Krüppel-like factor 6 is a transcriptional activator of autophagy in acute liver injury

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Krüppel-like factor 6 (KLF6) is a transcription factor and tumor suppressor. We previously identified KLF6 as mediator of hepatocyte glucose and lipid homeostasis. The loss or reduction of KLF6 is linked to the progression of hepatocellular carcinoma, but its contribution to liver regeneration and repair in acute liver injury are lacking so far. Here we explore the role of KLF6 in acute liver injury models in mice, and in patients with acute liver failure (ALF). KLF6 was induced in hepatocytes in ALF, and in both acetaminophen (APAP)- and carbon tetrachloride (CCl4)-treated mice. In mice with hepatocyte-specific Klf6 knockout (DeltaKlf6), cell proliferation following partial hepatectomy (PHx) was increased compared to controls. Interestingly, key autophagic markers and mediators LC3-II, Atg7 and Beclin1 were reduced in DeltaKlf6 mice livers. Using luciferase assay and ChIP, KLF6 was established as a direct transcriptional activator of ATG7 and BECLIN1, but was dependent on the presence of p53. Here we show, that KLF6 expression is induced in ALF and in the regenerating liver, where it activates autophagy by transcriptional induction of ATG7 and BECLIN1 in a p53-dependent manner. These findings couple the activity of an important growth inhibitor in liver to the induction of autophagy in hepatocytes.

Krüppel-like factor 6 (KLF6) is a ubiquitously expressed zinc finger transcription factor, which contributes to cell proliferation, differentiation, cell death and signal transduction1. Hepatocyte expression of KLF6 regulates hepatic fatty acid and glucose metabolism via transcriptional activation of liver glucokinase and posttranscriptional regulation of the nuclear receptor peroxisome proliferator activated receptor alpha (PPARα)2,3. KLF6-expression

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contributes to hepatic insulin resistance and the progression of non-alcoholic fatty liver disease (NAFLD) to non-alcoholic steatohepatitis (NASH) and NASH-cirrhosis. KLF6 also affects peroxisome proliferator activated receptor gamma (PPARγ)-signaling in NAFLD. Besides their metabolic functions, PPARα and PPARγ regulate cell proliferation and apoptosis. Furthermore, KLF6 has been identified as a tumor suppressor gene that is inactivated or downregulated in different cancers including prostate, colon and hepatocellular carcinomas. Consistent with its inhibitory effect on cell proliferation, KLF6 transactivates genes controlling cell proliferation, including p21, E-Cadherin and pituitary tumor-transforming gene 1 (PTTG1). Despite its clear growth regulatory activity in hepatic metabolism and cancer, there are no studies evaluating the role of KLF6 in liver regeneration and hepatocyte proliferation.

Acute liver injury and acute liver failure (ALF) are rare but serious conditions leading to hepatocyte death that occur in a previously healthy organ. ALF is characterized by rapid induction of hepatocyte necro-apoptosis, leading to jaundice, hepatic encephalopathy and coagulopathy. The underlying causes of ALF encompass autoimmune, viral, toxic or vascular diseases, with drug-induced liver injury and acetaminophen (APAP) poisoning as the most predominant etiologies in Western population. Acetaminophen is a widely used analgesic and antipyretic drug. Intake of high doses can result in ALF that is characterized by a rapid loss of liver cells and hepatic function due to enhanced production of reactive oxygen species (ROS), causing cellular stress and induction of cell death. Specific treatment (N-acetyl cysteine (NAC)) promotes liver regeneration by compensation of hepatic cell loss and induction of proliferation of remaining cells and by the activation and potential differentiation of quiescent progenitor cells.

Liver regeneration is governed by a delicate interplay of cytokines, chemokines and the activation of proliferative and anti-apoptotic signaling pathways. Recent studies have identified autophagy, a conserved mechanism to recycle cellular components in cell starvation, to play a role in hepatocellular regeneration in APAP-induced ALF by reduction of cellular stress. In this study, we aimed to investigate the role of KLF6 in liver regeneration following acute hepatocellular injury and ALF, and identified autophagy-related genes to be transcriptionally regulated by KLF6.

Results
KLF6 is induced in hepatocytes during acute human liver injury. We compared KLF6-expression by immunohistochemistry between liver tissue from patients with ALF and without (morbidly obese patients who underwent bariatric surgery without NASH (NAS < 2) or fibrosis; for patients’ demographical data see Supplementary Table S1). KLF6-expression was low in non-acute injury livers and localized primarily in the cytoplasm of cholangiocytes, with modest staining in the cytosol or nuclei of hepatocytes (Fig. 1A). In contrast, significantly higher nuclear KLF6-expression was detected in hepatocytes in liver tissue of ALF patients, while the bile duct regions showed low levels of KLF6 (Fig. 1B for quantification of nuclear KLF6 in hepatocytes see Supplementary Table S1).

KLF6 attenuates liver regeneration and autophagy after partial hepatectomy in mice. We performed 70% partial hepatectomy (PHx) in C57Bl/6-mice as an established model of liver regeneration. Animals were sacrificed 12h, 24h and 48h after PHx and the remnant liver was analyzed. Expression of Klf6 was significantly upregulated in liver tissue following PHx in wildtype mice (Fig. 2A) and, as observed in human ALF, was mostly detected in the nuclei of hepatocytes (Supplementary Figure S2A). Next, PHx was performed in mice with a hepatocyte specific Klf6-knockout (DeltaKlf6) compared to controls. Enhanced hepatocyte proliferation was observed in the absence of Klf6, as assessed by PCNA-staining (Fig. 2B for quantification of
Figure 2. KLF6 affects liver regeneration and expression levels of autophagy-related genes after partial hepatectomy (PHx). Klf6 expression levels were determined by qRT-PCR in mouse liver tissue before (pre-OP) and 12 h, 24 h or 48 h after 70% partial hepatectomy (PHx, n = 6/group) (A). Cell proliferation was assessed by quantification of PCNA positive cells in liver tissue of wildtype (wt) and DeltaKlf6 mice 72 h after PHx (B). Expression-levels of Atg7 (C) and Beclin1 (D) were measured by qRT-PCR in liver tissue of wt and DeltaKlf6 mice before and 12 h after PHx. Autophagy was assessed by LC3 Western blotting and quantified by densitometry of specific protein bands (E,F) in liver tissue of wt and DeltaKlf6 mice 72 h after PHx. Shown are representative Western blot images (E) and densitometric quantification of LC3-II-bands normalized to loading control beta-Actin (F); fold change versus control shown as mean ± SEM of n = 6 mice per group; full length Western blot images are given in Supplementary information). *Represents p-value < 0.05 and **Indicates p-value < 0.01 as assessed by 2-way ANOVA comparing wt mice with DeltaKlf6 animals at the same time point after PHx.
Table 1. Data from 12 h, 24 h or 72 h after partial hepatectomy (PHx) in wildtype or DeltaKlf6 mice. **p < 0.01 (wt vs. DeltaKlf6 at same time-point).

| Time post PHx | Wildtype (C57Bl/6) | DeltaKlf6 |
|---------------|--------------------|-----------|
| 12 h          | 53.33 ± 3.33       | 2259 ± 458.2** |
| 24 h          | 60.0 ± 7.07        | 4090 ± 720.1*** |
| 72 h          | 7.63 ± 0.38        | 8.06 ± 0.53  |

Table 2. Mouse baseline parameters after treatment with APAP (wildtype animals) or acute CCl4 treatment (wildtype and DeltaKlf6 animals). *p < 0.05; **p < 0.01; ***p < 0.001 versus vehicle control.

| APAP (500 mg/kg) | Vehicle (n = 6) | APAP (n = 8) |
|------------------|----------------|--------------|
| ALT [U/l]        | 53.33 ± 3.33   | 2259 ± 458.2** |
| AST [U/l]        | 60.0 ± 7.07    | 4090 ± 720.1*** |
| GLDH [U/l]       | 10.67 ± 0.67   | 215.5 ± 42.62** |
| Liver/bodyweight-ratio [%] | 7.63 ± 0.38 | 8.06 ± 0.53  |

PCNA positive cells and Supplementary Figure S2B for immunohistochemical PCNA images), and by quantifying liver-to-body-weight-ratios (Table 1). In KLF6-over-expressing HepG2 cells, following transient transfection with a KLF6-expression vector (pcIneo-KLF6), proliferation appeared attenuated compared to empty control vector (pcIneo) transfected control cells as assessed by BrdU cell proliferation assay (Supplementary Figure S2C).

Liver tissue from DeltaKlf6 mice 12 h after PHx was subjected to RNA-microarray analysis (Affymetrix GeneChip HT MG-430 PM), which revealed changes in expression of autophagy-related genes compared to wt controls (heatmap included in Supplementary Figure S2D). QRT-PCR confirmed significant reductions in Atg7 and Beclin1 expression in DeltaKlf6 livers before and 12 h after PHx compared to wt controls (Fig. 2C,D). Attenuation of LC3-II expression after PHx assessed by Western blot was correlated with loss of Klf6 in DeltaKlf6 mice (Fig. 2E,F). Western blot revealed high levels of LC3-II in livers of wt mice 72 h post PHx, which was significantly attenuated in the absence of Klf6 in liver tissue of DeltaKlf6 animals.

KLF6 induction parallels induction of autophagy in vivo and in cell culture. To investigate Klf6-expression in an established in vivo model of APAP-induced liver injury we employed C57Bl/6-mice that received an intra-peritoneal injection of APAP (500 mg/kg bodyweight) or saline in controls (H&E images of liver tissue from APAP- or vehicle-treated mice are shown in Supplementary Figure S3A). The animals were sacrificed 8 h after injection and levels of Klf6 gene expression in liver tissue were assessed by qRT-PCR. APAP-injection resulted in significant liver damage as indicated by increased serum ALT-, AST- and GLDH- levels 8 h after treatment (Table 2). Hepatic Klf6-expression was significantly increased 8 h after APAP-injection (Fig. 3A). Comparing vehicle treated C57Bl/6 mice with those receiving APAP injection; LC3-II-levels were significantly enhanced in murine liver tissue after APAP-injection (Fig. 3B, Supplementary Figure S3B for Western blot image). To evaluate Klf6 expression in another model of acute liver injury, we injected a single dose of CCl4 to Delta-Klf6 and wildtype animals. In livers of animals sacrificed 48 h after receiving an acute dose of CCl4, in parallel to acute liver damage (see Table 2 for serum parameters of liver injury) Klf6-expression was as well significantly upregulated, compared to mice treated with corn oil alone (Fig. 3C). In this model of acute injury LC3-II levels were induced after CCl4 injection, (Fig. 3D,E).

To validate the in vivo observations, we quantified KLF6-expression in APAP treated cell culture models. Therefore, we treated HepaRG cells, which resemble the metabolic function of human hepatocytes, with different concentrations of APAP (5 mM, 10 mM and 20 mM) for 24 h to induce cellular stress and damage. Here, KLF6 was significantly upregulated after APAP treatment in a dose-dependent fashion (Supplementary Figure S3C). Similarly, in HepG2 cells, treatment with APAP for 24 h significantly induced KLF6-levels (Supplementary Figure S3D). We then quantified autophagy-induction in APAP-treated HepG2 cells and observed increased LC3-II and p62 levels compared to control cells (Supplementary Figure S3E,F,H and I).

KLF6 induces autophagy and binds to promoter regions of BECLIN1 and ATG7. To verify the functional interaction between KLF6 and autophagy related targets, we transiently transfected HepG2 cells with an empty control vector (pcIneo) or a KLF6-expression vector (pcIneo-KLF6) in order to quantify autophagy induction in KLF6-over-expressing cells (Fig. 4). In parallel to KLF6-overexpression (Fig. 4A,B), LC3-II was
increased and p62 levels were decreased in these cells (Fig. 4C,D). To assess autophagosome formation, we performed transmission electron microscopy with control vector transfected HepG2 (pcIneo) cells and pcIneo-KLF6 transfected HepG2 cells. In KLF6 over-expressing HepG2 cells (Fig. 5C), there were more autophagy-positive cells compared to pcIneo-transfected HepG2 cells (Fig. 5A; for quantification of autophagy-positive cells see Supplementary Table S2). As a control for autophagy induction and autophagosome-formation we treated pcIneo-transfected HepG2 cells with 15 μM of rapamycin for 6 h (Fig. 5B). In addition, we performed Autophagy Tandem Sensor RFP-GFP-LC3B assay (Fig. 6), which confirmed increased formation of autophagosomes in KLF6-over-expressing HepG2 cells (Fig. 6; Supplementary Table S2). LC3-II turnover was assessed by Western blot in HepG2 (pcIneo) and KLF6 over-expressing HepG2 cells (pcIneo-KLF6) in the absence or presence of the lysosomal inhibitor chloroquine (100 μM for 24 h; Fig. 4C,D). In the absence of the inhibitor, KLF6 over-expression led to an increase of LC3-II and a decrease of p62 in comparison to pcIneo transfected cells. Incubation with the lysosomal inhibitor chloroquine resulted in a clear accumulation of LC3-II and a suppression of p62 in both pcIneo and in pcIneo-KLF6 cells. The use of the lysosomal inhibitor chloroquine demonstrated that autophagic flux occurs in these cells. However, in this experiment, there were no significant differences...
KLF6 belongs to the family of zinc finger proteins that regulate target genes and cellular pathways by binding to specific DNA motifs. We identified potential KLF6 binding motifs within the promoter regions of the autophagy related genes ATG7 and BECLIN1, and then confirmed transcriptional activation by luciferase reporter assays. To do so, we performed co-transfection with reporter plasmids in KLF6-overexpressing HepG2 cells and specific luciferase reporter plasmids carrying the promoter regions of ATG7 or BECLIN1. A background control was comprised of a commercially available random control vector containing a non-conserved, non-genic and non-repetitive fragment of equal length to the specific sequence upstream of the luciferase gene. As shown in Fig. 4E in HepG2 cells over-expressing KLF6, ATG7 promoter activity was significantly higher compared to control plasmid transfected cells. Thus, KLF6 transactivates ATG7 and therefore might influence the level of autophagy. Next, we performed chromatin immune precipitation assays (ChIP), which confirmed direct binding of KLF6 to the promoter regions of ATG7 and BECLIN1 (Fig. 4G). Interestingly, despite active binding of KLF6 to the BECLIN1 promoter, BECLIN1 luciferase activity was not altered by KLF6-overexpression in HepG2 cells (Fig. 4E). Predicted binding elements of KLF6 to promoter regions of ATG7 or BECLIN1 were assessed by using ChIP-seq data from KLF6-transfected HepG2 cells that were obtained from the NIH Encyclopedia of DNA Elements (ENCODE) database. This analysis clearly identified protein-DNA binding sides of KLF6 on regions encoding ATG7 and BECLIN1 (Supplementary Figure S2F+G).
The p53-dependent transcriptional activation of ATG7 and BECLIN1 by KLF6 is independent of apoptosis. A direct interaction between KLF6 and p53 has previously been demonstrated in the context of IGF-1 regulation. In contrast to KLF6, several direct and indirect interactions between autophagy and p53 have been identified. To investigate potential interactions between KLF6 and p53 in the context of autophagy induction, we used p53-deficient HepG2 cells to determine if KLF6 still leads to upregulation of autophagy-related genes in the absence of p53. To do so, we performed luciferase assays in KLF6-over-expressing HepG2 cells transfected with promoter-reporter constructs for ATG7 and BECLIN1. In contrast to p53-expressing HepG2 cells, the ATG7 promoter was not activated in KLF6-over-expressing HepG2 cells (Fig. 4F). Interestingly, the activation of BECLIN1 in HepG2 cells was enhanced in KLF6-over-expressing cells compared to control cells, pointing towards p53-dependent (ATG7) and p53-independent (BECLIN1) mechanisms, by which KLF6 regulates autophagy-related effector proteins.

However, LC3-II levels were obviously not changed in HepG2 cells treated with APAP or in HepG2 cells over-expressing KLF6 (Supplementary Figure S3G,J), implying that p53 is required to enhance LC3-II as a marker for increased autophagosome formation.

To elucidate potential non-transcriptional effects of KLF6 on autophagy induction, we further investigated its role in apoptosis induction. Following cellular stress, autophagy can block apoptosis or caspase activation and promote survival by clearance of reactive oxygen species or damaged proteins. A switch from autophagy to apoptosis may occur, since autophagic and apoptotic molecules including BECLIN1 and BCL-2 interact directly. Since p53 is also an activator of apoptosis and several mediators involved in autophagy induction also contribute to Caspase- regulation/apoptosis-regulation, we measured expression levels of the apoptosis-related molecules BAX, BAD and BCL-2. Expression of these genes was not changed in KLF6-over-expressing cells compared to empty vector transfected HepG2 cells. However, as previously published, expression levels of P21 were reduced in KLF6-over-expressing HepG2 cells (Supplementary Table S3). Additionally, we performed a Proteome Profiler human Apoptosis Array to analyze the expression profiles of 35 apoptosis-related proteins using cell lysates from normal HepG2 cells (pcIneo) and KLF6-over-expressing HepG2 cells. This array did not highlight any differences between control vector transfected and KLF6-over-expressing HepG2 cells (Supplementary Figure S2E).

Discussion

KLF6 is a growth suppressor gene and the inactivation of KLF6 is associated with multiple human tumors. Among several mechanisms of tumor suppression, KLF6 inhibits cell cycle progression and proliferation. However, the behavior of KLF6 during liver regeneration following acute liver injury has not been assessed to date. With this study we establish that KLF6 is induced and translocated to the nucleus in hepatocytes among different models of acute liver injury. This activation is associated with enhanced hepatocyte proliferation in early liver regeneration. We further identify KLF6 as a transcriptional activator of ATG7 and BECLIN1, thereby
establishing KLF6 as a novel mediator of autophagy. This novel function of KLF6 depends on the presence of p53, but appears to be independent of apoptosis. Healthy liver tissue has the ability to compensate for the loss of organ function in case of induced cell stress, acute injury or cell death. However, the excessive loss of functional liver tissue may lead to ALF. Following cell loss or death, activation of cell proliferation and regeneration, combined with attenuation of growth suppressor activity within remnant liver tissue restores liver cell mass. Downregulation of KLF6, a tumor suppressor gene that inhibits proliferation through induction of p21 and in synergy with p538,10,12 has been observed in primary liver tumors and is associated with a worse outcome in cancer4,11,33. Following PHx in mice, hepatocyte-specific deletion of Klf6 accelerates cell proliferation at early time points after resection. The later loss of growth induction in DeltaKlf6 mice suggests that mechanisms not related to hepatocellular Klf6 override its anti-proliferative effects as hepatocyte regeneration progresses. Furthermore, these observations might as well be confounded by Klf6-expression in non-parenchymal cells34,35. Here, cell proliferation was slightly reduced in in vitro experiments using KLF6-over-expressing HepG2 cells as shown by BrdU assay. Furthermore, KLF6-overexpression was accompanied with reduced expression levels of p21 in transiently transfected HepG2 cells. This transcription factor regulates cell cycle progression, DNA replication and repair by regulating the activity of different cyclin dependent kinases; its activation is controlled by the tumor suppressor protein p5336,37. Nonetheless, we observed a strong hepatocyte induction of KLF6 in models of acute liver injury and ALF patients, and an early proliferative advantage for hepatocyte-specific Klf6 knockout mice undergoing PHx.
A marked reduction of autophagic vesicles in hepatocytes was first observed in 1979 by Pfeifer in rats undergoing PHx\(^8\). More recently, autophagy has been established as an essential mechanism required for liver regeneration after PHx, since in liver-specific \(\text{Atg5}\) knockout mice liver regeneration and cell division are markedly impaired after PHx due to reduced ATP levels and decreased \(\beta\)-oxidation\(^9\). Here, utilizing a hepatocyte-specific \(\text{Klf6}\) knockout model, we identified \(\text{Klf6}\) as a transcriptional activator of the autophagy related genes \(\text{Atg7}\) and \(\text{Beclin1}\) in PHx and acute CCl\(_4\)-induced liver injury. Metabolism of APAP results in formation of NAPQI (N-acetyl-p-benzoquinone imine), which reacts with glutathione (GSH) to form GSH-adducts that can be secreted. In APAP overdose with progressive GSH-depletion NAPQI binds to cellular proteins and causes mitochondrial damages leading to cell death (mainly necrosis) and inflammation. In liver injury following APAP overdose, autophagy represses apoptosis, reduces cellular stress, inflammation and injury by removing damaged cells and organelles\(^22\). Ni et al. showed that SQSTM1/p62 plays an important role in reducing APAP protein adducts, while after shRNA-mediated p62-knockdown APAP protein adducts were increased in primary hepatocytes\(^35\).

In aging mice, autophagy and hepatocellular apoptosis are induced, leading to impaired liver regeneration following PHx\(^46\). In a related study, autophagy played a critical role in liver regeneration and in the preservation of cellular quality, preventing hepatocytes from becoming fully senescent and hypertrophic. This effect was most likely mediated by p21 and stimulation of interleukins\(^39\). Interestingly, in a PHx model, mTOR inhibition severely impaired liver regeneration and increased autophagy rate. These effects were partly reversed by stimulation of the IL-6 and HGF pathways\(^42\).

Our gene array data uncovered altered expression of autophagy-regulatory proteins in mice lacking hepatocyte \(\text{Klf6}\) (Delta\(\text{Klf6}\) mice) following PHx. Accordingly, we documented the parallel induction of autophagy and \(\text{Klf6}\) in several models of liver injury. In Delta\(\text{Klf6}\) mice, autophagy-induction was attenuated compared to controls and \(\text{Klf6}\)-over-expressing \(\text{HepG2}\) cells showed increased \(\text{Atg}^+\) accumulation and formation of autophagosomes, while there was no evidence for increased autophagic flux in conditions of \(\text{Klf6}\)-over-expression as compared to control conditions. We then analyzed whether \(\text{Klf6}\) functionally interacts with promoter regions of several autophagy-related genes, which contain conserved \(\text{Klf6}\)-binding motifs. ChIP assay analysis confirmed direct binding of \(\text{Klf6}\) to promoter regions of \(\text{Atg7}\) and \(\text{Beclin1}\). Interestingly, \(\text{Klf6}\)-mediated transcriptional activation of \(\text{Atg7}\) is dependent on \(\text{p53}\), since \(\text{Klf6}\)-overexpression activated the \(\text{Atg7}\) promoter in \(\text{HepG2}\), but not in \(\text{p53}\) deficient \(\text{Hep-G2-303}\) cells. Conversely, \(\text{Beclin1}\) transcriptional activation was induced by \(\text{Klf6}\)-overexpression under \(\text{p53}\) deficient conditions, while \(\text{Klf6}\) had no effect on \(\text{Beclin1}\) in \(\text{HepG2}\) cells.

A functional interaction between \(\text{Klf6}\) and \(\text{p53}\) has previously been described. Rubinstein et al. observed that a transcriptional effect of \(\text{Klf6}\) on the IGF-1 receptor is dependent on the presence of \(\text{p53}\), and \(\text{Klf6}\) itself is a transcriptional target of IGF1, which also requires \(\text{p53}\). \(\text{Klf6}\) can also repress \(\text{Mdm2}\), which binds to the tumor suppressor \(\text{p53}\) and thus accelerates its degradation in a mouse model of hepatocellular cancer\(^8\). Here, we observed a novel transcriptional activity of \(\text{Klf6}\) by inducing two autophagy related genes (\(\text{Beclin1}\) in \(\text{p53}\) deficient cells and \(\text{Atg7}\) in the presence of \(\text{p53}\)) is switched, based on the presence or absence of \(\text{p53}\). Beyond its role in autophagy, \(\text{Beclin1}\) has also been described as a tumor suppressor gene in many cancer types and shares a \(\text{BH3}\) domain with pro-apoptotic genes like \(\text{Bid}\) or \(\text{Bad}\). In our study expression levels of \(\text{Bax}\), \(\text{Bid}\) and \(\text{Bcl-2}\) were not changed in \(\text{Klf6}\)-over-expressing \(\text{HepG2}\) cells.

Furthermore, \(\text{Beclin1}\) can alter \(\text{p53}\) expression by regulating deubiquitination of \(\text{p53}\) by Usp10\(^45\). To date, no interaction between \(\text{Klf6}\) and either \(\text{Beclin1}\) or \(\text{Atg7}\) has been reported. Interestingly, the absence or presence of \(\text{p53}\) determines a pro-tumorigenic or tumor-suppressing property of autophagy in a mouse model of pancreatic cancer\(^45\). Thus, \(\text{Klf6}\) might serve as an important mediator in autophagy-induction but has no impact on apoptosis in the context of acute liver injury.

Taken together, our findings establish that \(\text{Klf6}\)-expression is induced in models of acute liver injury and in patients with \(\text{ALF}\). Here, we describe for the first time a direct transcriptional activation of autophagy-related genes by \(\text{Klf6}\). This transcriptional activation depends on the presence (\(\text{Atg7}\)) or absence (\(\text{Beclin1}\)) of \(\text{p53}\). Thus, \(\text{Klf6}\) drives autophagy-induction and autophagy-related cell death in acute liver injury.

**Material and Methods**

**Cell culture.** HepG2 cells were grown in DMEM-High-Glucose medium (Invitrogen, Carlsbad, CA, USA) with 10% of fetal bovine serum (FBS, Biochrom, Berlin, Germany), 1000 U/ml penicillin, 0.1 mg/ml streptomycin and 2 mM L-glutamine (PAA, Pasching, Austria). Cells were kept in an atmosphere with 5% CO\(_2\) under 37° C following manufacturer's instructions. BrdU assay was performed using the Cell Proliferation ELISA BrdU Kit following manufacturer's instructions (Roche, Mannheim, Germany). Luciferase assay was performed using LightSwitch-Luciferase assay system following manufacturer's instruction (SwitchGear Genomics).

**Transfection conditions, reporter assay and BrdU assay.** For transient transfection cells were seeded one-day prior transfection on different plate formats (6-well, 12-well, 96-well) at a density of 5 × 10\(^4\) cells/cm\(^2\). \(\text{Klf6}\)-over-expressing HepG2 cells were transfected using Transfectine (Bio-Rad, Munich, Germany) at a ratio of 3 µl Transfectine per µg DNA as recommended by the manufacturer. \(\text{Klf6}\)-expression plasmid pClneo-\(\text{Klf6}\) or empty control vector pClneo (Promega, Madison, WI, USA) were used at 80 ng per 3.9 cm\(^2\) well. For luciferase reporter assays HepG2 were co-transfected with pClneo or pClneo-\(\text{Klf6}\) and 100 ng of reporter plasmid vectors pLightSwitch-\(\text{ATG7}\), pLightSwitch-\(\text{Beclin1}\) or pLightSwitch-random control plasmid (SwitchGear Genomics, Menlo Park, CA, USA). Luciferase assay was performed using LightSwitch-Luciferase assay system following manufacturer's instruction (SwitchGear Genomics). BrdU assay was performed using the Cell Proliferation ELISA BrdU Kit following manufacturer's instructions (Roche, Mannheim, Germany).

**Transmission electron microscopy and Autophagy Tandem Sensor assay.** HepG2 cells were transfected as described above with pClneo or pClneo-\(\text{Klf6}\). For induction of autophagy and monitoring of autophagosome-formation, HepG2 cells were treated with 15 µM of Rapamycin for 6 h (Medchem Express, Menlo Park, CA, USA).
Monmouth Junctions, NJ USA). After incubation, cells were fixed for 2 h at room temperature using 2.5% glutaraldehyde in 0.1 M PB buffer (0.1 M Na2HPO4, 0.1 M KH2PO4 buffer). Cells were washed with PB buffer, removed from the cell culture dish; the cell pellet was postfixed in 2% osmium tetroxide, dehydrated in a graded series of alcohol and embedded in epoxy resin. Ultrathin sections were post-stained with uranyl acetate (1%) and lead citrate (0.4%). Sections were viewed in a Joel TEM1400 Plus (Joel, Tokyo, Japan). For visualization of autophagosomes in pclneo or pclneo-KLF6 transfected HepG2 cells we used the Premo™ Autophagy Tandem Sensor RFP-GFP-LC3B Kit (Thermo Scientific/Life Technologies, Darmstadt, Germany) according to manufacturer's protocol. Fixed cells were viewed with a Leica SP8 confocal microscope (Leica Microsystems, Wetzlar, Germany).

Chromatin immunoprecipitation assay. For Chromatin immunoprecipitation assay (ChIP) cells were cross-linked with a final concentration of 1% formaldehyde for 10 min at 37 °C, then washed and harvested in SDS lysis buffer (10% SDS; 0.5 M EDTA; 1 M Tris-HCl; containing protease inhibitor cocktail from Sigma-Aldrich, St. Louis, MO, USA) and sheared by sonication to fragment DNA. Samples were immunoprecipitated with 10 μg of anti-KLF6 antibody (polyclonal antibody KLF6 (R-173) or monoclonal antibody KLF6 (E-10) (Santa Cruz Biotechnologies, Dallas, TX, USA), anti-histone H3 antibody (Abcam, Cambridge, UK) or control IgG (Abcam) and protein-A/G agarose beads (Santa Cruz Biotechnologies). Following removal of cross-linked DNA/protein complexes by Proteinase K (Qiagen, Hilden, Germany) treatment, immunoprecipitated DNA was purified using QiAamp DNA Mini Kit (Qiagen) and used for PCR with ATG7 or BECLIN1 primers (Supplementary Table S3), encompassing the promoter region – 200 bp to – 400 bp upstream of transcriptional start site to amplify immunoprecipitated DNA. PCR products were visualized on an agarose gel.

Animals and surgical procedures. Mice with a floxed Klf6 targeting vector (C57Bl/6;129Sv; Genentech, San Francisco, CA, USA) were crossed with mice expressing Cre recombinase (Cre) under control of the albumin promoter (B6.Cg-Tg(Alb-cre)21 Mgn/J; Jackson Labs, Bar Harbor, ME, USA). After backcrossing, male off-spring expressing Cre with two floxed Klf6 alleles were used as the experimental group (‘Delta Klf6 min promoter (B6.Cg-Tg(Alb-cre)21 Mgn/J; Jackson Labs, Bar Habor, ME, USA)). Before surgical intervention animals were anesthetized, 70%PHx was performed by removing the left and median lobes of the liver. Mice were sac - ad libitum conditions were controlled; mice were allowed food and water after surgical intervention animals were anesthetized, 70%PHx was performed by removing the left and median lobes of the liver. Mice were sacrificed after 3 h, 12 h, 24 h, 48 h and 72 h following surgical intervention, respectively. Protocol for Affymetrix microarray analysis from liver tissue post PHx is given as Supplementary material. To induce APAP-induced liver injury C57Bl/6 mice received intraperitoneal injection of APAP (500 mg/kg bodyweight, Sigma-Aldrich) and were sacrificed 8 h after APAP-administration. Carbon tetrachloride (CCL4, Sigma-Aldrich)-induced acute liver injury was achieved by intra-peritoneal injection of 2 μl/g bodyweight of CCL4 or corn oil; animals were killed after 48 h. Experiments were conducted in three different facilities in accordance with relevant guidelines and regulations. Studies were approved by the Institutional Animal Care and Use Committee (IACUC) of Icahn School of Medicine at Mount Sinai (reference number LA09-00251), and the State authority for environment and animal welfare in Northrhine-Westfalia (LANUV, reference number 84-02.04-2013) for work conducted at the University of Duisburg-Essen and the RWTH Aachen. For baseline characteristics see Tables 1 and 2.

Ethical considerations. All investigations in human material and the use of patient samples were approved by the Ethics Committee (Institutional Review Board) of the University Hospital Essen (reference numbers: 14-6066-BO and 09-4252) and the study protocol conformed to the ethical guidelines of the Declaration of Helsinki. Sample allocation in non-acute liver injury patients that underwent bariatric surgery was undertaken following patients’ informed consent. As patient data and samples of the historic cohort of ALF patients were analyzed retrospectively from stored samples that were obtained for routine clinical use, informed consent from these subjects was explicitly not required according to the local ethics committee.

Histopathology and sample handling. Liver tissue from mice or ALF patients (Supplementary Table S13) was stored in 4.5% formalin-solution, paraffin-embedded and sectioned. Stainings were performed using standard protocols; rabbit anti-KLF6 (R-173; Santa Cruz Biotechnology). Liver tissue for RNA and protein isolation was frozen in liquid nitrogen. Total RNA and protein from liver tissue were isolated by TRIzol® extraction (Invitrogen), RNA was purified utilizing RNeasy Mini Kit (Qiagen). Protein lysates from cells were prepared using lysis buffer (50 mM Tris- HCl; 150 mM NaCl; 0.1% NP-40; 1% desoxycholic acid) containing complete mini EDTA-free protease inhibitor cocktail and phosphostop (Roche).

Quantitative real time PCR. Reverse transcription was performed with the QuantiTect-RT kit (Qiagen) using 1 μg of total RNA. Specific mRNA expression levels were measured by quantitative real-time-PCR (qRT-PCR) performed on a CFX96 Touch Real-Time PCR Detection System (Bio-Rad) using QuantiTect SYBR Green Kit (Qiagen) in a volume of 15 μl including 2 μl of cDNA. Oligonucleotide sequences of used primers are shown in Supplementary Table S4. Melting curves were collected to ascertain specificity of PCR-products. Changes in mRNA-expression were calculated by the ΔΔ-Ct method and are presented as foldchange in relation to expression of a reference gene (HPRT or Sdha).

Western blotting. For SDS-PAGE 30 μg of total protein were separated; immunoblotting was performed using standard procedures with the following primary antibodies: LC3 (Abcam), KLF6-R173 (Santa Cruz Biotechnologies), p62 (Enzo Lifesciences, Antwerpen, Belgium), β-Actin 13E5 and GAPDH 14C10 (Cell Signaling). After incubation with the appropriate horseradish peroxidase-conjugated secondary antibody, bound antibodies were visualized using ECL-Prime (GE Healthcare, Chalfont St. Giles, UK). Blotting images were generated using ChemiDoc System and Quantity One software (Bio-Rad) to quantify the densities of the bands.
Statistical analysis. Statistical significance was determined using an unpaired (or paired, when applicable), two-tailed t-test or by one-way ANOVA (with Tukey’s post-hoc test for individual experimental conditions) performed with GraphPad Prism 6 (GraphPad Software Inc., San Diego, CA, USA). Significance was assumed at \( p \leq 0.05 \). If not stated otherwise all data are presented as mean \( \pm \) SEM.

Data availability. Array data can be found at (http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE85381), under the accession number GSE85381.

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Author Contributions

S.S. (acquisition, analysis and interpretation of data; study design; statistical analysis; drafting and submission of the manuscript), P.M. (data acquisition cell culture; analysis and interpretation of data), J.B. (data acquisition patient samples), S.J. (acquisition and analysis of data), J.P.S. (editing of the manuscript), M.E.Z. (acquisition of data, APAP mice), V.H.G. (critical revision of the manuscript for important intellectual content), F.J.C. (acquisition of data; analysis and interpretation; statistical analysis), I.K. (acquisition of histological data), D.V. (acquisition of data, PHx studies), M.I.F. (analysis of histological data), Y.H. (analysis of ChIP-seq data), C.B.B. (analysis of ChIP-seq data), L.J.N. (acquisition of data, HepaRG cells), H.M. (critical revision of the manuscript for important intellectual content; technical support), K.N.F. (critical revision of the manuscript for important intellectual content; technical support), A.P. (acquisition of patient samples), H.A.B. (acquisition and analysis of histological data), S.L.F. (critical revision of the manuscript for important intellectual content), G.G. (obtained funding; critical revision of the manuscript for important intellectual content), A.C. (obtained funding; critical revision of the manuscript for important intellectual content), L.P.B. (study concept and design; acquisition, analysis and interpretation of data; statistical analysis; study supervision; drafting of the manuscript; obtained funding).

Additional Information

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