SIDT2 RNA Transporter Promotes Lung and Gastrointestinal Tumor Development

HIGHLIGHTS
- Loss of the SIDT2 double-stranded RNA (dsRNA) transporter leads to accumulation of dsRNA in tissues.
- This accumulation is associated with increased apoptosis.
- Reduced tumor burden in mouse models of lung adenocarcinoma and intestinal cancer.

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Article

SIDT2 RNA Transporter Promotes Lung and Gastrointestinal Tumor Development

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SUMMARY

RNautophagy is a newly described type of selective autophagy whereby cellular RNAs are transported into lysosomes for degradation. This process involves the transmembrane protein SIDT2, which transports double-stranded RNA (dsRNA) across the endolysosomal membrane. We previously demonstrated that SIDT2 is a transcriptional target of p53, but its role in tumorigenesis, if any, is unclear. Unexpectedly, we show here that Sidt2−/− mice with concurrent oncogenic KrasG12D activation develop significantly fewer tumors than littermate controls in a mouse model of lung adenocarcinoma. Consistent with this observation, loss of SIDT2 also leads to enhanced survival and delayed tumor development in an Apcmin−/− mouse model of intestinal cancer. Within the intestine, Apcmin−/−;Sidt2−/− mice display accumulation of dsRNA in association with increased phosphorylation of eIF2α and JNK as well as elevated rates of apoptosis. Taken together, our data demonstrate a role for SIDT2, and by extension RNautophagy, in promoting tumor development.

INTRODUCTION

The C. elegans double-stranded RNA (dsRNA) transporter SID-1 is conserved throughout much of animal evolution, and mammals possess two paralogs, SIDT1 and SIDT2 (Feinberg and Hunter, 2003; Shih and Hunter, 2011). SIDT2 is broadly expressed in mammalian tissue and localizes within late endosomes and lysosomes (Jialin et al., 2010; Nguyen et al., 2017). Human and mouse SIDT2 homologs show 95% sequence identity across the entire protein (832 amino acids) and 100% identity at the C-terminal 100 amino acids (Nguyen et al., 2017). Such a high degree of conservation implies a strongly selected function, and studies have recently emerged that shed light on the role of SIDT2 in mammals.

On the one hand, SIDT2 appears to have retained RNA transporter activity. This was initially suggested by the observation that the ectodomain of SIDT2 binds long dsRNA in vitro, similar to C. elegans SID-1 (Li et al., 2015). Consistent with this finding, we subsequently discovered that SIDT2 transports viral dsRNA and that this transport is important for anti-viral immunity (Nguyen et al., 2017). More specifically, we found that SIDT2 promotes the trafficking of internalized dsRNA across the endolysosomal membrane and into the cytoplasm, where it is recognized by RNA sensors, which in turn promote anti-viral, type I interferon (IFN) signaling. Loss of SIDT2 thus impairs IFN production and survival after viral infection is significantly reduced (Nguyen et al., 2017). In parallel, SIDT2 has also recently been reported to traffic RNAs into the lysosome for degradation in a novel process described as "RNautophagy" (Aizawa et al., 2016). These experiments—performed using cell-free biochemical assays—suggested that SIDT2 promotes destruction of endogenous RNAs by transporting them from the cytosol into the lysosomes. Such transport would thus be in the opposite direction to that described for viral RNAs, but is potentially consistent with previous observations that RNA transport by C. elegans SID-1 is bidirectional and dependent on RNA concentration (Shih and Hunter, 2011).

On the other hand, some studies have observed physiological effects of SIDT2 where the relationship to RNA transport, if any, is unclear. For example, mice lacking SIDT2 demonstrate impaired glucose tolerance, decreased serum insulin levels, and defective insulin secretion (Chang et al., 2016; Gao et al., 2013; Yu et al., 2015). Two recent studies also demonstrated that Sidt2−/− mice develop non-alcoholic fatty liver disease (Chen et al., 2018; Gao et al., 2016), with one suggesting that this is due to induction of endoplasmic reticulum stress (Gao et al., 2016) and the other proposing that it is the result of defective autophagy (Chen et al., 2018). Finally, work from our group has also demonstrated a potential role for SIDT2 in tumorigenesis (Brady et al., 2011). Specifically, we found that SIDT2 is a transcriptional target of the tumor suppressor p53, that SIDT2 overexpression in HrasV12;p53-null mouse embryo fibroblasts impairs cell
proliferation, and that small hairpin RNA-mediated knockdown of Sidt2 in a fibrosarcoma model leads to increased tumor growth following transplantation into immunocompromised Scid mice (Brady et al., 2011). Together with the observation that SIDT2 is transcriptionally downregulated in patient tumors compared with healthy tissue (Beck et al., 2017), these findings thus support a possible tumor suppressive role for SIDT2.

In the current study, we further investigated the role of SIDT2 in tumor development. Unexpectedly, we found that mice lacking SIDT2 display reduced tumor burden and increased survival in both lung adenocarcinoma (LUAD) and intestinal cancer models. Moreover, consistent with its role in dsRNA transport, loss of SIDT2 leads to accumulation of dsRNA, resulting in increased phosphorylation of eIF2α and elevated rates of apoptosis. Our findings therefore suggest that SIDT2, and by extension RNautophagy, play a role in promoting tumor development.

### RESULTS

#### Loss of SIDT2 Inhibits Lung Adenocarcinoma Development

Given the finding that Sidt2 is a p53 target gene, we sought to investigate its role in tumor suppression in vivo. Lung cancer is the leading cause of cancer deaths worldwide, and loss or mutation of p53 is common in this tumor type. Therefore, we examined the role of Sidt2 in LUAD tumorigenesis by employing an autochthonous mouse model in which mice conditionally express oncogenic Kras<sup>G12D</sup> under the control of a lox-STOP-lox element (Kras<sup>LSL-G12D</sup>). Intratracheal inoculation of adenoaviral Cre recombinase excises the STOP cassette, resulting in expression of Kras<sup>G12D</sup> specifically in lung cells. Kras<sup>G12D</sup> expression drives development of non-small-cell lung tumors, and loss of p53 promotes tumor progression in this model (Dudek et al., 2009). To assess the role of Sidt2 in tumorigenesis in this LUAD model, we crossed Sidt2<sup>−/−</sup> mice previously generated in our laboratory (Nguyen et al., 2017) with Kras<sup>LSL-G12D/−</sup> mice and subsequently assessed lung tumor burden in Kras<sup>LSL-G12D/−;Sidt2<sup>−/−</sup></sup> and Kras<sup>LSL-G12D/−;Sidt2<sup>−/−</sup></sup> mice 18 weeks after intratracheal adenoaviral inoculation. In contrast to our previous report suggesting that Sidt2 has a tumor suppressive role in fibrosarcoma, light microscopic analysis of H&E-stained lung sections showed that Sidt2<sup>−/−</sup> animals have reduced tumor burden (Figure 1A). This was confirmed with subsequent quantification, which showed that mice deficient in Sidt2 developed significantly fewer tumors (Figure 1B) and had a significant reduction in overall tumor burden (Figure 1C). Next, we wanted to investigate whether the loss of SIDT2 leads to an impairment of cellular proliferation. To do so, we compared the expression of Ki67, a cellular marker of proliferation, using immunohistochemical staining (Figure 1D). Consistent with an impairment in cellular proliferation, tumors from Kras<sup>LSL-G12D/−;Sidt2<sup>−/−</sup></sup> mice had significantly less Ki67-positive cells compared with controls (Figure 1E). Together, these results thus suggest that SIDT2 facilitates tumor development in the Kras<sup>G12D</sup> LUAD model.

#### Loss of SIDT2 Inhibits Growth of Apc<sup>−/−</sup> Intestinal Tumors

The difference in the role for Sidt2 in tumorigenesis in the mouse fibrosarcoma and LUAD models prompted us to test another mouse tumor model to examine for context dependency of Sidt2 in cancer. To this end, we chose the well characterized Apc<sup>−/−</sup> mouse model of intestinal cancer. These mice harbor a dominant mutation in the oncogenic Apc gene, which leads to spontaneous development of adenomatous polyps, primarily in the distal small intestine (DSI) (Moser et al., 1990; Su et al., 1992).

We subsequently generated Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice lacking Sidt2 (Figure S1) and monitored the animals over time, sacrificing them after the onset of anemia and/or signs of ill health associated with death in this model (e.g., hunching of the back, weight loss). Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice (median survival: 131 days) survived significantly longer than both Apc<sup>−/−</sup> and Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice (median survival: 93 and 99 days, respectively), suggesting that loss of SIDT2 impairs intestinal tumor development (Figure 2A). To investigate further, Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice were sacrificed at day 100 and appeared to have a lower tumor burden within the DSI compared with Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice (Figure 2B). To properly assess this, tumor number (Figures 2C–2E) and tumor area (Figures 2F–2H) were calculated in the DSI, medial small intestine (MSI), and proximal small intestine (PSI) of 100-day-old Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> and Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice. There was no difference in tumor number in the colon (Figure S2A) or PSI, whereas Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice had significantly fewer tumors than Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice in the MSI and DSI. Moreover, Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice also had smaller tumors than Apc<sup>−/−</sup>/Sidt2<sup>−/−</sup> mice in the DSI, MSI, and PSI, but again showed no difference in the colon, where tumors are uncommon (Figure S2B). Together, these results suggest that SIDT2 also facilitates tumor development in the Apc<sup>−/−</sup> mouse model of intestinal cancer.
As Apc\textsuperscript{min/+};Sidt2\textsuperscript{+/+} mice had significantly smaller tumors than Apc\textsuperscript{min/+};Sidt2\textsuperscript{min/+} mice across all segments of the small intestine (Figures 2G–2I), we hypothesized that loss of SIDT2 does not affect tumor initiation, but instead plays a role in the growth of tumors by impairing cell proliferation. To investigate this possibility, we compared the expression of Ki67 in tumors of Apc\textsuperscript{min/+};Sidt2\textsuperscript{+/+} and Apc\textsuperscript{min/+};Sidt2\textsuperscript{min/+} mice (Figure 3A). Consistent with the decrease in Ki67-positive cells observed in Kras\textsuperscript{LSL-G12D/+};Sidt2\textsuperscript{+/+} mice, Apc\textsuperscript{min/+};Sidt2\textsuperscript{min/+} mice had significantly less Ki67-positive staining overall (Figure 3B), as well as fewer intra-tumoral Ki67-positive cells (Figure 3C) compared with Apc\textsuperscript{min/+};Sidt2\textsuperscript{+/+} mice.

**SIDT2 Is Required to Prevent dsRNA Accumulation and PKR/eIF2\(\alpha\) Pathway Activation**

Given the role of SIDT2 in transporting dsRNA across the endolysosomal membrane (Nguyen et al., 2017), we next assessed the effect of SIDT2 on the subcellular localization of dsRNA within the DSI. To do so, we performed immunofluorescence staining on frozen sections of the DSI of 100-day-old Apc\textsuperscript{min/+};Sidt2\textsuperscript{+/+} and Apc\textsuperscript{min/+};Sidt2\textsuperscript{min/+} mice using the J2 monoclonal antibody (Figure 4A), which specifically detects dsRNA helices at least 40 bp in length, in a sequence-independent manner (Schonborn et al., 1991). Notably, staining for dsRNA was readily observed within the intestinal crypts of Apc\textsuperscript{min/+};Sidt2\textsuperscript{+/+} mice but was absent in crypts of Apc\textsuperscript{min/+};Sidt2\textsuperscript{min/+} animals and in other parts of the DSI, including tumors (Figure 4B). To confirm that this was not specific to the Apc\textsuperscript{min/+} mouse model, we also performed dsRNA staining in lungs of Kras\textsuperscript{LSL-G12D/+};Sidt2\textsuperscript{+/+} and Kras\textsuperscript{LSL-G12D/+}; Sidt2\textsuperscript{−/−} mice using immunohistochemistry (Figure S3A). Consistent with our previous data, we observed a significant increase in cytosolic dsRNA staining in Kras\textsuperscript{LSL-G12D/+}; Sidt2\textsuperscript{−/−} mice compared with controls (Figure S3B), suggesting that loss of SIDT2 leads to accumulation of dsRNA in the cytosol.

Cytosolic dsRNAs are bound by RNA-dependent protein kinase (PKR), leading to its autophosphorylation and activation (Garcia et al., 2006). Activated PKR subsequently phosphorylates the \(\alpha\) subunit of protein synthesis initiation factor eIF2 (eIF2\(\alpha\)), resulting in inhibition of protein translation as well as anti-viral
and anti-tumor effects (Gao et al., 2013; Gao et al., 2016). We therefore wished to determine whether the accumulation of dsRNA in cells deficient in SIDT2 was likely to activate PKR. Although we tested multiple antibodies raised against phosphorylated PKR, none showed an ability to recognize activated murine PKR in control samples via western blot (data not shown), so instead we compared phosphorylation of eIF2α.

Figure 2. \(Apc^{min/+};Sidt2^{-/-}\) Mice Have Enhanced Survival and Smaller Tumors Compared with Controls

(A) Kaplan-Meier survival curve of \(Apc^{min/+};Sidt2^{+/+}\), \(Apc^{min/+};Sidt2^{+/-}\), and \(Apc^{min/+};Sidt2^{-/-}\) mice. Median survival rates of \(Apc^{min/+};Sidt2^{+/+}\), \(Apc^{min/+};Sidt2^{+/-}\), and \(Apc^{min/+};Sidt2^{-/-}\) mice are 93, 99, and 131 days respectively.

(B–I) (B) Representative image of distal small intestine of 100-day-old \(Apc^{min/+};Sidt2^{+/+}\) and \(Apc^{min/+};Sidt2^{-/-}\) mouse. Total number (C–E) and area (F–H) of visible tumors in the colon and small intestine (distal, medial, and proximal) was quantified in 100-day-old \(Apc^{min/+};Sidt2^{+/+}\) (n = 12) and \(Apc^{min/+};Sidt2^{-/-}\) (n = 12) mice. Error bars represent mean ± SEM. *p < 0.05, **p < 0.01, ***p < 0.001 as calculated by unpaired Student’s t test. See also Figures S1 and S2.
proxy for PKR activation. Moreover, because we only observed SIDT2-dependent dsRNA accumulation in the intestinal crypts and not in tumors themselves, we analyzed p-eIF2α expression separately in non-tumor and tumor tissues from the DSI of Apcmin/+;Sidt2+/+ and Apcmin/+;Sidt2−/+ mice. Notably, Apcmin/+;Sidt2+/+ mice displayed higher p-eIF2α levels in non-tumor tissue (Figure 4C), consistent with dsRNA accumulation and activation of PKR within these cells. This SIDT2-dependent increase in p-eIF2α was less apparent in tumor tissue (Figure 4D).

In addition to its role in the inhibition of protein translation, PKR activation has been shown to mediate cellular stress responses via regulation of mitogen-activated protein kinases such as c-Jun n-terminal kinase (JNK) (Goh et al., 2000; Kim et al., 2014; Taghavi and Samuel, 2012) and promote apoptosis via caspase 8 and nuclear factor-κB (Gil and Esteban, 2000). In line with our hypothesis that PKR activation is increased in the intestinal crypts in the absence of SIDT2, we observed a concurrent increase in phosphorylation of JNK in normal intestinal tissue of Apcmin/+;Sidt2−/+ mice compared with Apcmin/+;Sidt2+/+ mice (Figures 5A and 5B). To assess whether loss of SIDT2 leads to increased caspase 8-mediated apoptosis, we assessed and compared cleavage of caspase 8 in the DSI of Apcmin/+;Sidt2−/+ and Apcmin/+;Sidt2+/+ mice and observed an increase in caspase 8 cleavage products in Apcmin/+;Sidt2−/+ normal intestinal tissue (Figures 5A and 5C). We next performed immunohistochemical staining on intestinal Swiss rolls of Apcmin/+;Sidt2−/+ and Apcmin/+;Sidt2+/+ mice (Figure 5D), which revealed an increased number of cleaved-caspase 3-positive cells within intestinal crypts lacking SIDT2 (Figure 5E). This was further confirmed via TUNEL staining in which Apcmin/+;Sidt2−/+ showed increased TUNEL-positive cells within

Figure 3. Loss of SIDT2 Impairs Tumor Proliferation

(A–C) (A) Representative H&E- and Ki67-stained histological sections of distal small intestine of Apcmin/+;Sidt2+/+ and Apcmin/+;Sidt2−/+ mice at 100 days of age. Quantification of (B) Ki67-positive staining area as a percentage of total tumor area and (C) average number of Ki67-positive cells per tumor. Analysis was performed on >20 high-power fields across three mice. Error bars represent mean ± SEM. ***p < 0.001 as calculated by unpaired Student’s t test.
intestinal crypts compared with controls (Figure 5F). Taken together, these data strongly imply that loss of SIDT2 leads to increased caspase 8- and caspase 3-mediated apoptosis within intestinal crypts, consistent with the restricted tumor growth observed in *Apc*<sup>min/+;Sidt2<sup>C0/C0</sup></sup> animals.

**Lower SIDT2 Expression Is Associated with Improved Survival in Different Human Cancers**

Finally, to explore the role of SIDT2 in human cancer, we determined whether different levels of intratumoral SIDT2 expression are associated with changes in patient survival. Using data collected by The Cancer Genome Atlas Research Network (http://cancergenome.nih.gov) and analyzed via The Pathology Atlas (Uhlen et al., 2017), we observed that lower intratumoral SIDT2 RNA levels were associated with significantly improved prognosis in 5 of 17 different cancers (renal, thyroid, gastric, glioma, urothelial) (Figures 6A–6E). However, consistent with a context-dependent role, intratumoral SIDT2 RNA levels showed no prognostic significance in 10 other cancers (including LUAD and colon cancer), and lower
intradatumal SIDT2 levels were actually associated with poorer survival in pancreatic and cervical cancers (Figure S5).

**DISCUSSION**

In this study, we show that the mammalian SID-1 ortholog SIDT2, which is a transcriptional target for p53, promotes tumor growth. Specifically, loss of SIDT2 in mice caused reduced tumor burden and enhanced survival, with the latter observation supported by data from patients with several different cancers in which lower SIDT2 expression was associated with an improved prognosis.

Mechanistically, our data from Apcmin animals suggest a model in which the absence of SIDT2 leads to impaired RNautophagy, accumulation of intracellular dsRNA, increased phosphorylation of elfF2a and JNK, and finally, increased apoptosis via activation of caspase 8 (Figure 7). Notably, when visualized, these changes were only observed in the intestinal crypts and not in tumors themselves, and is potentially in
keeping with the strong expression of SIDT2 observed within the crypts of human small intestine (Uhlen et al., 2017) (Figure S4). Nevertheless, such observations invite the question of how such crypt-related changes could impact subsequent tumor growth. One possible explanation is that the increased apoptosis observed in SIDT2-deficient mice affects cancer stem cells, which reside within the intestinal crypt and play a key role in subsequent tumor growth. Consistent with this, selective depletion of intestinal stem cells has previously been shown to restrict primary tumor growth in mice (de Sousa e Melo et al., 2017), and this would be in keeping with our observation that SIDT2-deficient tumors show reduced proliferation (Figure 3). Another possible explanation is that increased eIF2α activation in the absence of SIDT2 induces differentiation (and thus loss) of these same intestinal stem cells, as has been observed by others (Heijmans et al., 2013). Further work to investigate the specific effects of SIDT2 on cancer stem cell development will hopefully shed light on these possibilities.

Notwithstanding our inability to activate PKR (see below), PKR seems a likely candidate in mediating the downstream effects in our Apcmin Sidt2−/− mice. After all, PKR has well-established roles not only in binding and responding to intracellular dsRNA but also in inducing eIF2α phosphorylation, JNK activation, and caspase 8-mediated activation of caspase 3 to induce apoptosis. Consistent with our results, PKR expression

Figure 6. – Lower SIDT2 Expression Is Associated with Improved Survival in Some Cancers
(A–E) Kaplan-Meier curves of overall survival of patients with (A) renal, (B) thyroid, (C) gastric, and (D) urothelial cancer and (E) glioma stratified against SIDT2 expression from publicly available RNA-seq data. The results shown are in whole based upon data generated by the TCGA Research Network: http://cancergenome.nih.gov/.
See also Figure S5.
and auto-phosphorylation have previously been reported to be increased in multiple human malignancies, including colon and lung cancer (Kim et al., 2000, 2002), and those with higher p-PKR and p-eIF2a had significantly longer survival (Guo et al., 2013; He et al., 2011; Pataer et al., 2010).

Given the presence of intracellular dsRNA in \textit{Apcmin};\textit{Sidt2}\textsuperscript{-/-} intestinal crypts, we also assessed whether there was induction of a type I IFN response in these tissues. However, we were unable to detect upregulation of \textit{Ifn}\textsubscript{b} or various IFN-stimulated genes in tissues of \textit{Apcmin/+};\textit{Sidt2}\textsuperscript{-/-} mice (data not shown), suggesting that the reduced tumor burden observed in SIDT2-deficient mice is unlikely to be due to the anti-tumor effects of type I IFN (Dunn et al., 2006). This lack of a type I IFN response may also provide a clue as to the nature of the dsRNA that accumulates in the absence of SIDT2. Specifically, the type I IFN response to cytoplasmic dsRNA is mainly orchestrated by the RIG-I-like receptors, RIG-I and MDA-5 (Laessig and Hopfner, 2017; Yoneyama and Fujita, 2010). RIG-I specifically recognizes short dsRNA and ssRNA with 5’ triphosphate ends (Hornung et al., 2006), a common feature of viral RNAs, and MDA-5 is critical for the detection of long dsRNAs (>1,000 bp) (Kato et al., 2006; Peisley et al., 2012, 2011). The lack of a detectable type I IFN response in \textit{Apcmin/+};\textit{Sidt2}\textsuperscript{-/-} mice therefore suggests that the dsRNAs that accumulate in the intestinal crypts of these animals do not possess 5’ triphosphate ends and are not long enough to activate MDA-5. In contrast, PKR requires a minimum dsRNA region of only 30 bp (Lemaire et al., 2008; Manche et al., 1992) and can recognize RNAs with limited stem loop or duplex structures (Osman et al., 1999), including small interfering RNA (Puthenveettil et al., 2006; Sledz et al., 2003), small nucleolar RNA (Youssef et al., 2015), and bacterial RNAs (Hull and Bevilacqua, 2015). Indeed, PKR has recently been reported to bind endogenous nuclear dsRNAs during cell mitosis (Kim et al., 2014), noncoding Alu RNA and mitochondrial RNAs that are capable of forming intramolecular dsRNA structures (Kim et al., 2018). These RNA species may therefore be more likely to accumulate in the absence of SIDT2. At the same time, it has been proposed that autophagy is important for the degradation of many types of cytosolic RNAs, including retrotransposon, viral, and cellular messenger RNAs (Aizawa et al., 2016; Guo et al., 2014; Orvedahl et al., 2010), so impaired lysosomal degradation of RNA in the absence of SIDT2 could also lead to accumulation of these RNAs within the intestinal crypt. Future studies to identify the RNA cargo of SIDT2 within the intestine will clarify these possibilities.

Finally, it should be noted that the apparent protective effect of lower intratumoral SIDT2 levels on patient survival was limited to certain types of cancers. Moreover, in pancreatic and cervical cancers, lower intratumoral SIDT2 levels were associated with poorer survival. Thus, the role of SIDT2 in promoting tumor growth may only apply in specific contexts, and this may explain the apparent contradiction between the data described here and our earlier findings, namely, that SIDT2 functions as a tumor suppressor in a
fibrosarcoma model (Brady et al., 2011). Regardless, the results from this study identify a role for SIDT2 and
RNAutophagy in promoting cancer development in vivo and suggest the possibility that strategies to inhibit
SIDT2 and/or RNAutophagy could be a useful adjunct to existing treatment for certain types of cancer.

Limitations of Study
In this study, we were unable to directly show that the accumulation of dsRNA in Sidt2−/− mice leads to
increased PKR activation. This was despite trying a range of different approaches, including commercial
antibodies designed to detect phosphorylated murine PKR, phos-tag gels, and direct mass spectrometry
methods. Reliable detection of murine phospho-PKR is a problem that is well recognized in the field, and
future studies using Sidt2−/−;Pkr−/− animals may shed further light on the mechanistic interplay between
these two proteins in cancer development.

METHODS
All methods can be found in the accompanying Transparent Methods supplemental file.

SUPPLEMENTAL INFORMATION
Supplemental Information can be found online at https://doi.org/10.1016/j.isci.2019.09.009.

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AUTHOR CONTRIBUTIONS
K.C.P., T.A.N., K.T.B.-R., T.L.P., I.P.W., and L.D.A. designed experiments and/or analyzed the data. T.A.N.
and K.T.B.-R. performed experiments. K.C.P. and T.A.N. wrote the manuscript. K.C.P., L.D.A., and I.P.W.
supervised the project.

DECLARATION OF INTERESTS
The authors declare no competing interests.

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Supplemental Information

SIDT2 RNA Transporter Promotes Lung and Gastrointestinal Tumor Development

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Supplemental Figure 1

Sidt2 expression (Normalised to GAPDH)

Sidt2+/+ non-tumor
Sidt2−/− non-tumor
Sidt2+/+ tumor
Sidt2−/− tumor
Supplemental Figure 1 – *Sidt2* is expressed in normal intestinal and tumour tissue in the distal small intestine of *Apc*<sup>min/+</sup> mice. Related to Figure 2.

*Sidt2* expression in tumour and adjacent non-tumour tissue isolated from 100-day old *Sidt2*<sup>+/+</sup>:*Apc*<sup>min/+</sup> and *Sidt2*<sup>−/−</sup>:*Apc*<sup>min/+</sup> mice assessed via qRT-PCR. n = 5 mice per group. Data is plotted as mean ± SEM.
Supplemental Figure 2

A

Tumour area (mm²)

B

Tumour #
Supplemental Figure 2 – Loss of SIDT2 does not affect tumor burden in $Apc^{min/+}$

**mouse model.** Related to Figure 2.

Total number (**A**) and area (**B**) of visible tumors in the colon and small intestine (distal, medial and proximal) was quantified in 100-day old $Apc^{min/+};Sidt2^{+/+}$ (n=12) and $Apc^{min/+};Sidt2^{-/-}$ (n=12) mice. Error bars represent ± SEM.
Supplemental Figure 3

A

Kras\textsuperscript{LSL-G12D/+;Sidt2\textsuperscript{+/+}}

Kras\textsuperscript{LSL-G12D/+;Sidt2\textsuperscript{-/-}}

B

dsRNA positive area per mm\textsuperscript{2} tissue (%)

Supplemental Figure 3
Supplemental Figure 3 – Loss of SIDT2 leads to accumulation of cytosolic dsRNA in the lungs of \( Kras^{LSL-G12D/+}; Sidt2^{-/-} \) mice. Related to Figure 4.

(A) Representative image of dsRNA staining of lung sections from \( Kras^{LSL-G12D/+}; Sidt2^{+/+} \) and \( Kras^{LSL-G12D/+}; Sidt2^{-/-} \) mice. (B) Quantification of dsRNA-positive stained area per non-tumour area (\( n = 6 \) mice per genotype). Error bars represent ± SEM. * indicates \( P < 0.05 \) as calculated by Mann Whitney non-parametric test.
Supplemental Figure 4
Supplemental Figure 4 – Human SIDT2 is expressed in glandular crypts of small intestine. Related to Figure 4 and Figure 5.

Publicly accessible images from The Human Protein Atlas of immunohistochemical stained sections of human small intestine from 3 individual healthy patient samples shows strong cytoplasmic localisation of SIDT2 in glandular cells (Uhlen et al., 2017).
Supplemental Figure 5 – Lower SIDT2 expression is associated with lower survival for pancreatic and cervical cancer. Related to Figure 6.

Kaplan–Meier curves of overall survival of (A) cervical and (B) pancreatic cancer patients stratified against SIDT2 expression from publicly available RNAseq data. The results shown are based upon data generated by the TCGA Research Network: http://cancergenome.nih.gov/.
TRANSPARENT METHODS

Mice
Mice were bred and maintained in the animal facilities at the Walter and Eliza Hall Institute of Medical Research (WEHI) and at the Department of Radiation Oncology, Stanford University, according to national and institutional guidelines for animal care. Mice were housed in individual ventilated cages at 19 - 24 ºC and maintained on a 14 h light to 10 h dark cycle with continuous access to Barastoc Custom Mixed Ration (irradiated) and acidified and filtered water. Female and male mice were used in experiments and were pooled for analysis. All experimental procedures were approved by the relevant animal ethics committees at the WEHI and Stanford University.

Analysis of Kras$^{LSL-G12D/+}$ LUAD mouse model
Kras$^{LSL-G12D/+};Sidt2^{-/-}$ and Kras$^{LSL-G12D/+};Sidt2^{+/-}$ aged 6-8 weeks were inoculated with $4 \times 10^6$ PFU Adenovirus containing Cre recombinase (University of Iowa Viral Vector Core) by intratracheal intubation (DuPage et al., 2009). Eighteen weeks after inoculation, the lungs were harvested, fixed in 10% formalin, and bread-loafed into approximately 12 pieces per lung. The pieces were sectioned, stained with hematoxylin and eosin (H&E) as described below, and analyzed for tumor number and tumor burden.

Histological analyses
For histological examination of the intestine, colon, distal, medial and proximal portions of the small intestine were slit open longitudinally and the intraluminal contents removed. Each segment was then rolled up from the distal end to the proximal end using a “Swiss-rolling” technique (Williams et al., 2016). Preparations were then fixed in 10% (w/v) neutral-buffered formalin for at least 12 hours before embedding in paraffin, sectioned (3 µm), and prepared for general staining and immunohistochemistry (IHC). For frozen sections, Swiss roll preparations
were frozen and embedded in Optimal Cutting Temperature (OCT) using a PrestoCHILL system (Milestone), and sectioned (10 µm) for immunofluorescence staining. For H&E staining, slides were incubated with hematoxylin to stain nuclei (5 min), washed in dH₂O (1 min), incubated in 0.3% (v/v) acid ethanol to de-stain (1 dip), rinsed in dH₂O followed by Scott's tap water, then incubated in eosin (1 min). Slides were then rinsed in dH₂O, dehydrated, cleared and mounted.

**Immunohistochemistry and TUNEL staining**

Automated staining was performed using the Dako Omnis EnVision G2 template. Dewax was performed with Clearify Clearing Agent (Dako) for 15 minutes, and antigen retrieval was done with EnVision FLEX TRS, High pH (Dako) at 97ºC for 30 minutes. Antibody against Ki67 (Cell Signaling #9129) and cleaved Caspase-3 (Asp175) (R&D Systems) was diluted 1:100 in EnVision Flex Antibody Diluent (Dako) and incubated at 32ºC 60 minutes. Envision+ System- HRP Labelled Polymer Anti-Rabbit antibodies (Dako) were incubated for 20 min at 32ºC. Slides were counter-stained with Mayer Hematoxylin, dehydrated, cleared, and mounted with MM24 Mounting Medium (Surgipath-Leica). Tissue sections were imaged using the 3D Histech Slide Scanner and quantification analysis of Ki67 and cleaved caspase 3 positive cells was performed using ImageJ. For TUNEL staining, slides were prepared and stained using ApopTag® Red In Situ Apoptosis Detection Kit (Merk Millipore) according to manufacturer’s instructions and imaged on a Zeiss Axio Observer wide-field fluorescence microscope.

**Immunofluorescence staining of dsRNA**

Frozen sections were fixed in 4% paraformaldehyde for 10 min on ice and washed 3 times in cold PBS permeabilized using 0.1% Tween/PBS, blocked in 5% normal goat serum for 1 h and stained with J2 (SciCon) primary antibody (1:200) overnight. Slides were subsequently washed 3 times for 5 min in PBS and then incubated with anti-mouse Alexa-594 secondary antibody for 1 h at room temperature. Sections were washed 3 times for 5 min in PBS and then cover-
slipped and mounted using Fluoroshield mounting medium with DAPI (Sigma Aldrich). Stained sections were imaged on a Zeiss Axio Observer wide-field fluorescence microscope.

**Western blotting**

Intestinal tumor and adjacent non-tumor tissue were lysed in KALB lysis buffer supplemented with protease inhibitor and phosphatase inhibitor (Roche) and then homogenized using a QIAGEN TissueLyser II, according to manufacturer’s instructions. Homogenates were subsequently cleared by centrifugation at 13,000 rpm at 4°C for 20 minutes and denatured in 4x SDS PAGE sample buffer at 95°C for 5 min. 60µg of protein lysate was separated on NUPAGE Novex 4-12% Bis-Tris Gels (Life Technologies), and transferred electrophoretically to PVDF membranes, blocked in 5% BSA/TBST, incubated with the relevant primary antibodies overnight. Membranes were incubated for 1 h with horseradish peroxidase-conjugated secondary antibodies, washed, treated with Luminata Forte Western HRP substrate (Millipore), and visualized on the ChemiDoc MP system (Bio-Rad). Primary antibodies used were: total eIF2α (Cell Signaling, #9722, 1:1000), phospho-eIF2α (Cell Signaling, # 9721, 1:1000), phospho-JNK (Cell Signaling, #4668P, 1:1000), total JNK (Cell Signaling, #9252, 1:1000), pro-caspase 8 (WEHI in-house antibody, 1:1000), mouse specific cleaved caspase-8 (Asp387) (Cell Signaling #9429, 1:1000), Hsp70 (Thermo Fisher Scientific, #MA3-007, 1:10 000).

**Analysis of SIDT2 expression on cancer patient survival**

Maximally separated Kaplan–Meier curves of overall survival of cancer patients stratified against SIDT2 expression were generated from data by the TCGA Research Network: [http://cancergenome.nih.gov/](http://cancergenome.nih.gov/) and accessed via The Human Protein Atlas (Uhlen et al., 2017). Based on the FPKM value of SIDT2, patients were classified into two expression groups and the correlation between expression level and patient survival was examined.
Statistical analysis

Statistical analyses were performed in GraphPad Prism 7 software using unpaired, two-tailed student’s t-tests, except in the case of the survival analysis, where a generalized Wilcoxon (Gehan–Breslow) test was used to compare survival curves. P values < 0.05 were considered statistically significant.

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