocarbon receptor. *Nature* 2008;453:65–71.
- [97] van Grevenynghe J, Bernard M, Langouet S, Le Berre C, Fest T, Fardel O. Human CD34-positive hematopoietic stem cells constitute targets for carcinogenic polycyclic aromatic hydrocarbons. *J Pharmacol Exp Ther* 2005;314:693–702.
- [98] Yamaguchi K, Near RI, Matulka RA, Shneider A, Toselli P, Trombino AF, et al. Activation of the aryl hydrocarbon receptor/transcription factor and bone marrow stromal cell-dependent preB cell apoptosis. *J Immunol* 1997;158:2165–73.
- [99] Yoon BI, Li GX, Kitada K, Kawasaki Y, Igarashi K, Kodama Y, et al. Mechanisms of benzene-induced hematotoxicity and leukemogenicity: cDNA microarray analyses using mouse bone marrow tissue. *Environ Health Perspect* 2003;111:1411–20.
- [100] Hirabayashi Y, Inoue T. Toxicogenomics applied to hematotoxicology. In: Borlak J, editor. *Handbook of toxicogenomics*. Weinheim: Wiley-VCH, Verlag GmbH; 2005. p. 583–608. Chapter 24.

## Benzene-Induced Hematopoietic Neoplasms Including Myeloid Leukemia in *Trp53*-Deficient C57BL/6 and C3H/He Mice

Yasushi Kawasaki,<sup>\*1</sup> Yoko Hirabayashi,<sup>\*2</sup> Toyozo Kaneko,<sup>\*</sup> Jun Kanno,<sup>\*</sup> Yukio Kodama,<sup>\*</sup> Yuuko Matsushima,<sup>\*</sup> Yukio Ogawa,<sup>\*</sup> Minoru Saitoh,<sup>\*</sup> Kiyoshi Sekita,<sup>\*</sup> Osayuki Uchida,<sup>\*</sup> Takashi Umemura,<sup>\*</sup> Byung-Il Yoon,<sup>\*†</sup> and Tohru Inoue<sup>‡</sup>

<sup>\*</sup>Division of Cellular and Molecular Toxicology, Center for Biological Safety and Research, National Institute of Health Sciences, Tokyo 158-8501, Japan;

<sup>†</sup>Laboratory of Histology and Molecular Pathogenesis, School of Veterinary Medicine, Kangwon National University, Chuncheon 200-701, Republic of Korea;

and <sup>‡</sup>Center for Biological Safety and Research, National Institute of Health Sciences, Tokyo 158-8501, Japan

Received December 7, 2008; accepted May 11, 2009

This research focused on three major questions regarding benzene-induced hematopoietic neoplasms (HPNs). First, why are HPNs induced equivocally and at only threshold level with low-dose benzene exposure despite the significant genotoxicity of benzene even at low doses both in experiments and in epidemiology? Second, why is there no linear increase in incidence at high-dose exposure despite a lower acute toxicity ( $LD_{50} > 1000$  mg/kg body weight; WHO, 2003, *Benzene in drinking-water. Background document for development of WHO Guidelines for Drinking-Water Quality*)? Third, why are particular acute myeloid leukemias (AMLs) not commonly observed in mice, although AMLs are frequently observed in human cases of occupational exposure to benzene? In this study, we hypothesized that the threshold-like equivocal induction of HPNs at low-dose benzene exposure is based on DNA repair potential in wild-type mice and that the limited increase in HPNs at a high-dose exposure is due to excessive apoptosis in wild-type mice. To determine whether *Trp53* deficiency satisfies the above hypotheses by eliminating or reducing DNA repair and by allowing cells to escape apoptosis, we evaluated the incidence of benzene-induced HPNs in *Trp53*-deficient C57BL/6 mice with specific regard to AMLs. We also used C3H/He mice, AML prone, with *Trp53* deficiency to explore whether a higher incidence of AMLs on benzene exposure might explain the above human-murine differences. As a result, heterozygous *Trp53*-deficient mice of both strains showed a nonthreshold response of the incidence of HPNs at the lower dose, whereas both strains showed an increasing HPN incidence up to 100% with increasing benzene exposure dose, including AMLs, that developed 38% of heterozygous *Trp53*-deficient C3H/He mice compared to only 9% of wild-type mice exposed to the high dose. The detection of AMLs in heterozygous *Trp53*-deficient mice, even in the C57BL/6 strain, implies that benzene may be a potent inducer of AMLs also in mice with some strain differences.

<sup>1</sup> Deceased of apoplectic second cerebral attack on 6 August 2008 during follow-up study.

<sup>2</sup> To whom correspondence should be addressed at Division of Cellular and Molecular Toxicology, Center for Biological Safety and Research, National Institute of Health Sciences, 1-18-1 Kamiyoga, Setagayaku, Tokyo 158-8501, Japan. Fax: +81-3-3700-9647. E-mail: yokohira@nihs.go.jp.

**Key Words:** benzene; acute myeloid leukemia; hematopoietic neoplasms; C57BL/6; C3H/He; *Trp53*-deficient mice.

The association between chronic benzene exposure and its effect of hematopoietic impairment was first observed in tire workers by Santesson (1897). As additional cases were accumulated (Delore and Borgomano, 1928; Le Noir and Claude, 1897; Selling, 1910; Cabot, 1927; Smith, 1928), researchers found that benzene exposure induced not only bone marrow (BM) failure/aplastic anemia but also hematopoietic neoplasms (HPNs) including leukemias (Aksoy *et al.*, 1974; Penati and Vigliani, 1938). As reported in the literature, there is a narrow benzene exposure range for HPNs including leukemias and that for reversible or irreversible marrow aplasia both in humans and in experimental animals. The association between the benzene exposure and the cause of HPNs remained unclear until 1980, when Snyder *et al.* (1980) observed the first HPNs in mice induced by lifetime benzene exposure at 300 ppm, 6 h/day, and 5 days/week. Subsequently, Cronkite *et al.* (1982, 1984) confirmed the induction of HPNs through an exposure protocol that referenced the number of hematopoietic progenitor cells noted during the course of treatment.

The groundbreaking intermittent exposure protocols, developed by Cronkite *et al.* (1982, 1984), was originally intended not to exhaust the target cells but to maintain hematopoietic stem cells capable of transforming into HPNs. Indeed, a very high dose of benzene exposure in Swiss mice administered by gavage (500 mg/kg body weight for 4–5 days/week for 78 weeks) failed to induce any HPNs (Maltoni *et al.*, 1989), whereas exposure at lower doses of benzene for even 2 years by gavage using a protocol similar to that developed by the groups of Snyder and Cronkite (0, 25, 50, and 100 mg/kg body weight, 5 days/week) was found to induce HPNs at incidences of 8, 21, 20, and 31%, respectively (Huff *et al.*, 1989; NTP, 1986).

Subsequent studies further disclosed that benzene-induced hematotoxicity is mediated by aryl hydrocarbon receptors (Yoon *et al.*, 2002). The Snyder-Cronkite's protocol of