Invited Mini-review

CYP-humanized and Human Liver Chimeric Mouse Models for Studying Xenobiotic Metabolism and Toxicity

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ABBREVIATIONS: CYP, cytochrome P450; WT, wild-type
Preclinical evaluation of drug candidates in experimental animal models is an essential step in drug development. Humanized mouse models have emerged as a promising alternative to traditional animal models. The purpose of this mini-review is to provide a brief survey of currently available mouse models for studying human xenobiotic metabolism. Here, we describe both genetic humanization and human liver chimeric mouse models, focusing on the advantages and limitations while outlining their key features and applications. Although this field of biomedical science is relatively young, these humanized mouse models have the potential to transform preclinical drug testing and eventually lead to a more cost effective and rapid development of new therapies.
INTRODUCTION

Translating a drug from discovery to human therapy relies heavily on data from preclinical studies in animal models. However, many drug candidates fail during clinical trials because the experimental animal models used in preclinical studies poorly predict human xenobiotic metabolism. Such failures are caused in part by species differences in drug metabolizing enzymes (DME), which have evolved and adapted to the different metabolic conditions of each species. Mice, for instance, have an expanded set of DMEs referred to as the P450 cytochromes (CYPs). In mice, these DMEs are encoded by 72 functional genes, whereas humans possess only 27 (Nelson et al., 2004). Thus, drugs are often metabolized differently in mice and in humans. Reactive drug metabolites drive toxicity and their presence or absence is determined by the species-specific set of DMEs. Therefore, preclinical testing using a “humanized” system would be desirable before starting a clinical trial with a new drug.

There is growing interest and practice in utilizing humanized mouse models to overcome species differences in drug metabolism; the list of available humanized mouse models is rapidly expanding. Thus, although the topic has been frequently reviewed (Strom et al., 2010; Shen et al., 2011; Yoshizato et al., 2012; Kitamura and Sugihara, 2014; Sanoh and Ohta, 2014; Scheer and Wolf, 2014; Stiborova et al., 2014; Gonzalez et al., 2015; Scheer and Wilson, 2016; Yamazaki et al., 2016), it is worthwhile to revisit and update in the context of this special edition on humanized models of xenobiotic metabolism and toxicity.

It is necessary to stress that humanized mouse models are not humans. Though many of the available mouse models are valuable for revealing important aspects of human xenobiotic metabolism and response, none can perfectly replicate the human response. The purpose of this mini-review is to provide a brief survey of currently available mouse models for studying human
xenobiotic metabolism by outlining their key features, limitations, and application notes, in hopes of helping the readers to identify the appropriate models for their specific application. Efforts are made to discuss CYP-humanized mouse models, where one or more mouse CYPs are replaced by relevant human CYPs, together with human liver chimeric mouse models, where much of the mouse liver is replaced by human hepatocytes, given the current debate on the relative merits of the two distinct types of models.

### CYP-HUMANIZED MOUSE MODELS

CYP-humanization in mice typically involves cross-breeding of a human CYP-transgenic mouse model with a relevant mouse-Cyp knockout mouse model, or knocking in the human genes to replace the mouse genes. The human transgene fragment may include a single CYP gene or multiple neighboring CYP genes that are in close proximity and may share regulatory elements. The relevant knockout mouse may have one or multiple mouse Cyp genes deleted. The tissue specificity and expression levels of the human CYP transgene are not always identical to the situation in humans for a given transgenic mouse model. Thus, an effective application of a CYP-humanized mouse model for studying xenobiotic metabolism or toxicity requires detailed knowledge of the characteristics of each transgenic model as well as the mouse-Cyp knockout model utilized. Unfortunately, some of reported mouse models have not been characterized as thoroughly as others, which limits their usefulness for broad application.

Most human CYPs that are involved in xenobiotic metabolism, including members of the CYP1-4 gene families, have been introduced into the mouse genome as a transgene, as shown in Table 1. The reported characteristics of these human CYP-transgenic mouse models are summarized here, including the origin of the human transgene used for model generation, nature
of the promoter and regulatory components that control the expression of the transgene, and the main tissue sites of reported transgene expression. Additional information, such as transgene inducibility, occurrence of sexual dimorphism, and means of humanization, that are relevant to the usefulness or limitation of a given model, is further considered. Where available, applications of CYP-humanized mouse models in xenobiotic metabolism or toxicity studies, are briefly described. Discussions are organized by CYP gene families and subfamilies.

CYP1

*CYP1A1* and *CYP1A2* are neighboring genes arranged in a head-to-head orientation, which made it practical and necessary to produce a transgenic mouse that harbors both human genes (Jiang et al., 2005). Given the use of a Bacterial Artificial Chromosome (BAC) clone containing ample regulatory sequences of the human genes, both CYP1A1 and CYP1A2 are expressed in the same tissues in mice as in humans and demonstrate the expected inducibility by aryl hydrocarbon receptor (AhR) ligands (Jiang et al., 2005; Dradin et al., 2007; Shi et al., 2008). Humanization was made possible by crossing the *CYP1A*-transgenic mouse to the *Cyp1a1/1a2*-null mouse. Expression of the transgene supported effective disposition of oral benzo(a)pyrene (BaP) and provided partial rescue of BaP-induced toxicological phenotypes in the null mice (Dragin et al., 2007). This humanized mouse model has also been used to demonstrate ability of the human CYP1A transgenes to mediate PhiP (2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine, a dietary carcinogen)-induced colon carcinogenesis; the humanized model showed colon tumorigenesis under conditions that did not yield detectable tumors in wild-type (WT) mice (Cheung et al., 2011). More recently, the same model was utilized to show the role of human CYP1As in PhiP-induced
prostate carcinogenesis (Li et al., 2012) and the inhibitory effects of different forms of tocopherol on prostate cancer development (Chen et al., 2016).

CYP1A1/1A2-humanized mice have also been applied to studying drug metabolism. In one study utilizing the human-CYP1A1/1A2-transgenic/Cyp1a2-null mouse, the role of the human CYPs in theophylline disposition was demonstrated (Derkenne et al., 2005). Although the necessity to pre-induce transgene expression with a CYP1A inducer (2,3,7,8-tetrachlorodibenzo-p-dioxin, or TCDD, in this case) makes the study complicated to conduct and interpret, the fact that human CYP1A-specific metabolites are formed in vivo illustrated the potential utility of the model for in vivo drug metabolism studies. Two recent papers also described the utility of a newly generated CYP1A1/1A2-humanized model in studying the disposition of anticancer drugs; however, details regarding the mouse model were not provided (Lin et al., 2017; MacLeod et al., 2018).

Several issues may complicate the data interpretation or limit application of the current CYP1A1/1A2-humanized mouse model. Due to technical difficulties in separating human CYP1A1 and CYP1A2 proteins on immunoblots, the absolute levels of these proteins in various tissues of the transgenic or humanized mice have not been determined. The Cyp1a1-null mice were reportedly hyperresponsive to BaP-induced expression of Cyp1b1, which was not overcome by the transgenic expression of the human CYP1As (Dragin et al., 2007); it is unclear whether this property extends to induction of Cyp1b1 by other inducers. Given the overlapping substrate specificity between CYP1A1 and 1A2 and their known common responses to inducers, it would also be advantageous to have mouse models that express only one human CYP1A.

Although a human CYP1B1 transgenic mouse with an inducible tetracycline promoter was reported many years ago (Hwang et al., 2001), the model was not utilized for studies on CYP1B1.
function. A CYP1B1-humanized mouse model was recently generated by cross-breeding between a human \textit{CYP1B1}-BAC transgenic mouse and a \textit{Cyp1b1}-null mouse (Li et al., 2014a). Although this model contained the endogenous human promoter, constitutive expression of human CYP1B1 mRNA in the mouse liver and extrahepatic tissues was much lower than that of mouse CYP1B1; but human CYP1B1 protein was detectable in the liver after induction with TCDD (Madeen et al., 2017). The transgenic expression of human CYP1B1 was insufficient to drive dibenzo[def,p]chrysene-induced transplacental carcinogenesis according to comparisons of lung tumor data from WT, \textit{Cyp1b1}-null, and CYP1B1-humanized mice (Madeen et al., 2017). Further characterization of the constitutive and inducible expression of the human \textit{CYP1B1} transgene, particularly in extrahepatic target tissues, would facilitate application of the model in xenobiotic metabolism and toxicity studies.

CYP2

A \textit{CYP2A6}-transgenic mouse model was developed using the CYP2A6 cDNA driven by a liver-specific murine transthyretin promoter/enhancer (Zhang et al., 2005). CYP2A6 protein level in the transgenic mouse liver was within the range observed in human liver microsomes; however, the use of a surrogate promoter prohibits utility of the mouse model to study the transcriptional regulation of the \textit{CYP2A6} gene. The transgenic mouse liver displayed significantly higher coumarin 7-hydroxylation activities than WT mice, both \textit{in vitro} and \textit{in vivo}. Efforts are underway in the Ding laboratory to humanize CYP2A6, by intercrossing the \textit{CYP2A6}-transgenic mouse with the \textit{Cyp2abfgs}-null mouse, which has all \textit{Cyp} genes in the mouse \textit{Cyp2a, 2b, 2f, 2g,} and \textit{2s} subfamilies deleted (Li et al., 2014b). The resultant CYP2A6-humanized mouse should be valuable for studying the function of hepatic CYP2A6 in drug metabolism and chemical toxicity.
Nonetheless, a CYP2A6-BAC transgenic mouse that demonstrates human-like CYP2A6 expression in hepatocytes as well as extrahepatic tissues such as the lung is still needed.

A CYP2A13/2B6/2F1-transgenic mouse model was developed using a BAC clone containing the three closely situated genes CYP2A13, CYP2B6, and CYP2F1 (Wei et al., 2012). The tissue distribution of transgene expression closely resembled the known profile in humans, with a respiratory tract-selective expression of CYP2A13 and CYP2F1 and a hepatic expression of CYP2B6. Three humanized versions of this mouse model have been described. The initial study of a humanized model on a Cyp2a5-null background revealed the remarkable ability of the human transgenes to mediate lung tumorigenesis induced by the carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butane (NNK) (Megaraj et al., 2014). The same model was utilized to demonstrate the ability of lung inflammation to suppress CYP2A13 expression in vivo (Wu et al., 2013; Liu et al., 2015). In contrast, studies on styrene lung toxicity, utilizing a CYP2A13/2B6/2F1-humanized model on the Cyp2f2-null background, suggested that the human transgenes did not play a significant role (Cruzan et al., 2013).

A newer version of the humanized mice was prepared on Cyp2abfgs-null background; this null mouse was resistant to NNK-induced lung tumorigenesis (Li et al., 2014b). Studies using the CYP2A13/2B6/2F1-humanized model on the Cyp2abfgs-null background confirmed that human CYP2F1 is functional in the bioactivation of naphthalene, an acute lung toxicant and lung and nasal carcinogen, and that CYP2A13 and 2F1 are capable of mediating naphthalene toxicity in the lung and nasal mucosa in vivo (Li et al., 2017).

The polygenic nature of the CYP2A13/2B6/2F1-humanized model may limit the ability to identify specific roles of each of the CYP transgenes in the metabolism or toxicity of a given compound. This was overcome in part by the generation of a CYP2A13 transgenic mouse model,
in which the neighboring CYP2F1 and CYP2B6 genes were inactivated through targeted mutations in the BAC genomic clone, while preserving the regulatory sequences (Jia et al., 2014). A comparison of the CYP2A13-humanized model and CYP2A13/2B6/2F1-humanized model provided definitive data to support the role of CYP2A13 in NNK bioactivation in the lung (Jia et al., 2014) and the respective activities of CYP2A13 and CYP2F1 toward naphthalene (Li et al., 2017).

The hepatic expression, induction, and activity of CYP2B6 have also been characterized in the CYP2A13/2B6/2F1-humanized mouse models (Liu et al., 2015). The transgenic CYP2B6 was highly induced by phenobarbital and dexamethasone, known inducers of CYP2B6 in human liver, though a sexual dimorphism in the induction was observed, with males being more responsive to the inducers. The transgenic CYP2B6 was active in the metabolism of bupropion, a known CYP2B6 substrate drug; it also contributed to systemic clearance of nicotine. Notably, constitutive expression of CYP2B6 in the liver is low in this model (Li et al., 2018); studies on the in vivo roles of hepatic CYP2B6 in xenobiotic metabolism and toxicity should examine both naïve and inducer-treated mice.

Three different human CYP2C-transgenic mouse models have been reported. One was a CYP2C8-transgenic mouse, which, together with a human CYP2J2-transgenic mouse, was developed using human cDNA driven by the murine endothelium-specific Tie2 promoter (Lee et al., 2010). These mouse models, which were generated to study the role of renal CYP epoxygenase function in the regulation of blood pressure, have not been humanized (i.e. the corresponding mouse Cyps have not been removed). A CYP2C9-humanized mouse model was generated on a Cyp2c-null background; the CYP2C9 transgene was driven by the liver-specific albumin promoter while 14 of the 15 functional mouse Cyp2c genes (except Cyp2c44) were deleted (Scheer et al.,...
The transgenic CYP2C9 was active toward known CYP2C9 substrates tolbutamide and diclofenac (Scheer et al., 2012a). A CYP2C18/2C19-transgenic mouse was generated using a BAC genomic clone containing the complete CYP2C18/CYP2C19 genes (Lofgren et al., 2008). CYP2C18 and CYP2C19 mRNA expression exhibited sexual dimorphism in the transgenic mouse, in an apparent tissue-specific manner (Lofgren et al., 2008), and both genes were subject to regulation by androgen and growth hormones (Lofgren et al., 2009). Functional CYP2C19 protein was expressed mainly in the male mouse liver, as evidenced by microsomal immunoblot analysis and activity toward two known CYP2C19 substrates, R-omeprazole and S-mephenytoin; CYP2C18 protein was not detected in either liver or kidney. It is anticipated that a humanized version of the CYP2C18/2C19-transgenic mouse would be useful for in vivo studies of CYP2C19-mediated xenobiotic metabolism or toxicity in male mice.

Several CYP2D6 transgenic mouse models have been reported. The first CYP2D6-transgenic mouse was generated using a phage genomic clone containing the entire CYP2D6 gene and flanking sequences (Corchero et al., 2001). The model was referred to as a humanized mouse, since the mouse CYP2D enzymes have little activity toward some of the human CYP2D6 substrates, e.g., debrisoquine. Transgenic CYP2D6 was expressed in multiple mouse tissues, including liver, small intestine and kidney, as in humans; but, unlike in humans, the transgenic CYP2D6 was not expressed in the brain (Corchero et al., 2001; Miksys et al., 2005). This mouse model was used extensively to study the in vivo role of CYP2D6 in the metabolism of drugs, such as debrisoquine, and of various endogenous compounds, particularly the role of CYP2D6 in the metabolism of amines like serotonin (Yu et al., 2004; Cheung and Gonzalez, 2008; Shen and Yu, 2009; Wu et al., 2009; Winter et al., 2011). It has also been used to study in vivo regulation of CYP2D6 expression (Koh et al., 2014; Pan and Jeong, 2015; Pan et al., 2015; Kent and Jeong,
A second CYP2D6-transgenic mouse model was generated using a P1 artificial chromosome clone containing the complete human CYP2D locus; it was found to have CYP2D6 expression in the brain as well as in other tissues (Cheng et al., 2013). However, as far as we know, this model has not been used for the study of xenobiotic metabolism. Neither model has been crossed to a Cyp2d-null background.

A series of three CYP2D6-humanized mice (encoding CYP2D6.1, CYP2D6.2, and a novel CYP2D6 variant, CYP2D6.N) were produced on a Cyp2d-null background, using an expression cassette derived from a CYP2D6 BAC clone; the cassette consisted 9 kbp of promoter region and 3’-untranslated region, as well as all exons and introns, from a novel CYP2D6 allele (Scheer et al., 2012b). The CYP2D6.1 and CYP2D6.2 expression cassettes were produced via coding region modifications of the CYP2D6.N cassette. The CYP2D6.1 strain was only characterized on a heterozygous Cyp2d-null background, but the other two strains, particularly CYP2D6.2, were more thoroughly characterized. All three transgenic proteins were expressed in liver and intestine and metabolized known CYP2D6 substrates bufuralol or debrisoquine. One of these strains, CYP2D6.2, was used to study the role of CYP2D6 in the metabolism of primaquine (Potter et al., 2015) and the interaction between tamoxifen and several antidepressants, such as paroxetine, that are both substrates and inhibitors of CYP2D6 (MacLeod et al., 2017).

Two different human CYP2E1-transgenic mice have been reported. The first model was developed using a CYP2E1 cDNA driven by the murine albumin enhancer/promoter (Morgan et al., 2002). Given the known regulation of CYP2E1 expression by posttranslational mechanisms, it was not surprising that the transgenic protein was induced by chronic alcohol treatment. This overexpression model was used for studying role of CYP2E1 in alcohol-induced liver injury and other pathological changes (Butura et al., 2009) (Kathirvel et al., 2009), but the model has not been
humanized. Another CYP2E1-transgenic mouse model was developed using a BAC clone consisting of the complete CYP2E1 gene; the model was then humanized on the Cyp2e1-null background (Cheung et al., 2005). The humanized model was utilized to demonstrate the ability of human CYP2E1 in mediating acetaminophen-induced liver toxicity (Cheung et al., 2005) and ethanol-induced liver injury (Cederbaum, 2010; Lu et al., 2010).

CYP3

Several versions of human CYP3A-transgenic mice have been reported. A CYP3A4-transgenic mouse model was developed using a BAC clone consisting of the complete CYP3A4 gene (Granvil et al., 2003). CYP3A4 was expressed mainly in the small intestine of adult male mice in this model, which was utilized to demonstrate the importance of intestinal CYP3A4 in the first-pass metabolism of midazolam and the interaction between midazolam and ketoconazole (Granvil et al., 2003). Hepatic CYP3A4 expression was largely influenced by age and sex in this model (Yu et al., 2005), a phenomenon also observed in a BAC CYP3A4/3A7-transgenic mouse (Cheung et al., 2006; Felmlee et al., 2008) and an intercrossed CYP3A4/2D6-double transgenic mouse (Felmlee et al., 2008). The BAC clone that was used for the generation of the above CYP3A4-transgenic mice was further utilized to generate a new mouse model that harbored the CYP3A4 and CYP3A7 genes and are humanized for PXR (Ma et al., 2008). Notably, hepatic CYP3A4 expression in this mouse model still showed age-dependent suppression in adult males. Nonetheless, the incorporation of PXR humanization added a new dimension for application in drug metabolism research (Cheng et al., 2009; Cheng et al., 2011; Holmstock et al., 2013).

None of the above CYP3A4-transgenic strains was on a Cyp3a-null background, in contrast to another type of models where all or most of the endogenous mouse Cyp3a genes have been
removed, such as the “multiple humanized” Cyp3a-null (except for Cyp3a13) mouse model - the CYP3A4/3A7/PXR/CAR-humanized mouse (Hasegawa et al., 2011a). In a further improvement, humanized CYP2C9, CYP2D6, CYP3A4/7 models were combined with humanized PXR and CAR through sequential cross-breeding (Scheer et al., 2015). Both models have seen effective application (MacLeod et al., 2015; Chang et al., 2016; Ly et al., 2017; McMillan et al., 2018).

The transgenic expression and function of CYP3A7, which is restricted to the embryo in humans, have not been studied as extensively as for CYP3A4. An early model using CYP3A7 cDNA driven by the mouse metallothionein promoter supported CYP3A7 expression in adult tissues and demonstrated apparent activity toward aflatoxin B₁ (Li et al., 1996). The transgenic CYP3A7 from the CYP3A4/3A7 BAC transgenic mouse was developmentally regulated by glucocorticoids (Pang et al., 2012). However, few studies have examined role of CYP3A7 in fetal drug metabolism using these models.

In a different approach than BAC transgenesis, two similar lines of CYP3A4-transgenic mice were generated using CYP3A4 cDNA driven by the human Apolipoprotein E promoter (van Herwaarden et al., 2005). Transgenic CYP3A4, which was active toward cyclosporin and midazolam, was selectively expressed in the liver and, at lower levels, kidney. A complementary model developed using CYP3A4 cDNA driven by the mouse villin promoter was also generated, which expressed CYP3A4 selectively in duodenum, jejunum, ileum, and colon (van Herwaarden et al., 2007). Both models were humanized on the Cyp3a-null background. The two humanized models are not amenable for studies of transcriptional regulation of CYP3A4 or drug-drug interactions at the gene regulation step, as the CYP3A4 expression is controlled by heterologous promoters, rather than by the authentic human CYP3A4 promoter. However, they are valuable for studying the respective contributions of CYP3A4 in the two organs for the disposition of a variety
of drugs, as well as the impact of the interactions among the drugs on CYP3A4 enzyme function (van Herwaarden et al., 2007), (van Waterschoot et al., 2009; van Waterschoot et al., 2010; Mitsui et al., 2014; Choo et al., 2015) (Zhang et al., 2016).

A CYP3A (3A4, 3A5, 3A7, 3A43) (human artificial chromosome) transgenic mouse, humanized on a Cyp3a-null background, has also been reported; the transgenic CYPs showed human-like tissue specificity and developmental regulation, as well as ability to metabolize marker substrates for CYP3A4 and CYP3A7 (Kazuki et al., 2013). Notably, while this model does not show the age-dependent hepatic CYP3A4 suppression that was found in male CYP3A4-BAC transgenic mice (Yu et al., 2005), CYP3A4 expression level was significantly lower in males than in females (Kobayashi et al., 2017). The fetal expression of functional CYP3A7 in this mouse model allowed it to be used for demonstrating the ability of the human transgenes to support thalidomide-induced embryonic toxicity (Kazuki et al., 2016). However, the CYP3A5 transgene was of the non-expressed *3 allele, which has since been converted using gene editing technology to the *1 allele, yielding the first CYP3A-humanized mouse model with functional CYP3A5 protein in the liver and intestine (Abe et al., 2017).

CYP4

Few models of human CYP4 transgenic mice have been reported. Two lines of CYP4A11 transgenic mouse were generated using a BAC clone (Savas et al., 2009); the model has been utilized to study CYP4A11 regulation and protein modification, as well as its role in 20-hydroxyeicosatetraenoic acid (HETE)-dependent hypertension (Savas et al., 2016; Albertolle et al., 2017). A CYP4B1 transgenic mouse was prepared using CYP4B1 cDNA driven by the human apolipoprotein E gene promoter for hepatic expression; the transgenic CYP4B1 was active toward
lauric acid and 2-aminoﬂuorene (Imaoka et al., 2001). A CYP4F2-transgenic mouse was prepared using CYP4F2 cDNA driven by a kidney androgen-regulated protein (KAP) promoter for production of a His-tagged CYP4F2 protein in the renal proximal tubule epithelial cells; the protein was active in production of 20-HETE (Liu et al., 2009). None of these have been humanized or utilized for studies of drug metabolism.

**Challenges of genetic humanization**

Besides the many obvious advantages and successful applications, as described above, humanization by exchanging murine genes with their human orthologs (genetic humanization) also has some potential limitations.

1. **Species difference in regulation of the human CYP transgene.** Despite the efforts to humanize some relevant nuclear factors, such as PXR and CAR, the human CYP transgene(s) may be regulated by other factors, some of which we may not know or may not be able to humanize. Such differences in regulation may lead to species-specific drug-drug interactions that result from drug-induced changes in CYP expression in humanized mice, but not in humans, or vice versa.

2. **Incomplete humanization of all pathways and events related to drug absorption, distribution, metabolism, and disposition.** Species differences in competing phase I metabolism pathways, phase II metabolism, or transporters can affect in vivo pharmacokinetic outcome.

3. **Challenges in studying genetic variants.** Genetic polymorphisms of human CYP genes can be studied in the mouse models, but it may not be cost-effective. With the rapid advancement of the
gene editing technology, it is easier than ever to generate mice that produce variant CYP proteins for functional analysis. However, the large number of these variants, the lack of complete understanding of non-coding sequences’ role in transgene expression, and the need to characterize each model once generated, can be cost- and time-intensive.

4. Lack of complete characterization. Most currently available models are incompletely characterized or documented. Some of these models were produced for a purpose other than xenobiotic metabolism, which impacted the extent to which the model was analyzed. Critical information regarding potential compensatory changes in the mouse DME genes is incompletely analyzed at best. At a minimum, the tissue distribution, levels of transgene protein expression, and inducibility at major sites of transgene expression should be determined and compared to those of humans. Information on developmental expression and sex differences in transgene expression, as well as activity of the transgenic human CYP toward known substrates, are also important to document.

Understanding the properties of a given model under study, including its limitations, will ensure proper experimental design. The factors to consider may include the selection of control mouse strains, selection of proper genetic background, inclusion of necessary in vitro studies and in vivo pharmacokinetic analysis of test compounds for efficacy studies, and inducibility of the transgene by test compounds. Furthermore, incorporation of pharmacological inhibition approach for validation, as well as confirmation of transgene expression in the specific conditions used for testing xenobiotic metabolism/toxicity are also useful. It may also be advisable to validate key
findings in additional mouse models, such as the human liver chimeric mouse models described below.

HUMAN LIVER CHIMERIC MOUSE MODELS

Development of human liver chimeric mice

An interesting alternative to the problems faced by genetic humanization is to develop human liver chimeric mice. Transplantation of entire human hepatocytes, instead of only replacing the gene of interest in mouse hepatocytes, leads to a cellular chimerism in the liver and circumvents some of the aforementioned challenges. Hepatocyte transplantation is usually done via splenic injection of mice (Ponder et al., 1991). The hepatocytes migrate from the spleen into the liver where they integrate into the hepatic plates of the murine liver. Hepatocytes have also been transplanted into sites other than the liver such as the lymph nodes (Komori et al., 2012) or peritoneal cavity (Strom et al., 1999), but the need for proper drainage of the bile limits the long-term benefit of ectopic hepatocyte transplantation. Three different models of human liver chimeric mice have been described.

The alb-uPA mouse. The principles of human liver chimerism were established using the transgenic alb-uPA mouse (urokinase-type plasminogen activator expressed under the albumin promoter), which was the first mouse model in which the liver could be repopulated with human hepatocytes (Dandri et al., 2001; Mercer et al., 2001). The alb-uPA mouse was developed as a coagulation model by Ralph Brinster’s and Richard Palmiter’s laboratories (Heckel et al., 1990). As expected, many of the alb-uPA mice died neonatally due to bleeding. About half of the transgenic pups survived but underwent liver failure a few weeks after birth. Interestingly, a few
mice survived this second crisis and uPA serum levels gradually returned to normal levels within two months. Analysis of these mice revealed healthy looking nodules within the liver, which expanded over months and eventually completely replaced the sick liver. Molecular analyses demonstrated a genetic rearrangement that partially excised the toxic transgene (alb-uPA) within the nodules, which lead to clonal expansion of transgene-deficient hepatocytes (Sandgren et al., 1991). This natural selection phenomenon was subsequently recognized as a promising approach to efficiently expand transplanted healthy hepatocytes in a diseased liver. Rhim et al. were the first to prove this hypothesis in the alb-uPA mouse using healthy murine hepatocytes as a donor source (Rhim et al., 1994). Eventually, two independent groups generated the first human liver chimeric mice, both using the alb-uPA strain (Dandri et al., 2001; Mercer et al., 2001). The alb-uPA/SCID mouse, which is also immune deficient to prevent donor cell rejection, can reach high human chimerism (Tateno et al., 2004).

The pioneering work done in the alb-uPA strain opened the door to hepatocyte repopulation and particularly to human liver chimerism. However, the alb-uPA mouse has several disadvantages, (see below and Table 2); therefore updated versions of this strain (Weglarz et al., 2000; Suemizu et al., 2008; Tesfaye et al., 2013; Tateno et al., 2015) as well as new mouse genotypes amenable to human hepatocyte transplantation were developed (Washburn et al., 2011; Borel et al., 2017). We will limit this mini-review to human liver chimeric mice with high degree of human chimerism (>70% of the liver), which is essential for many in vivo applications, including drug metabolism.

**The FRG mouse.** Repopulation with nodules of healthy hepatocytes has also been observed in patients with hereditary tyrosinemia type I (HT-I) (Kvittingen et al., 1993). In this
case, the point mutation underlying the genetic disorder in the fumarylacetoacetate hydrolase (FAH) gene reverted to the WT allele (Kvittingen et al., 1994) by somatic mutation. Analogous to the rearranged uPA transgenic hepatocytes, the corrected FAH hepatocytes possess a growth advantage over the mutant cells and clonally expand to form nodules. This information in hand, it was apparent that the Fah^{-/} mouse could be repopulated with WT murine hepatocytes (Overturf et al., 1996) as shown previously for the uPA mouse (Rhim et al., 1994). Although Fah^{-/-} mice were similarly neonatally lethal, they had an advantage over the transgenic uPA predecessors: the toxicity resulting from the mutated Fah gene could be regulated by the small molecule drug nitisinone. After Fah^{-/-} mice receive transplantations, nitisinone is withdrawn to apply selection pressure for the transplanted, FAH-positive hepatocytes. In 2007, two groups independently established the Fah^{-/-}/Il2rg^{-/-}/Rag2^{-/-} (FRG) mouse strain as a human liver chimeric mouse model (Azuma et al., 2007; Bissig et al., 2007). Their results were comparable and demonstrated robust repopulation of adult FRG mice with both fresh and cryopreserved human hepatocytes. In addition, Azuma et al. showed serial transplantation of human hepatocytes in FRG mice (Azuma et al., 2007), while Bissig et al. demonstrated neonatal hepatocyte transplantation and viral transduction of transplanted human hepatocytes (Bissig et al., 2007). Humanized FRG mice were healthy and could achieve high human chimerism (<95% human)(Bissig et al., 2010).

The TK-NOG mouse. More recently, the TK-NOG mouse has been developed (Hasegawa et al., 2011b) for human liver chimerism. This strain contains the transgenic herpes simplex virus type 1 thymidine kinase (HSVtk) under the albumin promoter. HSVtk phosphorylates the drug ganciclovir, which leads to intoxication of the cell, while human hepatocytes without the transgene are not sensitive to the drug. Ganciclovir is administrated before the hepatocyte transplantation,
inducing intoxication of murine hepatocytes. In principle, this murine specific intoxication could be used repeatedly even after the human hepatocytes are transplanted, however, none of TK-NOG publications describe such a repeated application. This mouse strain has also been shown to reach high human chimerism both by immunostaining and by human albumin levels in the murine serum (Hasegawa et al., 2011b).

Utility of human liver chimeric mice for drug metabolism

Since the primary site of drug metabolism is the liver, human liver chimeric mice are an attractive alternative to conventional animal models when it comes to in vivo validation of a new drug. All three human liver chimeric mouse models discussed here have been used for drug studies: human toxicity (Yamamoto et al., 2007; Sato et al., 2008; Foster et al., 2012; Kakuni et al., 2012; Samuelsson et al., 2014; Xu et al., 2014; Xu et al., 2015), human drug metabolism profiling (Katoh et al., 2007; Inoue et al., 2008; Lootens et al., 2009a; Lootens et al., 2009b; Lootens et al., 2009c; Pozo et al., 2009; Lootens et al., 2011; Samuelsson et al., 2012; Sanoh et al., 2012b; Sanoh et al., 2012c; Schulz-Utermoehl et al., 2012; Yamazaki et al., 2012; Nishimura et al., 2013; Tanoue et al., 2013; Bateman et al., 2014; Samuelsson et al., 2014; Kamimura et al., 2015; Nakada et al., 2015; Wilson et al., 2018), drug-drug interaction (Hasegawa et al., 2012; Nishimura et al., 2013; Yamazaki et al., 2013; Suzuki et al., 2017; Uchida et al., 2018), human pharmacogenetic studies (Hu et al., 2013; Nishiyama et al., 2015), or other DME studies (Katoh and Yokoi, 2007; Inoue et al., 2009; Sanoh et al., 2012a; Schulz-Utermoehl et al., 2012; Tsukada et al., 2013; Suemizu et al., 2014; Nishiyama et al., 2015; Sanoh et al., 2015; Utoh et al., 2016; Kamimura et al., 2017; Shimizu et al., 2017; Yamazaki-Nishioka et al., 2018). A detailed analysis of all these studies is beyond the
scope of this review; we will confine our review to a few examples illustrating the utility of human liver chimeric mice for drug studies.

A recent study by Xu et al exemplifies the advantages of using human liver chimeric mouse models for hepatotoxicity over current preclinical models. In this study, the authors tested the dose response of the drug fialuridine (FIAU) in highly humanized TK-NOG mice (PMID:24736310). FIAU is a nucleoside analogue developed to treat hepatitis B viral infections. FIAU did not present any toxicity in preclinical animal models but was terminated in phase II clinical trials due to lactic acidosis in patients after long-term exposure to the drug, which led to liver complications and pancreatitis (PMID:7565947). The authors showed a dose-dependent liver toxicity in the human liver chimeric mouse group as opposed to the non-humanized control group. After 4 days of treatment with the highest dose of FIAU (400 mg/kg), only the chimeric group appeared lethargic and presented lactate and ALT elevations in plasma. Histologically, the liver tissue of these mice presented accumulation of lipids in the human regions but not in the corresponding mouse areas. Furthermore, analysis by electron microscopy demonstrated mitochondrial abnormalities in the human hepatocytes, which was previously demonstrated to be the cause of liver failure in humans.

Another study by Nakada showed that chimeric mouse models were able to generate specific human metabolites that are not present in other species (PMID:28194636). The glucuronide metabolite M1 of YM543, a selective inhibitor of the sodium-glucose co-transporter, was only detected in the blood and urine of humans and humanized uPA/SCID mice, but not the other species tested (cynomolgus monkey, rhesus monkey, marmoset, beagle dog, NZW rabbit, Hartley guinea pig, golden hamster and ICR mouse). Moreover, in vitro studies incubating human hepatocytes with YM543 did not show the presence of M1 metabolite, which demonstrates the
ability of chimeric mouse models to predict human drug metabolites beyond those detected in cell culture platforms.

These two studies highlight the utility of human liver chimeric mice and their ability to identify "human-like" profiles for metabolites, toxicity, and drug-drug interactions. There is optimism that human liver chimeric mouse technology will become an essential element in preclinical drug development, since such models have several distinct advantages. In contrast to clinical trials, the effect of drugs can be tested in an isogenic context in human liver chimeric mice, meaning that the control groups are repopulated with hepatocytes from the same donor. Hence, the experimental read-out is not biased by polymorphisms in CYPs or other drug processing enzymes. Alternatively, donor hepatocytes can be selected based on specific CYP profiles of particular relevance to the tested drug. From a practical standpoint, human liver chimeric mice offer the potential for gathering some unique data that are not available from clinical trials, in a controlled environment. The mice can be exposed to very high doses of an experimental drug, all the while the human liver tissue can be harvested and analyzed at any time after exposure – both settings are unlikely to be approved in clinical trials from an ethical perspective, yet deliver valuable information for moving a drug forward into the clinic. Despite these advantages, the field of human liver chimeric mice is still young and there is a lot of room for optimization and standardization.

Challenges of human liver chimeric mice

Besides the obvious benefits of using human liver chimeric mice for studying drug metabolism and toxicity, there are some general and model-specific limitations.
1. **Variability within human liver chimeric mice.** Contrary to inbred mice with a defined and well-characterized genotype and phenotype, human liver chimeric mice suffer from an increased variability. The variability is particularly related to the degree of human chimerism. It is difficult to control the degree of chimerism since many variables influence this outcome. Rigorous standard operating procedures can control some of this variation, but there is still much room for improvement in this area.

2. **Remaining murine liver and other drug metabolizing murine organs.** Current evidence suggests that a 100% humanization of the murine liver is not possible. We hypothesize that species incompatibilities are the main reason for this phenomenon, e.g. multiple ligand receptor systems that cannot communicate across the species barrier. Differences in fibroblast growth factor (Naugler et al., 2015) or growth hormone (Masumoto et al., 2007) signaling have been shown, with many more species-specific protein interactions likely. Irrespectively, the consequence of this limitation is that remaining murine liver cells express the full set of mouse DMEs. This is a significant problem since murine DMEs could be upregulated, or have higher affinities for certain drugs than their human counterparts. Also, some DMEs, such as the CYPs, have a high functional capacity; a reduction of the murine liver mass to 10% does not mean that the drug metabolizing capacity of the murine liver component is reduced to 10%. Additionally, all three chimeric mouse models (particularly the FRG mouse) have a higher incidence of murine liver cancer than WT mice. Although there might be little normal murine liver remaining in older mice, large areas of neoplastic tissue can contribute to drug metabolism in liver toxicity assays. Extrahepatic murine drug metabolism can also be a confounding problem, depending on the DMEs involved in a given drug’s metabolism.
3. **Immune deficiency in human liver chimeric mice.** The murine immune system has to be compromised in order to generate human liver chimeric mice. However, there are differences between mouse models. It seems clear that for all human liver chimeric mouse models T- and B-cell function needs to be eliminated, while there is a little bit more flexibility with NK cell function. For instance, the *alb-uPA* mouse has been crossed with the *Rag2<sup>−/−</sup>* (Dandri et al., 2001) strain (only T- and B-cell deficient) to successfully engraft human hepatocytes. This is in contrast to the *Fah<sup>−/−</sup>* mouse, which also requires depletion of NK cells (*Il2rg<sup>−/−</sup>*) for humanization (Bissig et al., 2007).

Many adverse drug reactions are mediated by the immune system. To detect such an event, a dual humanization with the hematopoietic system would be required. There are a few reports of such systems (summarized in (Bissig et al., 2016)); but further optimization is required in order to use these humanized mice for drug metabolism.

4. **Strain specific differences and limitations.** Human liver chimeric mice are bred on different genetic backgrounds. The importance of mouse genetic background has been well documented and elaborated for human hematopoietic xenograft models; however, the situation is not clear for human liver chimerism.

The model-specific limitations are related to the knockout gene or inserted transgene. Table 2 summarizes these challenges, which are often technical. Every model has limitations and no one is clearly superior to another. There has been only one group comparing two different human liver chimeric mouse models (*uPA* and *FRG*) using the same drug, troglitazone (Schulz-Utermoeohl et al., 2012; Samuelsson et al., 2014). That comparison was far from ideal, as the transplanted human hepatocytes were not from the same donor, the human liver chimeric mice were produced by different groups, and, most importantly, the mean human liver chimerism was different in the two
models. Nonetheless, analysis of troglitazone metabolites gave comparable results in humanized uPA and FRG mice (Schulz-Utermoehl et al., 2012; Samuelsson et al., 2014).

All these challenges, in combination with reduced scalability, appears to dampen the enthusiasm to broadly implement human liver chimeric mice in the pharmaceutical industry. Nevertheless, there have been several promising advancements in recent years and we expect that these kind of mouse models will increasingly be used.

**Next generation human liver chimeric mice**

Increasing human chimerism is essential when using human liver chimeric mice for drug metabolism studies; but, as discussed above, there are natural boundaries. Another way of increasing human over murine drug metabolism is to functionally inactivate mouse DME without reducing the murine liver tissue mass. A first such attempt was recently taken by crossing the Cyp3a knock-out mouse to the alb-uPA/SCID mouse (Kato et al., 2015; Nakada et al., 2015). Unfortunately, these mice upregulate the expression of several other CYP gene clusters, which defeats the purpose of the model. Therefore, we recently introduced a new humanized mouse strain in which we functionally inactivated all murine microsomal CYPs. This was achieved by using a conditional knockout of the NADPH-P450 oxidoreductase (Por^c/c) (Gu et al., 2003; Henderson et al., 2003; Wu et al., 2003), the electron donor for all microsomal CYPs. When combined with the Il2rg^−/−, Rag2^−/− and Fah^−/−, the novel PIRF strain was generated (Barzi et al., 2017). Humanized PIRF mice demonstrate higher levels of human-specific drug metabolites when compared to humanized FRG or non-humanized PIRF mice (Barzi et al., 2017). Ideally, the Por^c/c technology would be combined with new mouse strains that do not have higher incidence of murine liver
cancer, but for the time being this is a safe way of inactivating neoplastic and residual mouse liver drug metabolism.

**Perspectives**

Advancements in genetics and techniques to manipulate the mouse embryo have allowed generation of genetically humanized mouse models. Many CYP clusters have been humanized and used for a better understanding and prediction of human drug metabolism. The transcriptional and posttranscriptional regulation of these transgenic human CYPs is complex and may not be identical to their regulation in human cells, even though some improved mouse models (with inclusion of humanized transcriptional regulators) have been generated. In addition to further optimized CYP-humanized mouse models that will be developed as a result of continued efforts to increase the degree of genetic humanization, human liver chimeric mice are emerging as a promising alternative. These cellular chimeras have a very similar DME expression profile as human livers (Tateno et al., 2004); but their utility will be at the cost of other technical challenges, particularly the high experimental variability even in the hands of specialists. Nevertheless, overcoming these challenges is possible and a broader implementation of this technology seems likely.

In summary, there is clearly a need for better models for predicting human drug metabolism and toxicity. Currently available mouse models of genetic humanization and cellular chimeras both have their own advantages and limitations, and their usage should be determined by the scientific question under study. Recent advancements in gene cloning and editing technologies have accelerated the rate at which these models can be improved, and it is possible that humanized mouse models will transform preclinical drug testing in the near future.
Authorship Contributions

Wrote or contributed to the writing of the manuscript: KB, WH, MB, NK, LD, XF, FPP, QZ, XD
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Footnotes

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Conflict of Interest Statement

M.B. F.P.P and K.D.B. have financial interest in Avachrome Inc.
### TABLE 1. Human CYP-transgenic and CYP-humanized mouse models

<table>
<thead>
<tr>
<th>Model</th>
<th>Human CYP transgene structure</th>
<th>Promoter</th>
<th>Mouse gene knockout for humanization</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYP1A1/1A2-transgenic</td>
<td>Gene (BAC&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>Authentic&lt;sup&gt;c&lt;/sup&gt;</td>
<td>None</td>
<td>(Jiang et al., 2005)</td>
</tr>
<tr>
<td>CYP1A1/1A2 humanized</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>Cyp1a1.1a2-null</td>
<td>(Dragin et al., 2007)</td>
</tr>
<tr>
<td>CYP1B1-transgenic</td>
<td>cDNA</td>
<td>Tetracycline-regulated promoter</td>
<td>None</td>
<td>(Hwang et al., 2001)</td>
</tr>
<tr>
<td>CYP1B1 humanized</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>Cyp1b1-null</td>
<td>(Li et al., 2014a)</td>
</tr>
<tr>
<td>CYP2A6-transgenic</td>
<td>cDNA</td>
<td>Mouse transthyretin promoter and enhancer</td>
<td>None</td>
<td>(Zhang et al., 2005)</td>
</tr>
<tr>
<td>CYP2A13/2B6/2F1-transgenic</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>Cyp2a5-null, Cyp2f2-null, Cyp2abfgs-null</td>
<td>(Megaraj et al., 2014), (Cruzan et al., 2013), (Li et al., 2014b)</td>
</tr>
<tr>
<td>CYP2A13/2B6/2F1 humanized</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>Cyp2a5-null, Cyp2f2-null, Cyp2abfgs-null</td>
<td>(Megaraj et al., 2014), (Cruzan et al., 2013), (Li et al., 2014b)</td>
</tr>
<tr>
<td>CYP2A13-humanized</td>
<td>Gene (modified BAC)</td>
<td>Authentic</td>
<td>Cyp2abfgs-null</td>
<td>(Jia et al., 2014)</td>
</tr>
<tr>
<td>CYP2C8-transgenic</td>
<td>cDNA</td>
<td>Mouse Tie2 promoter and enhancer</td>
<td>None</td>
<td>(Lee et al., 2010)</td>
</tr>
<tr>
<td>CYP2C9-humanized</td>
<td>cDNA</td>
<td>Mouse albumin promoter</td>
<td>Cyp2e-null</td>
<td>(Scheer et al., 2012a)</td>
</tr>
<tr>
<td>CYP2C18/2C19-transgenic</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>None</td>
<td>(Lofgren et al., 2008)</td>
</tr>
<tr>
<td>CYP2D6-transgenic</td>
<td>Gene (PAC&lt;sup&gt;d&lt;/sup&gt;)</td>
<td>Authentic</td>
<td>None</td>
<td>(Cheng et al., 2013)</td>
</tr>
<tr>
<td>CYP2D6-humanized</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>Cyp2d-null</td>
<td>(Scheer et al., 2012b)</td>
</tr>
<tr>
<td>CYP2D6.1-humanized</td>
<td>Gene (modified BAC)</td>
<td>Authentic</td>
<td>Cyp2d-null</td>
<td>(Scheer et al., 2012b)</td>
</tr>
<tr>
<td>CYP2D6.2-humanized</td>
<td>Gene (modified BAC)</td>
<td>Authentic</td>
<td>Cyp2d-null</td>
<td>(Scheer et al., 2012b)</td>
</tr>
<tr>
<td>CYP2E1-transgenic</td>
<td>cDNA</td>
<td>Mouse albumin promoter or enhancer</td>
<td>None</td>
<td>(Morgan et al., 2002)</td>
</tr>
<tr>
<td>CYP2E1-humanized</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>Cyp2e1-null</td>
<td>(Cheung et al., 2005)</td>
</tr>
<tr>
<td>CYP2F2-transgenic</td>
<td>cDNA</td>
<td>Mouse Tie2 promoter and enhancer</td>
<td>None</td>
<td>(Lee et al., 2010)</td>
</tr>
<tr>
<td>CYP3A4-humanized</td>
<td>cDNA</td>
<td>Human ApoE promoter</td>
<td>None</td>
<td>(van Herwaarden et al., 2005)</td>
</tr>
<tr>
<td>CYP3A4-transgenic</td>
<td>cDNA</td>
<td>Human ApoE promoter or mouse villin promoter</td>
<td>Cyp3a-null</td>
<td>(van Herwaarden et al., 2007)</td>
</tr>
<tr>
<td>CYP3A4-transgenic</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>None</td>
<td>(Cheung et al., 2006)</td>
</tr>
<tr>
<td>CYP3A4-transgenic</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>None</td>
<td>(Ma et al., 2008)</td>
</tr>
<tr>
<td>CYP3A4/3A7-humanized</td>
<td>Gene (modified BAC)</td>
<td>Authentic (PXR-humanized)</td>
<td>None</td>
<td>(Hasegawa et al., 2011a)</td>
</tr>
<tr>
<td>CYP3A4/3A5<em>3/3A7/3A43</em>)-humanized</td>
<td>Gene (BAC&lt;sup&gt;c&lt;/sup&gt;)</td>
<td>Authentic (CYP3A5 not expressed)</td>
<td>Cyp3a-null</td>
<td>(Kazuki et al., 2013)</td>
</tr>
<tr>
<td>CYP3A4/3A5<em>1/3A7/3A43</em>)-humanized</td>
<td>Gene (modified BAC)</td>
<td>Authentic (CYP3A5 expressed)</td>
<td>Cyp3a-null</td>
<td>(Abe et al., 2017)</td>
</tr>
<tr>
<td>CYP4A11-transgenic</td>
<td>Gene (BAC)</td>
<td>Authentic</td>
<td>None</td>
<td>(Savas et al., 2009)</td>
</tr>
<tr>
<td>CYP4B1-transgenic</td>
<td>cDNA</td>
<td>Human ApoE promoter</td>
<td>None</td>
<td>(Imaeda et al., 2001)</td>
</tr>
<tr>
<td>CYP4F2-transgenic</td>
<td>cDNA (expressing His-tag)</td>
<td>Mouse KAP promoter</td>
<td>None</td>
<td>(Liu et al., 2009)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Models that are derived via cross-breeding between two different human CYP-transgenic models are not included.

<sup>b</sup>BAC, Bacterial Artificial Chromosome

<sup>c</sup>Original human CYP promoter was contained in the transgene

<sup>d</sup>P1 phage artificial chromosome

<sup>e</sup>Human artificial chromosome
### TABLE 2

Comparisons among the three human liver chimeric mouse models

<table>
<thead>
<tr>
<th>Strain</th>
<th>uPA</th>
<th>FRG</th>
<th>TK-NOG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Development/Genotype</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Tesfaye, A. et al. (2013)^3 – mup-uPA/SCID/Bg</td>
<td>Fah^+/Rag2^-/Il2rg^+/+ (FRG)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Tateno, C. et al. (2015)^4 – alb-cDNA-uPA/SCID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mechanism of murine liver injury</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Intoxication by liver overexpression of urokinase plasminogen activator (uPA)</td>
<td>• Accumulation of toxic tyrosine catabolites</td>
<td>• Generation of a toxic ganciclovir metabolite by expression of Herpes Simplex Virus thymidine kinase in the liver</td>
<td></td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Most experience</td>
<td>• Inducible system</td>
<td>• Inducible system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Hepatocyte transplantation at any age</td>
<td>• Hepatocyte transplantation at any age</td>
<td></td>
</tr>
<tr>
<td><strong>Drawbacks</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Non-inducible murine liver injury due to a constitutive uPA expression 1,4</td>
<td>• Human hepatocyte repopulation requires small molecular drug (nitisinone)</td>
<td>• Repopulation efficiency more hepatocyte donor dependent than other models</td>
<td></td>
</tr>
<tr>
<td>• Narrow window of hepatocyte transplantation 1,2,4</td>
<td>• Kidney disease due to FAH deficiency</td>
<td>• Selection pressure only applied before hepatocyte transplantation</td>
<td></td>
</tr>
<tr>
<td>• High post-natal mortality due to internal bleeding 1,2,4</td>
<td>• Cancer model with frequent liver tumors</td>
<td>• Low breeding efficiency due to male sterility</td>
<td></td>
</tr>
<tr>
<td>• Spontaneous deletion of the uPA transgene decreases human hepatocyte repopulation and increases liver tumors incidence 1,2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>