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TITLE:  Divergent Effects of Dendritic Cells on Pancreatitis

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Numbers dendritic cells (DCs) increased 100-fold in pancreata of mice with acute pancreatitis to account for nearly 15% of intrapancreatic leukocytes. Intrapancreatic DCs acquired a distinct immune phenotype in mice with acute pancreatitis; they expressed higher levels of major histocompatibility complex II and CD86 and increased production of interleukin-6, MCP–1, and TNFa. DC over-expansion exacerbated disease. However, DCs were also required for pancreatic viability; the exocrine pancreas died in mice that were depleted of DCs and challenged with caerulein or L-arginine. All mice with pancreatitis that were depleted of DCs died from acinar cell death within 4 days. These data suggest that DC have simultaneous paradoxical pro-inflammatory and protective effects in pancreatitis. Further investigations are warranted.
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Introduction

Pancreatitis is a significant public health concern and also is the most common precursor for pancreatic cancer. Our work investigates the role of dendritic cells in pancreatitis. Dendritic cells are professional antigen presenting cells which initiate innate and adaptive immune responses. Our work utilizes murine models and human tissues. Dendritic cells in mice express MHC II and the integrin CD11c. They are proficient in activating T cells and NK cells yet their role in pancreatitis has not previously been investigated.
**Body**

**Task 1.1.**

**Studies of DC expansion in pancreatitis:** To determine the prominence of dendritic cells (DC) in the context of pancreatic inflammation, we induced pancreatitis in mice using caerulein and characterized the leukocytes in the pancreas and spleen using flow cytometry. We found that DC increase substantially in number in acute and chronic pancreatitis (*Figure 1*).

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**Figure 1.** DC expand in pancreatitis. (a) Flow cytometry showing increased CD11c expression in pancreatitis compared with normal. (b) Bar graph comparing number of DC in spleen and pancreas in control (Ctl) or acute pancreatitis induced by caerulein (C). (c) Bar graph comparing total number of DC in control and chronic pancreatitis.

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**Studies of DC phenotype in pancreatitis:** We tested DC expression of MHC molecules, integrins (CD40, CD54), and co-stimulatory molecules (CD80, CD86) in the pancreas and spleen in control mice and in models of pancreatitis. We showed that DC matured in acute pancreatitis (*Figure 2*).

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**Figure 2.** Intra-pancreatic DC mature in pancreatitis. DC from the pancreata of saline (dotted lines) and caerulein-treated (solid lines) mice were gated and analyzed for surface marker expression by flow cytometry. DC mature and undergo a CD11b⁺CD8α⁻ myeloid shift in AP. Shaded histograms represent isotype controls.

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**Studies of DC immune function in pancreatitis:** (i) We measured DC production of immunogenic and regulatory cytokines and chemokines using a cytometric bead array and found that DC express high levels of inflammatory mediators in pancreatitis (*Figure 3a*). (ii) We measured DC expression of Toll-like

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**Figure 3.** DC are pro-inflammatory in pancreatitis. (a) The fraction of DC expressing various cytokines was tested in control pancreas (Ctl) and in caerulein-induced pancreatitis (C). (b) Expression of TLR7 on CD45⁺ cells and CD45⁻ cells was increased in pancreatitis.
receptors (TLRs) using flow cytometry and showed that pancreatic DC express increased TLRs in pancreatitis (Figure 3b).

**Studies of human DC in pancreatitis:** To investigate whether DC expand in human pancreatitis, we obtained specimens from human pancreatitis from the NYU Tissue Bank. We analyzed these for the presence of a DC infiltrate by immunohistochemistry using antibodies directed against DC-SIGN (CD209), CD1a, and CD123 which are diverse human DC markers (Figure 4).

**Task 1.2. To determine effects of DC expansion in pancreatitis**

**Bone Marrow-derived Dendritic Cell (BMDC) adoptive transfer exacerbates pancreatitis** - We generated BMDC in vitro from BM progenitors using GMCSF (20 ng/ml) in 8 day cultures. Mice were adoptively transferred with $1 \times 10^6$ BMDC after daily caerulein injections in models of chronic pancreatitis and severity of disease was determined by histological analysis. We showed that DC adoptive transfer exacerbated pancreatic inflammation and organ destruction (Figure 5a-f).

![Figure 4](image_url)

**Figure 4.** DC are prominent in the human pancreas. Immune cells in human pancreatitis expressed high DC-SIGN (CD209), and lower CD1a, and CD123.

![Figure 5](image_url)

**Figure 5.** DC exacerbate pancreatitis. Adoptive transfer of DC during pancreatitis induction resulted in worsened pancreatic inflammation (H&E staining), increased fibrosis (Sirius red staining), and increased organ destruction (evidenced by amylase and insulin staining. “C” represents pancreata of mice treated with caerulin pancreatitis only and “C+DC” represents pancreata of mice treated with caerulin + DC (n=8-10 mice/group).
**FMS-like tyrosine kinase 3 ligand (Flt3L) mediated DC expansion exacerbates pancreatitis** — To further elucidate the effects of DC on pancreatic injury, we administered Flt3L in vivo. Flt3L is a powerful DC growth factor that results in DC expansion in lymphoid and non-lymphoid organs. This recruited DC to the pancreas and exacerbated the severity of disease (Figure 6).

**Figure 6.** Flt3L mediated DC expansion exacerbates pancreatitis. “C” represents pancreata of mice treated with caerulein pancreatitis only, “Flt3L” group got Flt3 alone and “C+ Flt3” represents pancreata of mice treated with caerulein + Flt3. Pancreata were stained with H&E, Trichrome which measures fibrosis, and CD45 which measures immune infiltrate (n=5/group).

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**Task 1.3. To determine the effects of DC ablation in pancreatitis**

**Examination of DC Depletion in Pancreatitis:** We used CD11c.DTR mice, in which transient DC depletion can be effected for 48h during induction of pancreatitis by treatment with diphtheria toxin (DT; 4 ng/g). We tested the effects of DC depletion on severity of pancreatitis by histological analysis and and survival showed that DC depletion results in exacerbated disease (Figure 7a, b).

**Figure 7.** DC depletion exacerbates pancreatitis. (a) Pancreatitis was induced using L-arginine in controls or in the context of DC depletion. DC depletion resulted in exacerbated disease. (b) DC depletion also resulted in animal death in a survival experiment.
Task 2: To determine the role of DC in modulating both CD4$^+$ effector T cell differentiation and sterile inflammation in pancreatitis.

**Task 2.1.** To examine the primacy of the DC-Th2 axis in exacerbating pancreatitis

(i) To elucidate whether intra-pancreatic DC differentially induce Th2 differentiation, we harvested intra-pancreatic CD4$^+$ T cells from controls, pancreatitis mice (denoted “C” for caerulein), mice treated with DC alone (denoted “DC”), and pancreatitis mice adoptively transferred with DC (“C+DC”), and tested CD4$^+$ T cells for Th1, Th2, and Th17 differentiation in cell culture supernatant. We found that DC transfer increased Th2 differentiation in pancreatitis by enhancing production of IL-4 and IL-10 which are Th2 cytokines (Figure 8). Further, use of DC from MyD88-/- mice further enhanced Th2 differentiation. 25 mice were used for these experiments.

(ii) To test whether DC are required for Th-differentiation of pancreatic T cells, we harvested intra-pancreatic CD4$^+$ T cells from controls (Ctl), pancreatitis mice (C), and pancreatitis mice depleted of DC (“C-DC”) and tested CD4$^+$ T cells for Th1, Th2, and Th17 differentiation using a cytometric bead array. These experiments showed that depleting DC enhanced Th1 deviation as IL-6 and TNF-a were increased (Figure 9). 25 mice were used for these experiments.

(iii) To test whether DC in pancreatitis induce Th2 effector cells specific for pancreatic antigen, FACS-sorted pancreas-infiltrating CD4$^+$ T cells from pancreatic mice were cultured with pancreatic lyse- or mock-pulsed DCs. CD4$^+$ T cell activation was then determined by their expression of CD69, FAS ligand, and CD11b. Gray histograms represent isotype control. Median fluorescent indexes are shown for each group. These data show the antigen specificity of the T cells as T cells became activated by DC loaded with pancreatic lyase suggesting that the CD4 T cells respond to the presentation of pancreatic antigen (Figure 10). 90 mice were used for these experiments.

(iv) MHC II Knockout mice To further test whether DC induction of Th2-deviated CD4$^+$ T cells is the critical cellular mechanism behind DC exacerbation of pancreatitis, we employed MHC II$^{-/-}$ mice and β2-microglobulin$^{-/-}$ controls. MHC II$^{-/-}$ and β2-microglobulin$^{-/-}$ mice treated with caerulein were recipients of DC adoptive transfer (1x10$^6$ cells) to enhance pancreatic inflammation. We found that MHC II$^{-/-}$ mice (which lack Th2 signaling) were protected but not β2-microglobulin$^{-/-}$ mice (which lack Th1 signaling) confirming the primacy of the DC-Th2 axis (Figure 11). 50 Mice were used for these experiments.

(v) DC inactivation: We administered VAG539 which blocks Th2-deviation twice daily via oral gavage for the duration of the course of pancreatitis induction. We found reduced pancreatic injury on H&E in mice treated with caerulein + VAG539 with reduced evidence of intra-pancreatic inflammation and diminished Th2-deviation as evidenced by lower levels of IL-10 compared with mice treated with caerulein alone (Figure 12). 50 mice were used for these experiments.
(vi) MyD88 Blockade: Based on the known literature, MyD88 signaling is associated with strong Th1 polarization. Conversely, MyD88 inhibition or deletion in DC is associated with their Th2 deviation. Therefore, we postulated that MyD88 inhibition will worsen pancreatitis by favoring DC-Th2 deviation within the pancreas. We assessed the effects of MYD88 blockade on pancreatitis by histological analysis. We found that MyD88 inhibition resulted in exacerbated pancreatitis (Figure 13). Th2-deviation was also enhanced by MyD88 blockade (see Figure 1 above). 50 mice were used for these experiments.

**Task 2.2.** To determine whether DC clearance of necrotic cellular debris and apoptotic targets limits expansion of sterile inflammation in pancreatitis

(i) Intra-pancreatic DC capacity for clearance of apoptotic and necrotic cells: We tested the relative capacity of pancreatic DC to capture antigen as well as necrotic and apoptotic cells in pancreatitis. CD11c⁺MHCII⁺ DC harvested from pancreata of mice treated with caerulein captured FITC-Dextran at a higher rate than CD11c⁻MHCII⁺ antigen presenting cells from the same pancreata (Figure 14A). In addition, we found that pancreatic DC captured 7AAD⁺ necrotic cells at a far greater rate than other antigen presenting cells in pancreatitis (Figure 14B). Moreover, the uptake of 7AAD⁺ necrotic cellular debris (Figure 14C) and Annexin⁺ apoptotic bodies (Figure 14D) by MHC II⁺ cells was severely deficient in pancreata depleted of DC compared with pancreata with a normal complement of DC. Taken together, these data suggest that DC are primary in clearance of necrotic and apoptotic cells thereby limiting sterile inflammation in pancreatitis. 50 mice were used for these experiments.
(ii) Changes in sterile inflammation in pancreatitis upon DC depletion - DC have recently been assigned an important role in the clearance of cellular debris in inflammatory disease. Since we had previously showed that DC expand most sharply during the regeneration phase of pancreatitis, and DC depletion results in an marked increase in apoptotic cells and necrotic elements, we postulated that DC may have a primary role in clearance of cellular debris in pancreatitis, and, consequently, DC depletion may result in expansion of sterile inflammation in AP. In support of this notion, we found that C-DC treated pancreata have markedly higher levels of HMGB-1 (Figure 15A). We next determined the effects of DC depletion in pancreatitis (“C-DC”) on systemic inflammation. Mice were challenged for two days with caerulein after DC depletion or mock depletion. Serum levels of MCP-1 were measured at 48 hours. There was increased evidence of systemic inflammation when DC were depleted in pancreatitis (Figure 15B). Taken together, these data suggest that DC depletion increases inflammation in pancreatitis. Assays were performed in triplicate and repeated three times. 50 mice were used for these experiments.

Task 3: To determine the role of DC-PSC cross-talk in initiating fibrosis in chronic pancreatitis.

Task 3.1. To determine whether pancreatic DC can activate PSC in vitro

(i) Pancreatic stellate cell (PSC) Surface Phenotype: Using flow cytometry, we found that DC induce PSC expression of ICAM-1 (Figure 16a). DC also increased PSC expression of PDGF (Figure 16b). PSC morphology was unchanged (Figure 16c).
(ii) *PSC Proliferation and Migration* We found that DC reduce PSC proliferation (Figure 17a) but increase PSC migrational capacity in vitro using a transwell co-culture system (Figure 17b).

(iii) *PSC Production of Inflammatory Mediators* To test whether intra-pancreatic DC from mice with pancreatitis induce PSC to adopt a pro-inflammatory phenotype, PSC production of an array cytokines and chemokines specifically linked to progression of pancreatitis were measured after co-culture with DC. PSC production of inflammatory mediators were increased after DC co-culture (Figure 18).

(iv) *PSC Production of Extracellular Matrix Proteins* The ultimate effect of PSC activation in chronic pancreatitis is the deposition of extracellular matrix (ECM) proteins and modulators of the ECM such as matrix metalloproteinases (MMPs) and tissue inhibitors of metalloproteinases (TIMPs). We measured whether DC induce PSC production of ECM related genes but found no significant changes. Results of our PCR array comparing PSC + DC to PSC alone are shown (Figure 19).
(v) Human Correlative DC-PSC Studies

We extended our analysis to human systems. For human DC stimulators, 2x2 cm sections of non-tumorous pancreas were digested using Collagenase and Lin\(^{-}\)HLA-DR\(^{+}\) bulk pancreatic DC were isolated by FACS. As in our murine experiments, DC will be added to PSC for 48h in a 1:1 ratio before washing off the non-adherent DC. PSC were then tested 24h later for Collagen I production by western blotting. We found that DC do not induce PSC to make collagen I (Figure 20).

![Collagen, Type 1](image)

**Task 3.2.** To determine whether intra-pancreatic DC expansion activates PSC *in vivo*

**DC PSC experiments in vivo:** To test DC capacity to activate PSC *in vivo* during pancreatitis, we employed our experimental strategy of DC over-expansion in pancreatitis and, using immunohistochemistry, we tested PSC expression of Desmin and α-SMA. To further test the ability of DC to activate PSC *in vivo*, we isolated PSC from normal controls, mice with pancreatitis, and mice with pancreatitis supplemented with DC over-expansion and measure both the time course to α-SMA expression *in vitro* after PSC isolation as well as levels of PDGF and TGF-β in day 6 PSC cultures. However, all our in vivo data was negative and we did not appreciate DC activation of PSC *in vivo*.

**Task 3.3.** To determine the biochemical mechanism of DC induction of PSC

(i) TNF-α and IL-6: We postulated that intra-pancreatic DC production of TNF-α and IL-6 are necessary for maximal DC-induced PSC activation. We found that CpG treatment increases PSC expression of TNF-α and other cytokines shown in Figure 21. However, IL-6 was not upregulated.
(ii) Cell Signaling Pathways: Determining which PSC signaling pathway are induced by DC in pancreatitis can have therapeutic implications for targeting in experimental therapeutics. We found that ICAM expression in DC in necessary for their capacity to induce cytokine production in PSC (Figure 22a). Similarly, MyD88 expression in DC in necessary for their capacity to induce cytokine production in PSC (Figure 22b).

Fig. 22a

Fig. 22b
**Key Research Accomplishments**

- We showed DC expand and activate in mouse pancreatitis
- We showed that DC are prominent in human pancreatitis
- We showed that a balance of DC is needed in the pancreas as DC expansion results in worsened disease but complete DC ablation leads to organ destruction and death
- We showed DC induce Th2 differentiation in the pancreas
- We showed that DC depletion in pancreatitis results in upregulation of Th1 cytokines
- We showed that DC generate CD4 T cells that are specific to pancreatic antigen in pancreatitis
- We showed that blockade of the DC-Th2 axis ameliorates pancreatitis
- We showed that enhancement of the DC-Th2 axis exacerbates pancreatitis
- We showed that DC are primary in the clearance of necrotic debris in pancreatic cancer
- We showed that DC depletion in pancreatitis exacerbates sterile inflammation
- We showed that DC induce PSC expression of cytokines and chemokines
- We showed that DC do not induce PSC expression of ECM proteins
- We showed that DC induce PSC expression of cytokines and chemokines in a ICAM and MyD88 dependent manner
Reportable Outcomes

Publications:


Presentation at National Meeting:


This was an invited oral presentation at a national meeting. There was no published abstract.


There was no published abstracts
Conclusion

DC are an important component of the immune infiltrate in pancreatitis by induction of Th2 differentiation and in the clearance of necrotic debris. DC also active PSC to produce inflammatory mediators.
References

None
Appendices

Our publications follows (our in press publication is not published yet)
MyD88 inhibition amplifies dendritic cell capacity to promote pancreatic carcinogenesis via Th2 cells

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The transition of chronic pancreatic fibroinflammatory disease to neoplasia is a primary example of the paradigm linking inflammation to carcinogenesis. However, the cellular and molecular mediators bridging these entities are not well understood. Because TLR4 ligation can exacerbate pancreatic inflammation, we postulated that TLR4 activation drives pancreatic carcinogenesis. In this study, we show that lipopolysaccharide accelerates pancreatic tumorigenesis, whereas TLR4 inhibition is protective. Furthermore, blockade of the MyD88-independent TRIF pathway is protective against pancreatic cancer, whereas blockade of the MyD88–dependent pathway surprisingly exacerbates pancreatic inflammation and malignant progression. The protumorigenic and fibroinflammatory effects of MyD88 inhibition are mediated by dendritic cells (DCs), which induce pancreatic antigen–restricted Th2–deviated CD4+ T cells and promote the transition from pancreatitis to carcinoma. Our data implicate a primary role for DCs in pancreatic carcinogenesis and illustrate divergent pathways in which blockade of TLR4 signaling via TRIF is protective against pancreatic cancer and, conversely, MyD88 inhibition exacerbates pancreatic inflammation and neoplastic transformation by augmenting the DC–Th2 axis.

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inflammatory stroma may have a causative role in the neoplastic transformation of chronic pancreatitis.

DCs have recently emerged as important mediators of organ-specific fibroinflammatory disease. DCs are reported to be critical to toxin-induced pulmonary inflammation and the resulting interstitial pulmonary fibrosis (Bantsimba-Malanda et al., 2010). Our recent work in the study of liver disease identified DCs as important in modulating acute and chronic inflammation after hepatic insult (Connolly et al., 2009, 2011). TLR4 activation can also drive inflammation, and recent work in pancreatitis demonstrated that TLR4 ligation stimulates pancreatic inflammation (Sharif et al., 2009; Ding et al., 2010; Zhou et al., 2010). Based on this, we postulated a role for both DCs and TLR4 in neoplastic transformation of the pancreas. Our data show that TLR4 ligation is required for neoplastic progression of pancreatic cancer as blockade of either TLR4 or the MyD88-independent TRIF pathway is protective by regulating fibroinflammatory stromal expansion. Conversely, blockade of MyD88 surprisingly accelerates pancreatic tumor progression by augmenting DC capacity to generate intrapancreatic inflammation via induction of Th2-deviated CD4+ T cells.

RESULTS

TLR4 regulates pancreatic carcinogenesis

To determine the effects of TLR4 ligation on pancreatic tumor progression, we treated 4-wk-old p48Cre;KrasG12D mice with LPS and harvested pancreata 4 wk later. LPS greatly accelerated tumorigenesis as treated mice developed advanced pancreatic intraepithelial neoplasia (PanIN) lesions encased in a dense bed of fibroinflammatory stroma (Pan1) (Fig. 1, A–E). Conversely, saline-treated mice had grossly normal pancreata. Pancreata from LPS-treated p48Cre;KrasG12D mice also weighed roughly three times as much as controls (Fig. 1 B). Moreover, blockade of TLR4 in vivo protected p48Cre;KrasG12D mice against pancreatic tumorigenesis (Fig. 1, F and G). We postulated that the regulatory effects of TLR4 on pancreatic carcinogenesis result from modulation of inflammatory cell activation within the desmoplastic tumor stroma. To test this, we measured TLR4 expression on stromal leukocytes in normal pancreata and in pancreatic cancer. B cells, DCs, macrophages, and granulocytes each markedly increased their expression of TLR4 within the pancreatic cancer microenvironment (Fig. 1 H). Similarly, in human pancreatic cancer, there was robust expression of TLR4 on stromal leukocytes (Fig. 1 I). Moreover, we found elevated levels of TLR4 agonists (Fig. 1 J) and specific well-characterized DAMPs that bind TLR4 (Fig. 1 K) in human pancreatic duct fluid from cancer patients, suggesting there is ample substrate for TLR4 activation within the pancreatic cancer tumor microenvironment.

To definitively implicate peritumoral inflammation in mediating the effects of TLR4 activation on tumor progression, we made p48Cre;KrasG12D mice chimeric with TLR4 or the MyD88-independent TRIF pathway or the MyD88-dependent pathway, we selectively blocked each mechanism in p48Cre;KrasG12D mice using cell-permeable inhibitors. TRIF blockade (Fig. 2 E) prevented p48Cre;KrasG12D mice from developing accelerated carcinogenesis after treatment with caerulein (Fig. 2 F) or LPS (not depicted). Similarly, adoptive transfer of KrasG12D PDECs to TRIF−/− mice resulted in retarded tumor growth compared with KrasG12D PDECs to TRIF−/− mice (Fig. 2 G). Consistent with its regulatory effects in the tumor microenvironment, TRIF−/− mice were also protected against pancreatitis (Fig. 2 H). Notably, TLR3 ligand (polyinosinic:polycytidylic acid [Poly I:C]), which also signals via TRIF, similarly accelerated carcinogenesis in p48Cre;KrasG12D mice (Fig. 2 I).

In contrast to the protective effects of TRIF blockade, MyD88 inhibition (Fig. 3 A) markedly accelerated pancreatic carcinogenesis (Fig. 3, B–D). In particular, whereas control p48Cre;KrasG12D mice treated with caerulein developed metaplastic ducts and diffuse low-grade PanIN lesions, animals treated with MyD88 inhibitory peptide developed pancreatic tumors three to four times the size of controls (Fig. 3 B). On histological examination, MyD88 blockade resulted in invasive cribriforming pancreatic adenocarcinoma which exhibited a markedly higher proliferation rate and increased expression of p53 (Fig. 3 C) as well as foci of invasion as confirmed by...

For controls, we made age-matched p48Cre;KrasG12D mice chimeric using bone marrow derived from WT mice. Selected cohorts of chimeric mice were treated with caerulein to accelerate carcinogenesis as described previously (Carrière et al., 2009). WT chimeric p48Cre;KrasG12D mice treated with caerulein developed diffuse PanIN lesions, as expected. However, TLR4−/− chimeric p48Cre;KrasG12D mice were protected, exhibiting residual metaplastic ducts with cuboidal epithelia, suggesting that inflammatory cell TLR4 signaling can regulate pancreatic tumor progression (Fig. 2, A and B). Our extent of chimerism was >95% (not depicted; Bedrosian et al., 2011), and we confirmed deficient responses to LPS stimulation in TLR4−/− chimeric mice (Fig. 2 C). To further test whether the absence of TLR4 signaling in inflammatory cells is sufficient to retard tumor progression, we grafted WT and TLR4−/− mice with primary pancreatic ductal epithelial cells (PDECs) harboring oncogenic KRasG12D, which we have shown form well-differentiated pancreatic lesions encased in a large stromal component mimicking early human pancreatic adenocarcinoma (Agbunag et al., 2006; Pylayeva-Gupta et al., 2012). Tumor growth was markedly slower in TLR4−/− hosts, again indicating that inflammatory cell expression of TLR4 can modulate cancer progression (Fig. 2 D). Furthermore, because TLR4 generates inflammation via NF-κB and mitogen-activated protein (MAP) kinase, as anticipated, blockade of NF-κB and MAP kinase signaling partially protected LPS-treated p48Cre;KrasG12D mice from accelerated carcinogenesis (not depicted).

Dichotomous effects of TRIF and MyD88 signaling interruption

To test whether effects of TLR4 activation in pancreatic cancer are primarily mediated via the MyD88-independent TRIF pathway or the MyD88-dependent pathway, we selectively blocked each mechanism in p48Cre;KrasG12D mice using cell-permeable inhibitors. TRIF blockade (Fig. 2 E) prevented p48Cre;KrasG12D mice from developing accelerated carcinogenesis after treatment with caerulein (Fig. 2 F) or LPS (not depicted). Similarly, adoptive transfer of KrasG12D PDECs to TRIF−/− mice resulted in retarded tumor growth compared with KrasG12D PDECs to TRIF−/− mice (Fig. 2 G). Consistent with its regulatory effects in the tumor microenvironment, TRIF−/− mice were also protected against pancreatitis (Fig. 2 H). Notably, TLR3 ligand (polyinosinic:polycytidylic acid [Poly I:C]), which also signals via TRIF, similarly accelerated carcinogenesis in p48Cre;KrasG12D mice (Fig. 2 I).
Figure 1. TLR4 signaling modulates pancreatic carcinogenesis. (A–E) 4-wk-old p48Cre;KrasG12D mice were treated with saline or LPS and sacrificed at 4 wk. (A and B) Pancreata were stained with H&E, Trichrome, and CD45 (A) and weighed (B). (C–E) The presence of graded PanIN lesions (C), fibrotic area (D), and leukocytic infiltrate (E) were quantified by examining 10 high-powered fields (HPFs) per pancreas (n = 6 mice/group; ***, P < 0.001).
(F and G) 4-wk-old p48Cre;KrasG12D mice were treated with saline, caerulein, or caerulein + TLR4 inhibitor. Representative H&E-stained sections are shown, and the number of dysplastic ducts per HPF was calculated (n = 5 mice/group; ***, P < 0.001). (H) Live pancreatic mononuclear cells from 6-mo-old p48Cre;KrasG12D or WT mice were gated and costained for CD45, CD11c, CD3, F480, B220, Gr1, and TLR4. Median fluorescence for TLR4 is shown for specific cellular subsets. Data are representative of experiments repeated three times. (I) Sections of normal human pancreas (n = 3) and human pancreatic cancer (n = 19) were stained for TLR4. Representative images are shown, and data were quantified (***, P < 0.001). (J) Pancreatic duct fluid was harvested at the time of surgical resection from four patients with pancreatic cancer and two patients with benign endocrine tumors and tested for TLR4 ligand levels on HEK-Blue reporter cells (***, P < 0.001). (K) Pancreatic ductal fluid from two patients with pancreatic carcinoma was harvested at the time of operative duct transection and analyzed for HMGB-1 and S100A9 expression by Western blotting. Error bars indicate standard error of the mean.
positive staining for CK19 outside of ductal structures (Fig. 3 D). Gene sequencing revealed no somatic mutation in p53 (not depicted). To confirm that the tumor-promoting effects of MyD88 inhibition occur within inflammatory cells, we made p48Cre;KrasG12D mice chimeric with MyD88−/− bone marrow before caerulein treatment. Controls were made chimeric using WT bone marrow. MyD88−/− chimeric mice developed more extensive fibroinflammatory replacement of their

Figure 2. TLR4 regulation of pancreatic tumorigenesis and pancreatitis is mediated by stromal inflammatory cells and requires TRIF.

(A and B) p48Cre;KrasG12D mice were irradiated and made chimeric by bone marrow transfer from WT or TLR4−/− mice. 7 wk later, mice were treated with either saline or two doses of caerulein (C). Three weeks afterward, mice were sacrificed and pancreata were assessed by H&E. The fraction of dysplastic ducts was measured (n = 5/group; ***, P < 0.001). Insets show higher magnification. (C) WT chimeric and TLR4−/− chimeric mice were treated with 5 µg LPS. Serum cytokine levels were measured at 6 h (***, P < 0.001). (D) WT or TLR4−/− mice were adoptively transferred with intrapancreatic KrasG12D PDECs. Pancreata were harvested and weighted at 6 wk (n = 5 mice/group; ***, P < 0.001). (E) Raji cells were stimulated for 90 s with 1 µg/ml LPS in the presence of TRIF inhibitor (Pepinh-TRIF) or control peptide (Pepinh-Ctl). Expression of pIRF3 and β-actin was measured by Western blotting. (F) 4-wk-old p48Cre;KrasG12D mice were treated with saline, caerulein + control peptide, or caerulein + TRIF inhibitor. Representative H&E-stained sections are shown, and the number of dysplastic ducts per HPF was calculated (n = 5 mice/group; ***, P < 0.001). (G) WT or TRIF−/− mice were adoptively transferred with intrapancreatic KrasG12D PDECs. Pancreata were harvested and weighted at 6 wk (n = 4–5 mice/group; ***, P < 0.001). (H) Acute pancreatitis was induced using caerulein in WT or TRIF−/− mice. The fraction of viable acini was calculated (n = 4 mice/group; ***, P < 0.001). (I) 4-wk-old p48Cre;KrasG12D mice were treated with saline or Poly I:C before sacrifice 4 wk later. Representative H&E-stained sections are shown, and the number of PanIN lesions per HPF was quantified (n = 4 mice/group; ***, P < 0.001). Error bars indicate standard error of the mean.
Figure 3. MyD88 blockade accelerates malignant transformation and stromal inflammation. (A) Mice were treated with LPS and MyD88 inhibitory peptide (MyD88i) or control peptide. At 6 h, pancreata were assayed for expression of IRAK and p-IRAK. (B–D) p48Cre;KrasG12D mice were treated with caerulein for 2 d to accelerate carcinogenesis before sacrifice 3 wk later. In addition, mice were administered either MyD88 inhibitory peptide or control peptide. (B) Tumor size was recorded. (C and D) Paraffin-embedded pancreatic sections were stained using H&E and Ki67 and using mAbs directed against p53 (C) and CK19 (D) an epithelial cell marker (n = 6 mice/group). (E and F) WT chimeric and MyD88−/− chimeric p48Cre;KrasG12D mice were treated with caerulein and sacrificed at 3 wk. The fraction of metaplastic ducts and PanIN lesions was quantified (n = 4–6 mice/group; ***, P < 0.001). (G) KrasG12D PDECs were cultured with MyD88 inhibitory peptide or control peptide. Cells were pulsed with [3H]thymidine for 20 h, and its incorporation was measured. (H and I) MyD88−/− and WT mice were challenged with caerulein alone or caerulein + TRIF inhibitor or control peptide for 3 wk. Fibro-inflammatory changes were quantified (n = 4–6 mice/group; ***, P < 0.001). Error bars indicate standard error of the mean.
acinar architecture and advanced PanIN lesions compared with WT chimerics (Fig. 3, E and F). Furthermore, MyD88 inhibition did not appear to have direct effects on epithelial cells as Kras^{G12D} PDECs did not exhibit altered viability (not depicted) or an accelerated proliferative rate in vitro in response to MyD88 inhibitor (Fig. 3 G). In consort with these findings, which suggest that MyD88 inhibition activates peritumoral inflammatory cells compared with WT mice subject to pancreatitis, MyD88^{−/−} mice developed exacerbated pancreatic fibroinflammation, even in the context of TRIF inhibition (Fig. 3, H and I). Collectively, these data show that blockade of the MyD88-dependent pathway and the MyD88-independent TRIF pathway have distinctly opposite effects in benign and malignant pancreatic disease.

DCs and CD4+ T cells mediate effects of MyD88 inhibition in pancreatic disease

Because Th2-deviated CD4+ T cells have been implicated in pancreatic inflammation (Demols et al., 2000; Oiva et al., 2010) and MyD88 inhibition skews DC-mediated T cell differentiation toward the Th2 phenotype (Kaisho et al., 2002; Kapsenberg, 2003; Chen et al., 2010), we postulated that DCs may be the central cellular entity responsible for the exacerbated pancreatic inflammation and tumorigenesis associated with MyD88 inhibition by inducing effector Th2-deviated CD4+ T cells. To directly test whether DCs are responsible for exacerbated pancreatic disease in MyD88-deficient mice, we generated CD11c-Cre MyD88 Floxed^{−/−} mice, which are deficient in MyD88 signaling in CD11c^{+} DCs (Hou et al., 2008). We found minimal CD11c expression in other intrapancreatic leukocytes subsets (not depicted). CD11c-Cre MyD88 Floxed^{−/−} mice were then challenged with caerulein to induce pancreatitis. In consort with our hypothesis, CD11c-Cre MyD88 Floxed^{−/−} mice experienced exacerbated pancreatic fibroinflammatory disease compared with controls (Figs. 4 A and to a similar extent as pan-MyD88-deficient animals (not depicted). To determine whether MyD88 inhibition within DCs is also associated with accelerated pancreatic carcinogenesis, we made p48Cre;Kras^{G12D} mice chimeric using bone marrow from either WT or CD11c-Cre MyD88 Floxed^{−/−} mice followed by administration of caerulein 7 wk later. CD11c-Cre MyD88 Floxed^{−/−} chimeric p48Cre;Kras^{G12D} mice experienced accelerated cancer progression when compared with WT chimeric controls (Fig. 4 B).

Consistent with our hypothesis, we found that CD4^{+} T cell recruitment was increased >20-fold in pancreata of caerulein-treated MyD88^{−/−} mice compared with WT controls (not depicted) and MyD88 inhibition resulted in a significant Th2 deviation in both benign and malignant pancreatic disease (Fig. 4 C). Moreover, CD4^{+} T cell depletion (Miller et al., 2003) rescued mice from the exacerbated fibroinflammation (not depicted) and accelerated cancer progression (Fig. 4 D) associated with MyD88 inhibition. However, CD4^{+} T cell depletion did not rescue p48Cre;Kras^{G12D} mice with intact MyD88 signaling capacity (Fig. 4 D). Collectively, the aforementioned observations indicate that (a) MyD88 inhibition exclusively within DCs is sufficient to induce exacerbated pancreatic inflammation and carcinogenesis (Fig. 4, A and B) and (b) MyD88 blockade exacerbates pancreatic disease in a CD4^{+} T cell–dependent manner (Fig. 4 D).

To directly test whether the DC–Th2 axis is central to pancreatic inflammation, before beginning caerulein challenge in WT mice, we treated mice with VAG539, which binds the DC aryl hydrocarbon receptor in vivo and prevents DC induction of antigen-restricted Th2 cells as we and others have recently shown (Hauben et al., 2008; Connolly et al., 2011). We confirmed that intrapancreatic CD4^{+} T cells are prevented from Th2 deviation after treatment with VAG539 (Fig. 4 E). Consistent with our expectation, VAG539 markedly protected against pancreatic inflammation (Fig. 4 F). DCs expand in chronic pancreatitis and pancreatic adenocarcinoma

To further investigate the role of DCs in chronic pancreatic inflammation and malignant transformation, we examined the prevalence of DCs in pancreatic cancer and chronic pancreatitis. The fraction and total number of DCs were markedly increased in the pancreata of p48Cre;Kras^{G12D} mice compared with age-matched WT controls (Fig. 5, A–C). The surface phenotype of DCs infiltrating p48Cre;Kras^{G12D} pancreata differed from controls in that they contained a large B220^{+} plasmacytoid subset (Fig. 5 D) and an increased fraction of CD8^{+}CD11c^{−} lymphoid DCs (Fig. 5 E) and were highly mature, expressing elevated CD40 and CD86 (Fig. 5 E). To determine whether an intense DC infiltrate was similarly associated with human pancreatic cancer, we tested 19 human pancreatic carcinoma specimens for an array of DC markers. Consistent with our murine findings, there was a robust infiltrate of CD123^{+} cells, characteristic of plasmacytoid DCs, in all specimens tested (Fig. 5 F). DC-SIGN^{+} and CD11a^{+} cells were also present but in smaller numbers (Fig. 5 F).

To investigate whether DC expansion within the pancreas was a function of neoplasia or similarly associated with benign chronic pancreatic inflammation, we examined the prevalence of DCs, outside of the context of oncogenic Kras, in caerulein-induced chronic pancreatitis in WT mice. We found that DCs accounted for 1–3% of CD45^{+} leukocytes in normal pancreata but increased to 10–15% during chronic pancreatitis induction (Fig. 5 G). Moreover, the absolute number of pancreatic DCs increased 100-fold (Fig. 5 H). Conversely, the fraction of DCs in the spleen remained unchanged, implying a pancreas-specific expansion in chronic pancreatitis (Fig. 5 G). Collectively, these data show that a large DC infiltrate is a common feature in neoplastic and inflammatory pancreatic disease.

DCs exacerbate pancreatic fibroinflammation and ductal transformation

To directly test DC capacity to potentiate intrapancreatic inflammation via Th2 cells, we further expanded the pancreatic DC population by i.p. adoptive transfer of bone marrow–derived DCs to mice developing chronic pancreatitis. Creusot et al. (2009) reported that the plurality of bone marrow–derived
Figure 4. MyD88 blockade within DCs exacerbates pancreatic disease in a CD4+ T cell–dependent manner. (A) 4-wk-old CD11c-Cre MyD88 Floxed+/+ mice and control animals were treated with caerulein (C) for 3 wk to induce chronic pancreatitis. Pancreata were examined by Trichrome staining, and the fibroinflammatory area was quantified (n = 4 mice/group; ***, P < 0.001). (B) p48Cre;KrasG12D mice were made chimeric using bone marrow derived from WT or CD11c-Cre MyD88 Floxed+/+ mice. Chimeric mice were treated with caerulein and sacrificed at 3 wk (n = 4–5/group). Representative images are shown, and the fraction of graded PanIN lesions was quantified (***, P < 0.001). (C) CD4+ T cells were harvested from the pancreata of p48Cre;KrasG12D mice and caerulein–treated WT mice that were administered MyD88 inhibitory peptide or control peptide. IL-2 and IL-4 levels were measured in cell culture supernatant (***, P < 0.001). (D) 4-wk-old p48Cre;KrasG12D mice were treated with C, C + MyD88 inhibitor, C + GK1.5 to deplete CD4 T cells, C + MyD88 inhibitor + GK1.5, or additional controls. Mice were sacrificed at 3 wk, and the foci of invasive cancer were quantified by examining 10 HPFs per mouse (n = 5 mice/group; ***, P < 0.001). (E) IL-10 was measured in cell culture supernatant from purified pancreatic CD4+ T cells from mice treated for 2 d with saline, VAG539, caerulein, or caerulein + VAG539 (***, P < 0.001). (F) WT mice were treated with caerulein alone or caerulein + VAG539 for 3 wk. Representative HE-stained sections are shown (n = 4 mice/group), and fibroinflammatory changes were quantified (***, P < 0.001). Error bars indicate standard error of the mean.
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On average, >50% of the pancreatic surface area was replaced by fibroplasia in C+DC-treated mice (Fig. 6, A–C). This resulted in destruction of both the exocrine and endocrine pancreas, including a >60% reduction in acinar cell volume (Fig. 6, D and E), and a marked reduction in islet cell mass (Fig. 6 F). In consort with the latter findings, mice developed overt diabetes by 3 wk of C+DC challenge (Fig. 6 G). The severity of pancreatic exocrine destruction was exemplified by a roughly fourfold diminution in pancreatic-specific serum lipase levels in C+DC-treated mice (not depicted). Furthermore, DCs migrate to the peripancreatic tissues within 24 h after adoptive transfer and remain there for at least 12 d. After 3 wk of treatment with saline (Ctl), caerulein (C), DCs, or caerulein and DCs (C+DCs), pancreata were harvested and assessed for extent of fibrosis, inflammation, and endocrine and exocrine destruction.

Mice treated with C+DCs developed distortion of their pancreatic architecture including the formation of thick fibrous bands between lobules and effacement of the intralobular space with inflammatory fibroplasia (Fig. 6, A–C).
transfer in chronic pancreatitis resulted in pancreatic stellate cell activation in vivo as indicated by increased expression of periacinar desmin (Fig. 6, H and I) and α-SMA (Fig. 6, J and K) in pancreata of C+DC-treated mice. Pancreatic stellate cell activation is necessary for pancreatic fibrosis and neoplastic progression (Omary et al., 2007; Masamune et al., 2009). In addition, overexpansion of DCs in the context of pancreatitis resulted in the recruitment of a robust immune infiltrate.

To confirm the consistency of our findings, we tested whether DCs also exacerbated pancreatitis in a model of endogenous DC expansion using Flt3L (Fms-like tyrosine kinase-3 ligand; Maraskovsky et al., 1996). Mice treated with Flt3L for 10 d developed expansion of pancreatic DC populations between days 4 and 15 (Fig. 7 A). Inflammatory monocyte populations were not significantly expanded (Fig. 7 B). Moreover, treatment with Flt3L and simultaneous challenge with caerulein resulted in exacerbated acinar destruction, fibrosis, and inflammation (Fig. 7, C and D), suggesting that the effects of DC expansion in pancreatitis are not model specific.

In addition to the fibroinflammatory changes, a conspicuous phenotypic finding observed in pancreatitis associated with DC transfer is the widespread development of early PanIN lesions. Overall, ~50% of ducts were classified as PanINs in C+DC pancreata (Fig. 8, A and B). Affected ducts in C+DC-treated mice stained positively for Alcian blue (Fig. 8 C). Pancreata of control animals, including mice receiving DCs alone or caerulein alone, did not exhibit PanIN lesions after 3 wk of treatment. Furthermore, pancreata from C+DC-treated animals had a markedly high fraction of Ki67+ proliferating epithelial cells compared with controls (Fig. 8 D).

**DCs accelerate the growth of pancreatic tumors**

Prolonged duration of C+DC administration to WT mice for 3 mo resulted in greater fibrodsplastic obliteration of the pancreatic parenchyma and more diffuse PanIN lesions but not invasive carcinoma (Fig. 8 E). However, DCs markedly accelerated malignant transformation when transferred for...
transferred DCs from MyD88−/− mice to WT mice undergoing caerulein pancreatitis. As predicted, MyD88−/− DC transfer worsened pancreatitis (Fig. 9 A) and PanIN formation (Fig. 9 B) to a greater extent than WT DC transfer. Endocrine and exocrine pancreata were almost entirely replaced by collagen after MyD88−/− DC transfer, and >70% of ducts were PanINs. In addition, transfer of MyD88−/− DCs resulted in an approximately twofold increase in CD4+ T cell recruitment compared with transfer of WT DCs (Fig. 9 C). Collectively, these data support our findings using CD11c-Cre MyD88 Floxed+/+ mice (Fig. 4, A–D) and together suggest that DCs are sufficient to induce the exacerbated inflammation and dysplasia observed in the MyD88-deficient pancreata.

The DC–Th2 axis mediates exacerbated pancreatitis and transformation

Consistent with our hypothesis that suggests that the DC–CD4 axis can mediate pancreatic inflammation and transformation, we found that CD4+ T cell–deficient mice were protected from the effects of DC transfer in chronic pancreatitis (Fig. 9, D and E). Conversely, the absence of CD8+ T cells, B cells, neutrophils, and monocyte depletion or TNF blockade did not protect C+DC-treated mice (Fig. 9, D and E). Furthermore, in our pancreatic cancer model, CD4+ T cell depletion protected p48Cre;KrasG12D mice adoptively transferred with DCs (Fig. 9 F). CD4+ T cell depletion had similarly protective effects after transfer of MyD88−/− DCs (not depicted).

In line with the observations that CD4+ T cells are the critical effectors in DC-mediated pancreatic inflammation and transformation, we found that CD4+ T cell–deficient mice were protected from the effects of DC transfer in chronic pancreatitis (Fig. 9, D and E). Conversely, the absence of CD8+ T cells, B cells, neutrophils, and monocyte depletion or TNF blockade did not protect C+DC-treated mice (Fig. 9, D and E). Furthermore, in our pancreatic cancer model, CD4+ T cell depletion protected p48Cre;KrasG12D mice adoptively transferred with DCs from developing accelerated carcinogenesis (Fig. 9 F). CD4+ T cell depletion had similarly protective effects after transfer of MyD88−/− DCs (not depicted).

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In line with the observations that CD4+ T cells are the critical effectors in DC-mediated pancreatic inflammation and transformation, we found that the number of intrapancreatic CD4+ T cells and CD4/CD8 T cell ratio were markedly increased in mice adoptively transferred with DCs (Fig. 10, A and B). Furthermore, intrapancreatic CD4+ T cells in DC-treated mice exhibited a strong Th2 differentiation (Fig. 10 C). These effects were accentuated by transfer of MyD88−/− DCs (Fig. 10, A–C). In addition to the significant lack of intrapancreatic Th1 and Th17 differentiation, the fraction of intrapancreatic CD4+CD25+Foxp3+ regulatory T cells (Treg cells) was...
pancreas increases CD4+ T cell Th2 differentiation, which is required for the organ destructive, fibrotic, inflammatory, and dysplastic effects, and decreases the fraction of other T cell subsets, including Treg cells and CD8+ cells.

We postulated that DCs induce Th2-deviated CD4+ T cells by capturing antigen from the injured pancreas, which also markedly reduced in C+DC-treated animals (Fig. 10 I). Similarly, MHC II−/− mice, which are deficient in Th2 signaling, were protected from the effects of DC expansion in pancreatitis, whereas β2-microglobulin−/− mice deficient in CD8+ T cell signaling were not protected (Fig. 10, E and F). Collectively, our data suggest that DC expansion in the injured pancreas increases CD4+ T cell Th2 differentiation, which is required for the organ destructive, fibrotic, inflammatory, and dysplastic effects, and decreases the fraction of other T cell subsets, including Treg cells and CD8+ cells.

We postulated that DCs induce Th2-deviated CD4+ T cells by capturing antigen from the injured pancreas, which...
they present to naive T cells, thereby generating antigen-restricted effector cells. To test whether these effectors are specific to pancreatic antigen, CD4+ T cells from the pancreata of C+DC-treated WT mice were purified and cultured for 5 d with either mock-loaded DCs or DCs loaded with lysate from digested pancreata. CD4+ T cells co-cultured with pancreatic lysate-pulsed DCs exhibited increased activation compared with controls, implying pancreas-directed specificity (Fig. 10 G). Furthermore, transfer of CD4+ T cells from C+DC-treated WT mice to p48Cre;KrasG12D mice markedly accelerated pancreatic cancer development, whereas CD4+ T cell transfer from control mice did not have tumor-promoting effects (Fig. 10, H and I).

**DISCUSSION**

Pancreatic cancer is a devastating disease with very few effective treatment options as <5% of patients achieve cure (Vincent et al., 2011). Recent evidence suggests that rather than being a dormant component, pancreatic fibroinflammatory stroma impacts malignant transformation and disease progression.
Figure 10. DCs exacerbate pancreatic disease by inducing antigen-restricted Th2 cells. (A and B) The total number of CD4+ cells in the pancreata of mice treated with C+DCWT, C+DCMyD88−/−, and controls (A) and the fraction of intrapancreatic CD4+ or CD8+ T cells among all CD3+ cells (B) were measured by flow cytometry (***, P < 0.001). (C) CD4+ T cell differentiation in the pancreas of mice treated with C+DCWT, C+DCMyD88−/−, and controls was determined by measuring their production of Th1, Th2, and Th17 cytokines after FACS sorting. (D) The fraction of intrapancreatic Treg cells was determined by gating on CD45+CD25+ leukocytes and cross staining for CD4 and Foxp3. In vitro assays were repeated three times with similar results. (E and F) MHC II−/− and β2-microglobulin−/− mice treated with caerulein were recipients of DC transfer. A mean of four mice per group was used in these experiments (***, P < 0.001). (G) To determine the pancreatic antigen specificity of effector T cells, FACS-sorted pancreas-infiltrating CD4+ T cells from WT C+DC-treated mice were cultured with pancreatic lysate- or mock-pulsed DCs. CD4+ T cell activation was then determined by their expression of CD69, FAS ligand, and CD11b. Gray histograms represent isotype control. Median fluorescent indexes are shown for each group. Experiments were repeated three times with similar results. (H and I) p48Cre;KrasG12D mice were adoptively transferred for 5 wk with CD4+ T cells derived from control and C+DC-treated mice (n = 3/group). Representative H&E-stained sections and images of pancreata are shown (H), and the fraction of pancreatic area with preserved acinar architecture was measured (I; ***, P < 0.001). Error bars indicate standard error of the mean.
In particular, by releasing nutrient growth factors into the ne-
scient tumor microenvironment, such as insulin-like growth
factor and PDGF, the stromal component of pancreatic cancer
has been closely linked to carcinogenesis as well as tumor
growth and invasiveness (Wang et al., 2007; Mantovani et al.,
2010). We postulated that TLR4 may regulate stromal inflam-

mation as it has previously been implicated in benign pancre-
atic disease (Sharif et al., 2009). Our related findings that TLR4
is increased in expression on leukocytes within the tumor
microenvironment in humans and mice, that TLR4 ligands
such as HMGB-1 and S100A9 are rife within the tumor micro-
environment, and that TLR4 ligation accelerates carcinogene-
sis in mice lends insight into the mechanism of regulation
of pancreatic tumor progression by the inflammatory stroma. We
further show that TLR4 signaling via the MyD88-independent
TRIF pathway modulates pancreatic carcinogenesis as target-
ing TLR4 or TRIF prevents cancer progression in at risk pan-
creata. These data suggest that testing clinical-grade TLR4 or
TRIF inhibitors in pancreatic cancer would be appropriate
(Barrat and Coffman, 2008). Our findings also suggest that
there may possibly be a role for endogenous LPS derived from
gut bacteria in modulating pancreatic carcinogenesis. Indeed, a
role for the microbiome in carcinogenesis is rapidly emerging in
colon cancer and other malignancies (Ahn et al., 2012; Dapito
et al., 2012), and our data suggest mechanistic plausibility for
its possible influence on pancreatic oncogenesis. However, de-
finite linkage of pancreatic cancer development to the host
microbiome via TLR4 requires more exact investigation.

An equally compelling discovery in this study is that
MyD88 blockade vigorously accelerates pancreatic fibro-
inflammation as well as carcinogenesis. Most notably, MyD88
blockade resulted in invasive pancreatic adenocarcinoma
within 3 wk in p48Cre;KrasG12D mice treated with caerulein
compared with the development of early PanIN lesions in
age-matched mice with intact MyD88 signaling. Moreover,
malignant epithelial cells in MyD88-deficient mice exhibited
altered expression of p53 in the absence of an endogenous p53
mutation. Overexpression of p53 in pancreatic cancer has been
linked to peritumoral inflammation and is associated with
an aggressive oncogenic phenotype (Carrière et al., 2011). Our
findings contrast with studies linking MyD88 to inflammation and
carcinogenesis (Gase et al., 2007; Rakoff-Nahoum and
Medzhitov, 2007; Swann et al., 2008; Coste et al., 2010).
For example, Rakoff-Nahoum and Medzhitov (2007) crossed
APCmin/+ mice, which carry a germline mutation in the Apc
tumor suppressor gene, with MyD88-deficient mice and found
that the absence of MyD88 signaling resulted in a decreased
number of intestinal polyps and substantially improved sur-
vival. Recently, Coste et al. (2010) also showed that MyD88
plays a cell-autonomous role in Ras-mediated transformation
in mouse and human tissues. The proinflammatory and carci-
nogenic effects of MyD88 inhibition in the pancreas are un-
likely related to unremitting TRIF signaling as combined TRIF
and MyD88 blockade nonetheless resulted in severe pancreatic
disease. Rather, the resolution to our ostensibly paradoxical
finding lies in the fact that in the presence of MyD88 blockade,
DCs preferentially induce Th2 polarization (Kaisho et al., 2002;
Kapsenberg, 2003; Chen et al., 2010), which, in pancreatic dis-
ease, compensates for the inability to produce generalized in-
fammation via NF-κB (Fig. S1). We demonstrate that DCs
are the causal cellular component responsible for exacerbated
chronic pancreatitis and neoplasia upon MyD88 blockade
by using DC adoptive transfer experiments using MyD88−/−
DCs and by examining CD11c-Cre MyD88 Floxed−/+ mice,
which are deficient in MyD88 signaling exclusively within
CD11c+ cells.

The observation that DCs exacerbate pancreatic pathology
through the activation and expansion of pancreas-restricted
Th2-deviated CD4+ T cell population was supported by the
protection offered in MHC II−/− mice compared with
β2-microglobulin−/− mice, our finding that CD4+ T cells
derived from C+DC pancreata could accelerate tumorigenesis
when transferred to p48Cre;KrasG12D animals, and that deple-
tion of Th2-deviated CD4+ T cells protects against the proin-
flammatory and tumorigenic effects of DC adoptive transfer
or MyD88 blockade. Furthermore, given the intrapancreatic
expansion of Th2 cells upon DC transfer, and suppression of
CD8+, Th1, Th17, and Treg cell differentiation, and our obser-
vation that these effector T cells recognize pancreatic antigen,
a logical hypothesis governing the DC–Th2 axis in pancreatic
carcinogenesis is that infiltrating DCs capture pancreatic anti-
gen and induce antigen-restricted Th2 CD4+ T cell differen-
tiation, which then serve as the effector cell mediating cellular
injury and inflammation required for stromal activation and
neoplastic transition. Our discovery of the importance of Th2
polarization in pancreatic disease corresponds with recent
studies that have shown an association between Th2-mediated
inflammation and neoplastic development in patients with
maligna and in experimental models of colon carcinogenesis
(Osawa et al., 2006; Nevala et al., 2009). Human pancreatic
cancer is also marked by an extensive peritumoral Th2 infil-
tration, which is associated with reduced survival (De Monte
et al., 2011). The current data suggest that DCs are sufficient
to induce accelerated pancreatic tumorigenesis via induction
of pancreatic antigen–restricted Th2-deviated CD4+ T cells.
However, it is notable that CD4+ T cell depletion did not rescue
p48Cre;KrasG12D mice outside of the context of MyD88
blockade (Fig. 4 D), suggesting that alternate protumori-
genic mechanisms, rather than DC–CD4+ T cell activity,
may be primary in pancreata of p48Cre;KrasG12D mice with
intact MyD88 signaling pathways.

The paradigm linking inflammation and inflammatory
cells to carcinogenesis has been gaining consistent momentum
in the scientific literature (Colotta et al., 2009; Mantovani
et al., 2010). A heightened inflammatory milieu provides a
continuous supply of cytokines and growth factors that can
affect biological processes responsible for maintaining cellular
homeostasis, leading to genetic instability and an increased risk
of carcinogenesis (Greer and Whitcomb, 2009). Our experi-
ments revealed a robust, pancreas-specific expansion of DC
populations in animals subject to both benign and malignant
pancreatic disease and in human pancreatic cancer tissue.
We show that DC expansion within the inflamed pancreas leads to the formation of early PanIN lesions with high proliferative rates. Furthermore, DCs accelerate pancreatic tumor growth and are sufficient to induce altered expression of numerous cell cycle regulatory genes and tumor suppressor genes. DCs have been considered a potent tool in nature’s defense against carcinogenesis and tumor progression as DCs avidly capture tumor antigen in vivo and initiate both adaptive and innate antitumor immune responses (O’Neill et al., 2003). MyD88 mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003). MyD88 mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003). MyD88 mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003). MyD88 mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003). MyD88 mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003). MyD88 mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003). MyD88 mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003).

**MATERIALS AND METHODS**

**Animals and procedures.** Male C57BL/6 (H-2Kb) were purchased from Taconic and bred in-house. Transgenic mice deficient in CD4 T cells (B6.129S2-Cd4tm1Mak/J), CD8 T cells (B6.129S2-Cd8atm1Mak/J), B cells (B6.129S2-Igh-Crotm1Ccum/J), MHC II (B6.129S2-C2mmtm1Ccum/J), β2-microglobulin (B6.129P2-B2mmtm1J), TNF (B6.129S-TNFtm1Gkl/J), TRIF (C57BL/J-Traf3ip10tm1J), and TLR4 (B6.129S-Jtn-Tlr4tm1Fgl/J) were purchased from the Jackson Laboratory. p48Cre;KrasG12D mice, which develop pancreatic neoplasia endogenously by expressing a single mutant Kras allele in progenitor cells of the pancreas (gift of D. Tuveson, Cambridge Research Institute, Cambridge, England, UK), were generated by crossing LSL-KrasG12D mice with p48-Cre mice, which express Cre recombinase from a pancreatic progenitor-specific promoter (Hingorani et al., 2003). MyD88−/− mice were a gift of D. Levy (New York University School of Medicine, New York, NY). CD11c-Cre MyD88 Floxed−/+ mice, which are deficient in MyD88 exclusively within CD11c+ cells, were generated by breeding B6.129P2(SL/J)-MyD88tm1Kry/J mice with B6.Cg-Tg(Nex:cre)1-IresZ/J (The Jackson Laboratory) as reported previously (Hou et al., 2008). Bone marrow chimeric animals were created by irradiating 2-mo-old mice (100 Gy) followed by i.v. bone marrow transfer (106 cells) from nonirradiated donors as we have described previously (Bedrosian et al., 2011). Chimeric mice were used in experiments 7 wk later. To accelerate carcinogenesis in p48Cre;KrasG12D mice, two doses of caerulein (50 µg/kg; Sigma-Aldrich) were administered over 48 h as described previously with modifications, and mice were sacrificed at 3 wk (Carrière et al., 2009). Animals were housed in a clean vivarium and fed standard mouse chow. Animal procedures were approved by the New York University School of Medicine Institutional Animal Care and Use Committee.

**Cellular isolation, culture, and analysis.** Bone marrow–derived DCs were generated as described previously (Miller et al., 2002). In brief, bone marrow aspirates were cultured for 8 d in complete RPMI supplemented with 20 ng/ml murine GM-CSF. Pancreatic and splenic mononuclear cells were isolated by mechanical and chemical digestion using Collagenase IV (Sigma-Aldrich). For selected experiments, CD4+ T cells were purified from suspensions of pancreatic mononuclear cells using the MoFlo Cell Sorter (Beckman Coulter) and cultured with plate-bound anti-CD3. Cell culture supernatant was assayed in a cytometric bead array (BD).

**In vivo models.** Chronic pancreatitis was induced using seven consecutive daily i.p. injections of caerulein (50 µg/kg; Sigma-Aldrich) thrice weekly for 3–12 wk. In animals adoptively transferred with DCs, 106 bone marrow–derived DCs were administered i.p. thrice weekly. In selected animals, 10 µg Flt3L was administered i.p. for 10 d. In parallel, caerulein was administered thrice weekly for 2 wk starting on day 4 of Flt3L administration. For CD4+ T cell adoptive transfer experiments, 2 × 106 pancreatic CD4+ T cells were purified and transferred administered i.p. thrice weekly for 5 wk. To establish orthotopic pancreatic lesions, we grafted PDECs harboring oncogenic KrasG12D by direct intrapancreatic injection via laparotomy as we have described previously (Agbunag et al., 2006; Pylayeva-Gupta et al., 2012). Mice were sacrificed 6 wk after PDEC transfer. To deplete Gr1+ cells or CD4+ T cells, respectively, RB6-8C5 or GK1.5 was used as described previously (Connolly et al., 2010; Monoclonal Antibody Core Facility, Memorial Sloan Kettering Cancer Center). MyD88 inhibitory peptide or control peptide (200 µg; InvivoGen) was administered i.p. thrice weekly in selected experiments. NF-kB blockade was accomplished using the cell-permeable NEMO binding domain inhibitor (1 mg/kg/day; EMD Millipore). MAP kinase blockade was accomplished using PD98059 (2.5 µg/kg/day; InvivoGen). TLR4 and TRIF blockade was accomplished using a TLR4 inhibitory peptide (JMG-2011A; 100 µg thrice weekly; Imgenex) or an inhibitor of the TRIF adaptor protein (Pepnub-TRIF; 150 µg thrice weekly; InvivoGen), respectively. In selected experiments, mice were treated with 5 µg TLR4 ligand LPS or 80 µg TLR3 ligand Poly I:C thrice weekly (both InvivoGen). The novel immune modulator VAG539 (30 µg/kg/day; Novartis) was administered via oral gavage (Hellerbrand et al., 1996; Creusot et al., 2009). Serum levels of glucose and lipase were measured using an AU400 Chemistry Analyzer (Olympus).

**Western blotting.** For immunoblotting assays, cell lysates were prepared from whole pancreata or Kaji lymphoma cells. For our human experiments, proteins were also isolated from human pancreatic duct fluid harvested at surgery from patients undergoing pancreatic resection. Total protein was determined by the Lowry assay, and lysates were equilibrated onto a 10% polyacrylamide gel (30% acrylamide/Bis solution, 37:5:1, 2.6% C). Proteins were then electrotransferred to a polyvinylidene difluoride membrane at 90 V for 90 min. Subsequently, the polyvinylidene difluoride was immunoblotted using antibodies directed against pIRF3 (Cell Signaling Technology), HMG-1B, S100A9, IRAK, pIRAK, p21, p27, p53, Rb, and β-actin (Santa Cruz Biotechnology, Inc.). Levels of TLR4 agonists in pancreatic duct fluid were quantified on HEK-Blue cells (InvivoGen) using fixed quantities of TLR4 agonists as controls (Guo et al., 2009).
Flow cytometry. Cell surface marker analysis was performed by flow cytometry using the FACSCalibur (Beckman Coulter) after incubating 5 × 10^6 cells with 1 µg anti-FcγRIII/II antibody (2.4G2, Fc block; Monoclonal Antibody Core Facility, Memorial Sloan-Kettering Cancer Center) and then labeling with 1 µg FITC-, PE-, PerCP-, or APC-conjugated antibodies directed against MHC II (I-Ab), B220 (RA3-6B2), CD3e (17A2), CD4 (RM4-5), CD8α (53.6.7), CD11b (M1/70), CD11c (HL3), CD25 (PC6/15), CD40 (HM40-3), CD45.2 (104), CD69 (H1.2F3), CD86 (GL1), F/480 (BM8), Foxp3 (FJK–16s), FAS Ligand (MFL3), NK1.1 (PK1.36), and Gr1 (RB6–8C5; all BD, eBioscience, or BioLegend). Pancreatic mononuclear cells were also stained for TLR4 (Imgenex). Dead cells were excluded by staining with 7-amino-actinomycin D (BD).

Histology, immunohistochemistry, and microscopy. For histological analysis, paraffin-embedded or frozen sections were stained with hematoxylin and eosin (H&E), Gomori’s Trichrome, Alcian blue, or Picric acid–Sirius red. In addition, immunohistochemistry was performed using antibodies directed against CD3 (Invitrogen), CD4 (Abbiotech), p53 (Novocasta), CK19 (Developmental Studies Hybridoma Bank), Desmin (Sigma–Aldrich), to–SMα (Novus Biologicals), TLR4 (Imgenex), amylose (Sigma–Aldrich), CD11c, DC–SIGN, CD1a (BD), CD123, and insulin (Abcam). Photographs were taken using a DM2M microscope (Leica) and a digital camera (Optronics). Fluorescent images were captured on an Axiovert 200M fluorescence microscope (Carl Zeiss). Ductal dysplasia was identified and graded in a blinded manner according to established criteria (Hongori et al., 2003; Hruban et al., 2004). In brief, in PanIN I lesions, the normal cuboidal PDECs transition to columnar architecture. PanIN II lesions are associated with additional nuclear abnormalities such as loss of polarity. PanIN III lesions, or in situ carcinoma, show cribriforming, acinar destruction against MHC II (I-Ab), B220 (RA3-6B2), CD3e (17A2), CD4 (RM4-5), CD8α (53.6.7), CD11b (M1/70), CD11c (HL3), CD25 (PC6/15), CD40 (HM40-3), CD45.2 (104), CD69 (H1.2F3), CD86 (GL1), F/480 (BM8), Foxp3 (FJK–16s), FAS Ligand (MFL3), NK1.1 (PK1.36), and Gr1 (RB6–8C5; all BD, eBioscience, or BioLegend). Pancreatic mononuclear cells were also stained for TLR4 (Imgenex). Dead cells were excluded by staining with 7-amino-actinomycin D (BD).

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Figure S1. Divergent effects of modulating MyD88 and TRIF signaling on pancreatic carcinogenesis.