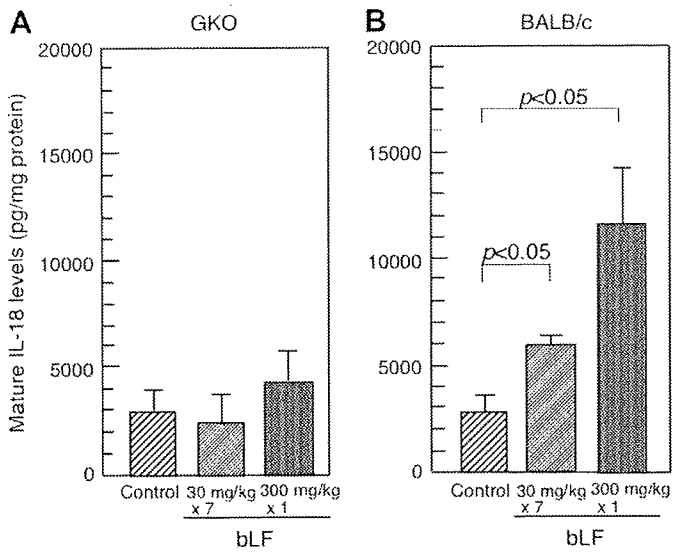

Fig. 11. Effect of bLF on mature IL-18 levels in the mucosa of the small intestine of GKO (A) and BALB/c (B) mice. bLF was administered orally at 30 mg/kg per day for 7 days or once at 300 mg/kg on day 7, and 3 h after last the administration the animals were anesthetized and killed, the jejunum removed, and mature IL-18 levels measured. Error bars represent the standard error ($n = 5$).

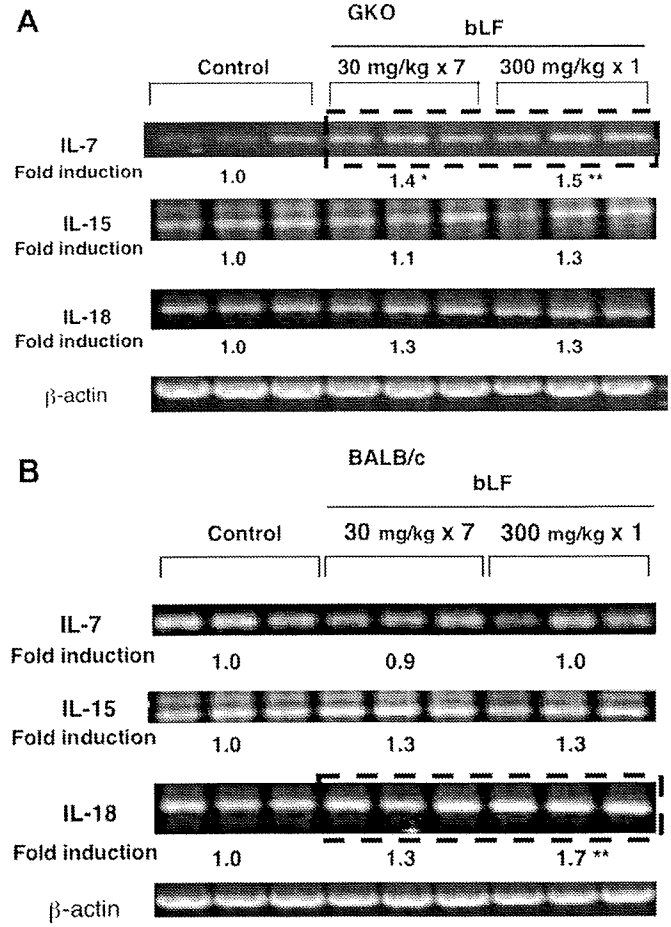

Fig. 12. Effect of bLF on the expression of IL-7, IL-15 and IL-18 mRNA in the mucosa of the small intestines of GKO (A) and BALB/c (B) female mice. bLF was administered orally at 30 mg/kg per day for 7 days or once at 300 mg/kg on day 7, and 3 h after the last administration of bLF the animals were anesthetized and killed and the jejunum removed. mRNA expression was detected by RT-PCR. Three mice were used for each condition. Expression of each transcript was normalized to β-actin and the mean expression values for each condition obtained. Numerical data represent the ratio of these values compared to the controls. Administration of bLF lead to an increase in IL-7 expression in GKO mice and to an increase in IL-18 expression in BALB/c mice. Data are representative of 2 independent experiments.

3.6. Analysis of caspase-1 expression and activity in the small intestine of GKO and BALB/c mice

Caspase-1 expression and activity in the small intestine of BALB/c mice is enhanced by treatment with bLF, and this effect is dependent on IFNγ. Therefore we investigated the role of IFNγ on bLF-mediated induction of caspase-1 expression and activity. In immunohistochemical and Western blot analysis, caspase-1 expression in epithelial cells of the small intestine was increased in both GKO and BALB/c mice after treatment with bLF (GKO: 1.6-fold; BALB/c: 1.9-fold). However, caspase-1 activity, as measured by generation of the cleaved-caspase-1 p-20 peptide, was markedly different between GKO and BALB/c mice (GKO: 0.8; BALB/c: 1.5-fold vs Control) (Fig. 13). Moreover, caspase-1 activity in the mucosa of the small intestine in GKO mice did not change following administration of bLF (120–123% of Control), but its activity in BALB/c mice was significantly enhanced (211–272% of Control, $p < 0.05$) (Table 2). Therefore, bLF induction of caspase-1 expression is not dependent on IFNγ, but generation of active caspase-1 is dependent on IFNγ.

3.7. Immunohistochemical analysis of various immune cells in the small intestine of GKO mice

bLF is thought to mediate its anti-metastasis activity by activation of immune cells in the intestine, and we have previously demonstrated that bLF increases the number of $CD4^+$ and $CD8^+$T and asialo GM_1^+ (NK) cells in BALB/c mice [9]. bLF treatment also inhibits Co26Lu metastasis to the lung in GKO mice, and this effect occurs in the absence of IFNγ, caspase-1, and IL-18. We therefore examined the effect of bLF on immune cells in the small intestine of GKO mice. $CD4^+$, IgM^+ (data not shown), and IgA^+ cells were significantly increased by treatment with bLF, but $CD8^+$ cells were not (Fig. 14).

$IL\text{-}7^+$ cells in the small intestine are mainly intraepithelial lymphocytes (IEL), fibroblasts, and vascular endothelial cells. bLF also caused a marked increase in the number of $IL\text{-}7^+$ intraepithelial lymphocytes in GKO mice (Fig. 15B). In contrast, bLF did not induce expression of IL-7 in the small intestine of BALB/c mice or an increase in $IL\text{-}7^+$ intraepithelial lymphocytes (data not shown).

$IFN\alpha^+$ cells exist in the lamina propria of the small intestine and the number of these cells was also increased by treatment with bLF in GKO mice, but not in BALB/c mice (Fig. 16). IFNα protein expression was increased (1.8-fold) as shown by Western blot analysis (data not shown).

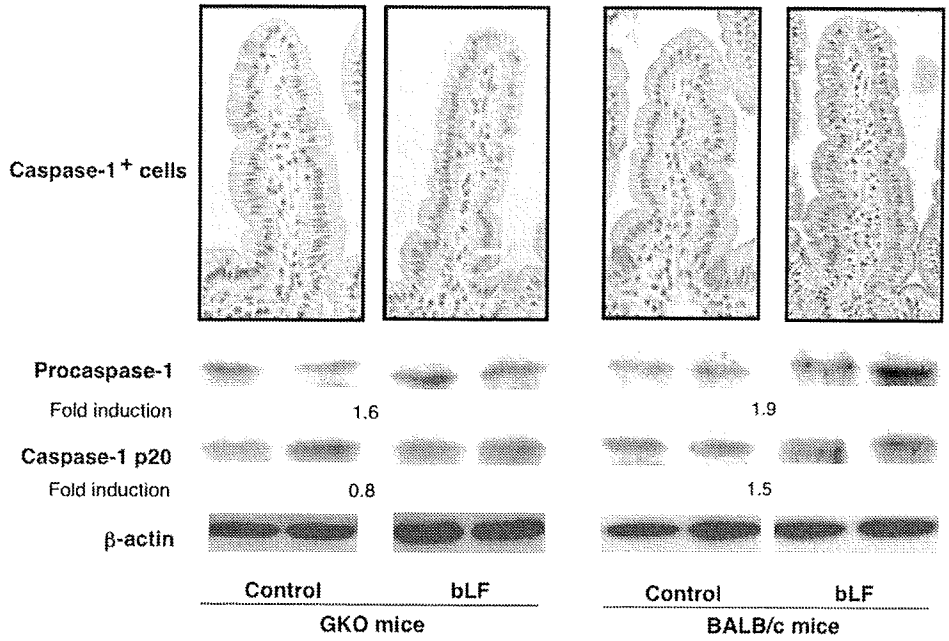

Fig. 13. Caspase-1$^+$ cells in the small intestine and Western blot analysis for procaspase-1 and active caspase-1 (caspase-1 p20). bLF was administered orally at 30 mg/kg per day for 7 days, and 3 h after the last administration of bLF the animals were anesthetized and killed, and the jejunum was removed. The results of two independent experiments are shown.

3.8. Anti-metastatic effects in tumor-bearing GKO mice by rmIL-18, rIFNαA/D, or rmIL-7 treatment

bLF inhibits Co26Lu metastasis to the lung in GKO mice in the absence of IFNγ, caspase-1, and IL-18. However, bLF induces IFNα and IL-7 in these mice. Therefore, we tested the effects of recombinant mature IL-18 (rmIL-18), recombinant IFNα (rIFNαA/D), and recombinant IL-7 (rIL-7) on Co26Lu metastasis to the lung in GKO mice. Intraperitoneal administration of IL-18 at 20 ng/mouse, IFNαA/D at 10^5 IU/mouse, or rmIL-7 at 0.1 μg/mouse caused significant retardation of tumor growth of subcutaneously implanted Co26Lu and also significant retardation of lung metastases (Table 3).

4. Discussion

LF is an important component of the innate immune system with potent antimicrobial activity and is found in a variety of exocrine secretions including gastrointestinal fluids. The small intestine has a well developed immune network that is involved in protection of the host from pathogens. For example, mucosa-associated bacteria (lactobacili and *E. coli*, etc.) in the small intestine can be potent stimulators of mononuclear cells of the intestinal lamina propria, inducing these cells to express IL-12 [39], which in turn activates intestinal immune cells and protects the small intestine against microbial infection. LF is part of the intestinal immune network [40–42]. It is an excellent marker of inflammatory bowel diseases such as ulcerative colitis and Crohn's disease [43], and fecal LF levels are also higher in patients with colorectal tumors than in healthy individuals [44]. Because ingested LF stimulates cytokine production [8] and enhances mucosal immunity [9], NK cell activity [10,11], LAK activity [11], neutrophil activity [12,13], and macrophage cytotoxicity [14,15], it is thought that orally ingested LF is also able to interact with epithelial cells and immune cells in the mucosa of the intestine.

Table 2
Effects of bLF on caspase-1 and -3 activities in the mucosa of the small intestine in GKO and BALB/c (WT) mice

Treatment (p.o.)	Caspase-1 activity	Caspase-3 activity (absorbance at 405 nm)
GKO mice ($n = 4$)		
Control (saline)	0.035 ± 0.002	0.214 ± 0.011
bLF (30 mg/kg × 7)	0.042 ± 0.011 (1.20)	
bLF (300 mg/kg × 1)	0.043 ± 0.012 (1.23)	0.221 ± 0.024 (1.03)
BALB/c (WT) mice ($n = 5$–7)		
Control (saline)	0.018 ± 0.003*	0.168 ± 0.014
bLF (30 mg/kg × 7)	0.049 ± 0.011* (2.72)	
bLF (300 mg/kg × 1)	0.038 ± 0.005 (2.11)	0.190 ± 0.026 (1.13)

Mucosal samples of the small intestine were diluted to 200 μg protein/50 μl. () = -fold. *$p < 0.05$.

There are several reports that administration of LF inhibits tumor growth and protects against carcinogenesis [18,45,46], reviewed in refs. [26,47,48]. In several rodent cancer models, it has been shown that this protective effect is associated with enhancement of the local intestinal mucosal immune response [9,16,47,49–52].

One pathway which appears to be an effector of LF is generation of mature IL-18 and consequent activation of immune cells. Administration of bLF induces expression of IL-18 in the small intestine [9,16,46]. IL-18 stimulates both Th1 and Th2 type T helper cells, CD8$^+$ effector T cells, NK cells, and LAK cells [10,11,17,53–56]; and up-regulation and/or enhanced activity of CD4$^+$ and CD8$^+$ effector T-lymphocytes and NK and LAK cells is also observed upon LF

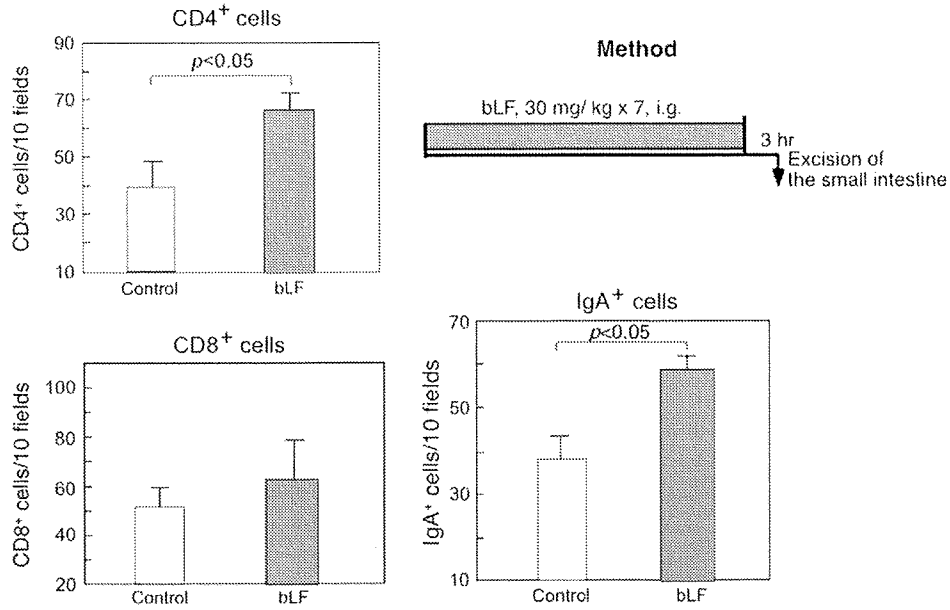

Fig. 14. Effects of bLF on the number of $CD4^+$, $CD8^+$, and IgA^+ cells in the lamina propria of the small intestine of GKO mice. bLF was administered orally at 30 mg/kg per day for 7 days, and 3 h after the last administration of bLF the animals were anesthetized and killed, and the jejunum was removed and the number of $CD4^+$, $CD8^+$, and IgA^+ cells counted. Error bars represent the standard error ($n = 5$).

administration [16,19,40,50,57]. LF also stimulates the induction and/or activation of B cells, macrophages, and neutrophils [54,58,59]. Wolf et al. report that hLF resulted in T cell-dependent tumor inhibition of head and neck squamous cell carcinoma *in vivo*, and that depletion of $CD3^+$ cells abolishes this effect [46]. Bezault et al. report that stimulation of NK cell activity is essential for LF-mediated prevention of metastasis in C57BL/6 mice: intraperitoneal administration of hLF to these mice inhibited the growth of solid tumors and prevented lung metastasis of murine melanoma cells, and this effect was lost upon deletion of NK cell function using antibody blocking experiments [18].

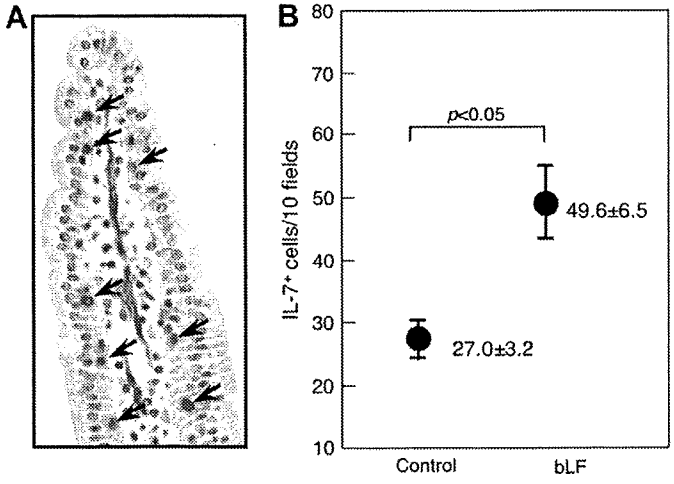

Fig. 15. Effects of bLF on the number of $IL\text{-}7^+$ cells in the small intestine of GKO mice. bLF was administered orally at 30 mg/kg per day for 7 days, and 3 h after the last administration of bLF the animals were anesthetized and killed, and the jejunum was removed. (A) $IL\text{-}7^+$ cells in the small intestine (arrows). (B) The number of $IL\text{-}7^+$ cells in the small intestine of GKO mice was significantly increased by treatment with bLF ($n = 5$).

In our study we confirmed the ability of bLF and digested bLF-peptides to induce expression of IL-18 and the generation of mature IL-18 in a variety of settings. Importantly, in IFNγ knockout (GKO) mice, bLF had no effect on IL-18 expression or maturation. Moreover, in settings in which bLF did induce generation of mature IL-18, maturation was abolished by caspase-1 inhibitors. Therefore, bLF-mediated induction of IL-18 expression is dependent upon IFNγ and bLF-mediated generation of mature IL-18 is dependent upon caspase-1.

Previously we showed that bLF can induce IFNγ in the intestine [50], and in this study we affirmed that bLF can induce expression of IFNγ by peritoneal macrophages and that both bLF and bLFcin can induce expression of IFNγ by Lewis Lung carcinoma cells. Moreover, bLF also induces expression

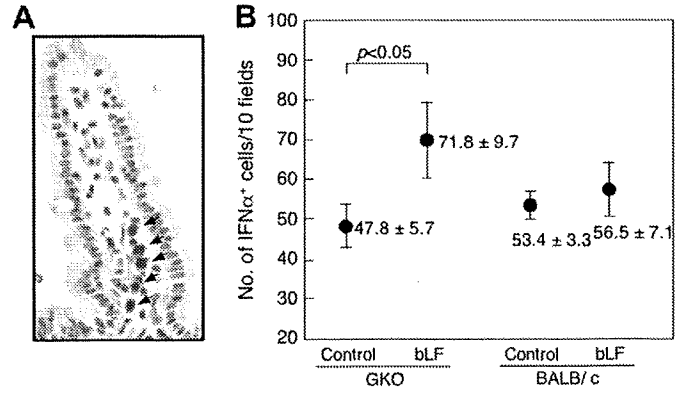

Fig. 16. Effects of bLF on the number of $IFN\alpha^+$ cells in the small intestine of GKO mice. bLF was administered orally at 30 mg/kg per day for 7 days, and 3 h after the last administration of bLF the animals were anesthetized and killed, and the jejunum was removed. (A) $IFN\alpha^+$ cells in the small intestine (arrows). (B) The number of $IFN\alpha^+$ cells in the small intestine of GKO mice was significantly increased by treatment with bLF ($n = 5$).

Table 3
Effect of IL-7, IL-18 and IFNαA/D on lung metastatic colony formation in Co26Lu-bearing GKO mice

Treatment (i.p.)	Dose (μg/mouse)	Tumor volume on day 20 (mm^3)	No. of metastatic colonies Median (range)	p-value
Control (saline)		1274 ± 254	233 (156–420)	
rmIL-7	0.1	1023 ± 68*	124 (53–165)	0.003
rmIL-7	1.0	1122 ± 172	143 (34–168)	0.007
rmIL-18	0.02	953 ± 55*	105 (51–169)	0.012
rIFNαA/D	1×10^5 IU	899 ± 59*	111 (91–168)	0.012

Cytokines were administered i.p. to Co26Lu-bearing GKO mice (5–7 mice/group) on days 10, 13, 17 and 20. *$p < 0.05$ vs Control.

of caspase-1 mRNA *in vivo*. However, while bLF administration results in generation of active caspase-1 in BALB/c mice, it has no effect on caspase-1 activity in GKO mice. Taken together, these results indicate that in BALB/c mice, bLF ingestion results in stimulation of IFNγ and caspase-1 expression; IFNγ in turn stimulates IL-18 expression and caspase-1 activity; and finally active caspase-1 cleaves pro-IL-18 to generate mature IL-18. The bLF stimulated generation of mature IL-18 subsequently acts on immune cells in the intestine which in turn effect the observed bLF anticarcinogenesis activity.

However, bLF also effects inhibition of tumor growth and metastasis in GKO mice, an animal model in which bLF administration does not result in induction of IFNγ expression or generation of caspase-1 activity or mature IL-18. This result is not inconsistent with some published reports. Kuhara et al. also report that bLF administration caused an increase in IFNγ and IL-18 and NK activity, however, bLF administration also caused increased NK activity in IL-18 KO mice [51]. In these mice, bLF induced increased expression of IFNα and IFNβ (type I IFNs) in Payer's patches and mesenteric lymph nodes, and blockade of induction of IFNα and IFNβ expression abolished bLF induction of NK activity. Using BALB/cByJ Jcl hypoglycemic mice, bLF administration does not result in elevated IFNγ or IL-18 expression [60]; however, bLF is host protective in this animal and does induce expression of IFNβ and IL-12. These cytokines are well characterized mediators of host defense against infections and cancer. bLF-mediated induction of IL-12 is also reported in other systems [61]. In the present study, we also show induction of type I IFNs and of interleukins other than IL-18 by bLF *in vitro* and in GKO mice *in vivo*. Therefore, administration of bLF can activate more than one effector pathway; which pathways are responsive to activation depend on the physiology of the gastrointestinal tract.

In the GKO mice, bLF did not induce IL-18 expression or maturation, but bLF did induce expression of IFNα and IL-7 and inhibited tumor growth and metastasis. In these mice, injection of recombinant murine IL-18 also inhibited tumor growth and metastasis. Thus, the IL-18 effector pathway is intact in GKO mice, but in the absence of IFNγ, bLF is unable to activate it. Importantly, injection of recombinant IFNαA/D or recombinant IL-7 also inhibited tumor growth and metastasis in these mice. Thus, in the absence of the IFNγ/IL-18 effector pathway, bLF is able to exert anticarcinogenesis activity by activation of a second effector pathway, an IFNα/IL-7 effector pathway.

Finally, it should be noted that bLF and bLFcin induced expression of IL-15 by peritoneal macrophages *in vitro*. That the induction of IL-15 was not observed when the entire intestinal mucosa was examined is not surprising since macrophages make up a very small proportion of this tissue. The specific role of IL-15, if any, in bLF-mediated immune modulation remains to be elucidated, however, IL-15 is a well known immune cell regulator [62–64] and could be a component of another bLF activated effector pathway.

5. Summary

Lactoferrin, originally isolated from milk, is an important component of the innate immune system. Several reports indicate that ingested lactoferrin can inhibit carcinogenesis. In this report we investigated effector pathways which link ingestion of lactoferrin to carcinogenesis. Our data support the concept that lactoferrin peptide fragments, especially lactoferricin, are able to stimulate cytokine production by cells in the mucosa of the small intestine. The subsequent activation of immune cells enhances immune surveillance, i.e., the ability of the immune system to recognize and remove malignant cells that arise during a person's lifetime, and lactoferrin's anticarcinogenesis effects are the result of this enhanced surveillance.

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A Medium-Term, Rapid Rat Bioassay Model for the Detection of Carcinogenic Potential of Chemicals

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ABSTRACT

The Ito Liver Model and the Ito Multi-organ Model are used in conjunction and constitute an efficient and rapid bioassay for the identification of both genotoxic and nongenotoxic carcinogenic chemicals. The Ito Liver Model is an 8-week bioassay system that uses the number and size of foci of hepatocytes positive for glutathione S-transferase placental form (GST-P) as the end-point marker. One hundred fifty-nine compounds were tested using the Ito Liver Model: 61 of 66 hepatocarcinogens tested positive, and 10 of 43 nonliver carcinogens were also positive. The false-positive detection of noncarcinogens was low; a single false-positive result was obtained from the 50 noncarcinogens tested. Since more than half of all known carcinogens are hepatocarcinogens in rodents, the initial 8-week bioassay is able to detect most carcinogens. The Ito Multi-organ Model is a 28-week bioassay system for the detection of carcinogens that were not identified by the Ito Liver Model. Results are evaluated by preneoplastic and neoplastic lesions in major organs. Forty-four compounds were tested using the Ito Multi-organ Model: 17 out of 17 liver carcinogens were positive, and 19 out of 22 (86%) nonliver carcinogens were positive. None of the 5 noncarcinogens tested positive.

Keywords: medium-term bioassay; carcinogens; liver GST-P; multi-organ.

INTRODUCTION

Identification and control of carcinogens in the environment are of prime importance to reduce cancer risk in humans. Long-term chronic administration assays for the detection of carcinogenicity and toxicity using rodents have been the standard for the evaluation of the carcinogenic potential of chemicals. The requirements call for testing in two rodent species, usually rats and mice, of each sex, at three dose levels (zero, low, middle, and high) of the test compound for 2 years.

Although this standard has long been used worldwide, 2-year carcinogenicity studies are too costly to test all the chemicals being introduced into the environment. Furthermore, there is political pressure to decrease the number of animals used for carcinogenicity testing because of animal welfare considerations (Ashby and Tennant 1991). A guideline proposed by the International Conference on Harmonization (ICH) recommends reducing long-term protocols by utilizing only one rodent species and replacing the second long-term rodent assay with an alternative bioassay (ICH Steering Committee 1997).

It is known that mutagenicity does not always correlate with carcinogenicity, and there are a variety of chemicals in use, typically represented by pesticides and herbicides, that are not mutagenic but are carcinogenic. A whole-body animal study is the only method to test the carcinogenic potential of a nongenotoxic chemical. Therefore, any alternative bioassay must be an *in vivo*, whole-body assay. Our laboratories have focused

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on the development of a rapid *in vivo* bioassay system able to detect both genotoxic and nongenotoxic carcinogens.

Since more than half of all known carcinogens are hepatocarcinogens in rodents, we initially focused on establishment of a medium-term liver bioassay system. We developed an 8-week rat liver bioassay, known as the Ito Liver Model, which is able to detect rat hepatocarcinogens with a high degree of accuracy (Shirai, Hirose, and Ito 1999). This protocol is cited in the sixth edition of *Casarett and Doull's TOXICOLOGY* as a potential alternative bioassay (Pitot and Dragan 2001). In addition, we developed a 28-week model, known as the as Ito Multi-organ Model, to detect carcinogens that are not identified by the Ito liver model.

Using the Ito Liver Model in conjunction with the Ito Multi-organ Model, most carcinogens can be identified after 8 weeks, and the remaining carcinogens can be identified after an additional 28 weeks. In the present review, the Ito Liver Model and the Ito Multi-organ Model are briefly described.

BACKGROUND

In 1976, Solt and Farber developed a protocol in which foci of liver cells expressing an altered repertoire of enzymes could be induced in rats within 4 weeks (Solt and Farber 1976). Their protocol was based on their observation that in rats treated with diethylnitrosamine (DEN) followed by the hepatocarcinogen 2-acetylaminofluorene (2-AAF), DEN-altered hepatocytes were able to respond to growth stimuli evoked by a two-thirds partial hepatectomy and form distinct foci. In contrast, normal hepatocytes were not able to respond to the growth stimuli because of the toxic effect of 2-AAF. This observation was described as a "selection process" by altered hepatocytes (Solt and Farber 1976). The application of this observation for carcinogen detection was examined by treating rats with test compounds to generate altered hepatocytes followed by feeding with 2-AAF and stimuli to induce hepatocyte proliferation, and the principle of the method was validated: treatment with representative carcinogens resulted in the formation of foci of altered hepatocytes (Tsuda, Lee, and Farber 1980).

In other studies, Peraino and associates reported a two-stage model in which hepatic tumor growth was enhanced by chemicals such as phenobarbital given after initiation with 2-AAF (Peraino et al. 1975, 1977, 1980). Their data suggested that a two-stage approach could be utilized for detection of carcinogenic responses to chemicals: either test compounds could given at the initiation stage followed by appropriate promoting agents or test compounds could be given during the promotion stage after initiation with DEN.

Based on the concepts presented above, we established an assay system to evaluate the hepatocarcinogenicity of chemicals for their promotion potential (Ito et al. 1996, 1997; Ito, Tamano, and Shirai 2003): we used the promotion potential of hepatocarcinogens because almost all carcinogens have a promotion effect when repeatedly administered (Peraino et al. 1975, 1977, 1980). The preneoplastic nature of altered hepatic foci and the usefulness of such lesions as indicators

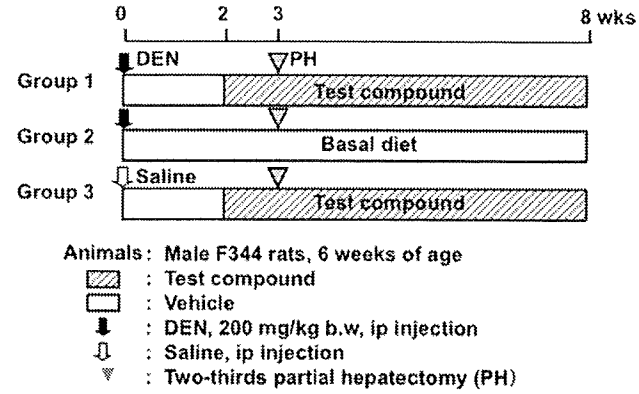

FIGURE 1.—Protocol of Ito Liver Model. Six-week-old male F344 rats are initially given a single intraperitoneal injection of diethylnitrosamine (200 mg/kg) to initiate liver carcinogenesis. Two weeks after initiation, the test compound is administered for 6 weeks. Animals are sacrificed at the end of week 8. All rats are subjected to two-thirds partial hepatectomy on week 3. The end-point marker is glutathione S-transferase placental form-positive (GST-P$^+$) liver cell foci. The numbers and sizes of GST-P$^+$ liver cell foci are analyzed using an image-analyzer and expressed as values per unit liver section (1 cm^2). When values, number, and/or area per unit area of GST-P$^+$ foci are significantly enhanced ($P < .05$) over the control value, a chemical is judged to possess carcinogenic potential for the liver.

of preneoplastic development are now well accepted (Bannasch 1986; Oesterle and Deml 1990; Tatematsu et al. 1977). The phenotypic characteristics of preneoplastic lesions in the liver have been extensively studied, and immunohistochemical staining for glutathione S-transferase placental form (GST-P) was found to be the best marker for visualization of lesions and their quantitative analysis (Ogiso et al. 1985; Tsuda et al. 2003, 1985).

ASSAY PROTOCOL AND RESULTS

Ito Liver Model

Figure 1 shows the protocol employed in Ito's laboratory as a medium-term liver bioassay model. Male F344 male rats, 5 weeks old, are divided into three groups consisting of 15-20 animals each. Group 1 is given a single intraperitoneal injection of DEN, 200 mg/kg b.w., dissolved in saline to initiate hepatocarcinogenesis. After 2 weeks, the rats receive a test compound mixed in the basal diet or drinking water or by repeated intraperitoneal, subcutaneous or intravenous injections. The rats are subjected to two-thirds partial hepatectomy (PH) at the end of week 3. Group 2 is given DEN and PH in the same manner as for group 1, but without administration of the test compound. Group 3 is injected with saline instead of DEN and then subjected to administration of the test compound and PH as in groups 1 and 2 (Figure 1). All animals are sacrificed at the end of week 8. The liver tissues, 3-4 slices from the cranial and caudal lobes of the right lateral lobe and caudal and/or cranial part of the caudal lobe, are excised and fixed in ice-cold acetone or 4% paraformaldehyde solution in phosphate buffer

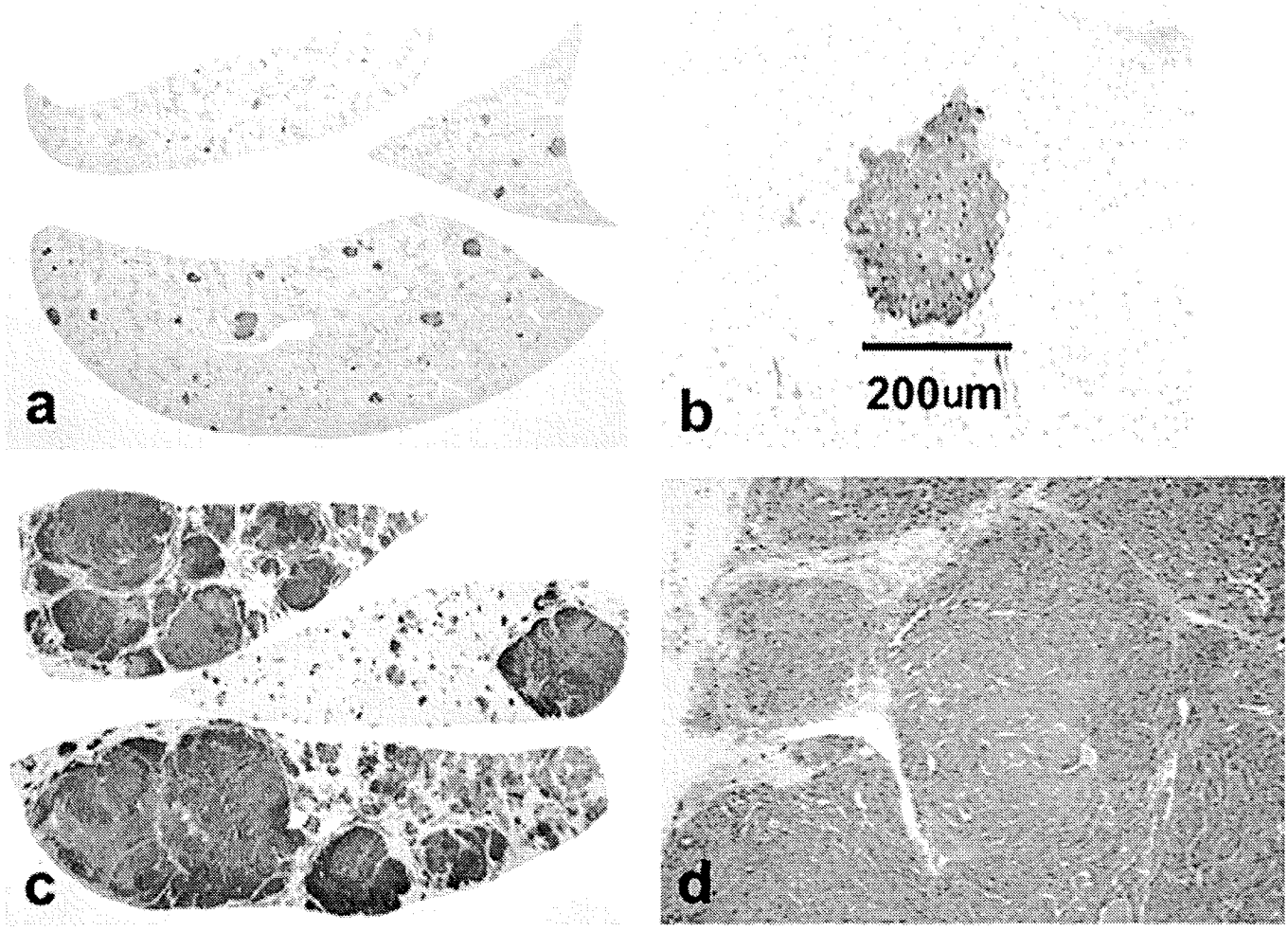

FIGURE 2.—GST-P-positive liver cell foci. Three to 4 slices from paraffin embedded liver (left) are immunostained with GST-P antibody. Lesions greater than 200μm (right) in diameter are included for counting. GST-P is consistently expressed from small foci to adenomas and hepatocellular carcinomas.

at pH. 7.4 for subsequent paraffin embedding and immunohistochemical demonstration of GST-P-positive foci. Numbers and areas of GST-P-positive foci more than 0.2 mm^2 in mean diameter are included for measuring by an image processor. The results are assessed by comparing the values between group 1 (DEN-test compounds) and group 2 (DEN alone). Group 3 serves to assay the potential of the test chemicals to induce GST-P-positive foci without prior DEN exposure. Statistical analysis of differences between means is carried out using Student's or Welch's *t*-tests after application of a preliminary *F*-test for equal variance, and scoring of carcinogenicity, promotion, or inhibition is made on the basis of differences in *P*-values between groups; positive = increase at $P < .05$ in either number or area of foci.

Until the protocol was finalized, the following were extensively investigated to maximize the predictive potential of the model (Hasegawa and Ito 1992; Ito et al. 1997, 1992; Shirai 1997; Shirai, Hirose, and Ito 1999):

1. use of PH as a tool for induction of hepatocyte proliferation,
2. the most suitable end-point marker enzyme,
3. whether results with GST-P-positive foci can predict carcinoma development in a dose dependent manner, and
4. specificity of the protocol for detection of carcinogens.

Since PH was introduced by Higgins and Anderson in 1931 (Higginson and Anderson 1931), it has been extensively employed for investigation of cell proliferation and regeneration. After two-thirds PH, the rodent liver recovers quickly and returns to near preoperative weight within 1 week with peak DNA synthesis at about 24 h; induction of hepatocyte growth factor appears to be one mechanism by which the liver recovers from PH (Matsumoto and Nakamura 1992). Use of hepatotoxins such as carbon tetrachloride (CCl_4) or D-galactosamine is

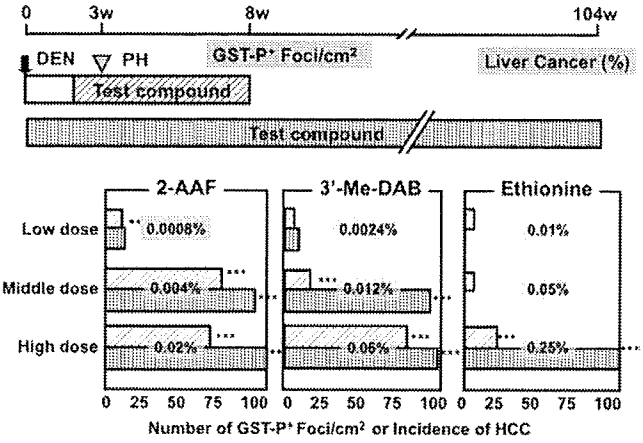

FIGURE 3.—Comparison of GST-P-positive foci and carcinoma. Results obtained from the Ito Liver Model and long-term 2-year studies are shown. Different doses of three representative hepatocarcinogens—2-acetylaminofluorene, 3'-methy-4-diaminoazobenzene, and ethionine—were administered. A clear correlation between GST-P-positive foci and the incidence of hepatocellular carcinomas can be seen. (a) A low magnification view of a slide from a rat treated with phenobarbital (0.05%, in the diet). (b) Smallest focus included for counting purposes. (c) A low-magnification view of a slide from a rat treated with 2-AAF (0.02%, in the diet). (d) Higher-magnification view of hepatocellular carcinoma: the carcinoma is clearly positive for GST-P.

TABLE 1.—Results for 159 Compounds in the Ito's Test

	No. of Positive Compounds/Examined (%)			
	Mutagenicity (Ames test)			
Test Compounds	Positive	Negative	Unknown	Total
Liver carcinogen	31/32(97)[a]	29/33(88)[b]	1/1(100)	61/66(92)
Non-liver carcinogen	7/26(27)	2/15(13)	1/2(50)	10/43(23)[d]
Not carcinogenic	0/6(0)	1/42(2)	0/2(0)	1/50(2)

[a] 4,4-Diaminodiphenylmethane gave negative results
[b] Four chemicals, Clofibrate, Di(2-ethylhexyl)adipate, Di(2-ethylhexyl)phthalate, Trichloroacetic acid, gave negative result.

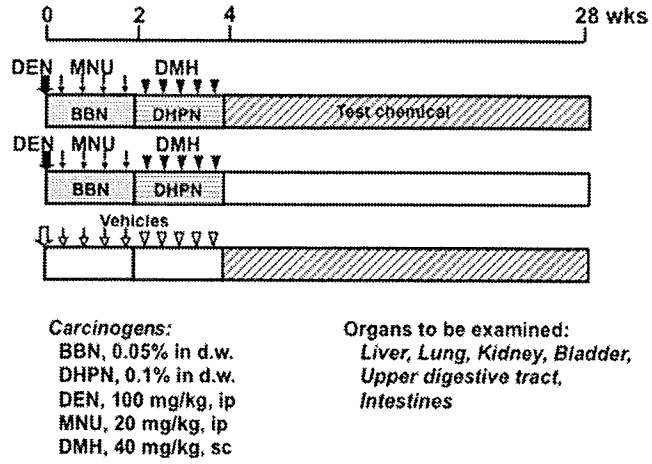

FIGURE 4.—Protocol of The Ito Multi-organ Model (DMBDD Model). Six-week-old F344 male rats are given i.p. injections of diethylnitrosamine (DEN, 100 mg/kg body wt.) and N-methylnitrosourea (MNU, 20 mg/kg body wt), s.c. injections of 1,2-dimethylhydrazine (DMH, 40 mg/kg body wt.), and 0.05% N-butyl-N-(4-hydroxybutyl)nitrosamine (BBN) and 0.1% 2,2'-dihydroxy-di-n-propylnitrosamine (DHPN), both in the drinking water, for a total initiation period of 4 weeks (DMBDD treatment). The test compound is then administered for the following 24 weeks. The rats are sacrificed at the end of week 28. The liver, lung, thyroid, kidney, bladder, upper digestive tract (esophagus and forestomach), and intestines are examined for preneoplastic and neoplastic lesions and compared with the control rats.

an alternative method to induce liver cell proliferation. However, neither of these agents stimulates cell proliferation equivalent to PH in our system because induction of cells to enter S-phase of the cell cycle by these chemicals is sluggish (data not shown).

We have not yet elucidated the role of cell proliferation induced by PH at week 3 in the appearance of liver cell foci. It is possible that a majority of carcinogens are toxic to hepatocytes, causing retardation of the compensatory regenerative response to PH by noninitiated hepatocytes, allowing focal expansion of initiated hepatocytes. In this regard, it is known that initiated cells reduce phase I CYP enzyme expression and increase phase II enzyme expression (Liu et al. 2005; Tsuda et al. 1996), and this altered enzyme expression enables them to escape the effects of toxic compounds.

The expression of several different enzymes is altered in liver preneoplastic lesions (Ogawa et al. 1982; Tsuda et al. 1992). We compared the use of a variety of enzyme markers to visualize liver lesions (Tsuda et al. 2003, 1984). GST-P was found to be the most appropriate for practical use and is expressed continuously from the early lesion to the appearance of hepatocellular carcinoma (Kitahara et al. 1984; Tsuda et al. 1996, 2003).

Several studies have shown the validity of using GST-P-positive foci as a surrogate end-point in predicting carcinogenic potential (Ogawa et al. 1982; Tatematsu et al. 1985; Tsuda et al. 1984, 1988). One of these studies is shown in Figure 3. There was a clear correlation between GST-P-positive foci and incidence of hepatocellular carcinomas after administration of different doses of the well-known hepatocarcinogens 2-acetylaminofluorene, 3'-methy-4-diaminoazobenzene, and ethionine (Hagiwara et al. 1993).

A total of 159 compounds were examined using the Ito Liver Model. They are classified into three categories (Table 1): (1) hepatocarcinogens; (2) carcinogens targeting organs other than the liver (nonhepatocarcinogens); and (3) compounds negative for carcinogenicity in 2-year tests in rats and mice (noncarcinogens). The compounds can also be divided into three categories according to their reported mutagenicity: mutagenic compounds, nonmutagenic compounds, and compounds with unknown mutagenic potential. Comparisons of the results obtained using the Ito Liver Model and reported *Salmonella* mutagenicity and long-term carcinogenicity testing are summarized in Table 1. It is especially noteworthy that the Ito Liver Model identified

TABLE 2.—Results of 44 Compounds in the Medium-term Multi-organ Carcinogenesis Bioassay (DMD/DMBDD Model)

	Positive Compounds/Examined (%)			
	Mutagenicity (Ames test)			
Test compounds	Positive	Negative	Unknown	Total
Liver carcinogen	12/12(100)	5/5(100)	0/0(0)	17/17(100)
Non-liver carcinogen	10/11(91)[a]	8/10(80)[b]	1/1(100)	19/22(86)
Not carcinogenic	0/1(0)	0/4(0)	0/0(0)	0/5(0)

[a] One negative compound is Benzo[a]pyrene
[b] Two negative compounds are Sesamol and Daminozide

59 of 64 (92%) liver carcinogens, irrespective of their mutagenicity, leaving only 5 false-negatives; 30 out of 31 (97%) mutagenic and 29 out of 33 (88%) nonmutagenic hepatocarcinogens were identified. Three out of the 4 nonmutagenic carcinogens that gave false-negative results were carcinogenic peroxisome proliferators, known to suppress GST-P expression. It is noteworthy that the false-positive and false-negative rates are 2.1% and 3.1%, respectively. It was also noted that many chemicals positive in the Ito Liver Model were hepatotoxins (Ward et al. 1989). These results clearly demonstrate that this medium-term liver bioassay is excellent for detection of liver carcinogens (Ito, Tamano, and Shirai 2003; Shirai 1997).

A formula for the validity of carcinogen screening tests is described by Cooper, Saracci, and Cole (1979). This formula evaluates five categories: sensitivity, specificity, predictive value (positive predictivity), false-positive rate, and false-negative rate of the screening test. When the Ito Liver Model was evaluated, all five categories demonstrated excellent values (Shirai, Hirose, and Ito 1999). The Ito Liver Model was accepted as an alternative protocol to replace one of the 2-year chronic administration assays at the Fourth International Conference on Harmonization (ICH Steering Committee 1997).

Ito Multi-organ Model (DMBDD Model)

The Ito Multi-organ Model was developed for the detection of carcinogens not identified by the Ito Liver Model. F344 male rats are given i.p. injections of diethylnitrosamine (DEN, 100 mg/kg body wt.) and N-methylnitrosourea (MNU, 20 mg/kg body wt), s.c. injections of 1,2-dimethylhydrazine (DMH, 40 mg/kg body wt.), and 0.05% N-butyl-N-(4- hydroxybutyl)nitrosamine (BBN) and 0.1% 2,2'-dihydroxy-di-n-propylnitrosamine (DHPN), both in the drinking water, for a total initiation period of 4 weeks (DMBDD treatment) (Akagi et al. 1995; Ito et al. 1996). Then rats are given the test compound in the diet or drinking water or by injection for the following 24 weeks. The animals are sacrificed at the end of week 28. The organs targeted by the 5 different carcinogens—the liver, lung, thyroid, kidney, bladder, upper digestive tract (esophagus and forestomach), and intestines—are histologically examined for preneoplastic and neoplastic lesion development (Fukushima et al. 1991; Ito et al. 1996).

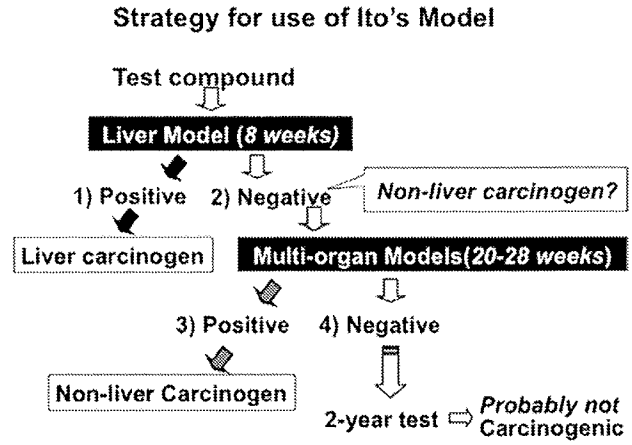

FIGURE 5.—Strategy for the Use of Ito's Model. (1) Positive compound in the liver model: is a liver carcinogen. (2) Negative compound in the liver model: test using the multi-organ model. (3) Positive compound in the multi-organ model: is a carcinogen. (4) Negative in both the liver and multi-organ models: is probably not carcinogenic.

A total of 44 compounds were examined using the Ito Multi-organ Model. A summary of the results is presented in Table 2. All 17 liver carcinogens tested positive, including peroxisome proliferators, and 19 of 22 nonliver carcinogens (86%) tested positive. The Ito Multi-organ Model was able to identify carcinogens irrespective of their mutagenicity; 22 of 23 mutagenic carcinogens and 13 of 15 nonmutagenic carcinogens were identified (Table 2).

The medium-term bioassay described here is a rapid, reliable, and practical tool for the prediction of the carcinogenic potential of chemicals. The strategy for the use of the Ito Model is presented in Figure 5.

1. Positive in liver model: carcinogen.
2. Negative in liver model: apply the multi-organ model.
3. Positive in the multi-organ model: carcinogen.
4. Negative in both the liver and multi-organ models: probably not carcinogenic.

The system is now internationally well recognized and recommended as an alternative carcinogenicity test.

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Involvement of macrophage inflammatory protein 1α (MIP1α) in promotion of rat lung and mammary carcinogenic activity of nanoscale titanium dioxide particles administered by intra-pulmonary spraying

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Titanium dioxide (TiO_2) is evaluated by World Health Organization/International Agency for Research on Cancer as a Group 2B carcinogen. The present study was conducted to detect carcinogenic activity of nanoscale TiO_2 administered by a novel intrapulmonary spraying (IPS)-initiation–promotion protocol in the rat lung. Female human c-Ha-*ras* proto-oncogene transgenic rat (H*ras*128) transgenic rats were treated first with *N*-nitrosobis(2-hydroxypropyl)amine (DHPN) in the drinking water and then with TiO_2 (rutile type, mean diameter 20 nm, without coating) by IPS. TiO_2 treatment significantly increased the multiplicity of DHPN-induced alveolar cell hyperplasias and adenomas in the lung, and the multiplicity of mammary adenocarcinomas, confirming the effectiveness of the IPS-initiation–promotion protocol. TiO_2 aggregates were localized exclusively in alveolar macrophages and had a mean diameter of 107.4 nm. To investigate the underlying mechanism of its carcinogenic effects, TiO_2 was administered to wild-type rats by IPS five times over 9 days. TiO_2 treatment significantly increased 8-hydroxydeoxy guanosine level, superoxide dismutase activity and macrophage inflammatory protein 1α (MIP1α) expression in the lung. MIP1α, detected in the cytoplasm of TiO_2-laden alveolar macrophages *in vivo* and in the media of rat primary alveolar macrophages treated with TiO_2 *in vitro*, enhanced proliferation of human lung cancer cells. Furthermore, MIP1α, also detected in the sera and mammary adenocarcinomas of TiO_2-treated H*ras*128 rats, enhanced proliferation of rat mammary carcinoma cells. These data indicate that secreted MIP1α from TiO_2-laden alveolar macrophages can cause cell proliferation in the alveoli and mammary gland and suggest that TiO_2 tumor promotion is mediated by MIP1α acting locally in the alveoli and distantly in the mammary gland after transport via the circulation.

Introduction

Inhalation of particles and fiber is well known to be strongly associated with increased lung cancer risk in the workplace (1,2). Although the size of fiber particles was reported to be closely related to risk (3), the precise role of particles and fibers in lung cancer induction has not yet been elucidated.

Titanium dioxide (TiO_2) particles of various sizes are manufactured worldwide in large quantities and are used in a wide range of applications. TiO_2 particles have long been considered to pose little risk to respiratory health because they are chemically and thermally stable. However, TiO_2 is classified as a Group 2B carcinogen, a possible carcinogen to humans, by World Health Organization/International Agency for Research on Cancer based on the findings of lung tumor induction in female rats (3,4). This overall evaluation includes nanoscale (<100 nm in diameter) and larger sized classes of TiO_2. At present, the mechanism underlying the development of rat lung tumors by inhalation of TiO_2 particles is unclear.

Inhalation of TiO_2 particles can occur both at the workplace, e.g. in manufacturing and packing sites, and also outside the workplace during their use (5–7). Exposure to airborne nanoparticles has been reported to be associated with a granulomatous inflammatory response in the lung (8). Inhalation studies of nanoparticles for cancer risk assessment is urgently needed, however, due to the high cost of long-term studies, available data is severely limited (9,10). The aim of this study is to understand the mechanism underlying rat lung carcinogenesis induced by inhalation of TiO_2 particles. We choose intrapulmonary spraying (IPS) because it does not require costly facilities, allows accurate dose control and approximates long-term inhalation studies (3,11).

We initially examined whether TiO_2 particles have carcinogenic activity in the rat lung using a novel IPS-initiation–promotion protocol (12,13). For these experiments, Sprague–Dawley (SD)-derived female human c-Ha-*ras* proto-oncogene transgenic rat (H*ras*128) transgenic rats, which are known to have the same carcinogen susceptibility phenotype in the lung as wild-type rats but are highly susceptible to mammary tumor induction (14–16), were treated with *N*-nitrosobis(2-hydroxypropyl)amine (DHPN) to initiate carcinogenesis and then treated with TiO_2 by IPS. We observed a promotion effect of TiO_2 particles in lung and mammary gland carcinogenesis.

To identify factors involved in this promotion effect, wild-type SD strain rats were treated with TiO_2 by IPS for 9 days. We found macrophage inflammatory protein 1α (MIP1α) was produced by TiO_2-laden alveolar macrophages in the lungs of rats treated with TiO_2. MIP1α is a member of the CC chemokine family and is primarily associated with cell adhesion and migration of multiple myeloma cells (17). It is reported to be produced by macrophages in response to a variety of inflammatory stimuli including TiO_2 (18). In the present study, MIP1α, detected in the medium of rat primary alveolar macrophages treated with TiO_2, enhanced proliferation of human lung cancer cells *in vitro*. MIP1α was also detected in the sera and mammary adenocarcinomas of TiO_2-treated H*ras*128 rats and enhanced proliferation of rat mammary carcinoma cells.

Materials and methods

Animals

Female transgenic rats carrying the H*ras*128 and female wild-type SD rats were obtained from CLEA Japan Co., Ltd (Tokyo, Japan) (15). The animals were housed in the animal center of Nagoya City University Medical School, maintained on a 12 h light–dark cycle and received Oriental MF basal diet (Oriental Yeast Co., Tokyo, Japan) and water *ad libitum*. The research was conducted according to the Guidelines for the Care and Use of Laboratory Animals of

Abbreviations: CCR1, C-C chemokine receptor type 1; DHPN, *N*-nitrosobis (2-hydroxypropyl) amine; ERK, extracellular signal-regulated kinase; GRO, growth-regulated oncogene; H*ras*128 rat, human c-Ha-*ras* proto-oncogene transgenic rat; IL, interleukin; IPS, intrapulmonary spraying; MEK1, MAPK/ERK kinase1; MIP1α, macrophage inflammatory protein 1α; 8-OHdG, 8-hydroxydeoxy guanosine; PBS, phosphate-buffered saline; ROS, reactive oxygen species; SD, Sprague–Dawley; SOD, superoxide dismutase; TEM, transmission electron microscopy; TiO_2, titanium dioxide.

Nagoya City University Medical School and the experimental protocol was approved by the Institutional Animal Care and Use Committee (H17-28).

Preparation of TiO_2 and IPS

TiO_2 particles (rutile type, without coating; with a mean primary size of 20 nm) were provided by Japan Cosmetic Association, Tokyo, Japan. TiO_2 particles were suspended in saline at 250 μg/ml or 500 μg/ml. The suspension was autoclaved and then sonicated for 20 min just before use. The TiO_2 suspension was intratracheally administered to animals under isoflurane anesthesia using a Microsprayer (Series IA-1B Intratracheal Aerosolizer, Penn-Century, Philadelphia, PA) connected to a 1 ml syringe; the nozzle of the sprayer was inserted into the trachea through the larynx and a total of 0.5 ml suspension was sprayed into the lungs synchronizing with spontaneous respiratory inhalation (IPS).

IPS-initiation–promotion protocol

Thirty-three female H*ras*128 rats aged 6 weeks were given 0.2% DHPN, (Wako Chemicals Co., Ltd Osaka, Japan) in the drinking water for 2 weeks and 9 rats were given drinking water without DHPN. Two weeks later, the rats were divided into four groups, DHPN alone (Group 1), DHPN followed by 250 μg/ml TiO_2 (Group 2), DHPN followed by 500 μg/ml TiO_2 (Group 3) and 500 μg/ml TiO_2 without DHPN (Group 4). The TiO_2 particle preparations were administered by IPS once every 2 weeks from the end of week 4 to week 16 (a total of seven times). The total amount of TiO_2 administered to Groups 1, 2, 3 and 4 were 0, 0.875, 1.75 and 1.75 mg per rat, respectively. Three days after the last treatment, animals were killed and the organs (brain, lung, liver, spleen, kidney, mammary gland, ovaries, uterus and neck lymph nodes) were excised and divided into two pieces; one piece was immediately frozen at −80°C and used for quantitative measurement of elemental titanium, and the other piece was fixed in 4% paraformaldehyde solution in phosphate-buffered saline (PBS) buffer adjusted to pH 7.3 and processed for light microscopic examination and transmission electron microscopy (TEM); the left lungs and inguinal mammary glands were used for elemental titanium analysis and the right lungs and inguinal mammary glands were used for microscopic examination.

IPS 9 day protocol

Twenty female SD rats (wild-type counterpart of H*ras*128) aged 10 weeks were treated by IPS with 0.5 ml suspension of 500 μg/ml TiO_2 particles in saline five times over a 9 day period (Figure 2A). The total amount of TiO_2 administered was 1.25 mg per rat. Six hours after the last dose, animals were killed and the lungs and inguinal mammary glands were excised. Fatty tissue surrounding the mammary gland was removed as much as possible. The left lungs and inguinal mammary glands were used for biochemical analysis, and the right lungs were fixed in 4% paraformaldehyde solution in PBS adjusted at pH 7.3 and processed for histopathological examination and immunohistochemistry.

Light microscopic and TEM observation of TiO_2 particles in the lung

Paraffin blocks were deparaffinized and embedded in epon resin and processed for TiO_2 particle observation and titanium element analysis, using a JEM-1010 transmission electron microscope (JEOL Co. Ltd, Tokyo, Japan) equipped with an X-ray microanalyzer (EDAX, Tokyo, Japan). Size analysis of TiO_2 particles was performed using TEM photos by an image analyzer system, (IPAP, Sumika Technos Corporation, Osaka, Japan). A total of 452 particles from alveolar macrophages from rats in Group 3 (DHPN followed by 500 μg/ml TiO_2) of the IPS-initiation–promotion study and a total of 2571 particles from alveolar macrophages from rats in the IPS 9 day study were measured.

Biochemical element analysis of titanium

For the detection of elemental titanium, frozen tissue samples of 50–100 mg were digested with 5 ml concentrated HNO_3 for 22 min in a microwave oven. Titanium in the digested solutions was determined by inductively coupled plasma–mass spectrometry (HP-4500, Hewlett-Packard Co., Houston, TX) under the following conditions: RF power, 1450 W; RF refraction current, 5 W; Plasma gas current, 15 l/min; Carrier gas current, 0.91 l/min; Peri pump, 0.2 r.p.s.; Monitoring mass-m/z 48 (Ti); Integrating interval, 0.1 s; Sampling period 0.31 s.

Analysis of superoxide dismutase activity, 8-hydroxydeoxy guanosine and cytokine levels

For the analysis of superoxide dismutase (SOD) activity, 8-hydroxydeoxy guanosine (8-OHdG) and cytokine levels, animals exposed to TiO_2 particles for 9 days were used. For 8-OHdG levels, genomic DNA was isolated from the left lung and inguinal mammary gland with a DNA Extractor WB Kit (Wako Chemicals Co. Ltd). 8-OHdG levels were determined with an 8-OHdG ELISA Check Kit (Japan Institute for the Control of Aging, Shizuoka, Japan) and by a custom service (OHG Institute Co., Ltd, Fukuoka, Japan). For the analysis of SOD activity and inflammation-related cytokines, tissue from the left lung and inguinal mammary glands was excised and rinsed with cold PBS three times and homogenized in 1 ml of T-PER, Tissue Protein Extraction Reagent (Pierce, Rockford, IL), containing 1% (vol/vol) proteinase inhibitor cocktail (Sigma–Aldrich, St Louis, MO). The homogenates were clarified by centrifugation at 10 000*g* for 5 min at 4°C. Protein content was measured using a BCA™ Protein Assay Kit (Pierce). SOD activity was determined using an SOD Assay Kit (Cayman Chemical Co., Ann Arbor, MI). The levels of interleukin (IL)-1α, IL-1β, IL-6, granulocyte-macrophage colony-stimulating factor, granulocyte colony-stimulating factor, tumor necrosis factor α, interferon γ, IL-18, monocyte chemotactic protein 1 and MIP1α, growth-regulated oncogene (GRO) and vascular endothelial growth factor were measured by Multiplex Suspension array (GeneticLab Co., Ltd, Sapporo, Japan).

Immunohistochemistry

CD68 and MIP1α were detected using anti-rat CD68 (BMA Biomedicals, Augst, Switzerland) and anti-rat MIP1α polyclonal antibodies (BioVision, Lyon, France). Both antibodies were diluted 1:100 in blocking solution and applied to slides, and the slides were incubated at 4°C overnight. The slides were then incubated for 1 h with biotinylated species-specific secondary antibodies diluted 1:500 (Vector Laboratories, Burlingame, CA) and visualized using avidin-conjugated alkaline phosphatase complex (ABC kit, Vector Laboratories) and Alkaline Phosphatase Substrate Kit (Vector Laboratories).

Isolation of primary alveolar macrophages and preparation of conditioned media

Wild-type female SD rats were given 0.5 ml 6% thioglycollate medium (Thioglycollate Medium II, Eiken Chemical Co., Ltd, Tokyo, Japan) by IPS on days 1, 3 and 5, and 6 h after the last treatment, the lungs were excised and minced with sterilized scissors in RPMI 1640 containing 10% fetal bovine serum (Wako Chemicals Co., Ltd) and antibiotics. The homogenate was washed twice and plated onto 6 cm dishes and incubated for 2 h at 37°C, 5% CO_2. The dishes were then washed with PBS three times to remove unattached cells and cell debris. Samples of the remaining adherent cells were cultured in chamber slides and immunostained for CD68 to confirm their identity as macrophages; ~98% of the cells were positive for CD68.

Primary alveolar macrophages were treated with vehicle or TiO_2 particles in saline suspension at a final concentration of 100 μg/ml and then incubated for 24 h in a 37°C, 5% CO_2 incubator. The conditioned medium was collected and diluted 5-fold with RPMI 1640; the conditioned medium had a final concentration of 2% fetal bovine serum.

Western blotting

For the detection of MIP1α, aliquots of 20 μg protein from the extracts of lung or mammary tissue were separated by 15% sodium dodecyl sulfate–polyacrylamide gel electrophoresis, transferred to nitrocellulose membranes and immunoblotted. For the detection of C-C chemokine receptor type 1 (CCR1), 10% sodium dodecyl sulfate–polyacrylamide gel electrophoresis was used for the separation. Membranes were probed overnight at 4°C with anti-rat MIP1α polyclonal antibody (BioVision) diluted at 1:100 or anti-CCR1 (Santa Cruz Biotechnology, Santa Cruz, CA) diluted at 1:100. The blots were washed and incubated for 1 h with biotinylated anti-species-specific secondary antibodies (Amersham Biosciences, Piscataway, NJ) and then visualized using ECL Western Blotting Detection Reagent (Amersham Biosciences). To ensure equal protein loading, the blots were striped with Restore Western Blot Stripping Buffer (Pierce) and reprobed with anti-β actin antibody (dilution 1:2000; Sigma–Aldrich) for 1 h at room temperature.

For the detection of serum MIP1α, GRO and IL-6, aliquots of 150 μg of protein from the sera of rats treated with TiO_2 for 16 weeks were subjected to sodium dodecyl sulfate–polyacrylamide gel electrophoresis. Anti-human GRO polyclonal antibody (BioVision) and anti-mouse IL-6 polyclonal antibody (Santa Cruz) were diluted 1:100. For detection of activated extracellular signal-regulated kinase (ERK) 1/2 and total ERK1/2, phospho ERK1/2 antiboby (Cell signaling Technology, Beverly, MA) and ERK1/2 antibody (Upstate, Lake placid, NY) were diluted 1:2000 and 1:25 000, respectively. The conditioned medium from alveolar macrophages, prepared as described above, was also subjected to western blot assay for MIP1α detection as described above. The blots were striped with Restore Western Blot Stripping Buffer (Pierce) and stained with Ponceau S solution (Sigma–Aldrich) for 10 min. The major band at 66 kDa was judged to be albumin and used as an internal control.

In vitro cell proliferation assay

A549 cells, a human lung cancer cell line, and the rat mammary cancer cell line C3 (19), derived from the H*ras*128 transgenic rats, were used in the *in vitro* cell proliferation assays. A549 or C3 cells were seeded into 96-well culture plates at 5×10^3 cells per well in 2% fetal bovine serum Dulbecco's modified Eagle's medium (Wako Chemicals Co., Ltd). After overnight incubation, the cells were treated as noted below, incubated for 72 h and the relative cell number was then determined.

To investigate the effect of culture supernatant from alveolar macrophages on A549 cell proliferation, their media were replaced with diluted conditioned medium, and the cells were incubated for 72 h with 0, 5, 10 and 20 μg/ml of anti-MIP1α neutralizing antibody (R&D Systems, Minneapolis, MN) or with 20 μg/ml of irrelevant IgG. To investigate the effect of recombinant cytokines on A549 cell proliferation, 10, 50 or 100 ng/ml of recombinant protein, rat MIP1α (R&D Systems), human GRO (R&D Systems) or human IL-6 (R&D Systems), was added to A549 cells. To investigate the role of ERK in MIP1α-stimulated cell proliferation, A549 cells, treated with or without 2×10^{-7} M of the specific MAPK/ERK kinase1 (MEK1) inhibitor PD98059 (Cell Signaling Technology) for 10 min, were treated with 50 ng/ml of MIP1α protein. To investigate the effect of reactive oxygen species (ROS) on cell proliferation, A549 cells, with or without pretreatment with 1 mM *N*-acetyl cysteine (Wako Chemicals Co. Ltd) for 30 min, were treated with 0.5 mM H_2O_2 (Wako Chemicals Co. Ltd). To investigate of the effects of MIP1α on rat mammary cells, C3 cells were treated with serially diluted recombinant rat MIP1α (0, 0.4, 2.0, 10 and 50 ng/ml, respectively; R&D Systems). For detecting the direct effect of TiO_2 particles on A549 and C3 cell proliferation, 5×10^3 A549 or C3 cells were cultured overnight and then treated with 10 or 50 μg/ml of TiO_2 particles.

After 72 h incubation, the relative cell number of A549 and C3 was determined using the Cell Counting Kit-8 (Dojindo Molecular Technologies, Rockville, MD) according to the manufacturer's instruction.

Statistical analysis

For *in vivo* data, statistical analysis was performed using the Kruskal–Wallis and Bonferroni–Dunn's multiple comparison tests. *In vitro* data are presented as means ± standard deviations. The statistical significance of *in vitro* findings was analyzed using a two-tailed Student's *t*-test and Bonferroni–Dunn's multiple comparison tests. A value of $P < 0.05$ was considered significant. The Spearman's rank correlation test was used to determine the association between TiO_2 dose and TiO_2 carcinogenic activity.

Results

Promoting effects of TiO_2 particles in DHPN-induced lung and mammary carcinogenesis

Prior to initiation of the IPS-initiation–promotion and IPS 9 day studies, we conducted a preliminary study to confirm whether IPS would be a good tool to deliver TiO_2 particles to the alveoli. Rats were treated by IPS with India ink. We observed that ink particles of ~50 to 500 μm in diameter were diffusely distributed throughout the alveoli space (data not shown), confirming that IPS could deliver TiO_2 particles to the alveoli.

Four groups of female H*ras*128 rats were treated with +/− DHPN to initiate carcinogenesis and then treated with TiO_2 by IPS for 12 weeks: Group 1, DHPN alone; Group 2, DHPN followed by 250 μg/ml TiO_2; Group 3, DHPN followed by 500 μg/ml TiO_2 and Group 4, 500 μg/ml TiO_2 without DHPN. Microscopic observation in the lung showed scattered inflammatory foci, alveolar cell hyperplasia (Figure 1A) and adenomas in the DHPN-treated rats. The multiplicity (numbers per square centimeter lung) of hyperplasias and adenomas in Group 3 (DHPN followed by 500 μg/ml TiO_2) were significantly increased compared with Group 1 (DHPN followed by saline, Table I), and the increase showed a dose-dependent correlation (rho = 0.630, $P = 0.001$ for hyperplasias and rho = 0.592, $P = 0.029$ for adenomas) by the Spearman's rank correlation test. In the mammary gland, TiO_2 treatment significantly increased the multiplicity of adenocarcinomas (Figure 1C) and tended to increase the weight of the mammary tumors (Figure 1C). In the rats, which received TiO_2 treatment without prior DHPN treatment, alveolar proliferative lesions were not observed although slight inflammatory lesions were observed.

TiO_2 was distributed primarily to the lung, but minor amounts of TiO_2 were also found in other organs (supplementary Figure 1A is available at *Carcinogenesis* Online).

Various sizes of TiO_2 aggregates were observed in alveolar macrophages (Figure 1B). The TiO_2-laden macrophages were evenly scattered throughout the lung alveoli. The number of hyperplasias with TiO_2-laden macrophages was dose dependently increased (supplementary Table 1 is available at *Carcinogenesis* Online). This result suggests that TiO_2-laden macrophages may be involved in the promotion of alveolar hyperplasia.

The size distribution of TiO_2 particle aggregate is shown in Figure 1D. Of 452 particle aggregates examined, 362 (80.1%) were nanosize, i.e. <100 nm. Overall, the average size was 84.9 nm and the median size was 44.4 nm.

IPS 9 day study—analysis of TiO_2

Female SD rats were treated with TiO_2 by IPS over a 9 day period (Figure 2A). Microscopic observation showed scattered inflammatory lesions with infiltration of numerous macrophages mixed with a few neutrophils and lymphocytes in TiO_2-treated animals. Overall, the number of macrophages in the alveoli was significantly increased in the TiO_2-treated animals (Figure 2B). As expected from the results of the IPS-initiation–promotion study, alveolar proliferative lesions were not observed (Figure 2C).

Morphologically, TiO_2 particles were observed as yellowish, polygonal bodies in the cytoplasm of cells (Figure 2D). These cells are morphologically distinct from neutrophils and strongly positive for CD68 (Figure 2E), indicating that the TiO_2 engulfing cells were macrophages. TiO_2 aggregates of various sizes were found in macrophages, and aggregates larger than a single macrophage were surrounded by multiple macrophages (supplementary Figure 1B is available at *Carcinogenesis* Online)

TEM also showed electron dense bodies in the cytoplasm of macrophages (Figure 2F and G). These bodies were found exclusively in macrophages and not found in the alveolar parenchyma, including alveolar epithelium and alveolar wall cells, or in any other cell type. The shape of the electron dense TiO_2 particles in the cytoplasm was quite similar to that observed in preparations taken from TiO_2 suspensions before administration (Figure 2H and supplementary Figure 1C and D is available at *Carcinogenesis* Online). Individual TiO_2 particles were rod-like in shape (supplementary Figure 1C is available at *Carcinogenesis* Online).

Element analysis by TEM and X-ray microanalysis indicated that these electron dense bodies were composed primarily of titanium particles (supplementary Figure 1E and F-1 and 1F-2 is available at *Carcinogenesis* Online). Titanium was not observed in the surrounding alveolar cells without electron dense bodies (supplementary Figure 1F-3 is available at *Carcinogenesis* Online). The size distribution of TiO_2 particle aggregates is shown in Figure 2I. Of 2571 particle aggregates examined, 1970 (76.6%) were <100 nm and five particles were >4000 nm in size. Overall, the average size was 107.4 nm and the median size was 48.1 nm.

IPS 9 day study—analysis of oxidative stress and inflammation-related factors in the lungs of wild-type rats

IPS of TiO_2 particles significantly increased SOD activity (Figure 3A) and 8-OHdG levels (Figure 3B) in the lungs of wild-type rats, but not in the mammary glands. Analysis of the expression levels of 12 cytokines using suspension array indicated that administration of TiO_2 particles significantly upregulated the expression of MIP1α, GRO and IL-6 in the lung tissue of wild-type rats (supplementary Table 2 is available at *Carcinogenesis* Online). MIP1α levels were slightly elevated (0.4 pg/mg protein) in the mammary gland (Figure 3C), although the elevation was not statistically significant. Elevation of MIP1α in the lung tissue of animals treated with TiO_2 particles was confirmed by western blotting (Figure 3D).

Immunohistochemically, MIP1α was detected in the cytoplasm of alveolar macrophages with phagocytosed TiO_2 particles (Figure 3E upper, stained in red) and these macrophages could be found in hyperplastic lesions of the lung (supplementary Figure 2A and B is available at *Carcinogenesis* Online). MIP1α was not detected in macrophages without TiO_2 particles (Figure 3E lower). Expression of CCR1, the major receptor of MIP1α, was observed in the lung; IPS of TiO_2 particles had little or no effect on CCR1 expression (supplementary Figure 2C is available at *Carcinogenesis* Online).

Effect of MIP1α on proliferation of a human lung cancer cell line in vitro

Alveolar macrophages were isolated from the lungs of SD rats and were confirmed to be macrophages by morphology and CD68 staining

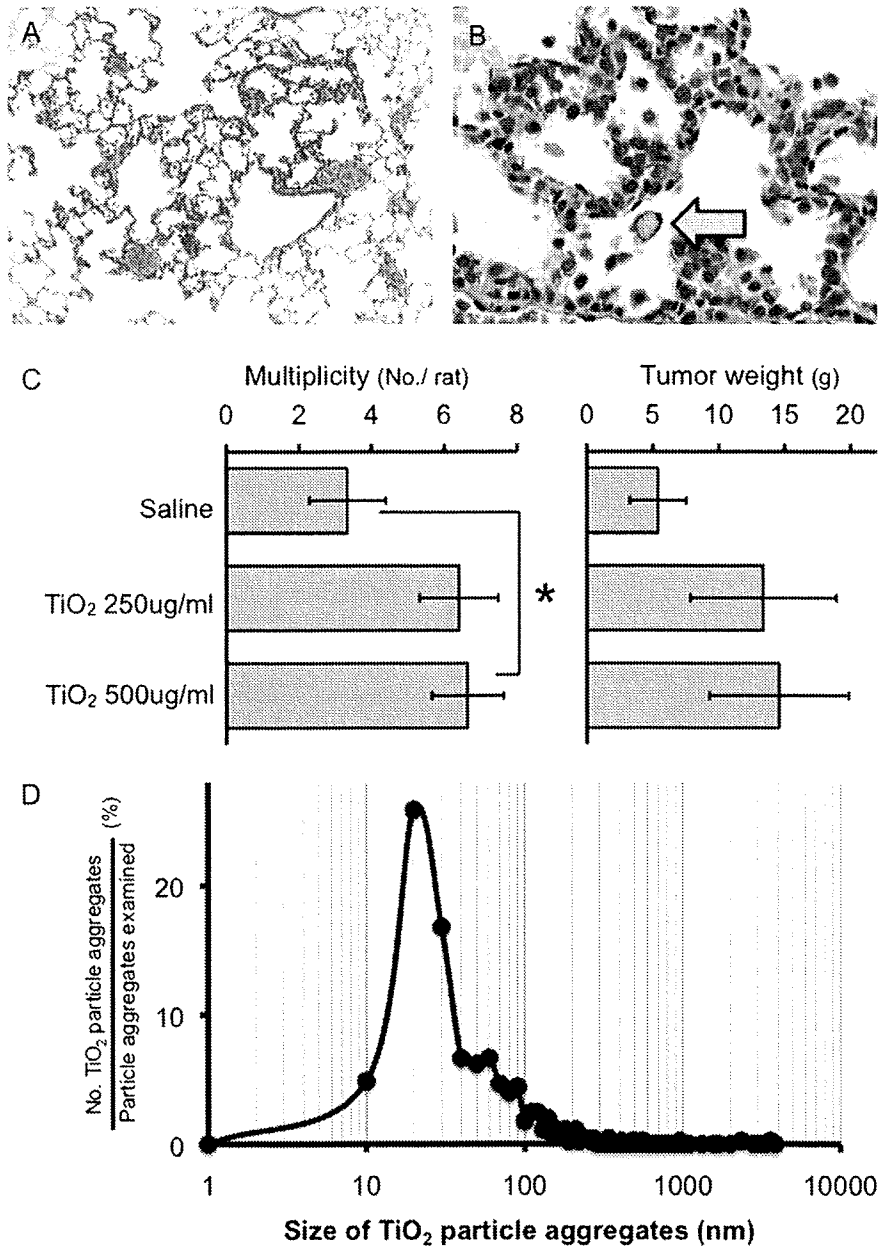

Fig. 1. Promoting effects of TiO_2 particles in DHPN-induced lung and mammary carcinogenesis (**A**) Alveolar hyperplasias observed in the lung of an H*ras*128 rat receiving DHPN and 500 μg/ml TiO_2 particles. (**B**) Alveolar macrophages with TiO_2 particles were also observed in hyperplasia lesions. (**C**) IPS of TiO_2 particles significantly increased the multiplicity of adenocarcinomas in the mammary gland and tended to increase the size of mammary tumors. (**D**) The size distribution of TiO_2 particle aggregates; among 452 particle aggregates examined, 362 (80.1%) were nanosize, i.e. <100 nm in diameter.

(data not shown). The macrophages were treated with TiO_2 particles suspended in saline (Figure 4A). TiO_2 induced secretion of MIP1α into the culture media (Figure 4B), and the culture medium collected from macrophages treated with TiO_2 particles promoted proliferation of A549 cells, whereas culture media collected from unexposed macrophages did not (Figure 4C). MIP1α neutralizing antibodies attenuated the promotion of A549 proliferation in a dose-dependent manner (Figure 4C). MIP1α-induced cell proliferation was also significantly suppressed by the ERK inhibitor PD98059 (Figure 4D). In addition, MIP1α increased ERK phosphorylation and PD98059 diminished ERK phosphorylation (Figure 4E).

We also examined the effect of MIP1α, GRO and IL-6, H_2O_2 and TiO_2 on the proliferation of A549 cells. MIP1α increased cell proliferation in a dose-dependent fashion, but GRO and IL-6 did not (supplementary Figure 3A–C is available at *Carcinogenesis* Online). H_2O_2 significantly suppressed cell proliferation, and antioxidant treatment diminished this suppression. Antioxidant treatment did not affect MIP1α-induced cell proliferation (supplementary Figure 3D is available at *Carcinogenesis* Online). These results suggest that ROS have no effect on tumor cell growth in this experiment.

In addition, TiO_2 did not directly increase proliferation of A549 cell (supplementary Figure 3E is available at *Carcinogenesis* Online).

Mechanism analysis of the promotion of mammary carcinogenesis

MIP1α was markedly elevated in the serum of the H*ras*128 rats treated with TiO_2 particles (Figure 5A). Serum levels of IL-6 were not changed by TiO_2 treatment and GRO was not detected in the serum

Table I. Effect of TiO2 on incidence and multiplicity of DHPN-induced alveolar hyperplasia and adenoma of the lung

Treatment	No. of rats	Alveolar hyperplasia		Lung adenoma	
		Incidence (%)	Multiplicity ## (no./cm^2)	Incidence (%)	Multiplicity # (no./cm^2)
Saline	9	9 (100)	5.91 ± 1.19	0	0
nTiO_2 250 mg/ml	10	10 (100)	7.36 ± 0.97*	1 (10)	0.10 ± 0.10
nTiO_2 500 mg/ml	11	11 (100)	11.05 ± 0.87**	4 (36)	0.46 ± 0.21*

*$P < 0.05$, **$P < 0.001$ versus saline control.
#$P < 0.05$, ##$P < 0.001$ in trend test (Spearman's rank correlation test).

(Figure 5A). MIP1α was slightly elevated in the mammary glands of these animals (Figure 5B); possibly, the elevated MIP1α detected in the mammary tissue was due to contamination by MIP1α in the serum. Recombinant MIP1α promoted the proliferation of C3 cells in a dose-dependent manner; a slight induction could be seen at a dose of 400 pg/ml and became statistically significant at the dose of 50 ng/ml (Figure 5C). Expression of CCR1, the major receptor of MIP1α, was observed in mammary tissue, and as in the lung, IPS of TiO_2 particles had little or no effect on CCR1 expression (data not shown). TiO_2 did not directly increase proliferation of C3 cells (supplementary Figure 3F is available at *Carcinogenesis* Online).

Discussion

To elucidate the mechanism underlying rat lung carcinogenesis by TiO_2 inhalation, we chose IPS. Although this method may be less physiological than the aerosol inhalation system, we observed that agglomerates and aggregates of TiO_2 particles from nano to micro size (mean diameter 107.4 nm) were diffusely distributed throughout the lung including peripheral alveoli, and they did not cause obstruction of the terminal bronchioles. Accordingly, IPS of TiO_2 particles can be expected to act similarly to aerosol inhalation of TiO_2.

Occupational exposure limits for TiO_2 in 13 countries or regions are 5–20 mg/m^3 (20), which results in TiO_2 exposure limits of 0.27–1.07 mg/kg body wt/day; calculations based on the human respiratory volume. In the present study, a total of 1.75 mg was administered per rat for 12 weeks in the high-dose group, resulting in a dose of 0.104 mg/kg body wt/day. Therefore, the dose we used in the present study was lower than the occupational exposure limit.

TiO_2, nanoscale and larger sized is evaluated as a Group 2B carcinogen by World Health Organization/International Agency for Research on Cancer (4) based on 2 year animal aerosol inhalation studies (3). We conducted the present carcinogenesis study using a two-step initiation–promotion protocol as a surrogate for a 2 year long-term protocol. Our study demonstrated that TiO_2 particles increased the multiplicity of alveolar cell hyperplasia and adenoma in the two-step IPS-initiation–promotion protocol. We used these lesions as endpoints in carcinogenicity testing because chemically induced tumors appear to be derived from hyperplasic lesions that progress to adenoma and carcinoma (21).

Several bioassay protocols based on the two-step carcinogenesis theory have been developed as practical and sensitive assays, and the compounds that exhibit promotion activity are considered to be carcinogens (22–29). Thus, our experimental design may be a practical surrogate for the long-term lung carcinogenesis protocol.

It should be noted that proliferative lesions including alveolar cell hyperplasia and adenomas were not found in the groups subjected to TiO_2 particle administration without prior treatment of DHPN. This is due to the weak carcinogenic potential and short duration of exposure to TiO_2 particles. Using the two-step IPS-initiation–promotion protocol, however, we did observe carcinogenic activity by this weak carcinogen. Thus, the two-step IPS-initiation–promotion protocol is an appropriate system to study carcinogenesis of TiO_2 particles and approximates long-term TiO_2 inhalation studies (3,11).

We next conducted a mechanism analysis of TiO_2 particle carcinogenesis focusing on the initial events induced by exposure to TiO_2 particles. Treatment with TiO_2 resulted in a modest infiltration of inflammatory cells into the alveolar space and septal wall, but the primary effect was a marked increase in the number of macrophages in the alveoli, and many of these macrophages contained phagocytosed TiO_2 particles. Alveolar macrophages play an important role in deposition and clearance of mineral fibers/particles, and macrophage activity is known to be strongly associated with inflammatory reactions and carcinogenesis caused by fibers and particles in the lung, including asbestos (30–33). ROS are known to be produced by macrophages upon particle phagocytosis (34,35). Clinical and experimental studies indicate that ROS production and resultant oxidative stress play an important role in cellular and tissue damage, inflammation and fibrosis in the lung. In our study, a significant increase in the activity of SOD and 8-OHdG formation in the lung were observed, indicating increased ROS production and DNA damage. Because macrophages are unable to detoxify TiO_2 particles, the reaction against these particles would be continuous over an extended period of time. This condition is associated with high levels of ROS production (36) and tissue toxicity (37).

Cytokine analysis of the lung tissue indicated that among the 12 cytokines examined, expression of IL-6, GRO and MIP1α were significantly higher in the TiO_2-treated group than in the vehicle group (supplementary Table 1 is available at *Carcinogenesis* Online). IL-6 is a pro-inflammatory cytokine that is involved in host defense as well as cancer development (38,39). IL-6 has been shown to be increased in lung tumor tissue (40,41) and in the sera of lung cancer patients (42). GRO, a member of the CXC chemokine family, has been shown to be involved in inflammatory responses, chemoattraction (43), carcinogenesis (44,45) and tumor progression (46). Thus, IL-6 and GRO may be involved in the promotion of lung carcinogenesis by TiO_2 (47).

Of the three cytokines induced by exposure to TiO_2 particles, however, we were particularly interested in MIP1α. This cytokine was not only induced in the lung tissue of TiO_2-treated rats, but, unlike IL-6 and GRO, it was also found in the serum of these animals. MIP1α is a member of the CC chemokine family and is primarily associated with cell adhesion and migration (17), proliferation and survival of myeloma cells (48). It is produced by macrophages in response to a variety of mineral particle-induced inflammatory stimuli (18). Our results indicate that expression of MIP1α by alveolar macrophages enhances the proliferation of A549 cells. Expression of CCR1, the major receptor of MIP1α, was observed in the lung tissue, rendering lung cells receptive to MIP1α induction of proliferation. Lung damage and inflammation induced by TiO_2 particles has also been reported to be associated with increased cell proliferation of lung epithelium cells (49), which is consistent with our results.

The MEK1–ERK-signaling pathway has been shown to be involved in CCR1 signaling (48). In the present study, the MEK1-specific inhibitor PD98059 suppressed MIP1α-induced cell proliferation and ERK phosphorylation. These results suggest that MEK1 is one of the downstream signaling molecules of MIP1α and the MEK1–ERK-signaling pathway may be partially involved in MIP1α signaling.

It should be noted that, in our IPS-initiation–promotion protocol, TiO_2 exposure also promoted DHPN-initiated mammary carcinogenesis. Our results suggest that MIP1α secreted by alveolar macrophages and transported via the circulatory system caused

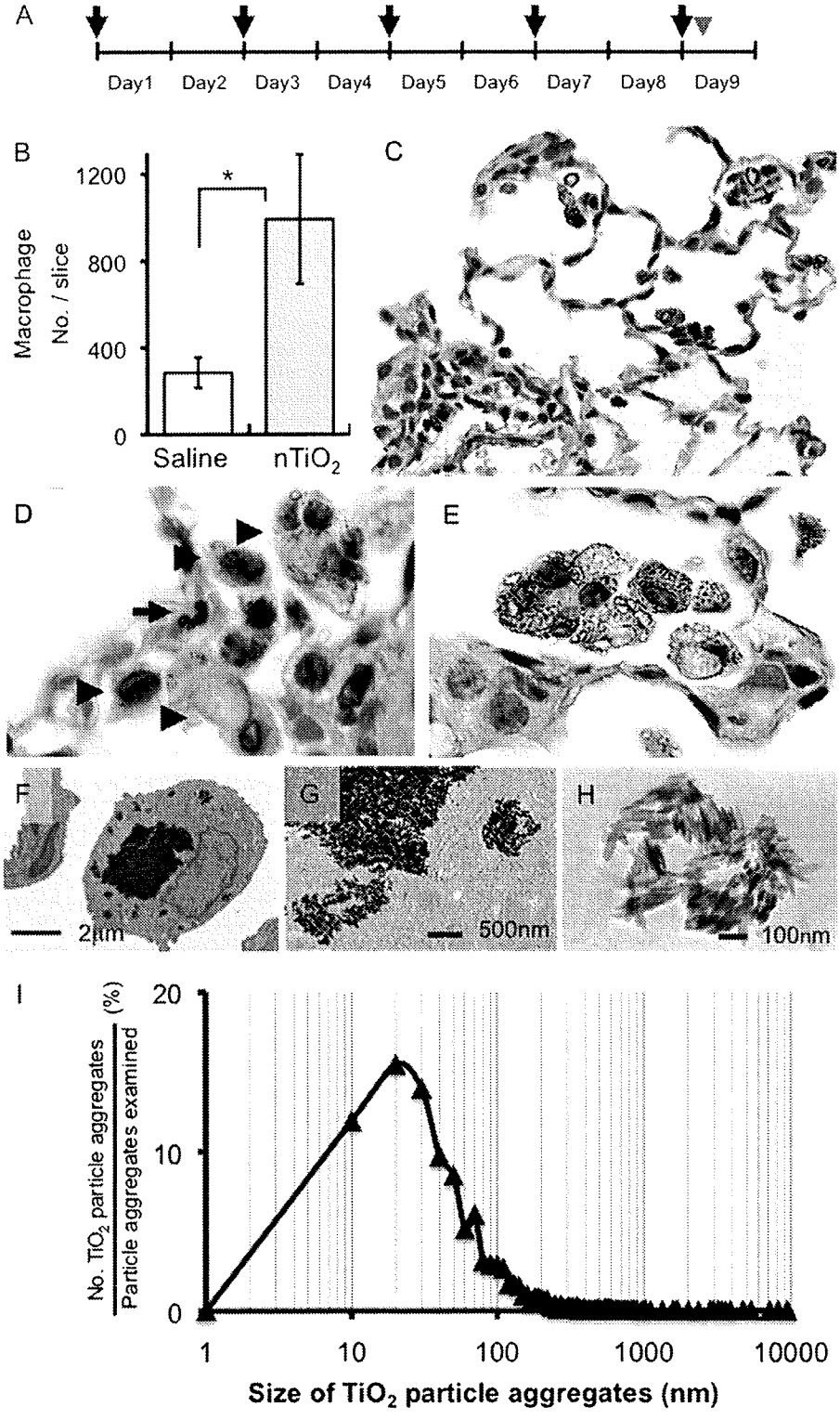

Fig. 2. TiO_2 particles in alveolar macrophages by light and electron microscopy (**A**) Twenty female SD rats (wild-type counterpart of H*ras*128) aged 10 weeks were treated by IPS with 0.5 ml suspension of 500 μg/ml TiO_2 particles in saline five times over a 9 day period. Arrows and arrowhead indicates IPS treatment and killing of the animals, respectively. (**B**) IPS of TiO_2 particles significantly increased the number of macrophages in the alveoli. (**C**) Inflammatory reactions were observed in the lung with slight infiltration of macrophages, neutrophils and lymphocytes. (**D**) TiO_2 particles were observed in alveolar macrophages (hematoxylin and eosin staining). Arrowheads indicate macrophages and the smaller cell indicated by the arrow is a neutrophil with its characteristic multilobular nucleus. (**E**) The multinucleated cells containing these particles were positive for the macrophage marker CD68 (Alkaline phosphatase reaction, red color). (**F**) TEM findings showed that TiO_2 particles of various sizes (~50 nm to 5 μm) were observed phagocytosed by alveolar macrophages. (**G**) Electron dense bodies were aggregates of TiO_2 particles. (**H**) TEM findings of TiO_2 particles in saline suspension before IPS. The shape of the TiO_2 particle aggregates was similar to those observed in macrophages. (**I**) The size distribution of TiO_2 particle aggregates: of 2571 particle aggregates examined, 1970 (77.1%) were <100 nm. The average size was 107.4 nm and the median size was 48.1 nm.

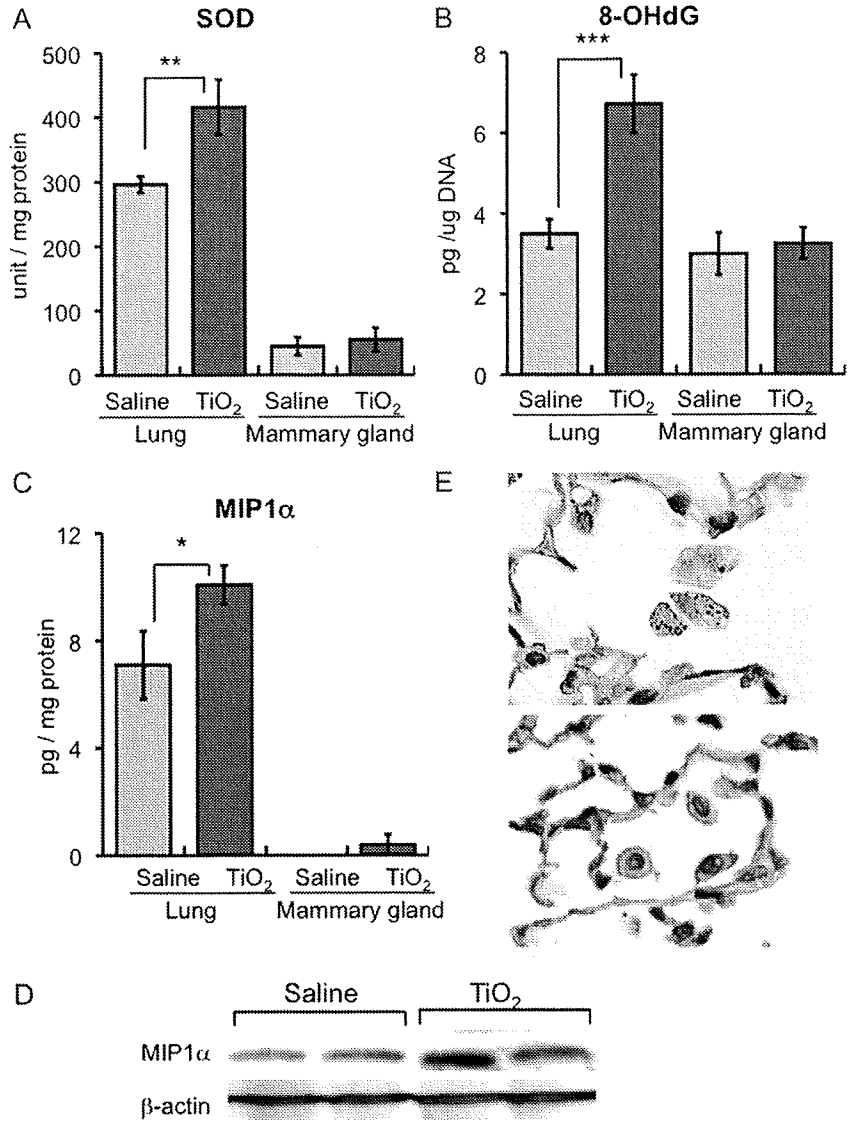

Fig. 3. Inflammatory factors upregulated in the lungs of wild-type rats by IT-spraying of TiO_2 particles in the IPS 9 day study (**A**) SOD activity and (**B**) 8-OHdG level in wild-type rats treated with TiO_2 particles or saline. (**C**) MIP1α protein level was significantly increased (142%) in the lung tissue of wild-type rats treated with TiO_2 (suspension array analysis). MIP1α was detected in the mammary gland of the TiO_2 group but not in the vehicle group. (**D**) In western blotting, expression of MIP1α was increased in the TiO_2 group compared with vehicle group. (**E**) MIP1α was immunohistochemically detected in alveolar macrophages containing TiO_2 particles (upper) but was not detected in macrophages of rats that were not exposed to TiO_2 particles (lower).

proliferation of mammary epithelial cells and thereby promoted mammary carcinogenesis. As with the lung, CCR1 was expressed by mammary cells, rendering these cells receptive to MIP1α induction of proliferation. While MIP1α secreted by alveolar macrophages would be diluted by the blood volume and while these levels may not be high enough to increase mammary cell proliferation in a short *in vitro* proliferation assay, it is possible that continuous low level stimulation over the course of 12 weeks could increase mammary cell proliferation in the environment of the mammary gland *in vivo*. Another possibility is that TiO_2 particles may act directly on the mammary gland after translocation to the mammary gland from the lung. However, TiO_2 exposure of mammary carcinoma cells did not induce proliferation *in vitro*. It must be understood that promotion of DHPN-induced mammary carcinogenesis by TiO_2 particles was observed in H*ras*128 female rats, and these animals are very highly susceptible to mammary carcinogenesis (50). Although, the effects we observed on promotion of mammary carcinogenesis in these animals may not be directly relevant to most humans, people at high risk for mammary carcinogenesis, such as individuals harboring BRCA mutations, may be a relevant population as regards the risk presented by nanoscale TiO_2.

Although our observations are based on results obtained with a mixed population of nanoscale and larger sized particle aggregates, size analysis indicated that 80.1% of them were nanoscale (<100 nm in diameter) in the 16 week IPS-initiation–promotion study and 76.6% were nanoscale in the IPS 9 day study. Thus, the results can be interpreted as being strongly associated with nanoscale particle aggregates.

In conclusion, the IPS-initiation–promotion protocol detected TiO_2 carcinogenic activity in the rat lung and is therefore comparable, at least for TiO_2 inhalation, to a long-term whole body inhalation carcinogenesis study. We also elucidated a plausible mechanism for the carcinogenic effect of TiO_2 particles in the rat lung. Phagocytosis of TiO_2 particles by alveolar macrophages resulted in ROS production and DNA damage and increased expression of MIP1α. MIP1α in turn was able to enhance proliferation of lung epithelium cells. Thus, lung

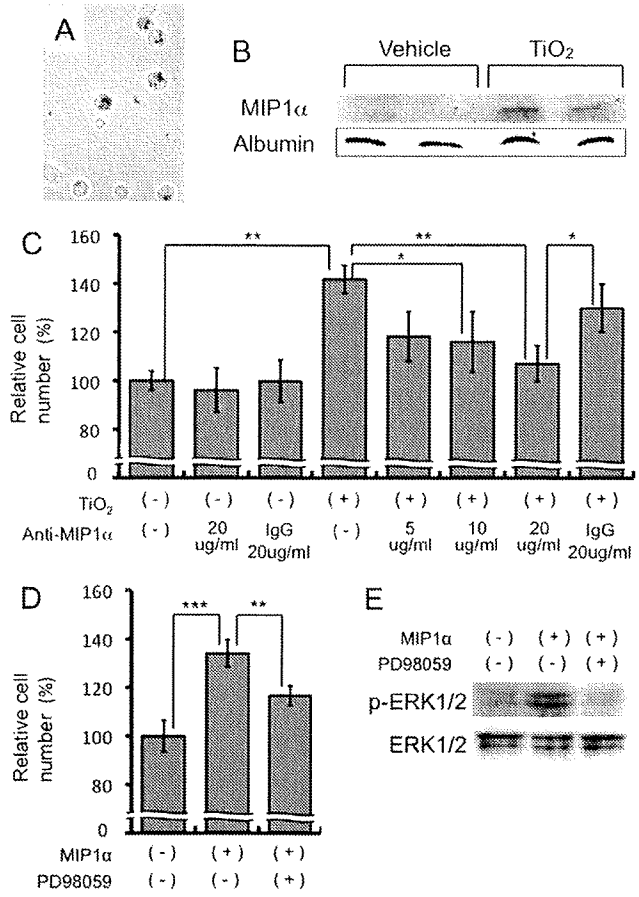

Fig. 4. Growth stimulation effects of conditioned medium from alveolar macrophages on human lung cancer cell lines. (**A**) Primary cultured alveolar macrophages of rats were treated with TiO_2 particles. (**B**) MIP1α was detected in the culture medium. (**C**) The number of A549 cells was significantly increased by addition of conditioned medium from alveolar macrophages treated with TiO_2 particles. MIP1α neutralizing antibody attenuated this effect in a dose-dependent manner. Irrelevant IgG was used as control antibody. (**D**) MIP1α-induced cell proliferation was significantly suppressed by the ERK inhibitor PD98059. (**E**) MIP1α increased ERK phosphorylation and PD98059 diminished this phosphorylation.

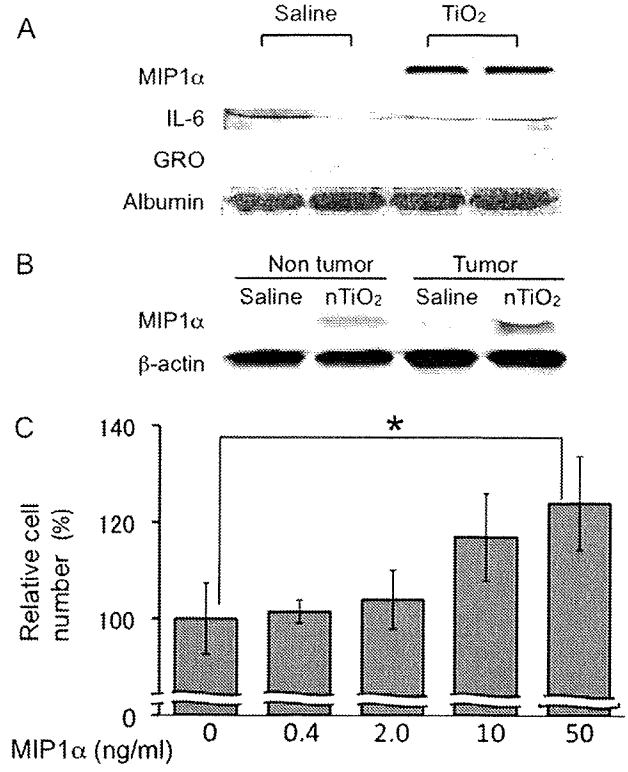

Fig. 5. Promotion effects of MIP1α on proliferation of a rat mammary cancer cell line, C3 (**A**) MIP1α was detected in the serum of the H*ras*128 rats treated with TiO_2 but not in vehicle control rats in the 16 week study. No difference in IL-6 in the serum was observed and GRO was not detected in the serum. (**B**) MIP1α levels are slightly elevated in non-tumor and tumor tissue of the mammary gland of animals treated by IPS with TiO_2 particles in the 16 week study. (**C**) Recombinant MIP1α increased the number of rat mammary carcinoma C3 cells in a dose-dependent manner ($P = 0.0127$).

tissue exposed to TiO_2 particles exhibits increase in both DNA damage and proliferation. Importantly, a similar mechanism would function in humans in the promotion of lung carcinogenesis associated with inhalation of TiO_2 particles and other nanoparticles with the capacity to form aggregates. In addition, TiO_2 administered to the lung had carcinogenic activity in the H*ras*128 transgenic rat mammary gland; this carcinogenic activity is probably mediated via serum MIP1α resulting from expression of MIP1α by alveolar macrophages. This finding may indicate that exposure of TiO_2 particles is a risk factor for mammary carcinogenesis in predisposed populations, such as individuals with BRCA mutations.

Supplementary material

Supplementary Figures 1–3 and Tables 1 and 2 can be found at http://carcin.oxfordjournals.org/

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