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ORIGINAL ARTICLE

Cell of origin affects tumour development and phenotype in pancreatic ductal adenocarcinoma

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ABSTRACT

Objective Pancreatic ductal adenocarcinoma (PDAC) is a highly aggressive tumour thought to arise from ductal cells via pancreatic intraepithelial neoplasia (PanIN) precursor lesions. Modelling of different genetic events in mice suggests both ductal and acinar cells can give rise to PDAC. However, the impact of cellular context alone on tumour development and phenotype is unknown.

Design We examined the contribution of cellular origin to PDAC development by inducing PDAC-associated mutations, $Kras^{G12D}$ expression and *Trp53* loss, specifically in ductal cells (*Sox9CreER;*$Kras^{LSL\text{-}G12D}$*;*$Trp53^{flox/flox}$ ('*Duct:KP*^{cKO}')) or acinar cells (*Ptf1a*^{CreER}*;*$Kras^{LSL\text{-}G12D}$*;*$Trp53^{flox/flox}$ ('*Acinar:KP*^{cKO}')) in mice. We then performed a thorough analysis of the resulting histopathological changes.

Results Both mouse models developed PDAC, but *Duct:KP*^{cKO} mice developed PDAC earlier than *Acinar:KP*^{cKO} mice. Tumour development was more rapid and associated with high-grade murine PanIN (mPanIN) lesions in *Duct:KP*^{cKO} mice. In contrast, *Acinar:KP*^{cKO} mice exhibited widespread metaplasia and low-grade as well as high-grade mPanINs with delayed progression to PDAC. Acinar-cell-derived tumours also had a higher prevalence of mucinous glandular features reminiscent of early mPanIN lesions.

Conclusion These findings indicate that ductal cells are primed to form *carcinoma in situ* that become invasive PDAC in the presence of oncogenic Kras and *Trp53* deletion, while acinar cells with the same mutations appear to require a prolonged period of transition or reprogramming to initiate PDAC. Our findings illustrate that PDAC can develop in multiple ways and the cellular context in which mutations are acquired has significant impact on precursor lesion initiation, disease progression and tumour phenotype.

Significance of this study

What is already known on this subject?

- Oncogenic $Kras^{G12D}$ mutations are hypothesised to initiate preneoplastic pancreatic lesions, called pancreatic intraepithelial neoplasia (PanIN), which subsequently acquire other genetic alterations, like *Trp53* loss, to form pancreatic ductal adenocarcinoma (PDAC).
- $Kras^{G12D}$ expression in acinar cells induces numerous low-grade murine PanIN (mPanIN) lesions, while few are induced from $Kras^{G12D}$-expressing ductal cells.
- $Kras^{G12D}$-expressing acinar cells can form PDAC in the presence of heterozygous mutations in *Trp53*, while homozygous mutations in *Trp53* are needed for $Kras^{G12D}$ to transform ductal cells.

What are the new findings?

- PDAC forms faster from ductal than acinar cells when the same mutations and conditions are present, demonstrating that cell of origin alone can affect tumour development.
- High-grade mPanIN are quickly induced from both $Kras^{G12D}$-expressing ductal and acinar cells lacking *Trp53*; however, ductal-cell-derived mPanIN3 become invasive faster than acinar-cell-derived mPanIN3.
- Acinar-cell-mediated tumourigenesis is associated with low-grade mPanINs and characteristics of low-grade mPanIN are found in acinar-cell-derived PDAC, suggesting that cell of origin can affect tumour phenotype.

How might it impact on clinical practice in the foreseeable future?

- Acinar and ductal cells are capable of initiating tumourigenesis in mice. These novel mouse models may be helpful in identifying the cellular origin of human disease in the future.
- These studies demonstrate that cell of origin alone could impact the development and phenotype of PDAC.
- Preclinical animal model studies should consider the important effects of cellular origin on the phenotype of PDAC and its response to treatment, and disease outcomes.

INTRODUCTION

Pancreatic ductal adenocarcinoma (PDAC) is characterised as a mass of haphazard ductules arranged in a desmoplastic stroma. The histological similarity of these ductules and associated precancerous lesions, called pancreatic intraepithelial neoplasia (PanIN), to pancreatic ductal cells suggested a lineage relationship and led to the development of tumour progression models that featured the normal ductal cell as the cellular origin of PDAC.[1] In these models, oncogenic Kras, one of the most common mutations in PDAC, is proposed to initiate low-grade PanIN from ductal cells. These lesions then acquire additional mutations, such as p16 or p53 loss, before becoming high-grade PanIN and

invasive PDAC.[1] However, acinar cells were found in early metaplastic ductules[2 3] and lineage traced into a ductal-cell-like fate,[4 5] suggesting that acinar cells could act as a cellular origin for PDAC. Indeed, multiple studies have shown that oncogenic Kras expression in murine acinar cells triggers widespread ductal metaplasia, murine PanIN (mPanIN) as well as PDAC.[6–11] In contrast, oncogenic Kras expression in ductal cells induces only a small number of low-grade mPanIN.[10 12] In sum, experimental evidence predominantly supports the potential of acinar cells to initiate mPanIN and PDAC; however, the data regarding ductal cell potential are limited.

Although ductal cells can contribute to mPanINs,[10 12] whether these ductal-cell-derived lesions progress in the same manner as acinar-cell-derived mPanIN or whether they are viable cell of origin for PDAC is unclear. Recent studies have started to directly compare the potential of acinar and ductal cells to initiate PDAC.[6 13 14] Using mouse models, these studies show that both ductal and acinar cells have the potential to form PDAC.[6 13 14] However, the acinar-cell-derived or ductal-cell-derived tumours were formed under different treatment conditions or with different genetic mutations[6 13 14]; therefore, it remains unclear whether the differences in tumour development or phenotype observed were a result of the treatment conditions, mutation combination or cellular origin. Thus, studies to specifically examine the cell-of-origin-specific effects are needed and could highlight the initiating cell as a source of PDAC heterogeneity.

To isolate the effect of cell of origin alone on PDAC initiation, development and phenotype, we used CreER-inducible mouse models to make the same genetic changes, expression of oncogenic $Kras^{G12D}$ and ablation *Trp53* (occurring in ~92% and ~27% of human PDAC samples, respectively[15]), in ductal or acinar cells. We found that cell of origin alone can impact the initiation and phenotype of PDAC.

MATERIALS AND METHODS

Mice

All described animal experiments were approved by the University of British Columbia and University of California, San Diego Animal Care and Use Committees. The sources and phenotypes for the mouse strains, as well as details of genotyping and endpoint monitoring strategies, are provided as online Supplemental Information. Recombination was induced by three subcutaneous injections of tamoxifen in corn oil (20 mg/mL) over 5 days at 0.125 g tamoxifen/g body mass.

Histology, immunohistochemical and immunofluorescence analyses

Paraffin-embedded or frozen sections were prepared and stained using haematoxylin and eosin, Alcian blue, immunohistochemical or immunofluorescence stains as described previously.[10 16–18] Histological and morphometric analyses were conducted by AYLL and JLK independently and verified by DFS (gastrointestinal pathologist). Detailed descriptions of staining and morphological assessment methods, as well as the antibodies used, are provided as online Supplemental Information.

Statistical analysis

Normal distribution, F-test of variance, and parametric and non-parametric P values were calculated in GraphPad Prism or Excel or statistical programming language R, V.3.4.1 (R Core Development Team, 2017) software. GraphPad Prism was used to calculate the mean and SEM. We performed a linear regression using the statistical programming language R, V.3.4.1 (R Core Development Team, 2017) to test if there was a significant ($P<0.05$) relationship between time post-tamoxifen injection and tumour number or size.

RESULTS

Loss of *Trp53* and activation of Kras in ductal compared with acinar cells shortens survival in mice

To determine how cellular origin affects the initiation and progression of PDAC, we generated mouse models in which a shared set of PDAC-associated mutations[15 19 20] in *Kras* and *Trp53* were induced in a cell-type-specific manner. Specifically, we used the Cre-dependent $Kras^{LSL\text{-}G12D}$ [21] and $Trp53^{flox}$ conditional alleles[22] to activate Kras and ablate p53 expression, respectively. To trace the fate of recombined cells, we also included a Cre-dependent $R26R^{YFP}$ reporter allele.[23] Finally, Cre-mediated recombination was induced in adult ductal or acinar cells using the tamoxifen-inducible *Sox9CreER* transgene[18 24] or $Ptf1a^{CreER}$ allele,[25] respectively. By combining all of these alleles through cross-breeding and injecting the offspring with tamoxifen at 3 to 4 weeks of age (figure 1A, B), we generated $Sox9CreER;Kras^{LSL\text{-}G12D};Trp53^{flox/flox};R26R^{YFP}$ (hereafter referred to as $Duct{:}KP^{cKO}$) and $Ptf1a^{CreER};Kras^{LSL\text{-}G12D};Trp53^{flox/flox};R26R^{YFP}$ (hereafter referred to as $Acinar{:}KP^{cKO}$) mice (figure 1A). Mice injected with tamoxifen but lacking the *Kras* oncogene were used as controls ($Sox9CreER;Trp53^{flox/flox};R26R^{YFP}$ or $Ptf1a^{CreER};Trp53^{flox/flox};R26R^{YFP}$ mice). Four weeks after tamoxifen injection, we observed highly efficient and specific labelling of $Sox9^{+}$ ductal or carboxypeptidase $A1^{+}$ ($Cpa1^{+}$) acinar cells in $Sox9CreER;Trp53^{flox/flox};R26R^{YFP}$ or $Ptf1a^{CreER};Trp53^{flox/flox};R26R^{YFP}$ mice, respectively (online supplementary figure S1A, B). As previously reported,[24 25] little or no recombination of the $R26R^{YFP}$ allele was observed in uninjected mice with the *Sox9CreER* or $Ptf1a^{CreER}$ allele, respectively (online supplementary figure S1C).

To examine the effect of activating Kras and ablating *Trp53* on ductal and acinar cells, we injected a cohort of $Duct{:}KP^{cKO}$ (n=19) and $Acinar{:}KP^{cKO}$ (n=9) mice with tamoxifen at 3 to 4 weeks of age and monitored the animals until their humane endpoint (figure 1B). In addition to the pancreas, this *Sox9CreER* allele[24] is expressed in the oral mucosa, mammary gland and lung. Therefore, 11 $Duct{:}KP^{cKO}$ mice reached their humane endpoint due to non-pancreatic masses, were censored from the PDAC-specific survival curve and excluded from further analysis (figure 1C). The remaining $Duct{:}KP^{cKO}$ mice (n=8) reached their humane endpoint within 10–13 weeks post-tamoxifen injection (figure 1C). In contrast, $Acinar{:}KP^{cKO}$ mice reached their humane endpoint at 15–23 weeks post-tamoxifen injection (figure 1C). On necropsy, we found pancreatic tumours (figure 1D) in $Duct{:}KP^{cKO}$ and $Acinar{:}KP^{cKO}$ mice that blocked the bile duct resulting in jaundice, penetrated the small bowel and/or induced large amounts of haemorrhagic or clear ascites fluid (table 1). Control $Sox9CreER;Trp53^{flox/flox};R26R^{YFP}$ or $Ptf1a^{CreER};Trp53^{flox/flox};R26R^{YFP}$ mice of similar or older ages were anatomically normal (figure 1D and data not shown). Occasionally, local splenic, duodenal or perineural invasion (seven of eight $Duct{:}KP^{cKO}$ mice and five of eight $Acinar{:}KP^{cKO}$ mice) was observed. Distant metastases to the peritoneal wall, diaphragm and potentially liver were observed only in $Duct{:}KP^{cKO}$ mice (six of eight $Duct{:}KP^{cKO}$ mice) (online supplementary figure S1D–F and table 1). However, the small liver adenocarcinomas could not be definitively distinguished as cholangiocarcinoma versus metastatic PDAC; therefore, the lineage of these liver lesions is uncertain. Together, these data suggested that loss

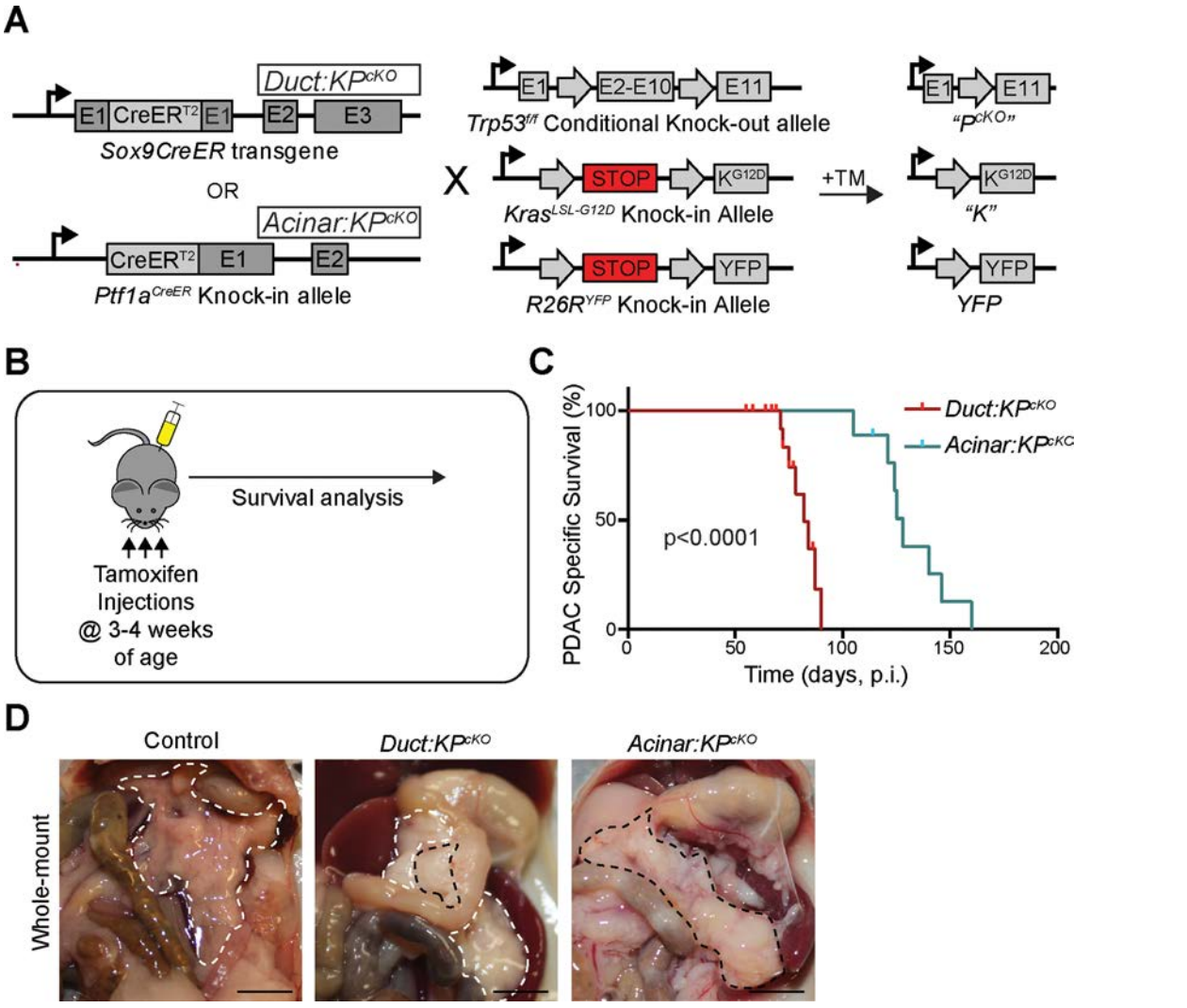

Figure 1 Kras^{G12D}-expressing ductal cells form tumours earlier than acinar cells in the absence of *Trp53*. (A) Schematic of the alleles in the *Sox9CreER;Kras*$^{LSL\text{-}G12D}$*;Trp53*$^{flox/flox}$*;R26R*^{YFP} (*Duct:KP*^{cKO}) and *Ptf1a*^{CreER}*;Kras*$^{LSL\text{-}G12D}$*;Trp53*$^{flox/flox}$*;R26R*^{YFP} (*Acinar:KP*^{cKO}) mouse models used in this study. Tamoxifen (TM) injection induces Cre-mediated DNA recombination and results in expression of oncogenic Kras^{G12D} from the *Kras*$^{LSL\text{-}G12D}$ ('*K*') allele and the YFP lineage label from the *R26R*^{YFP} allele. In addition, TM injection induces the deletion of exons 2–10 from the *Trp53*^{flox} ('*P*^{cKO}') allele and loss of p53 expression. (B) *Duct:KP*^{cKO} (n=19) and *Acinar:KP*^{cKO} (n=9) mice were injected three times on alternating days with TM beginning at 3–4 weeks of age. The mice were monitored until they reached their humane endpoint to determine survival duration. (C) The median disease-specific survival of *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice (82 vs 128 days, P<0.0001). Mice euthanised due to non-pancreatic reasons were censored (hash marks). (D) Representative gross anatomical photographs of the mouse abdomen from *Sox9CreER;Trp53*$^{flox/flox}$*;R26R*^{YFP} (control), *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice. White or black dashed lines outline either normal parenchyma or tumours, respectively. PDAC, pancreatic ductal adenocarcinoma; p.i., post-tamoxifen injection. Scale bars: 5 mm.

of *Trp53* in Kras^{G12D}-expressing ductal or acinar cells induced PDAC. However, *Acinar:KP*^{cKO} mice had a median PDAC-specific survival period that was approximately 7 weeks longer than *Duct:KP*^{cKO} mice (P<0.0001) and did not have any signs of distant metastases (table 1), suggesting that cell of origin alone can affect tumour development and phenotype.

Cell of origin affects PDAC histology and timing

To determine whether differences in the survival outcomes of *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice were due to distinct tumour attributes, we extensively characterised the tumours in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice. Pancreata from both *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice, but not controls, had solid tumour nodules, ranging from small, distinct nodes to complete displacement of the normal parenchyma by tumours (figure 1D and figure 2A, tumours outlined with white dashed line). Haematoxylin and eosin staining confirmed that these tumours were composed of glandular structures arranged in a haphazard pattern (figure 2B) consistent with PDAC. Further characterisation by immunohistochemical staining demonstrated that tumours from both genotypes were ductal in nature (Cytokeratin 19^{+}, figure 2C and table 1; Sox9^{+} and Hnf1b^{+}, online supplementary figure S2A) and arose from YFP^{+} lineage traced cells (figure 2C) that had recombined the *Kras*$^{LSL\text{-}KrasG12D}$ and *Trp53*^{flox} loci (online supplementary figure S2B) and lacked p53 expression (online supplementary figure S2C, arrowheads indicate p53^{+} stromal cells). Histologically, tumours from *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice were predominantly composed of moderately differentiated cells arranged in small glandular structures surrounded by collagen-rich stroma (figure 2B, D and online supplementary figure

Table 1 Characterisation of *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice

Genotype	Mouse ID	Time (days, p.i.)	Jaundice	Liver lesion	Distant met		Local invasion			Ascites	Cytokeratin 19 IHC	Histological type		Tumour area (% of total pancreatic area)
					Diaphragm	Peritoneum	Spleen	Duodenum	PNI/LVI/BVI			Large-gland	Mucinous-gland	
Duct:KP^{cKO}	144	71			X	X	X	X	X		+++	0/7	2/7	90
	107	72	X	X				X			+++	0/4	1/4	41
	469	75	X	X				X		B	+++	0/10	0/10	48
	499	78		X					X	B	+++	0/4	0/4	92
	433	82		X				X			+++	0/8	0/8	87
	479	84		X	X	X			X	B	+++	0/5	0/5	86
	477	87									+++	0/5	0/5	42
	369	90						X			+++	0/5	0/4	42
Acinar:KP^{cKO}	97	105	X								+++	3/5	0/5	18
	23	121						X			+++	0/5	1/5	49
	94	124								C	+++	3/8	0/8	41
	27	125							X		+++	1/3	1/3	98
	100	128	X								+++	3/5	0/5	69
	52	140	X					X	X		+++	1/5	0/5	41
	92	146					X		X	B	+++	0/4	2/4	82
	33	160					X	X	X	C	+++	0/6	4/6	82

B, haemorrhagic ascites fluid; BVI, blood vessel invasion; C, clear ascites fluid; ID, mouse identification number; IHC, immunohistochemistry; LVI, lymphatic invasion; met, metastasis; p.i., post-injection; PNI, perineural invasion; X, characteristic present; +++, strong positive IHC positivity.

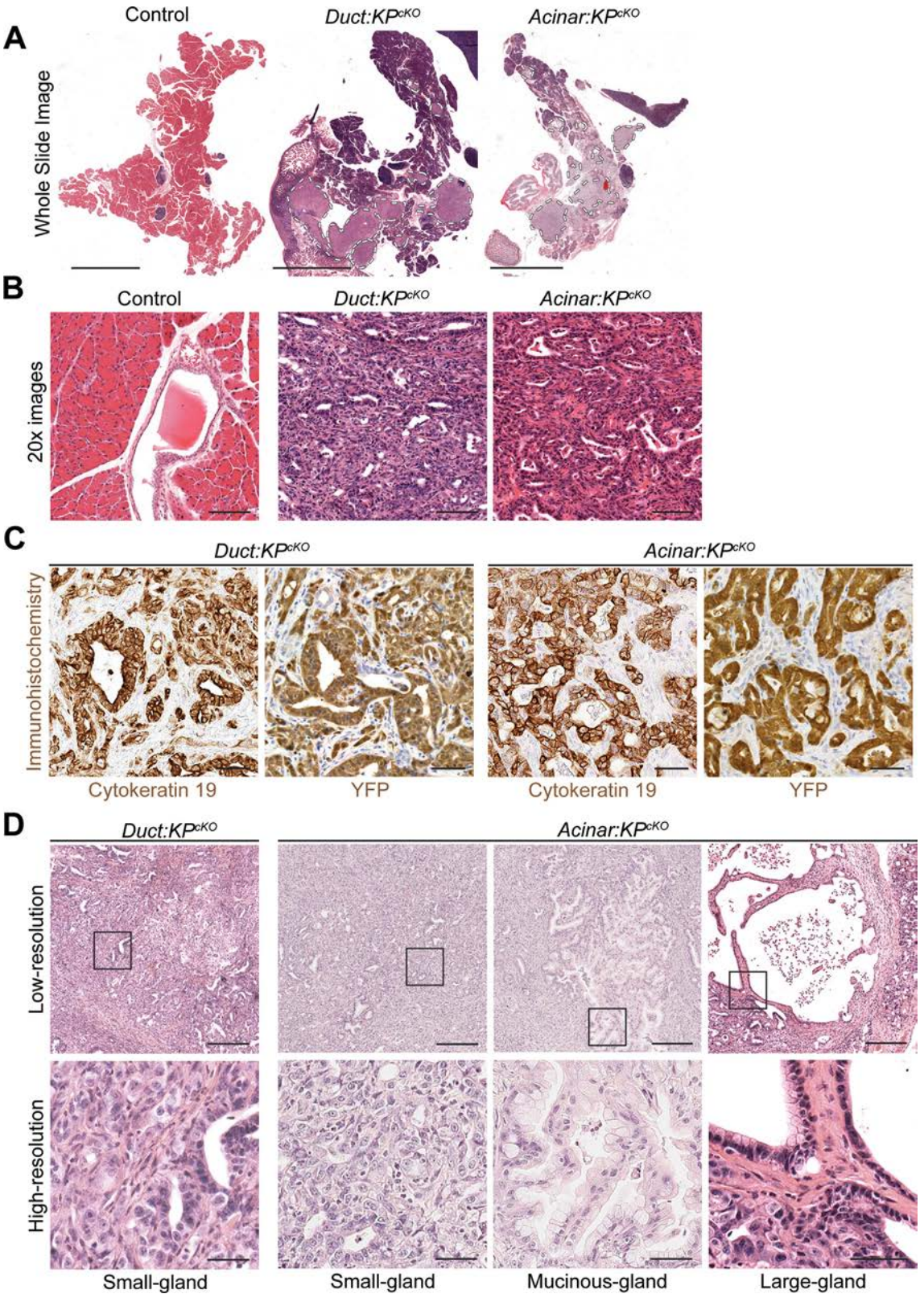

Figure 2 *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice develop pancreatic ductal adenocarcinoma (PDAC). Representative whole-section (A) and high-magnification (B) images of *Sox9CreER;Trp53*$^{flox/flox}$*;R26R*^{YFP} (control), *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} pancreata stained with H&E. Tumours are outlined with dashed lines in (A). (B) H&E staining shows that PDAC in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice are predominantly moderately to poorly differentiated. (C) Immunohistochemistry for ductal cell marker, Cytokeratin 19, and the YFP lineage marker demonstrates that duct-like tumours in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice arise from ductal and acinar cells, respectively. (D) Low-magnification (top row) and high-magnification (bottom row) images of H&E staining of the different histological tumour phenotypes observed in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice. The small-gland phenotype was observed in both mouse models. The mucinous-gland and large-gland phenotypes were found more often in *Acinar:KP*^{cKO} mice and rarely, if ever, in *Duct:KP*^{cKO} mice. Scale bars: 5 mm (A), 100 µm (B), 200 µm (D, top) and 50 µm (D, bottom and C).

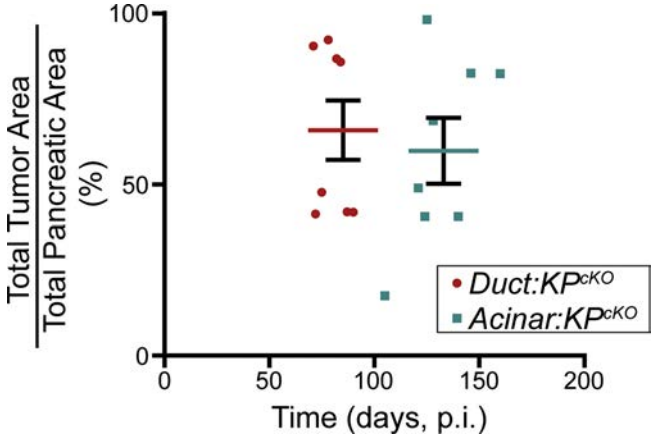

Figure 3 Tumour burden in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice at humane endpoint is similar, but reaches the peak amount earlier in *Duct:KP*^{cKO} mice. Quantification of the pancreatic area displaced by tumour area in individual *Duct:KP*^{cKO} (n=8) and *Acinar:KP*^{cKO} (n=8) mice at their humane endpoint (66.0%±8.7% vs 60.0%±9.7%, P=0.4) plotted against time post-tamoxifen injection (p.i.). All values shown as mean±SEM.

S3). However, areas of well-differentiated and poorly differentiated epithelium were also present (online supplementary figure S3A) that had higher and lower amounts of stroma, respectively (online supplementary figure S3B, C). Interestingly, a number of tumours from *Acinar:KP*^{cKO} mice, but rarely *Duct:KP*^{cKO} mice, were composed of atypical glands with abundant supranuclear mucin resembling mPanIN lesions (denoted as 'Mucinous-gland') or larger atypical gland structures (denoted as 'Large-gland') (figure 2D and table 1). Although there were some differences in the histological appearance of *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} tumours that correlated with the amount of stroma present in the tumour, on average, the amount of pancreatic area displaced by tumours was similar in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice at their respective endpoints (figure 3). In addition, no difference in the size, number or location of individual tumours was observed (online supplementary figure S4A–C). Altogether, our thorough characterisation of *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} tumours suggested that there were some phenotypic differences in tumours arising from different cell types. However, the most striking observation made was that the tumour burden reached its peak earlier in *Duct:KP*^{cKO} compared with *Acinar:KP*^{cKO} mice (figure 3). This suggests differences in the timing of tumour initiation from ductal and acinar cells may underlie the differences in survival of *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice.

Tumours initiate earlier in *Duct:KP*^{cKO} compared with *Acinar:KP*^{cKO} mice

To study tumour initiation in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice, we examined pancreata from these mouse models at time points approximately at or before the earliest death observed in each model (table 1). Specifically, we injected mice of both genotypes at 3 to 4 weeks of age with tamoxifen (n=4 per time point) and then collected and analysed the size and number of tumours arising in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} pancreata between 2 and 8 or 4 and 16 weeks post-injection, respectively (figure 4A). At 4 weeks post-tamoxifen injection, we found that two *Duct:KP*^{cKO} mice already had a microscopic tumour less than 1 mm in size (figure 4B, C, online supplementary figure S5A and S5C, tumours denoted by arrowheads). Subsequently, the number of tumours in *Duct:KP*^{cKO} mice significantly increased

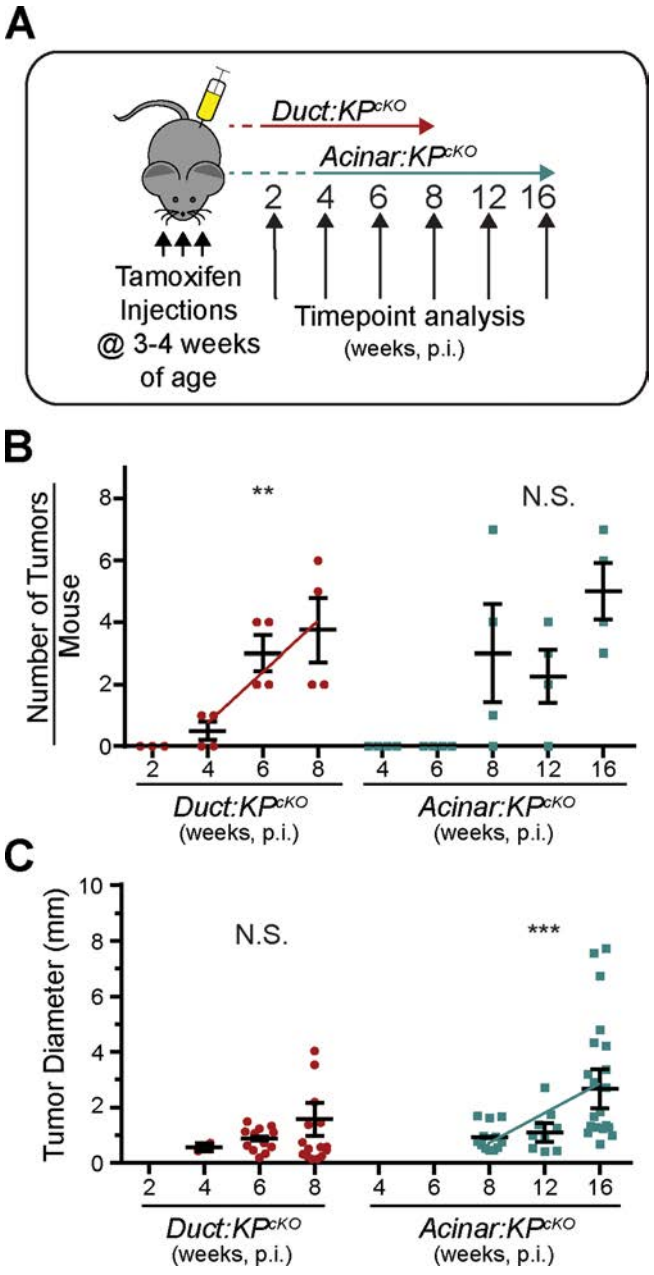

Figure 4 Tumours arise earlier in *Duct:KP*^{cKO} compared with *Acinar:KP*^{cKO} mice. (A) Schematic describing the experimental design. *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice (n=4) were injected with tamoxifen at 3–4 weeks of age and euthanised at 2, 4, 6 and 8 weeks post-injection (p.i.) or 4, 6, 8, 12 and 16 weeks p.i. for *Duct:KP*^{cKO} or *Acinar:KP*^{cKO} mice, respectively. Quantification of the number of tumours present (B) and the cross-sectional diameter of each tumour (C) in these *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice revealed that tumours initiated earlier from ductal compared with acinar cells. Trend lines in the graph indicate significant correlations between time and tumour number (B) or size (C). All values shown as mean±SEM. **P<0.01, ***P<0.001. N.S., not significant.

with respect to time (P<0.01). The size of the tumours did not significantly increase with time (P=0.3672), likely because the continual generation small tumours reduced the overall average (figure 4B, C and online supplementary figure S5A). In contrast, no tumours were observed in *Acinar:KP*^{cKO} mice until 8 weeks post-tamoxifen injection (figure 4B, C, online supplementary figure S5B and S5D, tumours denoted by arrowheads) and the increase in the number of tumours after 8 weeks did

not correlate with time (figure 4B, P=0.2632). Once tumours formed in *Acinar:KP^{cKO}* mice, though, their size significantly increased with time (figure 4C, P<0.001) suggesting that growth was a more dominant mechanism than tumour initiation in the acinar-cell-derived mouse model. Taken together, these data suggest that differences in the time of PDAC initiation resulted in the distinct survival intervals of *Duct:KP^{cKO}* and *Acinar:KP^{cKO}* mice. In support of this, the 4-week delay in tumour initiation observed in the *Acinar:KP^{cKO}* mouse model approximately matched the difference in time (34 days) between the first animals of each model succumbing to the disease (figure 1C and table 1).

Duct:KP^{cKO} mice develop only high-grade mPanINs, which progress to invasive PDAC faster than those from *acinar:KP^{cKO}* mice

Since we observed earlier PDAC initiation from ductal compared with acinar cells, we next examined whether this was a result of differences in precursor lesion initiation and/or progression. To do this, we quantified the number and grade of mPanINs present per pancreatic section from *Duct:KP^{cKO}* and *Acinar:KP^{cKO}* pancreata harvested between 2 and 8 or 4 and 16 weeks post-injection, respectively (figure 4A). Consistent with previous studies showing that Kras^{G12D}-expressing acinar cells form abundant low-grade mPanINs,[7–11 16] at 4 weeks post-injection, we found numerous low-grade mPanIN lesions in *Acinar:KP^{cKO}* pancreata and they increased in number over time (figure 5A, B). We also found high-grade mPanIN in *Acinar:KP^{cKO}* mice beginning at 4 weeks post-injection and the number increased to approximately 20 mPanIN3 lesions per section per mouse by 16 weeks post-injection (figure 5B). This suggests that a progression from low-grade to high-grade mPanIN could occur from Kras^{G12D}-expressing acinar cells in the absence of *Trp53*. In contrast, we found a small number of mPanIN3, but no mPanIN1, lesions in *Duct:KP^{cKO}* mice at all time points analysed (figure 5A, B). Interestingly, the number of mPanIN3 lesions in *Duct:KP^{cKO}* and *Acinar:KP^{cKO}* mice were comparable at 4 weeks post-injection (~1 per section per mouse) (figure 5B). However, *Duct:KP^{cKO}* mice already had small microtumours at this time point (figure 4B, C), while *Acinar:KP^{cKO}* mice did not develop invasive lesions for another month (figure 4B). Together, these data suggest that the reduced survival time of *Duct:KP^{cKO}* compared with *Acinar:KP^{cKO}* mice may be due to the increased propensity of Kras^{G12D}-expressing ductal cells to induce mPanIN3 that convert to invasive PDAC in the absence of *Trp53*.

To ensure that the discrepancy in mPanIN3 progression was not due to differential recombination of the *Trp53^{flox}* allele in Kras^{G12D}-expressing acinar and ductal cells, we used p53 immunohistochemistry to examine p53 status in mPanIN from *Duct:KP^{cKO}* and *Acinar:KP^{cKO}* pancreata. Ductal-cell-derived and acinar-cell-derived mPanIN3 were both uniformly p53-negative (online supplementary figure S6A), suggesting that these lesions arose from *Trp53*-ablated cells. Thus, the presence of p53 does not explain the delayed progression of acinar-cell-derived mPanIN3 to PDAC. In contrast to mPanIN3 lesions, p53 expression in the acinar-cell-derived low-grade mPanIN was more variable with some lesions completely lacking p53, and others expressing high levels of p53 (online supplementary figure S6B). Thus, the large parenchymal area displaced by abnormal duct-like lesions (approximately 30%) (online supplementary figure S6C) in some *Acinar:KP^{cKO}* pancreata is likely composed of low-grade Kras^{G12D+}p53^{-} and Kras^{G12D+}p53^{+} lesions, while mPanIN3 and PDAC arise from Kras^{G12D+}p53^{-} cells.

To examine potential differences between acinar-cell-derived and ductal-cell-derived mPanIN3, we examined whether cell death or proliferation might differ in these lesions. We found little to no cell death, as denoted by cleaved caspase 3 positivity, in the mPanIN3 lesions (online supplementary figure S6D), and the average per cent of Ki67^{+} cells per mPanIN3 was similar between cellular origins (figure 5C, D, P=0.09792). However, the variance in the number of proliferating cells between the ductal and acinar cell model was significantly different (figure 5D, F-test, P=0.01372). This suggests that there was more heterogeneity in the proliferative rate of acinar-cell-derived compared with ductal-cell-derived mPanIN3 lesions, which could underlie some of the differences in mPanIN3 progression between cellular origins.

Acinar-cell-derived PDAC often retains molecular properties associated with low-grade mPanIN

Because mucinous low-grade mPanINs were more prevalent in *Acinar:KP^{cKO}* compared with *Duct:KP^{cKO}* mice (figure 5B) and tumours derived from acinar cells tended to contain more highly mucinous glands (figure 2D and table 1), we next asked whether tumours formed from acinar cells might retain a molecular 'memory' of their transition through a low-grade mucinous mPanIN stage. To address this question, we examined whether acinar-cell-derived PDAC maintained characteristics typical of low-grade mPanINs, such as expression of acidic mucins or Mucin 5AC (Muc5AC).[26] We found that acinar-cell-derived tumours had moderate to strong levels of Alcian blue (acidic mucin stain) and Muc5AC staining that frequently, but not exclusively, correlated with histological areas containing mucinous glands (figure 6A–C). Quantification of the per cent total tumour area occupied by Alcian blue^{+} or Muc5AC^{+} glands in *Acinar:KP^{cKO}* and *Duct:KP^{cKO}* mice (n=8 for each genotype) illustrated that acinar-cell-derived tumours on average contained more acidic mucins and Muc5AC expression than ductal-cell-derived PDAC (figure 6C, D, P<0.001 and P<0.05, respectively). Importantly, the Alcian blue and Muc5AC positivity was not restricted to tumours we previously characterised as 'large-gland' or 'mucinous-gland', but was found in a larger number of acinar-cell-derived PDAC. Altogether, our data showed that low-grade mPanIN characteristics and premalignant low-grade mPanINs are highly associated with acinar-cell-derived but not ductal-cell-derived PDAC. This suggests that the developmental route of acinar-cell-derived and ductal-cell-derived tumours in mice can impact tumour histopathology, as well as the molecular phenotype.

Recent studies have described a number of different PDAC subtypes. To determine whether acinar-cell-derived or ductal-cell-derived PDAC may be similar to these molecular subtypes, we performed immunohistochemistry for one of the markers associated with the 'classical' PDAC subtype, Keratin 20 (CK20).[27] We found that the signal for this marker was very intense in the highly mucinous glands of acinar-cell-derived PDAC (figure 6E). Quantification of CK20 signal in ductal-cell-derived and acinar-cell-derived PDAC indicates that CK20 is significantly higher in acinar-cell-derived compared with ductal-cell-derived tumours (figure 6F). This suggests that at least some of the acinar-cell-derived tumours may be similar to the 'classical' subtype of PDAC. However, a more comprehensive analysis of multiple markers is needed before cell of origin can be implicated as a source of heterogeneity in PDAC.

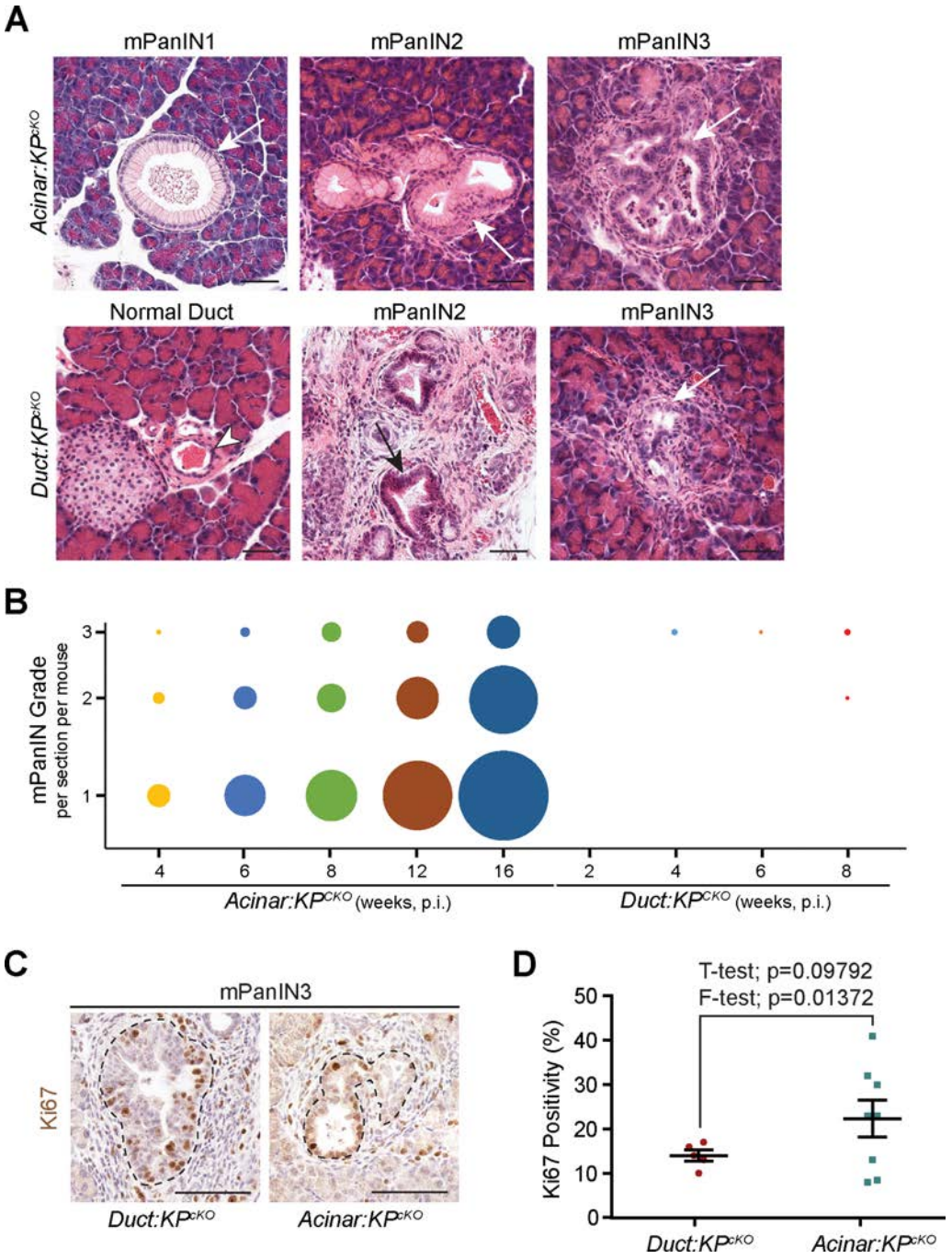

Figure 5 Kras^{G12D} expression and loss of p53 induces a spectrum of murine pancreatic intraepithelial neoplasia (mPanIN) lesions from acinar cells, but predominately high-grade mPanIN from ductal cells. (A) Representative images of haematoxylin and eosin stained normal duct (arrowhead), mPanIN1, 2 or 3 lesions (arrows) found in *Acinar:KP*^{cKO} and *Duct:KP*^{cKO} mice. No mPanIN1 lesions were observed in *Duct:KP*^{cKO} mice. (B) Quantification of the average number of mPanIN lesions of each grade present per section per mouse at the indicated time points post-tamoxifen injection (p.i.) in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice. The number of mPanIN1 in the *Acinar:KP*^{cKO} line at 16 weeks post-injection was set to 1 and the other circles represent the fraction of mPanIN present per time point or grade in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice relative to that sample. Immunohistochemistry for proliferation marker Ki67 (C) and quantification of the Ki67^{+} cells per mPanIN3 (D) in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice. Scale bar: 50 µm (A), 100 µm (C).

DISCUSSION

Ductal cells are a cellular origin of mPanIN-associated PDAC

Our study demonstrates that Kras^{G12D}-expressing ductal cells quickly form high-grade mPanIN and convert to PDAC in the absence of *Trp53*. The absence of low-grade PanIN, which readily form from acinar cells,[8 10 11 16] in *Duct:KP*^{cKO} mice even though a small number of Cpa1^{+} cells are labelled by the *Sox9CreER* allele argues that acinar cells are not contributing to the tumourigenesis observed in *Duct:KP*^{cKO} mice. In addition, the absence of low-grade mPanIN in our study, as well as that of Bailey *et al*,[6] suggests that ductal cells do not need to transition through a low-grade mPanIN stage to form PDAC in the absence of functional *Trp53*. Typically, only PanIN3 and PDAC are thought to possess mutations in *Trp53*.[28 29] Thus, the animal models in ours and Bailey *et al*[6] studies may provide

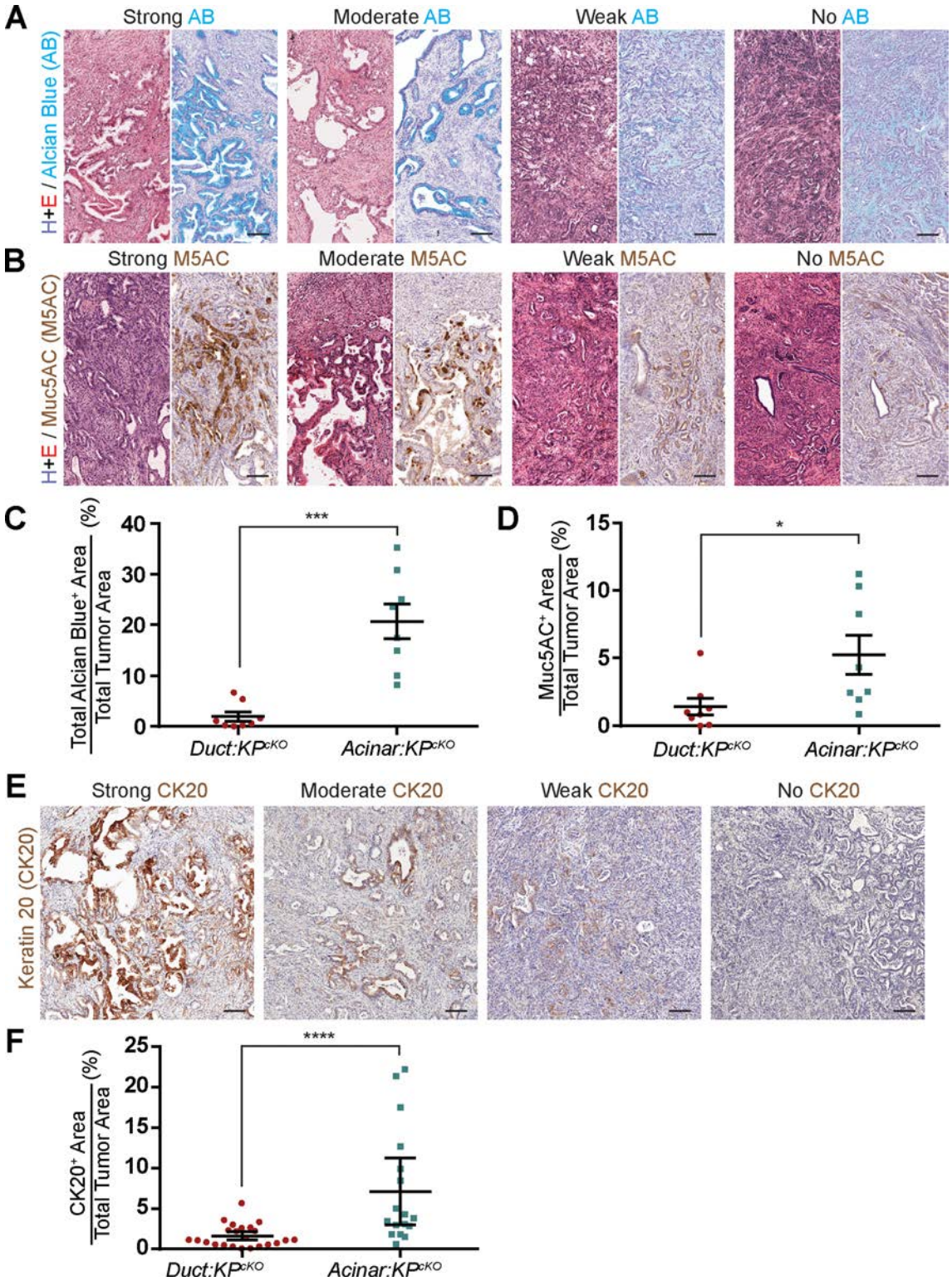

Figure 6 Glandular areas containing gastric mucin expression are more prevalent in tumours from *Acinar:KP*^{cKO} compared with *Duct:KP*^{cKO} mice. Representative images of tumour areas from *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice stained with H&E (A–B, left panels) or Alcian blue (AB) (A, right panels) or Mucin 5AC (Muc5AC or M5AC) (B, right panels). Light Alcian blue staining in the stroma or Muc5AC staining in blood vessels or blood cells was classified as negative. The Muc5AC staining is likely an artefact of the anti-mouse secondary antibody. Quantification of the per cent of AB (C) or Muc5AC (D) positive tumour area in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice (AB: 20.7% vs 2%, respectively, P<0.001 (***) and Muc5AC: 5.3% vs 1.4%, respectively, P<0.05 (*)). (E) Representative images of tumour areas from *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice stained with Cytokeratin 20 (CK20). Quantification of the per cent of CK20-positive tumour area in *Duct:KP*^{cKO} and *Acinar:KP*^{cKO} mice (P<0.0001 (****)). All values shown as mean±SEM. Scale bar: 100 µm (A–B).

mutations sufficient for tumour formation and result in ductal cells bypassing the low-grade mPanIN stage. Importantly, these findings do not supersede previous observations that $Kras^{G12D}$-expressing ductal cells form low-grade mPanINs.[10 12] Although the tumourigenic potential of the ductal-cell-derived mPanINs were not examined in previous studies,[10 12] our subsequent studies demonstrated that loss of the tumour suppressor *Pten* alone (*Sox9CreER;Pten*$^{flox/flox}$ mice) in ductal cells could result in low-grade as well as high-grade mPanIN that were associated with PDAC in the context of large duct metaplasia.[30] In addition, combining oncogenic Kras expression with heterozygous loss of *Pten* in ductal cells (*Sox9CreER;Kras*$^{LSL\text{-}G12D}$*;Pten*$^{flox/+}$ mice) promoted mPanIN-associated PDAC induction.[30] Although our studies suggest that ductal cells are capable of initiating tumourigenesis via the proposed PanIN progression model,[1] this is likely dependent on genetic context and PanINs may not always be necessary. Thus, the current PanIN progression model[1] may only capture a simplified picture of the way tumours develop, and this model may need to be revised to incorporate the context of specific genetic mutations and distinct cells of origin.

Acinar-cell-derived tumourigenesis is delayed and more stochastic than ductal-cell-derived tumourigenesis

In contrast to *Duct:KP*^{cKO} mice, *Acinar:KP*^{cKO} mice develop the entire spectrum of low-grade to high-grade mPanIN lesions from $Kras^{G12D}$-expressing p53-negative cells. This suggests that acinar-cell-derived mPanINs might follow a progression model where low-grade mPanIN precede high-grade mPanIN.[1] Unlike ductal cells, acinar cells must change a large portion of their transcriptional programme to become ductal-cell-like mPanIN and PDAC. Thus, it is possible that this acinar-to-ductal-cell-like transition slows the initiation of PDAC from most $Kras^{G12D}$-expressing, p53-deleted acinar cells and favours the accumulation of lesions at multiple stages of the acinar-cell-to-PDAC progression scheme.[16] In support of this theory, we found (1) mPanIN lesions of all grades accumulate with time in *Acinar:KP*^{cKO} mice; (2) some acinar-cell-derived PDAC had large areas of highly mucinous glands and maintained strong expression of low-grade mPanIN markers; and (3) the duration of time until *Acinar:KP*^{cKO} mice initiated tumours or reached their humane endpoint varied widely from mouse to mouse, but was very predictable for the *Duct:KP*^{cKO} mouse model. Altogether, these data suggest that acinar-cell-mediated tumourigenesis may be a halting or stochastic process requiring additional epigenetic or genetic events to occur for progression to PDAC. As a result of this randomised process of progression, we might expect that PDAC arising from acinar cells would be more heterogeneous. Consistent with this, we observed a greater number of histological phenotypes and variability in mucin and CK20 expression in acinar-cell-derived versus ductal-cell-derived PDAC. Thus, the process of acinar-cell-to-PDAC transformation, at least in mice, is highly variable and results in more intertumoural heterogeneity.

Not only are acinar-cell-derived and ductal-cell-derived PDAC associated with different grade of mPanIN, it appears that mPanIN3 derived from acinar cells are not equivalent to those from ductal cells. A number of possible brakes or checkpoints could underlie the differences in acinar-cell-derived versus ductal-cell-derived tumourigenesis from mPanIN3. For example, previous studies have shown that the acinar-cell-differentiation programme limits the number of acinar cells switching to the ductal-cell-like mPanIN fate in response to the Kras oncogene.[31–35] Moreover, removing $Kras^{G12D}$ reverts these mPanIN cells to the acinar cell fate.[36] Thus, the transcriptional or epigenetic status of the terminally differentiated acinar cell may persist for some time once they have converted to duct-like cells and potentially limit PDAC initiation. Although a similar transcriptional mechanism for the ductal cell fate has been proposed to limit induction of cystic precursor lesions from ductal cells,[37] the role of this programme in ductal-cell-mediated mPanIN and PDAC is unknown.

Another potential cellular programme known to limit acinar-cell-mediated mPanIN and PDAC formation is oncogene-induced senescence. Guerra and colleagues demonstrated that $Kras^{G12V}$ expression in acinar cells induces low-grade mPanIN lesions that become senescent or growth arrested.[38] Thus, induction of cell cycle arrest proteins, like p16, might be important for halting acinar-cell-derived tumourigenesis. In support of this, we observed a greater variation in proliferation in acinar-cell-derived PanIN3 lesions compared with their ductal-cell-derived counterparts. This variation could be due to localised inflammation that previous studies demonstrated reduced the growth-arrested phenotype in acinar-cell-derived mPanIN.[38] This suggests that increased inflammation due to pancreatitis could specifically decrease the latency of acinar-cell-derived tumourigenesis. The role of senescence in ductal-cell-mediated mPanIN formation and progression, however, is unclear and the growth arrest associated with $Kras^{G12D}$ expression may not occur in this cell type or it may be completely dependent on p53.

Finally, the biggest difference between *Acinar:KP*^{cKO} and *Duct:KP*^{cKO} mice is the quicker transition of ductal-cell-derived mPanIN3, or ductal *carcinoma in situ*, into invasive lesions. Therefore, the increased propensity of cells within ductal-cell-derived mPanIN to invade the basement membrane and move into the stroma becoming PDAC could underlie the differences in mPanIN3 derived from different cell types. Consistent with a role for invasion in the difference between ductal-cell-derived and acinar-cell-derived tumourigenesis, we observed metastases to the diaphragm and peritoneum in two *Duct:KP*^{cKO} mice, but distant metastases were not present in *Acinar:KP*^{cKO} mice. While these observations are based on a limited number of animals, the data support the conclusion that ductal-cell-derived tumourigenesis is associated with a more invasive phenotype. Additional studies examining the differential expression of factors involved in cell-to-cell adhesion or the epithelial-to-mesenchymal transition could illuminate potential molecular mechanisms underlying this difference in invasiveness. In sum, future studies are needed to examine each of these specific candidate programmes to gain mechanistic insight into why ductal-cell-derived mPanIN induce PDAC more rapidly than their acinar-cell-derived counterparts.

Impact of more than one cellular origin of PDAC on preclinical PDAC models

Many studies have characterised the specific effects of distinct genetic mutations on PDAC initiation and development, with the majority of studies using pan-pancreatic mouse models driven by combining the *Pdx1-Cre* or *Ptf1a*^{Cre} alleles with the *Kras*$^{LSL\text{-}G12D}$ allele and conditional knockout alleles for the gene of interest.[39–42] This would result in both acinar and ductal cells expressing oncogenic Kras and losing expression of the gene of interest. In the case of *Trp53*, evidence from our study and that of Bailey *et al*[6] would suggest that ductal and acinar cells respond differently to whether the activity of one or both alleles of *Trp53* is lost.[6] Specifically, Bailey *et al*[6] found that heterozygous *Trp53R172H* mutations in $Kras^{G12D}$-expressing acinar but not ductal cells induced PDAC. In contrast, we found homozygous disruption of *Trp53* in both $Kras^{G12D}$-expressing

ductal and acinar cells induced PDAC, but acinar cells required more time for PDAC induction.[6] This suggests there may be cell-of-origin-specific effects at play in pan-pancreatic mouse models that have been previously unrecognised. For example, our data would predict that the first tumours observed in *Pdx1-Cre;Kras*$^{LSL\text{-}G12D/+}$*;Trp53*$^{flox/+}$ or *Pdx1-Cre;Kras*$^{LSL\text{-}G12D}$*;Trp53*$^{R172H/+}$ mice may be acinar-cell derived; however, the initial tumours found in *Pdx1-Cre;Kras*$^{LSL\text{-}G12D/+}$*;Trp53*$^{flox/flox}$ or *Pdx1-Cre;Kras*$^{LSL\text{-}G12D}$*;Trp53*$^{R172H/R172H}$ mice could instead be ductal-cell derived due to faster carcinoma initiation from this cell type. It is possible that other confounding factors, such as any effect of the embryonic context, may complicate whether observations in our cell-type-specific mouse models could be simply extrapolated to embryonically induced pancreatic cancer models. Nevertheless, it is clear from our studies and others[6 9 14] that even subtly changing the genetic context (homozygous vs heterozygous mutation) could dramatically change the PDAC cellular origin and potentially tumour phenotype. Therefore, greater care should be taken to analyse genetic mutations in the context of the adult cell types from which PDAC likely arises.

Significance of more than one PDAC cell of origin

We have shown that cell of origin is an important factor to consider when using mouse models to study PDAC. It can affect tumour initiation and progression and may also affect the tumour phenotype. This raises the possibility that cell of origin may underlie the generation of interpatient tumour heterogeneity and differential clinical outcomes. Interestingly, one of the main phenotypes distinguishing acinar-cell-mediated and ductal-cell-mediated tumourigenesis appears to be the accumulation of low-grade and high-grade mPanIN lesions during acinar-cell-mediated tumourigenesis. Recent studies examining the number of PanIN lesions of different grades adjacent to resected tumours have found that patients can be separated into two general groups: those with the entire spectrum of PanIN lesions (PanIN1–3) and those with no PanIN3 and little or no PanIN1.[43–45] Interestingly, the latter patients have a significantly worse prognosis compared with those who had a higher number of PanINs. Because PanINs that give rise to PDAC are likely obscured by the growing tumour, a larger number of PanINs present in the resection margin is likely the result of a field effect. In addition, Kras^{G12D}-expressing acinar cells are more susceptible to inflammation and more easily give rise to mPanIN. Therefore, the accumulation of PanINs in the resected margin may indicate that these patients have a predisposition for their acinar cells to induce tumours. However, those patients with very little evidence of a field effect may have been predisposed to form ductal-cell-derived PDAC that developed with very little impact on the rest of the pancreatic parenchyma. While our data suggest just one possibility to explain the aforementioned correlates, definitively connecting these clinical observations with our observations of tumourigenesis in mouse models will require generation of transcriptional or genetic signatures of acinar-cell-specific and ductal-cell-specific tumours. These signatures could then be correlated with clinical outcomes to examine the role of cellular origin in human PDAC.

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Contributors AYLL, CLD and JLK acquired, analysed and interpreted the experiments and performed mouse husbandry; SZ acquired data and KS contributed to the analysis of the PDAC phenotypes; AYLL and JLK wrote the manuscript; DFS provided advice on pathological classification of the tissue samples and critically reviewed the manuscript; MS and JLK obtained funding, supervised the study and critically reviewed the manuscript; JLK conceived of the study concept and design. All authors reviewed and approved of the submitted manuscript.

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Cell of origin affects tumour development and phenotype in pancreatic ductal adenocarcinoma

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Notes