Phosphatase Conjugate Substrate Kit™ (Bio-Rad Lab., Hercules, CA), with exposure times ranging from 5 to 10 min.

Enzyme assays. Determination of microsomal BaP hydroxylase (Nebert and Gelboin, 1968) and ethoxyresorufin *O*-deethylase (**EROD**) (Burke et al., 1977) activities principally represent CYP1A1 activity. Acetanilide 4-hydroxylase (Shertzer et al., 2001) and methoxyresorufin *O*-demethylase (**MROD**) (Berthou et al., 1992; Hamm et al., 1998; Shertzer et al., 2001) activities principally (but not exclusively) represent CYP1A2 activity. These enzymes were assayed by the methods cited. Although the MROD spectrophotofluororometric assay is sensitive and reliable, it has been demonstrated (Hamm et al., 1998) that the MROD assay is not the most suitable for estimating CYP1A2 activity. In *Cyp1a2(−/−)* knockout mice, it was shown that hepatic MROD activity was increased 70-fold by TCDD treatment, indicating that other TCDD-inducible enzymes contribute to inducible MROD activity. In contrast, acetanilide 4-hydroxylase activity in *Cyp1a2(−/−)* knockout mice was induced only 2-fold by dioxin (Shertzer et al., 2001), suggesting that it is by far the preferred enzyme activity for estimating CYP1A2 catalytic expression.

Biohazard precaution. TCDD is highly toxic and regarded as a likely human carcinogen. All personnel were instructed in safe handling procedures. Lab coats, gloves and masks were worn at all times, and contaminated materials were collected separately for disposal by the Hazardous Waste Unit or by independent contractors. TCDD-treated mice were housed separately, and their carcasses regarded as contaminated biological materials. TCDD-treated cells in culture, and culture medium from these cells, were also regarded as contaminated biological materials.

Statistical analysis. Statistical significance between groups was determined by analysis-of-variance among groups and Student's *t*-test between groups. All assays were performed in duplicate or triplicate, and repeated at least twice. Statistical analyses were also carried out with the use of SAS® statistical software (SAS Institute Inc.; Cary, NC) and Sigma Plot (Systat Software, Inc., Point Richmond, CA).

Results and discussion

Factors affecting CYP expression

In a previous study of the entire gastrointestinal tract (Uno et al., 2008), large differences in basal but especially inducible CYP1A1 and CYP1A2 mRNA and protein levels were seen. This variability appears to depend on the route-of-administration and the target organ being studied: oral versus intraperitoneal administration of TCDD or BaP can drastically alter CYP1 mRNA levels in various cell types of the intestine, from tongue to colon (Uno et al., 2008). In two studies comparing humanized mice with wild-type controls (Dragin et al., 2007; Shi et al., 2008), large differences were also observed in human CYP1A1 or CYP1A2 mRNA, compared with mouse CYP1A1 or CYP1A2 mRNA. In the chimeric *uPA/SCID* humanized mouse, although CYP1A1 was not studied, large variability in CYP1A2 expression has also been seen (Katoh et al., 2008).

Reasons for differences in human transgene expression in humanized mouse tissues include: [a] genotype of the volunteer from whom the BAC library was derived (Jiang et al., 2005) or from whose hepatocytes were infused into a *uPA(+/+)/SCID* mouse (Katoh et al., 2008; [b] chromosomal location of the randomly inserted BAC transgene affecting transgene expression, *i.e.* the "neighborhood effect" (Bedell et al., 1996; Milot et al., 1996; Olson et al., 1996; Muller et al., 2001); [c] genetic background (modifier genes) of a particular inbred strain that can influence transgene expression (Bonyadi et al., 1997; Cranston and Fishel, 1999; Bennett et al., 2000); and [d] a BAC containing the human gene(s) (Jiang et al., 2005; Cheung et al., 2005) which does not include *trans*-regulatory, or all of the *cis*-regulatory, sites needed for "normal" expression of the transgene(s) in each mouse tissue or cell type studied.

Comparison of human versus mouse CYP1A1 mRNA levels in liver

Fig. 1A compares human and mouse CYP1A1 mRNA copy numbers in the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* line, B6 wild-type mice containing no human transgenes, chimeric *uPA/SCID* mice (**chimera**), and *uPA(+/+)/SCID* control mice containing no human hepatocytes (*uPA/SCID* mice). Human basal CYP1A1 mRNA levels in the liver of *hCYP1A1_1A2* and chimeric mice were quite low, having $\sim 1.3\times10^{7}$ and $\sim 1.2\times10^{7}$ transcript copy numbers (per μg total RNA), respectively; both were strikingly increased by TCDD to $\sim 7.3\times10^{9}$ and $\sim 2.0\times10^{9}$ copy numbers, respectively.

Mouse basal CYP1A1 mRNA levels in B6, chimeric, and *uPA/SCID* mice (Fig. 1A) were also quite low ($\sim 1.8\times10^{6}$, $\sim 1.7\times10^{6}$, and 1.0×10^{6} copy numbers, respectively), but all were dramatically induced by TCDD to $\sim 2.5\times10^{8}$, $\sim 8.0\times10^{7}$, and $\sim 1.5\times10^{8}$ copy numbers, respectively. As expected, no human CYP1A1 mRNA was detected in B6 or *uPA/SCID* mice, and no mouse CYP1A1 mRNA was detected in the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* line.

Comparison of human versus mouse CYP1A2 mRNA levels in liver

Human basal CYP1A2 mRNA levels in *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* and chimeric mice (Fig. 1B) were low ($\sim 2.6\times10^{8}$ and $\sim 0.89\times10^{8}$ transcript copy numbers, respectively). Both were significantly elevated by TCDD to $\sim 9.7\times10^{8}$ and $\sim 7.7\times10^{8}$ copy numbers, respectively.

Mouse basal CYP1A2 mRNA concentrations in B6, chimeric, and *uPA/SCID* mice were also low ($\sim 2.2\times10^{8}$, $\sim 0.16\times10^{8}$ and $\sim 1.2\times10^{8}$ copy numbers, respectively); all three were significantly induced by TCDD to $\sim 4.2\times10^{9}$, $\sim 0.73\times10^{9}$, and 2.8×10^{9} copy numbers, respectively (Fig. 1B). As expected, no human CYP1A2 mRNA was detected in B6 and *uPA/SCID* mice, and no mouse CYP1A2 mRNA was detected in the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* line.

Comparison of human versus mouse CYP1A1 and CYP1A2 mRNA levels

It should be noted that the basal expression levels of human and mouse CYP1A2 mRNA ($1–3\times10^{8}$ copy numbers) were much higher (Fig. 1) than those of CYP1A1 mRNA ($\sim 10^{7}$ copy numbers). This conclusion supports the results of studies long ago (Nebert, 1989; Eaton et al., 1995). The induction of human and mouse CYP1A1 and CYP1A2 mRNAs by TCDD is also well known (Nebert, 1989; Eaton et al., 1995; Nebert et al., 2004).

A previous report (Shi et al., 2008) compared the expression of CYP1A1 and CYP1A2 mRNA in liver between two humanized *CYP1A1_1A2_Cyp1a1/1a2(−/−)* lines and the B6 inbred mouse: maximally-induced mRNA levels of mouse CYP1A1 were described as ~10 times higher than those of human CYP1A1; in contrast, maximally-induced mRNA levels of mouse CYP1A2 were <2-fold higher than those of human CYP1A2 in liver. However, the present study (in which we find a mouse/human induced CYP1A1 ratio of ~0.03 and a mouse/human induced CYP1A2 ratio of ~4) appears not to be consistent with this previous report.

The previous report also found that maximally-induced mRNA levels of human CYP1A2 in liver were ~12 times higher than those of human CYP1A1, whereas maximally-induced mRNA levels of mouse CYP1A2 were ~3-fold greater than those of mouse CYP1A1 (Shi et al., 2008). In the present study, these ratios are 0.13 and 16.8, respectively. These large differences in the calculated ratios clearly reflect the

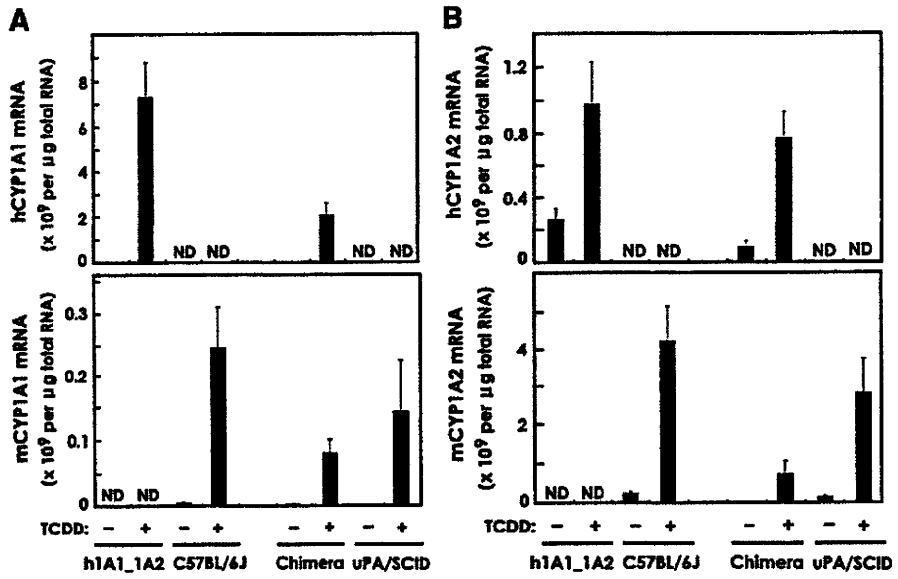

Fig. 1. Human (*upper panels*) versus mouse (*lower panels*) CYP1A1 (A) and CYP1A2 (B) mRNA copy numbers in liver from the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)_Ahr*$^{+/+}$ mouse line, B6 inbred mouse, chimeric mouse, and *uPA/SCID* mouse—with, versus without, TCDD pretreatment. When administered, TCDD (25 µg/kg body weight 24 h before killing) was given intraperitoneally. "ND" (nondetectable by qRT-PCR) denotes nothing above background, whereas absence of "ND" (detectable, but extremely low by qRT-PCR) denotes something measurable above background. On *Y*-axis: **h**CYP1A1 or **h**CYP1A2 = human mRNA; **m**CYP1A1 or **m**CYP1A2 = mouse mRNA. For this figure and Fig. 4, the method for determining the copy number of mRNA molecules per µg total RNA is given in "Materials & methods". Note the different labels on the *Y*-axes of these figures. *Bars* and *brackets* denote means ± S.E.M., respectively ($N = 3$ independent experiments).

disparity between the "relative values" given in the previous report and the "absolute values" (*i.e.* copy numbers per µg total RNA) in the present study.

Human induced and basal CYP1A2 mRNA copy numbers in chimeric mice were 73–80% lower than those in *uPA/SCID* mice (Fig. 1B). This decrease can easily be explained when the human hepatocyte-replacement rate (73%–83%) is taken into account. This finding supports the notion that human hepatocytes in chimeric mice liver are affected by TCDD independently from mouse hepatocytes, suggesting that human hepatocytes in chimeric mice liver can mimic those in human liver.

The induction rate (Fig. 1) of human CYP1A1 mRNA in the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* line is quite remarkable (>500-fold), whereas that in chimeric mouse was not nearly as high (~170-fold). In contrast, the induction rate of human CYP1A2 mRNA in *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mice was ~3.7-fold, whereas that in the chimera was higher (~8.7-fold). These differences in fold-induction could be due to differences in the transcription regulatory regions associated with each of the two genes—if we assume that human and mouse genomic regulatory motifs might differ in their ability to govern these two human transgenes. This might not be a valid assumption, however, because many transcription factors and their DNA-binding motifs are highly conserved among vertebrates and, indeed, in some cases down to the fly, worm and yeast.

The BAC carrying the human *CYP1A1_CYP1A2* locus includes the 23.3-kb bidirectional promoter, plus 56 kb 3′-ward of *CYP1A1* and 86 kb 3′-ward of *CYP1A2* (Jiang et al., 2005). The transgenes in the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mouse thus would carry human *cis*-regulatory motifs only within these sequences responsible for TCDD up-regulation, whereas expression of the human *CYP1A1* and *CYP1A2* genes in chimeric mice should be controlled by any and all of the human *cis*- and *trans*-regulatory enhancers in the same way as they are in human liver hepatocytes.

The expression level of mouse CYP1A1 induced mRNA in B6 is comparable to that in *uPA/SCID* mice and might also be comparable to that in chimeric mice when the human hepatocyte-replacement rate is taken into consideration. A similar conclusion might also be reached if one compares the expression levels of mouse induced CYP1A2 mRNA among B6, chimeric, and *uPA/SCID* mice. As a whole, we conclude that the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* line and the human hepatocyte chimeric mouse show similar expression levels of basal mRNA for the human *CYP1A1* and *CYP1A2* genes. Likewise, there are similar expression levels of TCDD-induced mRNA for these two genes, although their extent of induction is variable.

Comparison of human versus mouse CYP1A1 and CYP1A2 protein levels in liver

Western immunoblots of liver were carried out from the four mouse types, control versus TCDD-pretreated (Fig. 2). The polyvalent antiserum was raised against rat CYP1A1/1A2 and thus is not likely to recognize equally the human and mouse CYP1A1 and CYP1A2 proteins; consequently, a strict quantitative comparison of the human versus mouse orthologous protein concentrations is not possible. This problem has been recognized before and discussed in detail (Jiang et al., 2005).

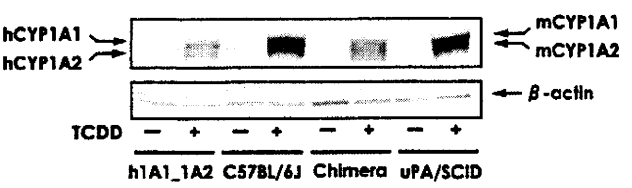

Fig. 2. Western immunoblot analysis of mouse versus human hepatic CYP1A1 and CYP1A2 proteins in the same mouse lines as in Fig. 1, using a polyclonal antibody that recognizes both mammalian CYP1A1 and CYP1A2. TCDD-induced mouse and human CYP1A1 proteins are both ~56.0 kDa, whereas TCDD-induced mouse and human CYP1A2 proteins are both ~54.5 kDa. Lanes 1–2 represent human CYP1A proteins only, whereas lanes 5–6 represent ~78% human CYP1A proteins and ~22% mouse CYP1A proteins. Lanes 3–4 and 7–8 depict only mouse CYP1A proteins. We used β-actin mRNA as a control for standardizing the amount of protein loaded per lane. The amount of microsomal protein (10 µg) loaded per lane was constant for all lanes.

Comparison of human versus mouse CYP1A1 and CYP1A2 TCDD-induced enzyme activities in liver

For BaP hydroxylase and EROD as two activities associated predominantly with CYP1A1, the correlations between enzyme activities (Fig. 3A) and mRNA levels (Fig. 1A) are extremely variable for BaP hydroxylase but quite consistent for EROD activity. Thus, B6 mice exhibit one-half as much TCDD-induced BaP hydroxylase activity (per unit of mCYP1A1 mRNA) as *uPA/SCID* mice (Table 2). The B6 mouse shows ~170 times more induced BaP hydroxylase activity (per unit of mCYP1A1 mRNA), compared with the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mouse's induced BaP hydroxylase activity (per unit of hCYP1A1 mRNA). Chimeric mice exhibit ~6.2-fold more induced BaP hydroxylase activity (per unit of hCYP1A1 mRNA) than *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mice (Table 2). The *uPA/SCID* mouse shows ~42 times more induced BaP hydroxylase activity (per unit of mCYP1A1 mRNA), compared with the chimeric mouse's induced BaP hydroxylase activity (per unit of hCYP1A1 mRNA).

In contrast, B6 mice display about the same amount of TCDD-induced EROD activity (per unit of mCYP1A1 mRNA) as *uPA/SCID* mice (Table 2). The B6 mouse shows ~54 times more induced EROD activity (per unit of mCYP1A1 mRNA), compared with the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mouse's induced EROD activity (per unit of hCYP1A1 mRNA). Chimeric mice exhibit ~1.7 times more induced EROD activity (per unit of hCYP1A1 mRNA) than *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mice (Table 2). The *uPA/SCID* mouse shows ~39 times more induced EROD activity (per unit of mCYP1A1 mRNA), compared with the chimeric mouse's induced EROD activity (per unit of hCYP1A1 mRNA).

Why does the humanized *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mouse carry so little enzyme activity toward BaP, compared with the chimeric mouse? This difference can be explained from the human hepatocyte-replacement rate (73%–83%) in chimeric mice. The liver of chimeric mice carries 73%–83% human hepatocytes, which exhibit extremely low BaP hydroxylase activity.

For acetanilide 4-hydroxylase and MROD as two activities associated predominantly with CYP1A2, the correlations between enzyme activities (Fig. 3B) and mRNA levels (Fig. 1B) are very much consistent with one another. B6 mice show virtually the same amount of TCDD-induced acetanilide 4-hydroxylase activity (per unit of mCYP1A2 mRNA) as *uPA/SCID* mice (Table 2). The B6 mouse shows about the same amount of induced acetanilide 4-hydroxylase activity (per unit of mCYP1A2 mRNA), compared with the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mouse's induced acetanilide 4-hydroxylase activity (per unit of hCYP1A2 mRNA). Chimeric mice exhibit twice as much induced acetanilide 4-hydroxylase activity (per unit of hCYP1A2 mRNA) than *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mice (Table 2). The chimeric mouse shows ~2.3-fold more induced acetanilide 4-hydroxylase activity (per unit of mCYP1A2 mRNA), compared with the *uPA/SCID* mouse's induced acetanilide 4-hydroxylase activity (per unit of hCYP1A2 mRNA).

B6 mice exhibit one-half as much TCDD-induced MROD activity (per unit of mCYP1A2 mRNA) as *uPA/SCID* mice (Table 2). The *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mouse shows ~2-fold more induced MROD activity (per unit of mCYP1A2 mRNA), compared with the B6 mouse's induced MROD activity (per unit of hCYP1A2 mRNA). The *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* mice exhibit ~2.4 times more in-

Table 2
Ratios of mouse liver TCDD-induced enzymic activities per unit of mRNA*.

	mCYP1A1		hCYP1A1	
B6 mouse	7600±2700	h1A1_1A2	44±13	BaP hydroxylase
uPA/SCID	11,400±3000	Chimera	270±62	
B6 mouse	230±64	h1A1_1A2	4.3±1.3	EROD activity
uPA/SCID	290±95	Chimera	7.4±3.1	
	mCYP1A2		**hCYP1A2**	
B6 mouse	490±84	h1A1_1A2	600±220	Acetanilide
uPA/SCID	510±200	Chimera	1200±390	4-hydroxylase
B6 mouse	5.4±1.0	h1A1_1A2	14±5.5	MROD activity
uPA/SCID	13±5.2	Chimera	5.6±0.3	

* For BaP hydroxylase, these ratios represent FU/min/mg protein divided by mRNA × 10^9 per μg total RNA. For the other three enzyme activities, these ratios represent pmol/min/mg protein divided by mRNA × 10^9 per μg total RNA. Values are expressed as means ± S.E.

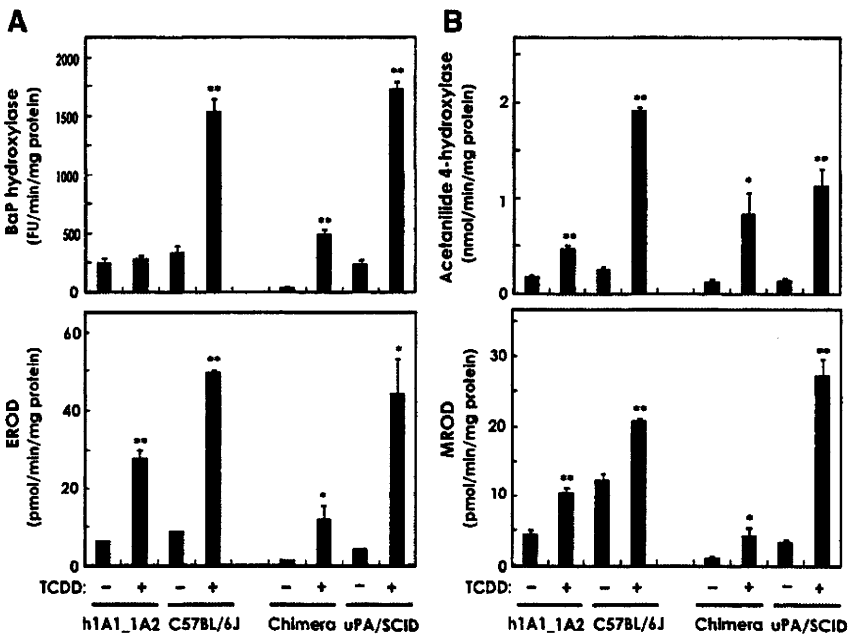

Fig. 3. (A) BaP hydroxylase and EROD activity (both representing largely CYP1A1), and (B) acetanilide 4-hydroxylase and MROD activity (both representing largely CYP1A2) in liver microsomes from the same mouse lines as in Fig. 1. FU, fluorescent units. *$P<0.05$ and **$P<0.01$, when comparing TCDD-pretreated with no pretreatment.

duced MROD activity (per unit of hCYP1A2 mRNA) than chimeric mice (Table 2). The *uPA/SCID* mouse shows twice as much induced MROD activity (per unit of mCYP1A2 mRNA), compared with the chimeric mouse's induced MROD activity (per unit of hCYP1A2 mRNA). Expression of CYP1A2 catalytic activity, relative to CYP1A2 mRNA levels, in the humanized *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* and chimeric mouse lines is therefore very robust and within 2-fold similar to that expressed in mouse liver.

Comparison of human versus mouse CYP1A1 and CYP1A2 mRNA levels in hepatoma-derived cell culture lines

Animal rights' activists have urged scientists to study physiological functions in cell cultures rather than using live laboratory animals. Many studies have shown, however, that parameters found in cell culture do not accurately reflect what happens in the intact animal.

How does the expression of the *CYP1A1* and *CYP1A2* genes in intact liver compare with that in hepatoma-derived established cell lines? In HepG2 cells (Fig. 4A), human basal CYP1A1 mRNA was negligible, whereas human TCDD-induced CYP1A1 mRNA gave $\sim 5.4\times10^{4}$ copy numbers (per μg total RNA). In Hepa-1c1c7 cells (Fig. 4A), mouse basal versus TCDD-induced CYP1A1 mRNA showed $\sim 0.35\times10^{8}$ and $\sim 1.9\times10^{8}$ copy numbers, respectively. Mouse CYP1A1 mRNA was not detected in HepG2, and human CYP1A1 mRNA was not detected in Hepa-1c1c7 cells.

In HepG2 cells (Fig. 4B), human basal versus TCDD-induced CYP1A2 mRNA gave $\sim 0.27\times10^{6}$ and $\sim 4.8\times10^{6}$ copy numbers, respectively. In Hepa-1c1c7 cells (Fig. 4B), mouse basal versus TCDD-induced CYP1A2 mRNA showed $\sim 0.14\times10^{6}$ and $\sim 1.2\times10^{6}$ copies, respectively. Mouse CYP1A2 mRNA was not detected in HepG2, and human CYP1A2 mRNA was not detected in Hepa-1c1c7 cells.

Thus, in livers of the *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* and chimeric mice, the copy number of human induced CYP1A1 mRNA is 7.5 and 2.6 times, respectively, greater than that of human induced CYP1A2 mRNA. On the other hand, in the HepG2 liver-derived established cell line, the copy number of human induced CYP1A1 mRNA is more than 1100 times greater than that of human induced CYP1A2 mRNA. In livers of the B6 and *uPA/SCID* mice, the copy number of mouse induced CYP1A2 mRNA is 40-fold and 20-fold, respectively, greater than that of mouse induced CYP1A1 mRNA; in contrast, in the Hepa-1c1c7 established cell line, the copy number of mouse induced CYP1A1 mRNA is almost 1600-fold greater than that of mouse maximally-inducible CYP1A2 mRNA. This decline in *CYP1A2* gene expression seen in established cell lines reflects the well-known fact that numerous "housekeeping" genes such as *CYP1A2* are extinguished, or are greatly decreased in expression—in tumor cells as well as "established", or transformed, cell lines in culture (Owens et al., 1975; Nebert, 2006). However, such suppression often does not occur for the *CYP1A1* gene in differentiated tumors, including the HepG2 and Hepa-1c1c7 hepatoma-derived cell lines (Owens et al., 1975; Nebert, 2006).

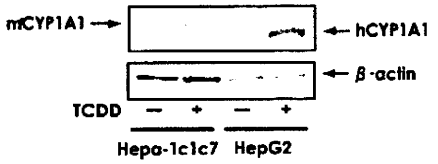

Fig. 5. Western immunoblot analysis of mouse versus human hepatic CYP1A1 and CYP1A2 proteins in the same cell culture lines as in Fig. 4. Everything is the same as that described for the Western blot in Fig. 2. The amount of cell culture protein (10 μg) loaded per lane was constant for all lanes.

Comparison of human versus mouse CYP1A1 and CYP1A2 protein levels in hepatoma-derived cell culture lines

We carried out Western immunoblots of Hepa-1c1c7 and HepG2 cells, control versus TCDD-pretreated (Fig. 5). The human CYP1A1 protein appears to migrate more rapidly than the mouse CYP1A1 protein. We believe the level of CYP1A2 protein was so low that it was not detected in either established hepatoma cell line.

Comparison of human versus mouse CYP1A1 and CYP1A2 TCDD-induced enzyme activities in hepatoma-derived cell culture lines

Different from what was found in mouse liver, the correlations between enzyme activities (Fig. 6A) and mRNA levels (Fig. 4A) are extremely variable for EROD activity but more consistent for BaP

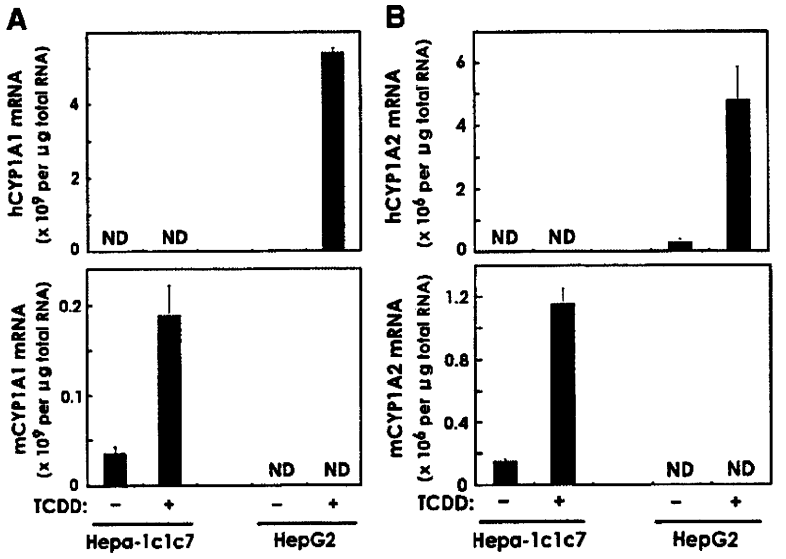

Fig. 4. Human (*upper panels*) versus mouse (*lower panels*) CYP1A1 (A) and CYP1A2 (B) mRNA copy numbers in mouse Hepa-1c1c7 cells and human HepG2 cells—with, versus without, TCDD exposure (10 nM for 24 h) in culture. Abbreviations are the same as those in Fig. 1.

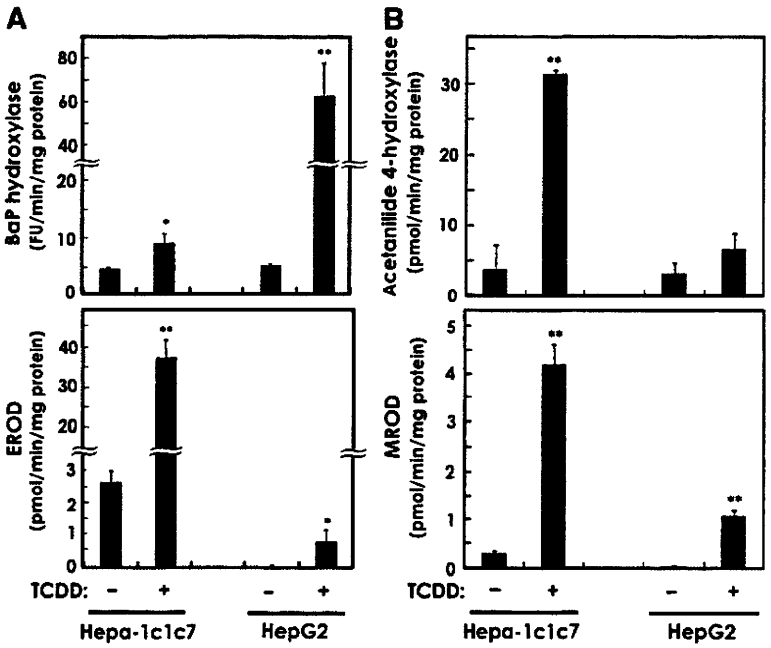

Fig. 6. (A) BaP hydroxylase and EROD activity (both representing largely CYP1A1), and (B) acetanilide 4-hydroxylase and MROD activity (both representing largely CYP1A2) in the same cell culture lines as in Fig. 4. *$P<0.05$ and **$P<0.01$, when comparing TCDD-pretreated with no pretreatment.

hydroxylase activity. Hepa-1c1c7 cells show ~4.8 times more TCDD-induced BaP hydroxylase activity (per unit of mCYP1A1 mRNA) than HepG2 cells exhibit for induced BaP hydroxylase activity (per unit of hCYP1A1 mRNA) (Table 3). Hepa-1c1c7 cells show ~1500 times more TCDD-induced EROD activity (per unit of mCYP1A1 mRNA) than HepG2 cells exhibit for induced EROD activity (per unit of hCYP1A1 mRNA). For whatever reason, HepG2 cells do not display very high induced BaP hydroxylase activity, and their induced EROD activity is extremely low.

For acetanilide 4-hydroxylase and MROD as two activities associated predominantly with CYP1A2, the correlations between enzyme activities (Fig. 6B) and mRNA levels (Fig. 6B) are better than those with CYP1A1. Hepa-1c1c7 cells show ~16-fold more TCDD-induced acetanilide 4-hydroxylase activity (per unit of mCYP1A2 mRNA) than HepG2 cells exhibit for induced acetanilide 4-hydroxylase activity (per unit of hCYP1A2 mRNA) (Table 3). Hepa-1c1c7 cells show ~15-fold more TCDD-induced MROD activity (per unit of mCYP1A2 mRNA) than HepG2 cells exhibit for induced MROD activity (per unit of hCYP1A2 mRNA). Therefore, HepG2 cells do not express either CYP1A1 or CYP1A2 activities nearly as robustly as do Hepa-1c1c7 cells.

Table 3
Ratios of hepatoma-derived cell line TCDD-induced enzymic activities per unit of mRNA*.

	mCYP1A1		hCYP1A1	
Hepa-1c1c7	55 ± 21	HepG2	11 ± 2.5	BaP hydroxylase
Hepa-1c1c7	210 ± 48	HepG2	0.14 ± 0.06	EROD activity
	mCYP1A2		**hCYP1A2**	
Hepa-1c1c7	27,000 ± 2400	HepG2	1800 ± 930	Acetanilide 4-hydroxylase
Hepa-1c1c7	3700 ± 480	HepG2	250 ± 85	MROD activity

* For BaP hydroxylase, these ratios represent FU/min/mg protein divided by mRNA × 10^4 per μg total RNA. For the other three enzyme activities, these ratios represent pmol/min/mg protein divided by mRNA × 10^3 per μg total RNA. Values are expressed as means ± S.E.

Conclusions

In this study we have measured the amount of variability between human and mouse CYP1A mRNA and protein levels and corresponding enzyme activities in the humanized *hCYP1A1_1A2_Cyp1a1/1a2(−/−)* and chimeric *uPA/SCID* lines, by comparing these parameters with those seen in wild-type mice from which these two lines were derived. We have also compared these mRNA and protein levels and corresponding enzyme activities in mouse hepatoma-derived Hepa-1c1c7 and human hepatoblastoma-derived HepG2 established cell culture lines. Clearly, the CYP1A1/CYP1A2 activity ratios in these hepatoma-derived established cell lines are not accurate indicators of those in liver from the intact mouse. Undoubtedly, this discrepancy is primarily caused by the dramatically lowered CYP1A2 mRNA levels—presumably due to "extinction" of the normal expression of the *CYP1A2* gene in these hepatoma-derived established cell lines. Not only very low CYP1A2 enzyme activity per unit of mRNA was seen in both Hepa-1c1c7 and HepG2 cells, but also low CYP1A1 enzyme activity per unit of hCYP1A1 mRNA was found in HepG2 cells.

Comparing liver of the two humanized mouse lines with liver of mice from which these two humanized lines were derived was most disturbing when one examined CYP1A1-specific (BaP and ethoxyresorufin) and CYP1A2-specific (acetanilide and methoxyresorufin) substrates metabolized—per unit of mCYP1A1, hCYP1A1, mCYP1A2 or hCYP1A2 mRNA. The hCYP1A1 in mouse liver was between 38 and more than 170 times less efficient than mCYP1A1 in the hydroxylation of BaP and about 54-fold less efficient in EROD activity. In contrast, hCYP1A2 in mouse liver appeared to function nearly equivalent to mCYP1A2 in wild-type mouse liver.

The levels of human CYP1A1 and CYP1A2 mRNA in both humanized mouse lines appear to be quite compatible with what might be expected among individual persons in any human population. It is very clear, however, that substrate specificity varies widely, independent of human versus mouse CYP1A1/1A2 mRNA or protein concentrations. Nevertheless, keeping this caveats in mind, both of these lines should still be useful for studies in human risk assessment, toxicology, pharmacology, and other medical subspecialties.

Note added in proof

A recent study (Wilson et al., 2008) is directly relevant to the problems addressed in our present manuscript. This study involves Tc1 hepatocytes, derived from an aneuploid mouse strain carrying human chromosome (Chr) 21 in addition to the entire mouse genome. The authors compared the regulation of human genes in Tc1 cells to that of the mouse orthologous genes in these same cells, using mouse wild-type versus human wild-type cells as controls. Regulation in the nuclei of Tc1 cells was compared at three levels: binding of transcription factors to DNA, modification of histones, and gene expression. The binding patterns of HNF1α, HNF4α and HNF6 on human Chr 21 in Tc1 cells matched closely those seen in human wild-type cells, rather than those seen in mouse wild-type cells. Similarly, histone modifications–as well as gene expression (the amount of mRNA transcribed)–showed human-specific, instead of mouse-specific, patterns on human Chr 21 in Tc1 cells. The authors concluded that it is the regulatory DNA sequence, rather than any other species-specific factor, which is the single most important determinant of gene expression (Wilson et al., 2008).

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Inhibition of Transforming Growth Factor β Signaling by Halofuginone as a Modality for Pancreas Fibrosis Prevention

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Objectives: Chronic pancreatitis is characterized by inflammation and fibrosis. We evaluated the efficacy of halofuginone, an inhibitor of collagen synthesis and myofibroblast activation, in preventing cerulein-induced pancreas fibrosis.

Methods: Collagen synthesis was evaluated by in situ hybridization and staining. Levels of prolyl 4-hydroxylase β (P4Hβ), cytoglobin/stellate cell activation–associated protein (Cygb/STAP), transgelin, tissue inhibitors of metalloproteinases, serum response factor, transforming growth factor β (TGFβ), Smad3, and pancreatitis-associated protein 1 (PAP-1) were determined by immunohistochemistry. Metalloproteinase activity was evaluated by zymography.

Results: Halofuginone prevented cerulein-dependent increase in collagen synthesis, collagen cross-linking enzyme P4Hβ, Cygb/STAP, and tissue inhibitors of metalloproteinase 2. Halofuginone did not affect TGFβ levels in cerulein-treated mice but inhibited serum response factor synthesis and Smad3 phosphorylation. In culture, halofuginone inhibited pancreatic stellate cell (PSC) proliferation and TGFβ-dependent increase in Cygb/STAP and transgelin synthesis and metalloproteinase 2 activity. Halofuginone increased c-Jun N-terminal kinase phosphorylation in PSCs derived from cerulein-treated mice. Halofuginone prevented the increase in acinar cell proliferation and further increased the cerulein-dependent PAP-1 synthesis.

Conclusions: Halofuginone inhibits Smad3 phosphorylation and increases c-Jun N-terminal kinase phosphorylation, leading to the inhibition of PSC activation and consequent prevention of fibrosis. Halofuginone increased the synthesis of PAP-1, which further reduces pancreas fibrosis. Thus, halofuginone might serve as a novel therapy for pancreas fibrosis.

Key Words: myofibroblasts, pancreatic stellate cells, Smad, collagen, transgelin, cytoglobin

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Chronic pancreatitis is a progressive disease, characterized by inflammation, fibrosis, and atrophy of the gland tissue, which results in impaired exocrine and endocrine functions of the pancreas.[1] The cellular mechanisms governing pancreas fibrosis are shared among the various insults and, in many aspects, mirror the scarring and wound-healing processes of other tissues. Pancreas fibrosis, regardless of the cause, is characterized by an increase in extracellular matrix (ECM) constituents, although their relative distribution within the pancreas varies with the site and nature of the insult.[2] In the injured pancreas, the pancreatic stellate cells (PSCs) constitute the major source of ECM proteins.[3] These cells are usually quiescent, with a low proliferation rate; however, upon activation, they differentiate into myofibroblastlike cells with high proliferative capacity. The activated PSCs migrate to sites of tissue damage, where they synthesize ECM components to promote tissue repair.[4] The intracellular signaling mechanisms regulating PSC activation include the mitogen-activated protein kinase (MAPK) pathway, which plays a major role in ethanol- and acetaldehyde-dependent activation of PSC, phosphatidylinositol-3-kinase, and protein kinase C.[5]

The transition to the myofibroblastlike phenotype is associated with increased expression of specific smooth muscle genes such as α smooth muscle actin and transgelin (SM22α) and of specific markers such as cytoglobin/stellate cell activation–associated protein (Cygb/STAP) in fibrotic lesions of the pancreas.[6] Pancreatic stellate cells can be activated directly by alcohol consumption[7] or by cytokines derived from the immigrating inflammatory cells.[8,9] Platelet-derived growth factor is the major promoter of PSC migration, whereas transforming growth factor β (TGFβ) affects ECM production via a Smad-associated pathway. Upon phosphorylation by the TGFβ receptor, Smad3 enters the nucleus to modulate the transcription of target genes.[10] Smad3 links TGFβ signaling directly to the serum response factor (SRF)–associated regulatory network that controls the expression of smooth muscle–specific genes.[11,12] The predominant ECM protein synthesized by the PSCs is collagen type I, although increases in the gene expression of other types of collagens and other matrix proteins have also been reported.[13] Pancreas fibrosis may also result from a relative imbalance between the production and degradation of matrix proteins.[14] The PSCs constitute the source of various matrix metalloproteinases (MMPs) and tissue inhibitors of MMPs (TIMPs), which are necessary for ECM remodeling under the control of TGFβ.[15,16]

In addition to the morbidity and mortality caused by chronic pancreatitis, patients with this disease also have a substantially increased risk of developing pancreatic cancer. The PSCs play a major role in the growth and development of pancreas adenocarcinoma, which has a remarkable fibrotic component regulated by the TGFβ pathway.[4,17,18] The desmoplasia is created by activated PSCs, which are stimulated by the cancer cells, thereby influencing tumor aggressiveness.[19] Given that activated PSCs not only are the principal effector cells in pancreas fibrosis but also play a major role in pancreas carcinoma, it seems that targeting the fibroblast-to-PSC transition might be a promising therapeutic approach, for which there is a great unmet need.

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Halofuginone, an analog of the plant alkaloid febrifugine, has been found to inhibit the activation of hepatic stellate cells (HSCs)[20,21] and the stromal fibroblast-to-myofibroblast transition in the tumor microenvironment.[22] Halofuginone overcame TGFβ-induced collagen synthesis by inhibiting Smad3 phosphorylation downstream of the TGFβ signaling pathway.[23] In animal models in which excess collagen is the hallmark of the disease, halofuginone prevented the increase in collagen synthesis. These models included mice afflicted with chronic graft-versus-host disease and tight-skin mice, rats with pulmonary fibrosis, and rats that developed adhesions at various sites.[23–25] When given to rats that exhibited established fibrosis, halofuginone caused almost a complete resolution of the fibrotic condition.[20] In addition, halofuginone markedly improved the capacity of a cirrhotic liver to regenerate after partial hepatectomy[26] by affecting the expression of early genes of liver regeneration under the control of TGFβ.[27,28] Topical treatment with halofuginone of a patient with chronic graft-versus-host disease and of patients with scleroderma elicited a transient attenuation of collagen α_1(I) gene expression and improvements in skin scores, thus demonstrating human clinical efficacy.[25,29]

In the present study, we evaluated the efficacy of halofuginone in inhibiting pancreas fibrosis in mice, with particular emphasis on TGFβ-dependent PSC activation and ECM production.

MATERIALS AND METHODS

Materials

Halofuginone bromhydrate was obtained from Collgard Biopharmaceuticals Ltd (Tel Aviv, Israel). Cerulein and β-casein were from Sigma (St Louis, Mo). Antibodies to Cygb/STAP were prepared according to Nakatani et al.[6] Smad3 and phosphorylated Smad3 (P-Smad3) antibodies were from Abcam (Cambridge, United Kingdom). Serum response factor antibodies were from Santa Cruz Biotechnology Inc (Santa Cruz, Calif). The proliferating cell nuclear antigen (PCNA) staining kit was from Zymed Laboratories (San Francisco, Calif). Metalloproteinase 2 and P4Hβ monoclonal antibodies were from Acris (Hiddenhausen, Germany), and TIMP1 and TIMP2 monoclonal antibodies were from Lab Vision (Fremont, Calif). Polyclonal antibodies to phospho-Akt (S^{473}P-AKT), phospho-ERK/MAPK (P-p44), total Akt and total ERK/MAPK (p44), and monoclonal antibody to total c-Jun N-terminal kinase (JNK) 1 were from Cell Signaling Technologies (Danvers, Mass). Active-JNK (P-JNK1) and active p38 (P-p38) antibodies were from Promega (Madison, Wis). Rabbit polyclonal antibodies against human pancreatitis-associated protein 1 (PAP-1) were prepared as described previously.[30]

Animal Model of Pancreas Fibrosis

Male ICR mice (Harlan Laboratories, Jerusalem, Israel) were kept under standard conditions with free access to water and chow. Fibrosis was induced in mice (n = 10) by repeated (every 6 h) intraperitoneal injections of cerulein (50 μg/kg) twice weekly for 4 or 8 weeks according to Neuschwander-Tetri et al.[31] Halofuginone was administered intraperitoneally to mice (n = 10) at 4 μg per animal, 3 times per week as described by Bruck et al,[20] starting at the same time as the cerulein. Untreated mice (n = 10) and mice treated only with halofuginone (n = 10) were used as controls. All animal experiments were carried out according to the guidelines of the Volcani Center Institutional Committee for Care and Use of Laboratory Animals (Bet Dagan, Israel).

Preparation of Sections, In Situ Hybridization, and Immunohistochemistry

Pancreas samples were fixed overnight in 4% paraformaldehyde in phosphate-buffered saline at 4°C. Serial 5-μm sections were prepared after the samples had been embedded in Paraplast (McCormick Scientific, St Louis, Mo). Collagenous and noncollagenous proteins were differentially stained with 0.1% Sirius red and 0.1% Fast green as a counterstain, in saturated picric acid. By this procedure, collagen is stained red. Collagen levels were quantified by image analysis (ImagePro; Media Cybernetics, Silver Spring, Md). At least 20 photographs were taken for each analysis per each treatment at each time point. The results were calculated as the red area divided by the total red and green area and presented as arbitrary units of the mean (SE). Special care was taken to exclude the blank areas, which probably represented artifacts. In situ hybridization with a digoxigenin-labeled collagen α_1(I) probe was performed as described by Bruck et al.[20] No signal was observed with the sense probe. For immunohistochemistry, the following antibodies were used: SRF (diluted 1:500), TGFβ1 (1:400), Cygb/STAP (1:700), Smad3 (1:200), P-Smad2/3 (1:700), P4Hβ (1:25), TIMP1 (1:50), TIMP2 (1:250), and PAP-1 (1:10). In all cases, at least 5 slides from all the animals within the group were evaluated blindly to the animal grouping.

Cell Culture

Pancreatic stellate cells were prepared from either control mice or mice treated with a single injection of cerulein (50 μg/kg). After 24 hours, the pancreas was excised, freed from fat and lymph nodes, and digested with collagenase IV (0.02%), and the resulting cell suspension was centrifuged at 1200*g* for 5 minutes. The cells were washed and resuspended in Dulbecco's modified essential medium (DMEM) containing 10% fetal bovine serum and antibiotics (100-U/mL penicillin, 100-mg/mL streptomycin) and plated on 6-well plates with the same medium.[32] No significant differences were observed in the cell yield between the control and cerulein-treated mice, and almost all the cells were stained positive for Cygb/STAP or SM22α. All of the cells were incubated at 37°C in a humidified atmosphere containing 5% carbon dioxide. The cells were incubated with serum-free DMEM for 6 hours and were then treated with fresh medium containing halofuginone (20 or 50 nmol/L), TGFβ (3 ng/mL), or both for an additional 24 hours. Cellular viability was determined by trypan blue exclusion. At the end of the incubation period, the cells were either counted directly with a cell counter (Coulter Electronics, Bath, United Kingdom) or resuspended in 500 μL of lysis buffer consisting of 1-mmol/L EDTA, 50-mmol/L Tris (pH, 7.5), 150-mmol/L NaCl, 10% glycerol, 1% Nonidet P40, and a 1:100 dilution of protease and phosphatase inhibitor cocktail (Sigma).

Western Blot

Protein lysate (30 μg) from either tissue or cells was electrophoresed on a 10% sodium dodecyl sulfate–polyacrylamide gel and transferred onto a nitrocellulose membrane. Nonspecific binding sites were blocked with 5% low-fat milk, and the membranes were incubated overnight with the appropriate antibodies for SM22α (1:5000), Cygb/STAP (1:1000), MMP-2 (1:200), phospho-Akt (1:1000), phosphor–ERK/MAPK (1:2000), total Akt and total ERK/MAPK (1:1500), active

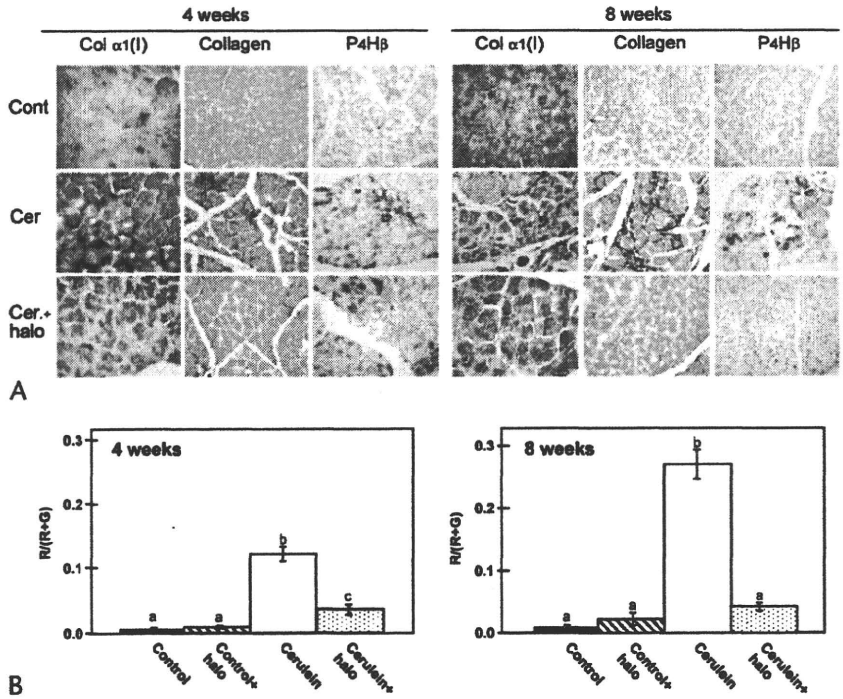

FIGURE 1. Effect of halofuginone on cerulein-dependent synthesis of collagen and P4Hβ, a collagen cross-linking enzyme. Mice were treated with cerulein for 4 or 8 weeks with or without halofuginone, after which pancreas biopsies were taken for histology. A, Collagen α_1(I) gene expression was determined by in situ hybridization, collagen level was evaluated by Sirius red staining, and P4Hβ was determined by immunohistochemistry. B, Image analysis of pancreas collagen levels. In each column, means without a common letter differ significantly ($P < 0.05$) according to Duncan multiple range test.

JNK (1:5000), active p38 (1:2000), and monoclonal antibody to total JNK (1:1000).

Zymography

Conditioned medium samples were analyzed for MMP activity, which was determined in a 10% sodium dodecyl sulfate–polyacrylamide gel impregnated with gelatin (0.01%) or β-casein (1.0 mg/mL). Proteins were separated on the gel under nonreducing conditions, followed by 1 hour of incubation in 2.5% Triton X-100 and 16 hours of incubation in 50-mmol/L Tris (pH, 7.6), 0.2-mol/L NaCl, and 5-mmol/L $CaCl_2$ at 37°C. After the incubation period, the gels were stained with 0.5% Coomassie G 250 in methanol/acetic acid/water (30:10:60, vol/vol/vol).

Statistical Analysis

The results are presented as the mean (SD). The significance of differences among different groups was determined by analysis of variance. In each column, means without a common letter differ significantly ($P < 0.05$) according to Duncan multiple range test.

RESULTS

Halofuginone Inhibits Pancreas Fibrosis

Pancreas fibrosis is the result of a dynamic cascade of mechanisms beginning with acinar cell injury and followed by inflammation and PSC activation. After 4 weeks of cerulein treatment, we observed a major increase in the number of PSCs expressing the collagen α_1(I) gene, the synthesis of large quantities of collagen surrounding the acinar cells, and positive staining for P4Hβ, one of the major enzymes responsible for collagen cross-linking and maturation (Fig. 1A). Collagen accumulated in the pancreas with time, and after an additional 4 weeks of cerulein treatment, a further increase in collagen content and P4Hβ level was observed. Halofuginone prevented the increase in fibrosis in a time-dependent fashion, as demonstrated by reductions in the expression of the collagen α_1(I) gene, in collagen content, and in the level of P4Hβ. After 4 weeks of halofuginone treatment, the collagen level was significantly lower than that of the cerulein-treated mice but was still higher than that of the control mice. After 8 weeks of halofuginone treatment, the collagen level was significantly lower than that of the cerulein-treated mice and did not differ from that of the control untreated mice (Fig. 1B). Halofuginone alone had no effect on the collagen content or other histologic parameters in the control untreated mice (data not shown).

Halofuginone Inhibits PSC Activation

In addition to enhancing collagen synthesis, activated PSCs are also characterized by increased proliferation and expression of SM22α and Cygb/STAP genes under the control of TGFβ. After 4 weeks of cerulein treatment, a major increase in the number of PSCs exhibiting Cygb/STAP was observed, which persisted for at least 8 weeks. Halofuginone reduced the number of Cygb/STAP-positive cells in the pancreas (Fig. 2A) and inhibited the TGFβ-induced Cygb/STAP levels in primary PSCs in cultures derived from the pancreas of control and cerulein-treated mice (Fig. 2B). Transgelin is induced during transdifferentiation of fibroblasts to myofibroblasts at the time of stromal tissue remodeling under the

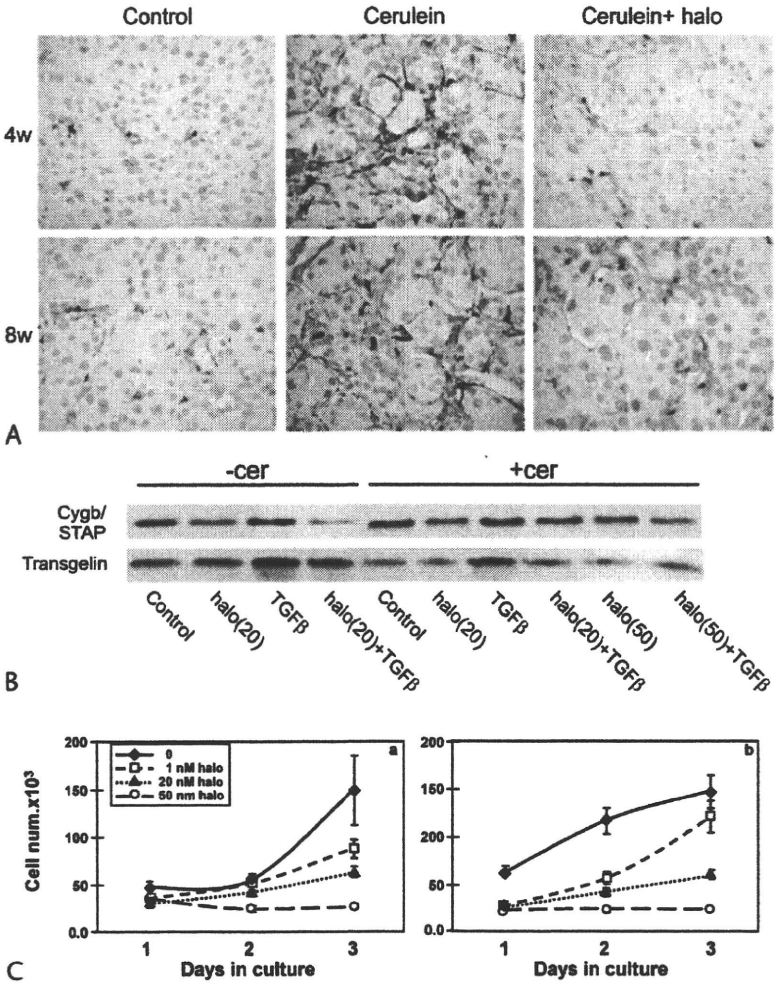

FIGURE 2. Effect of halofuginone on the synthesis of Cygb/STAP and SM22α and on PSC proliferation. A, Immunohistochemistry of Cygb/STAP in pancreas biopsies of mice treated for 4 or 8 weeks with cerulein, with or without halofuginone. B, Western blotting of Cygb/STAP and SM22α of PSCs derived from either control or cerulein-treated mice. The cells were incubated for 18 hours with TGFβ (3 ng/mL), halofuginone, or their combination. C, Primary PSCs were incubated with various concentrations of halofuginone, and cell proliferation was estimated directly by cell counting.

control of TGFβ. The PSCs in culture from control and cerulein-treated mice synthesized SM22α, which was upregulated by TGFβ. Halofuginone prevented the TGFβ-dependent SM22α synthesis in cultured primary PSCs derived from either control or cerulein-treated mice (Fig. 2B). The inhibitory effect of halofuginone on Cygb/STAP and SM22α synthesis was accompanied by a dose-dependent inhibition of proliferation of PSCs derived from either the normal pancreas or cerulein-treated mice (Fig. 2C). All of these findings were consistent with halofuginone inhibition of PSC activation.

Halofuginone and Matrix Degradation

The levels of TIMP1 and TIMP2 were increased in the pancreas after cerulein treatment, but only the TIMP2 level was inhibited by halofuginone (Fig. 3A). Metalloproteinase 2 is one of the major MMPs involved in pancreas fibrosis under the control of TGFβ.[14-16] Halofuginone had only a minimal, if any, effect on MMP-2 levels in the control mice. Cerulein treatment caused an increase in MMP-2 levels, which were further increased after halofuginone treatment (Fig. 3B). In culture, a major increase in basal MMP-2 activity was observed in conditioned medium of PSCs derived from cerulein-treated mice compared with controls (Fig. 3C). Halofuginone had no effect on the basal level of MMP-2 activity but inhibited the TGFβ-dependent increase in its activity by PSCs derived from control and cerulein-treated mice (Fig. 3D). In contrast, halofuginone increased MMP-3 activity, but only in PSCs derived from cerulein-treated mice (Fig. 3E).

Halofuginone Inhibits TGFβ Signaling

Almost no TGFβ was observed in the control untreated pancreas, whereas in the cerulein-treated mice, a major increase in its level was observed, mostly in the acinar cells but also in some of the PSCs (Fig. 4). Halofuginone treatment did not cause any change in the level of TGFβ, in agreement with previous studies suggesting that halofuginone affects TGFβ signaling downstream in its pathway.[23] Halofuginone treatment eliminated the synthesis of SRF, which was observed exclusively in the PSCs of the cerulein-treated pancreas. In the untreated pancreas, Smad3 was observed only in endothelial cells

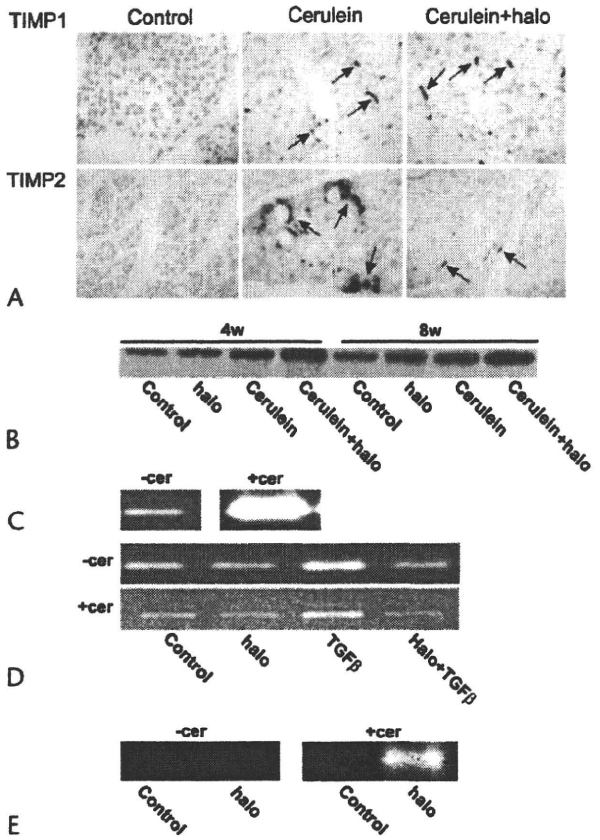

FIGURE 3. Halofuginone and the ECM degradation pathway. A, Immunohistochemistry of TIMP1 and TIMP2 in the pancreas after 8 weeks of cerulein treatment, with or without halofuginone. B, Western blotting with MMP-2 antibodies of pancreas extracts. C, Gelatin zymography for evaluation of MMP-2 activity in conditioned medium of PSCs derived from the cerulein-treated or untreated pancreas. Note the high levels of MMP-2 activity in conditioned medium of PSCs derived from the cerulein-treated pancreas. D, Effect of halofuginone on MMP-2 activity. E, Metalloproteinase 3 in conditioned medium collected from PSCs derived from the normal and the cerulein-treated pancreas.

surrounding the blood vessels, and no P-Smad3 was observed in any cell type. After cerulein treatment, increases in Smad3 and P-Smad3 were observed. Smad3 was observed mostly in the PSCs, whereas P-Smad3 was observed in the acinar cells and the PSCs. Halofuginone had no effect on the level of Smad3 protein expression, whereas complete elimination of P-Smad3 was observed after halofuginone treatment (Fig. 4).

Intracellular PSC Signaling Is Affected by Halofuginone

We evaluated the effect of halofuginone on the phosphorylation of key proteins in the MAPK pathways—JNK, MAPK/ERK, and p38 MAPK—and on Akt in PSCs derived from the control and the cerulein-treated pancreas (Fig. 5). Levels of phosphorylated JNK and, to a much lesser extent, phosphorylated MAPK/ERK were higher in the PSCs derived from the cerulein-treated pancreas relative to controls and were further increased after halofuginone treatment. Equal levels of phosphorylated Akt and p38 MAPK were observed in PSCs derived from control and cerulein-treated mice and were unaltered after halofuginone treatment.

Halofuginone Affects Cerulein-Dependent Acinar Cell Proliferation and PAP-1 Synthesis

Fully differentiated pancreatic acinar cells are capable of replication and can reenter the cell cycle to restore lost acinar tissue.[44] Only a small number of PCNA-positive acinar cells were detected in the untreated pancreas, whereas after cerulein treatment, a major increase in PCNA-positive cells was observed (Fig. 6). Halofuginone prevented this increase only in the early stages of pancreas fibrosis development. In pathologic situations, the acinar cells are the main source of PAP-1.[33] Almost no PAP-1 was synthesized by the control untreated pancreas or by the pancreas of mice treated with halofuginone alone. Cerulein caused increased PAP-1 synthesis, which was more evident after 4 weeks of treatment, and halofuginone caused a further increase in this synthesis (Fig. 7).

DISCUSSION

Chronic pancreatitis is characterized by pancreatic inflammation and fibrosis, eventually leading to destruction of pancreatic parenchyma and loss of exocrine and endocrine functions. In response to pancreatic injury or inflammation, PSCs are activated into highly proliferative myofibroblastlike cells that express smooth muscle proteins and produce ECM components. Administration of cerulein caused a major increase in the synthesis of fibrosis-related and TGFβ-dependent proteins such as collagen type I and P4Hβ (Fig. 1), consistent with other models of pancreatitis.[34,35] Halofuginone inhibited PSC activation, in agreement with previous observations of inhibition of HSC and tumor myofibroblast activation,[20,22,23] as evidenced by the following findings. (1) There was inhibition of synthesis of collagen type I, the major ECM protein, and of P4Hβ, the main enzyme responsible for its cross-linking (Fig. 1). The Sirius red staining that remained after halofuginone treatment may partly represent collagen type III, which also increases in pancreas fibrosis[35] but is not affected by halofuginone.[36] Halofuginone also inhibited collagen synthesis in severe hyperstimulation and obstruction pancreatitis in rats.[37] (2) There was inhibition of the expression of specific markers expressed in activated PSCs, such as Cygb/STAP, and of TGFβ-dependent increases in muscle-specific genes such as SM22α (Figs. 2A, B). (3) There was inhibition of PSC proliferation (Fig. 2C). All of the inhibited parameters are characteristic of activated PSCs. Transforming growth factor β is known to regulate PSC activation and to inhibit its proliferation. Although halofuginone inhibited TGFβ signaling, incubation of the PSC with halofuginone resulted in a dose-dependent inhibition of cell proliferation (Fig. 2C). These results suggest that halofuginone may have additional targets involved in cell proliferation, for example, within the MAPK signaling pathway (Fig. 5).

The course of chronic pancreatitis is characterized by recurrent episodes of acute pancreatitis, which cause parenchymal injury and necrosis, accompanied by fibrosis, chronic inflammation, and parenchymal cell loss, all of which increase with each successive episode. Hypoxia and hypoxia-related genes are upregulated during cerulein-induced acute pancreatitis.[38] It is interesting to note that the synthesis of Cygb/STAP and collagen P4Hβ is controlled by hypoxia.[39,40] Cytoglobin/stellate cell activation–associated protein is probably involved in cellular oxygen homeostasis and supply and plays a role as an oxygen reservoir that is used under hypoxic conditions to protect the tissue from oxidative stress.[41]

Regardless of the cause of the insult resulting in pancreas fibrosis, extensive ECM remodeling is required. In the first

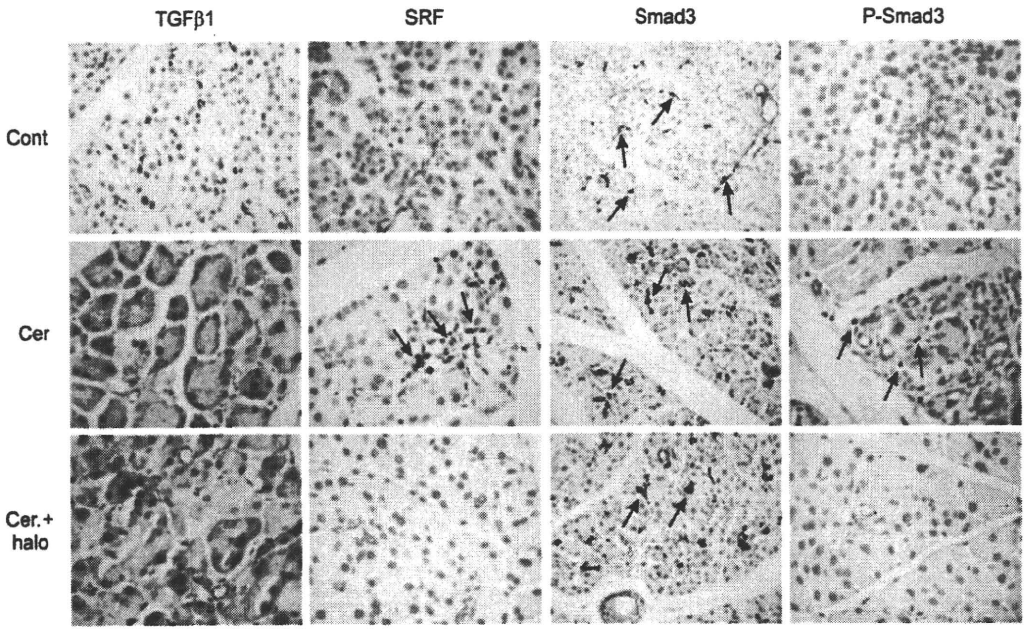

FIGURE 4. Halofuginone and TGFβ signaling. Transforming growth factor β, SRF, Smad3, and P-Smad3 levels were determined by immunohistochemistry in pancreas biopsies after 8 weeks of cerulein treatment, with or without halofuginone. Cells expressing the specific proteins are indicated by arrows. Note that halofuginone did not affect TGFβ levels but prevented the cerulein-dependent increases in SRF and P-Smad3, but not Smad3, levels.

step, transient local degradation of the ECM occurs, either by proteases of the plasminogen or by the MMP systems. The balance between the MMPs and their inhibitors is pivotal in the remodeling of the ECM. Tissue inhibitors of MMP-1 and TIMP2, derived from the activated PSCs,[16] are increased in the pancreas of cerulein-treated mice (Fig. 3A). Although both TIMPs are under the control of TGFβ, the regulation of TIMP1 is probably not Smad3-dependent. The Smad-containing complexes do not interact with the promoter-proximal activator protein 1 site of TIMP1 that is required for TGFβ activation; therefore, TGFβ was able to stimulate TIMP1 synthesis in a Smad-knockout cell line.[42] This could explain the observation that halofuginone, an inhibitor of Smad3 phosphorylation downstream of TGFβ signaling[21,23] (Fig. 4), inhibited only the synthesis of TIMP2 but not that of TIMP1 (Fig. 3A), as has been observed in chemically induced liver fibrosis.[20] Pancreatic stellate cells have the capacity to synthesize a number of MMPs under the control of TGFβ.[16] The PSCs derived from cerulein-treated mice exhibited much higher MMP-2 activity than those derived from the control mice, and the difference persisted even after several passages in culture (Fig. 3C). This may imply a fundamental genomic change while they are in the fibrotic tissue, or it may reflect the disparity in their origin. Halofuginone prevented the TGFβ-dependent increase in MMP-2 activity in both cell populations (Fig. 3D), but it increased MMP-3 activity only in the cells derived from cerulein-treated mice. These results are consistent with the effects of halofuginone on MMP activity observed in HSCs in culture and in rat hepatic-induced fibrosis.[43]

Transforming growth factor β is synthesized by the PSCs and was upregulated in the cerulein-treated pancreas (Fig. 4). Halofuginone, which has been found to overcome TGFβ-induced collagen synthesis without affecting TGFβ receptor expression,[23] did not affect TGFβ levels in the cerulein-treated mice, suggesting that halofuginone's target is probably downstream of the TGFβ-receptor interaction, along the Smad3 pathway. Indeed, halofuginone decreased the levels of P-Smad2/3 in the cerulein-treated pancreas without affecting the total level of Smad3, in agreement with previous findings.[21,23] Smad3, in conjunction with SRF, is a major mediator of TGFβ signaling, which results in transcription of smooth muscle–specific genes.[11] Serum response factor induces smooth muscle cell (SMC) gene expression, and the dominant-negative mutant of SRF blocks TGFβ-induced SMC genes.[44] In activated HSCs, TGFβ upregulates SRF synthesis, resulting in SMC gene expression.[45] The entire conditional inactivation of the SRF gene in the pancreas leads to severe pancreatitis,[46] although in the present study, in the cerulein-treated pancreas, SRF was upregulated exclusively by the PSCs, probably because of cerulein-dependent increases in TGFβ synthesis and Smad3 phosphorylation (Fig. 4). Halofuginone inhibited SRF synthesis without affecting the level of TGFβ, which again suggests that halofuginone inhibits smooth muscle gene expression and ECM production by inhibiting Smad3 phosphorylation downstream of TGFβ signaling, resulting in inhibition of PSC activation.

The PSCs derived from the pancreas of cerulein-treated mice exhibited much higher levels of phosphorylated JNK and, to a lesser extent, of MAPK/ERK, but not of p38 kinase or Akt. Halofuginone further increased JNK phosphorylation in the cerulein-treated PSCs. The JNK has been implicated as a repressor of TGFβ gene expression, and it contributes to the regulation of autocrine TGFβ-mediated biologic responses,[47] suggesting that there is cross-talk between the 2 signaling pathways. It is interesting to note that halofuginone causes increased phosphorylation of c-Jun transcription factor, a major JNK substrate, in Tsk/+ mouse fibroblasts in culture and in vivo, in correlation with a decrease in collagen synthesis.[48]

Halofuginone affects not only the stellate cells but also the epithelial cells of the tissue. In the liver, halofuginone stimulates insulin growth factor binding protein 1 synthesis by the hepatocytes, and the secreted insulin growth factor binding

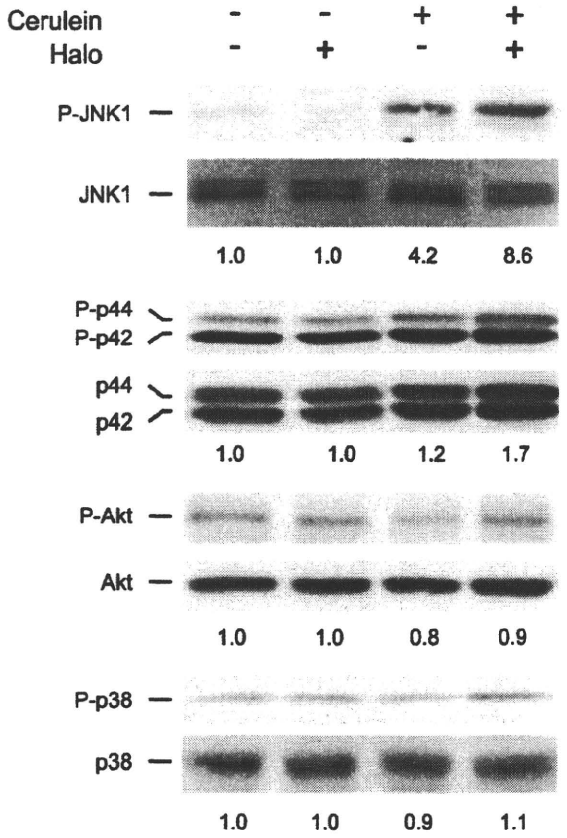

FIGURE 5. Halofuginone and JNK, MAPK, and Akt signaling in PSCs. Cells derived from the pancreas of control and cerulein-treated mice were cultured in the presence or absence of halofuginone (20 mmol/L). At the end of the incubation, cell extracts were blotted with the appropriate antibodies. Halofuginone further increased the cerulein-dependent phosphorylation of JNK and, to a lesser extent, the phosphorylation of MAPK/ERK. No effect of cerulein or halofuginone on Akt or p38 phosphorylation was observed.

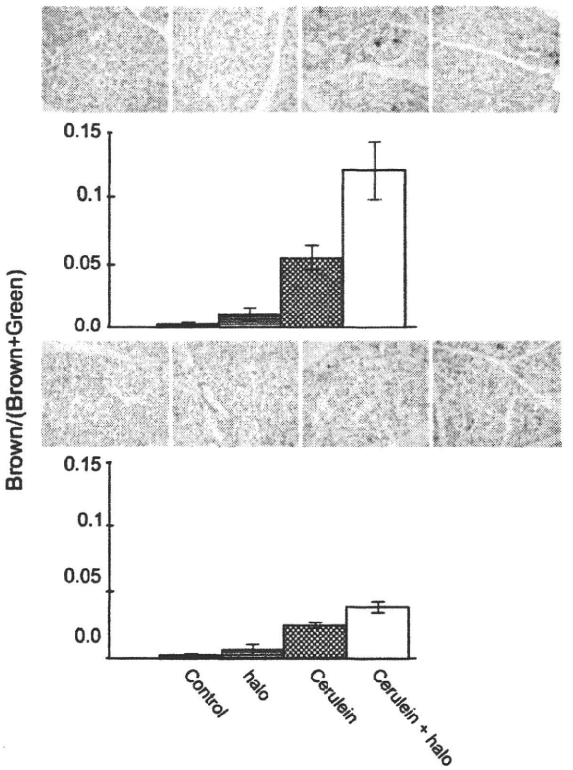

FIGURE 7. Halofuginone and PAP-1 synthesis. Pancreas biopsies were taken after 4 and 8 weeks of cerulein treatment, with and without halofuginone, immunostained with PAP-1 antibodies, and subjected to image analysis. In each panel, means without a common letter differ significantly ($P < 0.05$) according to Duncan multiple range test.

protein 1 inhibits HSC migration.[27] In the pancreas, PAP-1 is expressed at a level related to the severity of cerulein-induced pancreatitis in the acute phase.[49] Halofuginone prevented the cerulein-dependent increase in acinar cell proliferation and increased the synthesis of anti-inflammatory cytokine PAP-1 (Figs. 6, 7), which may further reduce PSC activation and matrix synthesis, by inhibiting inflammation. Halofuginone also inhibited rat inflammation after severe hyperstimulation and obstruction pancreatitis.[37]

In conclusion, we demonstrated that halofuginone prevents cerulein-dependent PSC activation by inhibiting Smad3

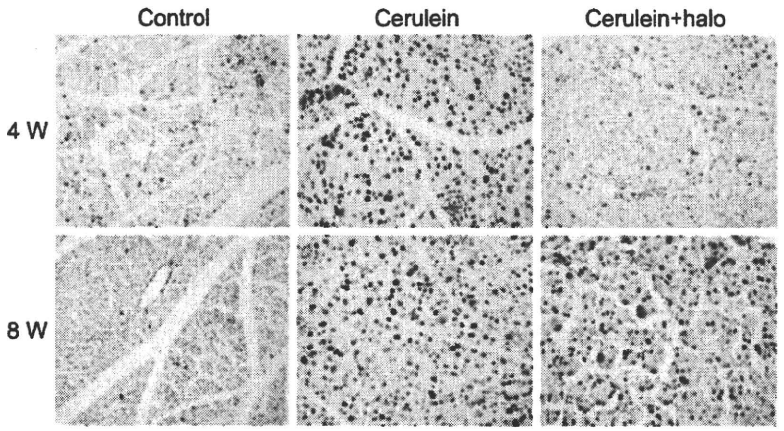

FIGURE 6. Halofuginone and acinar cell proliferation. Pancreas biopsies were taken after 4 and 8 weeks of cerulein treatment, with and without halofuginone, and were immunostained with PCNA antibodies. Halofuginone prevented the increase in acinar cell proliferation after only 4 weeks of treatment.

phosphorylation downstream of TGFβ signaling and via JNK phosphorylation. In addition, halofuginone increases the synthesis of the anti-inflammatory cytokine PAP-1 by the acinar cells, which can further reduce pancreas fibrosis. These results suggest that halofuginone, which has already exhibited human clinical efficacy[25,29] and is currently being evaluated in clinical trials for various indications,[50] could serve as a novel therapy for pancreas fibrosis.

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series モデル動物利用マニュアル

生物機能モデルと新しいリソース・リサーチツール

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第1節　マウス
第2項　ヒト型マウス

（3）ヒト肝臓置換ヒト型マウス

1. はじめに

人間が健康的な生活を維持するためには疾病の治療・克服が必要であり，現代においても既知疾患や新規感染症に対して，より効果的でより安全な新薬の開発が途切れることなく続けられている。このような新薬の開発には，ヒトでの有効性や安全性を推測するための実験データが必要であり，多くの場合には実験動物を利用して得られた結果より外挿されている。しかし，実験動物から得られた結果には，種の違いから生じる様々な“差”が含まれており，この差が原因となって新薬開発に遅延が生じるケースは数多く，新薬を待望する人々にとっての障害となっている。このような新薬開発の遅延を防ぐためには，可能な限り早い時点でヒトまたはヒトに限りなく近い環境での実験データを得ることが必要と考えられる。㈱フェニックスバイオ(広島県東広島市)が生産するヒト肝細胞キメラマウスは，ヒト肝細胞がマウス肝臓内で持続的かつ機能的に存在している点で，肝臓に関して限りなくヒトに近い環境を提供するモデル動物である。

このヒト肝細胞キメラマウスの作製には，現在までに少なくとも8つの研究団体が成功している。Dandri[1]らドイツのグループおよびMercer[2]らカナダのグループ(2001年)，我々のグループ[3](2004年)，Meuleman[4]らベルギーのグループ(2005年)，Morosan[5]らフランスのグループ(2006年)，Azuma[6]ら米国のグループ(2007年)およびSuemizu[7]ら日本のグループ(2008年)である。これらの団体が生産するヒト肝細胞キメラマウスには，肝障害と免疫不全の形質を併せ持つホストマウスを用いている点とヒト肝細胞を注入移植している点が共通している。我々は，2004年よりヒト肝細胞キメラマウスの生産を開始している。

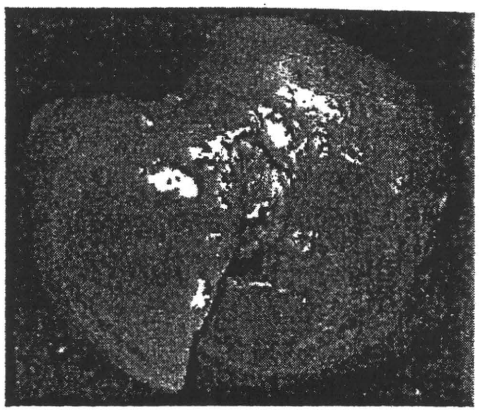

図1　PXBマウス肝臓(13週齢)

70%以上のマウス肝細胞がヒト肝細胞に置換されている。

我々が生産するヒト肝細胞キメラマウスの特徴は，ヒト肝細胞によるマウス肝細胞の置換率が70％以上という基準を満たしている点である(図1)。この基準を満たしたヒト肝細胞キメラマウスを，フェニックスバイオではPXBマウス®と称し，ヒト肝細胞に関連する様々な研究を目的とした受託試験に利用可能なリソースとして生産する体制を築いてきた。現在では，1ヵ月あたりのPXBマウスの生産数が150～200匹，総移植動物数に占めるPXBマウスの歩留りがおよそ60％であり，同一のヒト肝細胞ロットによるPXBマウスの供給期間は1年以上という体制が整っている。

本稿では，ヒト肝細胞に関連する研究分野におけるPXBマウスの有用性についてまとめる。

2. PXBマウスの生産

PXBマウスの生産には，ヒト肝細胞とホストマウスが必要となる。我々がPXBマウスの生産に利用しているヒト肝細胞は，インフォームドコンセントに基づいてドナーから提供された米国からの輸入凍結ヒト肝細胞である。

我々がPXBマウスの生産用に用いているホストマウスは，urokinase-type plasminogen activator (uPA)の過剰発現に由来する肝障害の形質を持つマウス(B6SJL-TgN(Alb1Plau)144Bri，遺伝子型：$uPA^{+/+}$)と，機能的なTおよびBリンパ球欠失に由来する重症複合免疫不全の形質を持つマウス(Fox Chase SCID C.B-17/Icr-*scid*/*scid* Jcl，遺伝子型：SCID)の2つの系統を交配させることによって得られたマウスであり，遺伝子型は$uPA^{+/+}$/SCIDである。

$uPA^{+/+}$マウスは，Heckel[8]らによって作製されたトランスジェニックマウスであり，導入遺伝子には，直列に並んだ5つのmouse uPA遺伝子とalbumin enhancer/promoter，さらにhuman growth hormone(hGH)の配列の一部が含まれている。uPAは生体内において，セリンプロテアーゼ活性によりプラスミノーゲンをプラスミンに変換し，フィブリンを溶解する役割を担っている。通常，野生型マウス体内での血漿中uPA濃度は0.5 ng/mL以下(ELISAを用いたuPA濃度測定による)であるが，$uPA^{+/+}$マウスでは，胎仔肝細胞でアルブミン産生が開始されると同時にalbumin enhancer/promoterによって肝細胞特異的にuPAの産生が誘導されて細胞外に分泌されるため，出生時にはuPAが高発現した状態にある。血漿中uPA濃度は，出生後にピーク値5.0 ng/mLと野生型マウスの10倍高値を示した後に少しずつ低下する推移を示す[9]。このような胎仔期～新生仔期のuPA過剰生産によって，$uPA^{+/+}$マウスの肝臓は，肉眼的に白色(図2)を呈しており，組織学的には肝細胞の細胞質に微細な顆粒に取り囲まれた小胞が蓄積している像が確認される[9]。肝機能の指標となるALTは高値を示しており[9]，肝障害の形質が発現していることが確認できる。また，細胞の有糸分裂機能は正常であるものの，細胞内で発現するuPAによって細胞増殖が抑制され，細胞増殖頻度が低下している[9]。これらの現象が，移植されたヒト肝細胞の増殖に適した生体内環境を提供していると考えられている。一方，$uPA^{+/+}$マウスでは，少ない頻度ながらも細胞増殖が成立する過程において，uPA遺伝子の欠失が起ることが報告されている[9]。本来，直列に5つ導入されたuPA遺伝子うちのいくつかが欠失すると，肝細胞内でのuPA発現量が低下し，マウス肝細胞は本来の性状を取り戻して活発な増殖を開始して肉眼的に正常な肝細胞の色調(小豆色または赤色)を呈する斑状の領域を形成する。このuPA遺伝子欠失領域は，$uPA^{+/+}$マウスにおいて10週齢以降に発生することが報告されており[9]，当所におけるホストマウスにおいても同様に確認されている。

図2　ホストマウス肝臓(4週齢)

ヒト肝細胞移植前

ホストマウスに必要な免疫不全の形質を持つSCIDマウスは，Bosmaらによって発見された点突然変異体であり，その変異は，DNA依存性タン

パク質リン酸化酵素のサブユニットP350に発生している[10]。SCIDマウスは，機能的なTおよびBリンパ球を欠くことで重度の免疫不全状態を示し，多くの異種動物間移植実験において利用されている。PXBマウスの生産においても，SCIDの形質はヒト肝細胞を寛容するため必須の役割を果たしている。

ヒト肝細胞とホストマウスを利用する移植作業と移植後のモニタリングの内容は，次の通りである。ヒト肝細胞は，移植当日に融解し，浮遊した状態に調製した後に移植に利用する。また，ホストマウスには，週齢2～4かつ体重6～8 gの仔動物を選択している。ホストマウスに麻酔を施した状態で右横臥位に保定し，左側腹部を開腹した後に脾臓を露出させる。その後，ヒト肝細胞をマウス1匹あたりおよそ0.2～1.0×10^6 cellsの細胞数で脾臓内に注入移植し，切開部を縫合する。

脾臓内に注入移植されたヒト肝細胞は，門脈を経由して肝臓に達した後に類洞からディッセ腔へと移動し，その後生着した部位で増殖・分化のサイクルを繰り返すと考えられている。ヒト肝細胞が，ディッセ腔へと到達する詳細なメカニズムは明らかになっていないが，我々は，セリンプロテアーゼ活性を持つuPAによる影響ではないかと考えている。

ディッセ腔に生着・増殖・分化したヒト肝細胞では機能的な細胞活動が営まれるため，主要な遺伝子の発現やタンパク質合成・分泌が観察される。我々は，マウス肝臓組織内に占めるヒト肝細胞の割合の増加に伴って，マウス血液中に分泌されるヒト肝細胞由来タンパク質の濃度が増加することを利用してヒト肝細胞による置換率を予想している。予想に利用しているタンパク質は，ヒトアルブミン(h-Alb)であり，移植後3週間以降，血液をサンプルとして免疫比濁法により血中h-Alb濃度測定を実施している。図3には，PXBマウスの規格(ヒト肝細胞による予想置換率：70％以上，週齢：10～14，体重：12 g以上)を満たす個体群

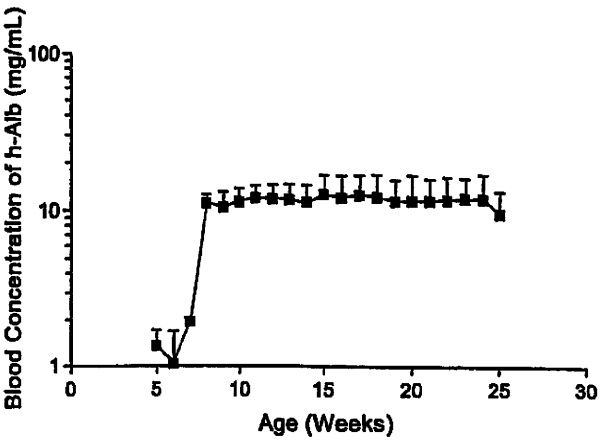

図3　PXBマウスの血中ヒトアルブミン濃度推移

10週齢を経過すると血中h-Alb濃度は安定して推移する。

での血中h-Alb濃度推移を示した。5～9週齢(移植後2～6週間)にかけて顕著なh-Alb濃度の上昇が確認される。この時期はPXBマウスの肝臓内でヒト肝細胞が対数増殖期にあると考えている。10週齢を経過すると，血中h-Alb濃度はプラトーに達する。

ヒト肝細胞による置換率の予測は，血中h-Alb濃度測定結果とヒト肝細胞置換率測定結果との相関曲線に基づいて実施される。相関曲線を求めるために，ヒト肝細胞に特異的に結合する抗ヒトサイトケラチン8/18(hCK8/18)抗体を用いた免疫組織化学染色によってヒト肝細胞置換率を求めている(図4)。染色に用いる肝組織片は，1個体の肝臓につき7つの葉から1ヵ所ずつ採取しており，各々の試料についてhCK8/18免疫染色を施した後，画像解析によって組織断面積に占めるヒト肝細胞の割合を算出している。図5には，5才，男児，黒人ドナーの肝細胞を用いて作製したPXBマウスの血中h-Alb濃度測定結果とヒト肝細胞置換率測定結果との相関曲線を示す。血中h-Alb濃度がヒト肝細胞置換率と高い相関関係にあることが明らかであり，その関係が指数関数で示されていることが確認できる。このようなリファレンスデータの収集は，PXBマウス生産用に採用される

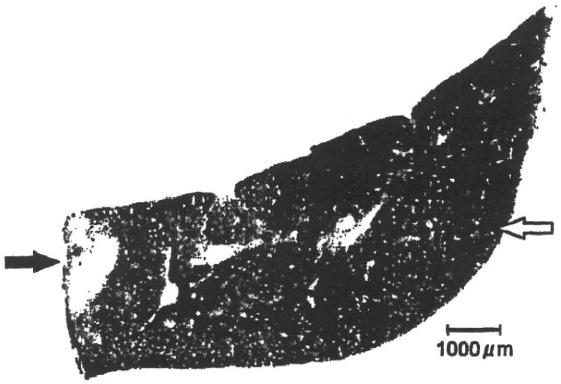

図4　抗ヒトサイトケラチン8/18抗体を用いた免疫組織化学染色

PXBマウスでは70％以上のマウス肝細胞がヒト肝細胞によって置換されている。
黒矢印：マウス肝細胞領域，白矢印：ヒト肝細胞領域

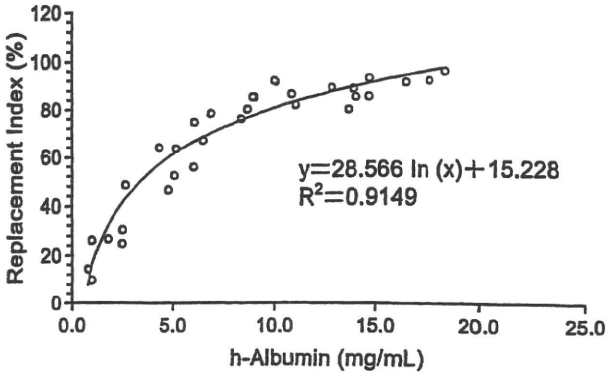

図5　PXBマウスの血中ヒトアルブミン濃度測定結果とヒト肝細胞置換率測定結果との相関曲線

血中ヒトアルブミン濃度とヒト肝細胞置換率が高い相関性を示す。

表1　ホストマウスおよびPXBマウスの飼育条件

仕　様	ISO14644-1 清浄度クラス6相当
温　度	20～26℃
湿　度	42～72％
室　圧	ホストマウスコロニーおよびPXBの生産飼育施設では陽圧制御，P2A実験施設では陰圧制御を実施
照明時間	12時間周期(8:00～20:00)
換　気	常時換気(HEPAフィルターろ過)
飼育ケージ	ポリカーボネート製マウス用ケージ
床　敷	実験動物用床敷ペパークリーン
飼　料	γ線照射滅菌した，げっ歯類用飼料チャールスリバーフォーミュラー(CRF-1)を自由摂取させている。PXBマウスには特別にビタミンCを添加したCRF-1を与えている。この他，SCIDの形質を持つキメラマウスおよびホストマウスへのカリニ肺炎病原体の感染を防御する目的で，スルフォメトキサゾールおよびトリメトプリム配合した特殊飼料を所定の期間中に給餌している。
飲　水	東広島市水道局より供給される水道水をオートクレーブ滅菌した後，次亜塩酸を添加したものをマウス用給水ボトルに容れ，自由摂取させている。

全ての凍結ヒト肝細胞ロットについて個別に実施されている。

3. PXBマウスの飼育

以上に紹介した方法で生産したPXBマウスの飼育は，ホストマウスと共に微生物学的清浄度が維持されたクリーンルームで行われている(表1)。これは，SCIDの形質を保有する動物を微生物感染から保護することを目的とした対応である。適切な飼育環境を与えることで，PXBマウスは10週間以上安定した体重推移(図6)と血中h-Alb濃度推移(図3)を維持することができる。ただし，死亡率は無処置の飼育期間中であっても1週間におよそ1.5％という数値を示している。