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Abstract: The c-Jun N-terminal kinase (JNK) signaling pathway mediates adaptation to stress signals and has been associated with cell death, cell proliferation, and malignant transformation in the liver. However, up to now, its function was experimentally studied mainly in young mice. By generating mice with combined conditional ablation of Jnk1 and Jnk2 in liver parenchymal cells (LPCs) (JNK1/2\textsuperscript{LP C−KO} mice; KO, knockout), we unraveled a function of the JNK pathway in the regulation of liver homeostasis during aging. Aging JNK1/2\textsuperscript{LP C−KO} mice spontaneously developed large biliary cysts that originated from the biliary cell compartment. Mechanistically, we could show that cyst formation in livers of JNK1/2\textsuperscript{LP C−KO} mice was dependent on receptor-interacting protein kinase 1 (RIPK1), a known regulator of cell survival, apoptosis, and necroptosis. In line with this, we showed that RIPK1 was overexpressed in the human cyst epithelium of a subset of patients with polycystic liver disease. Collectively, these data reveal a functional interaction between JNK signaling and RIPK1 in age-related progressive cyst development. Thus, they provide a functional linkage between stress adaptation and programmed cell death (PCD) in the maintenance of liver homeostasis during aging.

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JNK signaling prevents biliary cyst formation through a CASPASE-8–dependent function of RIPK1 during aging

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The c-Jun N-terminal kinase (JNK) signaling pathway mediates adaptation to stress signals and has been associated with cell death, cell proliferation, and malignant transformation in the liver. However, up to now, its function was experimentally studied mainly in young mice. By generating mice with combined conditional ablation of Jnk1 and Jnk2 in liver parenchymal cells (LPCs) (Jnk1/2LPC-KO mice; KO, knockout), we unraveled a function of the JNK pathway in the regulation of liver homeostasis during aging. Aging Jnk1/2LPC-KO mice spontaneously developed large biliary cysts that originated from the biliary cell compartment. Mechanistically, we could show that cyst formation in livers of Jnk1/2LPC-KO mice was dependent on receptor-interacting protein kinase 1 (RIPK1), a known regulator of cell survival, apoptosis, and necroptosis. In line with this, we showed that RIPK1 was overexpressed in the human cyst epithelium of a subset of patients with polycystic liver disease. Collectively, these data reveal a functional interaction between JNK signaling and RIPK1 in age-related progressive cyst development. Thus, they provide a functional linkage between stress adaptation and programmed cell death (PCD) in the maintenance of liver homeostasis during aging.

Significance

JNK signaling has been studied intensively in models of liver physiology and disease, but previous studies had focused on young mice. However, it had not been recognized that JNK plays a fundamental role in maintaining liver homeostasis and preventing the formation of biliary cysts in aging mice. These observations call for caution in all long-term pharmacological inhibition strategies targeting the JNK pathway. Finally, our results provide evidence of a molecular link between JNK and the cell-death mediator RIPK1. The specific overexpression of RIPK1 in cysts of a subset of patients with polycystic liver disease suggests that RIPK1 might be mechanistically involved in the pathogenesis of human biliary cysts.

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The authors declare no competing interest.

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generated by combining Jnk1 floxed and Jnk2 floxed mice with albumin-Cre mice (5). While these mice showed a clear phenotype in the mediation of liver steatosis when fed a high-fat diet, a spontaneous phenotype of mice with conditional ablation of Jnk1 and Jnk2 was not reported until the age of 24 wk (5). Therefore, in the present study, we examined the potential roles of JNK signaling during aging and unraveled a role of JNK signaling in the maintenance of hepatic and biliary homeostasis.

Results

Combined Ablation of Jnk1 and Jnk2 in Liver Parenchymal Cells Triggers Intrahepatic Cyst Development in Aging Mice. To explore the hepatic function of the JNK pathway during aging, Jnk1FL (floxed, FL) mice and Jnk2FL mice were interbred with alfp-cre mice to generate animals with conditional deletion of Jnk1 (JNK1LPC-KO) (knockout, KO), Jnk2 (JNK2LPC-KO), or both Jnk1 and Jnk2 (JNK1/2LPC-KO) in liver parenchymal cells (LPCs) including hepatocytes and cholangiocytes, as JNK1/2−/− mice are embryonically lethal (SI Appendix, Fig. S1A and B) (6–9). Littermates carrying the respective loxP-flanked alleles but lacking expression of Cre recombinase were used as wild-type (WT) controls. We first examined JNK1LPC-KO and JNK2LPC-KO single-mutant mice at 6 and 52 wk of age and did not detect any phenotypic alterations at these time points (SI Appendix, Fig. S1C–F). Macroscopic and microscopic analyses of the liver did not reveal alterations in hepatic architecture (SI Appendix, Fig. S1 C–F). Moreover, serological analyses in 6- and 52-wk-old mice did not reveal alterations in alanine aminotransferase (ALT) and glutamate dehydrogenase (GLDH) levels between JNK1LPC-KO mice, JNK2LPC-KO mice, and WT control mice. Of note, JNK1LPC-KO mice showed slightly elevated alkaline phosphate (AP) levels at 6 wk of age, which were no longer altered at the age of 52 wk (SI Appendix, Fig. S1 D and F). AP levels of JNK2LPC-KO mice were comparable to those of WT animals in both age groups (SI Appendix, Fig. S1 D and F).

Given the functional redundancy between JNK1 and JNK2, we next analyzed mice with combined ablation of Jnk1 and Jnk2 in LPCs. At the age of 6 wk, livers of JNK1/2LPC-KO mice did not show macroscopic alterations and the liver weight-to-body weight ratios were comparable to WT animals (Fig. 1A and B). Interestingly, microscopic analyses of the livers of JNK1/2LPC-KO mice revealed the presence of necrotic areas, which had not been seen in single-Jnk mutant animals (Fig. 1A). In addition, these mice showed a profound change in liver architecture with increasing age. As such, at the age of 52 and 66 wk, JNK1/2LPC-KO mice developed large multilocular biliary cysts, which were visible macroscopically and microscopically (Fig. 1C and SI Appendix, Fig. S2A). In addition, analysis of 52-wk-old JNK1/2LPC-KO mice showed that the liver weight-to-body weight ratio was significantly lower compared to WT mice (Fig. 1D).

![Fig. 1. Combined deletion of Jnk1/2 in LPCs induces massive liver cyst formation in old mice. (A) Representative macroscopic liver pictures (Left), hematoxylin and eosin (H&E) staining (Middle), and pan-CK staining (Right) of 6-wk-old WT and JNK1/2LPC-KO animals. (B) Liver weight-to-body weight ratio of 6-wk-old WT and JNK1/2LPC-KO animals. n = 10. (C) Macroscopic picture (Left), H&E staining (Middle), and pan-CK staining (Right) of 52-wk-old WT and JNK1/2LPC-KO animals. (D) Liver weight-to-body weight ratio of 52-wk-old WT and JNK1/2LPC-KO and WT animals. n = 5. (E) Macroscopic picture (Left), H&E staining (Middle), and pan-CK staining (Right) of 52-wk-old JNK1/2Δhep and WT animals. (F) Liver weight-to-body weight ratio of 52-wk-old JNK1/2Δhep and WT animals. n = 10 to 20. n.s., not significant; *P < 0.05, ***P < 0.001.](https://doi.org/10.1073/pnas.2007194118)
double-knockout mice showed a significantly increased liver weight-to-body weight ratio compared with WT mice (Fig. ID). Histologically, cysts were lined by pan-cytokeratin–positive (pan-CK) biliary epithelial cells (Fig. IC and SI Appendix, Fig. S2A), similar to cysts found in human (hereditary) fibropolycystic diseases of the liver, such as Caroli disease/syndrome (SI Appendix, Fig. S2B) (10–13).

A previous study analyzed the protein profile of cyst fluids from different human polycystic liver diseases by mass spectrometry and found a serum-like protein pattern (14). To determine the protein profile of the cyst found in JNK1/2Δhep mice, we performed a mass spectrometry analysis, which also revealed a high content of proteins typical for serum samples like albumin, serotransferrin, complement 3, and various isoforms of α-1-antitrypsin (SI Appendix, Table S1 and Dataset S1). In addition, we could also detect unusually high levels of several nonserum proteins like clusterin, which is a predominantly serum protein linked to processes like regulation of inflammation, lipid transport, apoptosis, and cell differentiation (15, 16).

Conditional ablation of Jnk1 and Jnk2 in JNK1/2Δhep mice was driven by an αf–cre transgenic line, which mediates conditional ablation of floxed genes in hepatocytes, cholangiocytes, as well as hepatoblasts and precursor cells at embryonic day 10.5 (8, 17). To test if this unexpected cyst phenotype was independent of this specific cre line, we next generated conditional JNK1/2−cre transgenic line, which mediates conditional ablation of floxed genes in hepatocytes, cholangiocytes, as well as hepatoblasts and precursor cells at embryonic day 10.5 (8, 17). To test if this unexpected cyst phenotype was independent of this specific cre line, we next generated conditional JNK1/2Δhep mice with an alternative cre line widely used in the field, namely the albumin-cre line, which targets the same albumin-expressing cell compartment as the αf–promotor (17) (SI Appendix, Fig. S2C). Macroscopic and microscopic analyses of the livers of JNK1/2Δhep mice revealed that these mice also developed progressive biliary cysts with increasing age, which were clearly visible after 1 y (Fig. IE). They also showed increased liver weight-to-body weight ratios (Fig. IF), suggesting that the phenotype was not dependent on the alpha-feto-protein element activated in immature precursors of liver parenchymal cells in αf–cre mice. An in situ hybridization in 52-wk-old Jnk1/2Δhep mice also revealed that the deletion of Jnk remained stable throughout the aging process (SI Appendix, Fig. S2D). Importantly, we did not find any dysplastic changes in the progressed lesions in aged animals (up to 52 to 66 wk) nor invasive or infiltrative growth (Figs. IC and E and 2B and SI Appendix, Fig. S2A). Finally, we conclude that the cyst phenotype was caused by bacterial infection, we performed PCR for 16S ribosomal DNA in cyst tissue, which revealed no evidence of the presence of bacteria (SI Appendix, Fig. S2F).

Taken together, biliary cyst formation was observed in two distinct genetically modified mouse models with conditional hepatic ablation of Jnk1/2, showing that the phenotype occurred independent of the specific cre line used to target these floxed genes in parenchymal liver cells.

Combined Deletion of Jnk1 and Jnk2 in LPCs Is Associated with Spontaneous Liver Injury. Next, we aimed at analyzing the molecular mechanism underlying cyst development in mice with conditional ablation of Jnk1 and Jnk2 in parenchymal liver cells. JNK1/2ΔLPC mice displayed areas of liver cell necrosis already at a young age, indicating the potential involvement of programmed cell death (PCD) in the mediation of the phenotype of JNK1/2-deficient livers (Fig. I4) (18). Further, we measured serum levels of surrogate markers of liver and biliary injury in the distinct knockout models at 6 and 52 wk of age. This analysis revealed that ALT and GLDH levels were significantly increased in JNK1/2ΔLPC mice at 6 wk of age and remained high at 52 wk of age, suggesting that hepatocyte cell death and potentially necrosis might be involved in cyst formation (Fig. 2A and B). In contrast, AP as well as total bile acid levels as markers for cholestasis showed no significant elevation in JNK1/2ΔLPC mice at 52 wk of age when compared with control animals, indicating a functional biliary system in JNK1/2ΔLPC mice up to this age (Fig. 2A–C).

To further examine if—beyond the observed morphological signs of spontaneous necrosis in young JNK1/2ΔLPC mice (Fig. I4)—also apoptosis could be involved in the mediation of liver injury, we performed Western blot analysis for CASPASE-3 cleavage. This analysis revealed slightly increased levels of the cleaved form of CASPASE-3 in 6-wk-old JNK1/2ΔLPC mice (Fig. 2D). Together, these findings provided evidence that the development of biliary cysts in JNK1/2ΔLPC mice was associated...
with spontaneous necrosis and apoptosis of parenchymal liver cells.

**Cyst Formation in JNK1/2LPC-KO Mice Is Not Rescued by Genetic Inhibition of Apoptosis or Necroptosis.** In order to further dissect the molecular mechanism of biliary cyst development in Jnk1/2LPC-KO mice, we evaluated if blockage of either apoptosis or necroptosis might ameliorate this dramatic phenotype or might even rescue Jnk double-mutant mice from cyst development. To test this, we generated mice with combined deletion of Jnk1/2 together with either Caspase-8 (JNK1/2/CASP-8LPC-KO) or Mlkl (JNK1/2/MLKL-LPC-KO) (blockage of necroptosis) in LPCs (*SI Appendix*, Fig. S3A). Analysis of JNK1/2/CASP-8LPC-KO mice showed that the additional deletion of Caspase-8 did not rescue cyst formation at 52 wk of age (Fig. 3 A–C). Histological and immunohistochemical analyses confirmed the presence of biliary cysts (macroscopically and microscopically visible) and also necrotic areas in JNK1/2/CASP-8LPC-KO mice (Fig. 3 B and C). Further analysis of the liver weight-to-body weight ratios and additional quantification of the fluid-filled tissue cavities revealed no significant differences between JNK1/2/LPC-KO and JNK1/2/CASP-8LPC-KO mice (Fig. 3 C and D).

Since the inhibition of apoptosis in JNK1/2LPC-KO mice did not lead to a rescue of the liver cyst phenotype, we next examined the function of necroptosis in this model. Additional ablation of Mlkl in JNK1/2LPC-KO mice did not rescue from cyst development either and showed pronounced cyst formation in 52-wk-old mice (Fig. 3 A–C). Analysis confirmed a significant increase in liver weight-to-body weight ratios (Fig. 3D), while quantification of fluid-filled spaces showed no significant increase between JNK1/2LPC-KO and JNK1/2/MLKL-LPC-KO mice (Fig. 3E). Of note, the presumable necrotic areas remained present in 6-wk-old JNK1/2/MLKL-LPC-KO animals (Fig. 3B and *SI Appendix*, Fig. S3B), arguing that these necrotic areas did not reflect pure necroptosis. Neither additional deletion of Caspase-8 nor additional deletion of Mlkl led to a significant change in serum levels of ALT and GLDH (Fig. 3F).

**Cyst Development in JNK1/2LPC-KO Mice Is Mediated by a CASPASE-8–Related Function of RIPK1.** Based on the finding that—despite no changes in the overall degree of spontaneous liver injury measured by serum levels of liver enzymes like ALT—hepatic cyst development was not substantially influenced by genetic modifications of either Caspase-8 or Mlkl alone, we hypothesized that targeting simultaneously both cell-death pathways through additional deletion of Ripk1 in JNK1/2LPC-KO mice might rescue cyst formation (*SI Appendix*, Fig. S4A). Receptor-interacting protein kinase 1 (RIPK1) is a central molecule in the regulation of survival, apoptosis, and necroptosis and an important interaction partner of CASPASE-8 as well as mixed lineage kinase domain-like pseudokinase (MLKL) (20–24). In line with this hypothesis, we found RIPK1 expression up-regulated in cystic areas of JNK1/2LPC-KO mice (*SI Appendix*, Fig. S4B). Strikingly, additional deletion of Ripk1 prevented the development of macroscopically visible cysts in JNK1/2LPC-KO mice and almost completely rescued the biliary phenotype at the microscopic level (Fig. 4 A–C). In line with this, quantification of liver weight-to-body weight ratio and the area of fluid-filled cavities revealed significant reduction upon ablation of Ripk1 (Fig. 4 D and E). Interestingly, despite the rescue from cyst development, additional deletion of Ripk1 did not significantly alter ALT, GLDH, and AP serum levels (Fig. 4F and *SI Appendix*, Fig. S4C) but led to a significant reduction of the necrotic areas compared with JNK1/2LPC-KO animals, suggesting ameliorated but ongoing hepatocellular damage (*SI Appendix*, Fig. S4D).

We have previously shown that hepatocytic RIPK1 not only mediates cell death through its kinase activity but is also capable of inhibiting CASPASE-8–dependent apoptosis through a kinase-independent scaffolding function (24). In order to test the functional interaction of RIPK1 with CASPASE-8 in cyst formation of JNK1/2LPC-KO mice, we intercrossed JNK1/2RIPK1/CASP-8LPC-KO mice with Caspase-8LPC-KO mice (JNK1/2/RIPK1/CASP-8LPC-KO) (*SI Appendix*, Fig. S4A). Strikingly, the massive cyst phenotype, which was lost in JNK1/2/RIPK1LPC-KO mice, was fully restored in quadruple-knockout mice with an additional loss of Caspase-8 (Fig. 4 A–E). Of note, CASP-8LPC-KO mice did not show any signs of liver cyst formation with increasing age (*SI Appendix*, Fig. S4E). Additional deletion of Caspase-8 in JNK1/2RIPK1LPC-KO mice did not lead to a reinduction of the formation of necrotic areas, which again argues for divergent mechanisms leading to both a hepatocellular and biliary phenotype in JNK1/2LPC-KO mice (*SI Appendix*, Fig. S4D).

RIPK1 and CASPASE-8 were previously shown to have a cell death-independent function in the regulation of DNA-damage responses and compensatory proliferation as the basis of cancer development in the liver (25). To test if this respective pathway was specifically altered upon additional ablation of Ripk1 and Caspase-8, we performed immunohistochemical analysis of liver tissues from JNK1/2LPC-KO, JNK1/2/RIPK1LPC-KO, and JNK1/2RIPK1/CASP-8LPC-KO mice for markers of proliferation (Ki67) and DNA-damage responses (phosphorylation of histone H2A.X serine 139 [H2A.X]). Additional ablation of Ripk1 and Caspase-8 did not affect proliferation or DNA damage responses (Fig. 5A and Hepatocytes (Fig. 5B) and also did not change numbers in γH2A.X-positive LPCs (Fig. 5C) compared with JNK1/2LPC-KO mice. This argues against a role of DNA-damage response in the RIPK1/CASPASE-8–dependent mediation of the cyst phenotype in JNK1/2LPC-KO mice, suggesting that a cell-death function of RIPK1 may be responsible for the phenotype. This function might occur eventually on a single-cell basis, which is not reflected by conventional molecular analyses.

**Cyst Formation in JNK1/2LPC-KO Mice Primarily Originates from Cholangiocytes.** We finally aimed at further dissecting the cell type of origin for cyst development in JNK1/2LPC-KO mice. For this, we generated a mouse line with an inducible deletion of JNK1/2 primarily in the biliary cell compartment using the Sox9CreERT2 mouse line, which primarily targets the biliary cell compartment and additionally few single perportal hepatocytes (26). Of note, JNK1/2Sox9CreERT2 mice developed massive macroscopically and microscopically visible cysts, which resembled the phenotype of JNK1/2LPC-KO mice, 48 wk after tamoxifen injection (Fig. 6A). This finding provided evidence that the phenotype in JNK1/2LPC-KO mice arose dominantly from the biliary cell compartment.

To further substantiate this hypothesis, we performed a three-dimensional imaging analysis of the liver cysts in JNK1/2LPC-KO mice based on the reconstruction of optical serial immunofluorescence images to get a comprehensive understanding of the liver cyst origin, architecture, and connection to the biliary network (Fig. 6B). This interconnectivity analysis identified the cysts as focally dilated duct structures, which most likely originated from the intrahepatic ducts and ductules, whereas biliary metaplastic hepatocytes were not detected. An additional “surface reconstruction” showed a progressive stepwise cystic transformation of intrahepatic bile ducts in JNK1/2LPC-KO animals at the indicated ages and a morphological connection of these dilated structures, providing further morphological evidence that the cysts in JNK1/2LPC-KO, JNK1/2Ripk1, and JNK1/2Sox9CreERT2 mice arose from the biliary system itself rather than from, for example, transdifferentiated hepatocytes.

To further analyze the potential function of RIPK1 in Jnk1/2-deficient cholangiocytes, we performed a kinase activity-profiling microarray focusing on threonine/serine kinases. This array analyzes 144 peptide substrates with known phosphorylation sites.
Fig. 3. Additional deletion of Caspase-8 or Mikl does not significantly reduce cyst formation in JNK1/2LPC-KO mice. (A) Representative macroscopic liver pictures of WT (Left), JNK1/2LPC-KO (Middle Left), JNK1/2/CASP-8LPC-KO (Middle Right), and JNK1/2/MLKL-LPC-KO (Right) animals at the age of 6 wk (Top) and 52 wk (Bottom). (B) Representative H&E-stained liver sections of WT (Left), JNK1/2LPC-KO (Middle Left), JNK1/2/CASP-8LPC-KO (Middle Right), and JNK1/2/MLKL-LPC-KO (Right) animals at the age of 6 wk (Top) and 52 wk (Bottom). (C) Representative pan-CK-stained liver sections of WT (Left), JNK1/2LPC-KO (Middle Left), JNK1/2/CASP-8LPC-KO (Middle Right), and JNK1/2/MLKL-LPC-KO (Right) animals at the age of 6 wk (Top) and 52 wk (Bottom). (D) Liver weight-to-body weight ratio of 52-wk-old WT, JNK1/2LPC-KO, JNK1/2/CASP-8LPC-KO, and JNK1/2/MLKL-LPC-KO animals. n = 5 to 8. (E) Quantification of fluid-filled tissue cavities, including liver cysts, biliary ducts, and blood vessels, of 52-wk-old WT, JNK1/2LPC-KO, JNK1/2/CASP-8LPC-KO, and JNK1/2/MLKL-LPC-KO mice. n = 6 to 8. (F) Serum analysis of ALT, GLDH, and AP in 52-wk-old WT, JNK1/2LPC-KO, JNK1/2/CASP-8LPC-KO, and JNK1/2/MLKL-LPC-KO mice. n = 6. *P < 0.05.
Compared with solvent treatment (inhibition) of several different kinases, including the p38 network analysis in relation to RIPK1 revealed the activation of JNK resulted in a specifically altered activation pattern, implicating a compensatory signal cascade activation upon JNK inhibition (S7 and S8). Of note, it was previously suggested that deletion of p38 can lead to compensatory hyperactivation of other MAPKs. As such, deletion of p38α substrates MK2 and MK3 (MAPKAPK3), which did not appear in the activity profile of solvent-treated cells (SI Appendix, Figs. S7 and S8). Of note, it was previously suggested that deletion or inhibition of MAPKs can lead to compensatory hyperactivation of other MAPKs. As such, deletion of p38α leads to hyperactivation of JNK in hepatocytes (27). Moreover, previous studies suggested that MK2 can phosphorylate RIPK1 in response to proinflammatory stimuli, such as TNF, thereby modulating its activity (28). Therefore, these data suggest a molecular link between JNK deletion/inhibition, MK2 and/or MK3 activation, and biliary cyst formation through the modulation of RIPK1 activity.

RIPK1 Expression Is Found in a Subset of Patients with Polycystic Liver Disease. We finally aimed at providing evidence for a potential relevance of RIPK1 in the development of human (hereditary) fibropolycystic diseases of the liver. For this, we evaluated the protein levels of RIPK1 in human liver samples of various entities belonging to the group of (hereditary) fibropolycystic diseases of the liver. For this, we evaluated the protein levels of RIPK1 in human liver samples of various entities belonging to the group of (hereditary) fibropolycystic diseases of the liver (Fig. 7D and E and SI Appendix, Table S2), suggesting that RIPK1 might play a specific role in the pathogenesis of hepatic cyst formation, as it does in mice with JNK1/2-deficient cholangiocytes.
Discussion

Stress-activated kinases like JNKs play a crucial role in various physiological and pathophysiological processes such as proliferation, invasive migration, therapy resistance, and PCD (18). However, like many other signaling pathways, their specific function in the liver in mouse disease models was previously studied using young mice (5). Compared with humans, this translates to the situation in adolescents, while many liver diseases such as metabolic diseases typically manifest in elderly people. Hence, liver diseases of the elderly are often not adequately represented by experimental models (29), suggesting that more attention needs to be drawn to phenotypic changes and molecular alterations during aging. Here, we investigated the hepatic function of JNK1/2 and could show a function of JNK1/2, RIPK1, and CASPASE-8 in the maintenance of biliary homeostasis during aging.

Several diseases associated with biliary cysts belong to the group of (hereditary) fibropolycystic diseases of the liver, characterized by the development of several large cysts and a broad range of severity (30). Entities belonging to this disease spectrum include autosomal dominant and autosomal recessive polycystic (30, 31) Caroli disease/syndrome as well as biliary microhamartoma (von Meyenburg complex). Caroli disease represents a rare congenital disease with cystic dilation of the bile ducts leading to congenital cysts of the intrahepatic bile ducts (32). Complications are related to impaired bile drainage, providing the basis for recurrent cholangitis and progressive liver fibrosis leading to portal hypertension, which may require liver transplantation (32, 33). The molecular mechanisms underlying (hereditary) fibropolycystic diseases of the liver are still incompletely understood, although germline mutations have been identified which are associated with specific forms such as mutations of the genes Pkd1 and Pkd2 in autosomal dominant polycystic kidney disease (ADPKD) (30, 32, 33).
Fig. 6. Liver cysts in JNK1/2 ablated livers originate from bile duct cells. (A) Representative macroscopic liver picture (Left), H&E staining (Middle), and pan-CK staining (Right) of 52-wk-old WT and JNK1/2 Sox9-cre/ERT2 animals 48 wk after tamoxifen injection. (B) Stepwise cystic transformation of intrahepatic bile ducts in JNK1/2LPC-KO animals. Representative CK19 immunohistochemistry stainings (first row) and three-dimensional (3D) analysis of pan-CK/DAPI–immunostained intrahepatic bile ducts/ductules showing progressive stepwise cystic transformation of intrahepatic bile ducts/ductules in JNK1/2LPC-KO animals at the indicated age (low-magnification 3D maximum-intensity projection, second row; corresponding optical 2D view and 3D maximum-intensity projection of enlarged insets, third and fourth rows; corresponding 3D pan-CK + surface/interconnectivity analysis using the IMARIS surface protocol where different colors represent individual interconnected panCK+ segments, fifth row). White dashed lines, portal tract; white dashed circles, portal vein; BD, bile duct; PV, portal vein. (Scale bars, 50 μm.)
Previous studies linked JNKs to PKD, but the function of JNK signaling in these diseases was not clearly defined. An early study showed that silencing of polycystin-1 (the protein product of Pkd1) enhanced thrombin-induced apoptosis, JNK activation, and BCL-2 degradation in Madin-Darby canine kidney cells (34). Furthermore, analysis of cpc mice, which are used as a mouse model of PKD and carry a mutation of the gene Cys1 (Cystin-1), also revealed an increase of JNK phosphorylation in the cystic kidney tissue (35). In contrast, DBA2-pcy/pcy mice—another PKD mouse model—showed a down-regulation of JNK phosphorylation in the cyst epithelium (36). However, these studies were focused on kidney cysts. We are not aware of data focusing on the role of JNK-dependent signaling in (hereditary) fibropolycystic diseases of the liver.

In this study, we found that deletion of Jnk1 and Jnk2 in LPCs resulted in massive cyst formation in aging mice. We identified these cysts as focal dilated duct structures which were morphologically connected and originated from the intrahepatic bile duct system. Of note, we could not detect neoplastic or dysplastic development (39, 40). Of note, JNK1/2-dependent function of molecules known to regulate PCD in the development of biliary cysts in JNK1/2ΔLPC-KO mice. While the additional deletion of Caspase-8 or Mlkl alone did not rescue the cyst phenotype in JNK1/2ΔLPC-KO, additional deletion of Ripk1 prevented biliary cyst formation (Figs. 3 and 4). At present, the exact nature of this functional interaction is not clear. While JNK1/2ΔLPC-KO mice showed liver injury to a certain degree, we did not detect a significant alteration of overall liver injury measured by serum enzymes like ALT, GLDH, or AP when we additionally deleted Mlkl (blockage of necroptosis; tendency to more cyst development), Caspase-8 [blockage of apoptosis and potential activation of necroptosis (19); tendency to less cyst development], or Ripk1 [inhibition of necroptosis/potential activation of apoptosis (24); rescue from cyst development] (Fig. 4). This finding appears counterintuitive at first glance, but could have two alternative functional explanations.

First, RIPK1 and CASPASE-8 could exert cell death-independent functions in JNK1/2ΔLPC-KO mice to promote biliary cyst formation. As such, previous studies including our own revealed that CASPASE-8 and RIPK1 ensure tissue homeostasis by forming signaling complexes which can sense DNA damage or control chromosome segregation during mitosis, a function that might be relevant in the biliary cyst phenotype in JNK1/2ΔLPC-KO mice. A disruption of complex formation, be it through knockout or pharmacological inhibition of CASPASE-8 or RIPK1, resulted in genetic/chromosomal instability that could trigger carcinogenesis (21, 25). This respective DNA damage-sensing mechanism acted via JNK and resulted in the phosphorylation of histone H2A.X (γH2A.X). However, while analysis of 52-wk-old JNK1/2ΔLPC-KO mice revealed a moderately increased level of γH2A.X, this level was not affected by the additional deletion of Ripk1 or Ripk1/Caspase-8, arguing against the involvement of this respective RIPK1/CASPASE-8-dependent DNA-damage response pathway in biliary cyst formation of JNK1/2ΔLPC-KO mice. Recently, a direct proproliferative function of RIPK1 was suggested in CCA. Of note, it was suggested that this respective function does not only depend on p38, ERK1/2, and AP-1 but also on the presence of JNK (41). To exclude a proliferation-promoting function of RIPK1 as a crucial element for cyst formation, we examined the level of proliferation in the liver tissue of the different KO mice. Remarkably, we could not detect a significant difference in epithelial cell proliferation between JNK1/2ΔLPC-KO, JNK1/2/Ripk1ΔLPC-KO, and JNK1/2/Ripk1ΔCasp-8ΔLPC-KO mice, arguing against a direct RIPK1-dependent modulation of biliary cyst formation.
cell proliferation as the reason for liver cyst development through a CaspASE-8-dependent function of RIPK1 during aging.

Materials and Methods

Generation of Genetically Modified Mouse Models. Mice carrying loxP site-flanked (floxed) alleles of Jnk1 (Jnk1Δ/Δ) and Jnk2 (Jnk2Δ/Δ) were crossed to alfp-Cre transgenic mice to generate a liver parenchymal cell-specific knockout (LPK-KO) of both genes (6–8). Double-knockout mice (Jnk1Δ/ΔJnk2Δ/Δ) were generated by intercrossing Jnk1LPK-KO and Jnk2LPK-KO single-mutant mice. Mice with combined conditional deletions of Jnk1/2 and Caspase-8 (Jnk1/2/Jnk2/Casp-8LPK-KO) or additional conditional deletion of Ripk1 (Ripk1FL/FL) or Mkl1 (Mkl1Δ/Δ) in Jnk1Δ/ΔJnk2Δ/Δ mice were generated by intercrossing the respective lines to generate (FL/FL)Jnk1/2/Jnk2/LPC-KO mice. Jnk1Δ/ΔJnk2Δ/Δ mice were crossed with mice carrying the gene for an estrogen receptor-dependent inducibleCre recombinase under control of the Sox9 promoter (26). Cre expression was activated by a single injection of 100 μg/kg tamoxifen (solved in 10% EOH and 90% sunflower oil) at the age of 4 to 5 wk. In all experiments, littermates carrying the respective loxP-flanked alleles but lacking expression of Cre recombinase were used as WT controls. Mice were bred on a mixed C57BL/6J-129Sv strain genetic background. Only sex and age-matched animals were compared. All animals mentioned up to this point were treated in full compliance with the guidelines for animal care approved by the Federal Ministry for Nature, Environment and Consumers’ Protection of the state of North Rhine-Westphalia and was performed in accordance to the respective national, federal, and institutional regulations.

Mice with LPK-specific Jnk1/2 deletion, designated as Jnk1/2Δ/Δmice, were generated by intercrossing Jnk1Δ/Δ and Jnk2−/− mice, which have been described previously (6, 7). All intercrossings and experiments involving Jnk1/2Δ/Δ mice were performed at the University of Zurich. All procedures and protocols were approved by the Cantonal Veterinary Office (Zurich, Switzerland).

More detailed information on the materials and methods used in this study is provided in SI Appendix, Materials and Methods.

Data Availability. All study data are included in the article and/or supporting information.

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1. R. F. Schwabe, T. Luedde, Apoptosis and necroptosis in the liver: A matter of life and death. Nat. Rev. Gastroenterol. Hepatol. 15, 738–752 (2018).
2. G. Sabio, R. J. Davis, TNF and MAP kinase signalling pathways. Semin. Immunol. 26, 237–245 (2014).
3. E. Seki, D. A. Brenner, M. Karin, A liver full of JNK: Signaling in regulation of cell function and disease pathogenesis, and clinical approaches. Gastro-enterology 143, 307–320 (2012).
4. C. V. Yuan et al., The Jnk1 and Jnk2 protein kinases are required for regional specific apoptosis during early brain development. Neuron 22, 667–699 (1999).
5. S. Vernia et al., The PPARα-FGFR21 hormone axis contributes to metabolic regulation by the hepatic JNK signaling pathway. Cell Metab. 20, 512–525 (2014).
6. M. Das et al., Suppression of p38-dependent senescence by the JNK signal transduction pathway. Proc. Natl. Acad. Sci. U.S.A. 104, 15759–15764 (2007).
7. M. S. Han et al., JNK expression by macrophages promotes obesity-induced insulin resistance and inflammation. Science 339, 218–222 (2013).
8. C. Kellenkord, C. Opher, K. Anlag, G. Schütz, F. Tronche, Hepatocyte-specific expression of Cre recombinase. Genesis 26, 151–153 (2000).
9. K. Saltiel et al., Defective endoplasmic reticulum (ER) stress signaling and altered apoptosis in the absence of both JNK1 and JNK2. Mech. Dev. 89, 115–124 (1999).
10. M. Mavlikieva et al., Caroli syndrome: A clinical case with detailed histopathological analysis. Clin. J. Gastroenterol. 12, 106–111 (2019).
11. J. R. Macmillan, C. Cousinard, R. Soupaout, P. Porcher, J. Eteve, A new disease, undoubtedly congenital, of the bile ducts: Unilateral cystic dilatation of the hepatic ducts. Sem. Hop. 34, 496–502 (1958).
12. J. R. Macmillan, C. Cousinard, R. Soupaout, P. Porcher, J. Eteve, A new disease, undoubtedly congenital, of the bile ducts: Unilateral cystic dilatation of the hepatic ducts; attempt at classification. Sem. Hop. 34, 488–495 (1958).
13. G. Marnone et al., Magnetic resonance imaging of fibropolycystic liver disease: The hepatobiliary ductal plate malformations. Abdom. Radiol. (N.Y.) 44, 2156–2171 (2019).
14. E. Waanders et al., Hepatocystin is not secreted in cyst fluid of hepatocystin mutant polycystic liver patients. J. Proteome Res. 7, 2490–2495 (2008).

More detailed information on the materials and methods used in this study is provided in SI Appendix, Materials and Methods.
15. D. N. Dhanasekaran, E. P. Reddy, JNK-signaling: A multiplexing hub in programmed cell death. Genes Cancer 8, 682–694 (2017).

16. M. Vucur et al., RIP3 inhibits inflammatory hepatocarcinogenesis but promotes cholesterol by controlling caspase-8- and JNK-dependent compensatory cell proliferation. Cell Rep. 4, 776–788 (2013).

17. C. Koppe et al., On RIPK1 and caspase-8: Enure chromosomal stability independently of their role in cell death and inflammation. Mol. Cell 73, 413–428.e7 (2019).

18. A. T. Schneider, J. Gautheron, F. Tacke, M. Vucur, T. Luedde, Receptor interacting protein kinase 1 (RIPK1) in hepatocytes does not mediate murine acetaminophen toxicity. Hepatology 64, 306–308 (2016).

19. C. Koppe et al., IkB kinase-controlled biliary homeostasis and hepatocarcinogenesis in mice by phosphorylating the cell-death mediator receptor-interacting protein kinase 1. Hepatology 64, 1217–1231 (2016).

20. A. T. Schneider et al., RIPK1 suppresses a TRAF2-dependent pathway to liver cancer. Cancer Cell 31, 94–109 (2017).

21. Y. Boege et al., A dual role of caspase-8 in triggering and sensing proliferation-associated DNA damage, a key determinant of liver cancer development. Cancer Cell 32, 342–359.e10 (2017).

22. J. L. Kopp et al., Sox9+ ductal cells are multipotent progenitors throughout development but do not produce new endocrine cells in the normal or injured adult pancreas. Development 138, 653–665 (2011).

23. J. Heinrichsdorff, T. Luedde, E. Perdiguero, A. R. Nebreda, M. Pasparakis, p38 alpha MAPK inhibits JNK activation and collaborates with IkappaB kinase 2 to prevent endotoxin-induced liver failure. EMBO Rep. 9, 1048–1054 (2008).

24. M. B. Menon et al., p38MAPK/MKK2-dependent phosphorylation controls cytotoxic RIPK1 signalling in infection and inflammation. Nat. Cell Biol. 19, 1248–1259 (2017).

25. A. Jacobs, A. S. Warda, J. Verbeek, D. Cassiman, P. Spincemaille, An overview of mouse models of nonalcoholic steatohepatitis: From past to present. Curr. Protoc. Mouse Biol. 6, 185–200 (2016).

26. L. F. M. van de Laarschot, J. P. H. Drents, Genetics and mechanisms of hepatic cystogenesis. Biochim. Biophys. Acta Mol. Basis Dis. 1864, 1491–1497 (2018).

27. J. Heinrichsdorff, T. Luedde, E. Perdiguero, A. R. Nebreda, M. Pasparakis, p38 alpha MAPK inhibits JNK activation and collaborates with IkappaB kinase 2 to prevent endotoxin-induced liver failure. EMBO Rep. 9, 1048–1054 (2008).

28. M. B. Menon et al., p38MAPK/MKK2-dependent phosphorylation controls cytotoxic RIPK1 signalling in infection and inflammation. Nat. Cell Biol. 19, 1248–1259 (2017).

29. A. Jacobs, A. S. Warda, J. Verbeek, D. Cassiman, P. Spincemaille, An overview of mouse models of nonalcoholic steatohepatitis: From past to present. Curr. Protoc. Mouse Biol. 6, 185–200 (2016).

30. L. F. M. van de Laarschot, J. P. H. Drents, Genetics and mechanisms of hepatic cystogenesis. Biochim. Biophys. Acta Mol. Basis Dis. 1864, 1491–1497 (2018).

31. S. Acar et al., Liver transplantation for polycystic liver disease due to huge liver with related complications: A case report. Transplant. Proc. 49, 603–605 (2017).