Title
Targeting IL-17B-IL-17RB signaling with an anti-IL-17RB antibody blocks pancreatic cancer metastasis by silencing multiple chemokines

Permalink
https://escholarship.org/uc/item/2qq2957c

Journal
Journal of Experimental Medicine, 212(3)

ISSN
0022-1007

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Publication Date
2015

DOI
10.1084/jem.20141702

Peer reviewed
Pancreatic cancer is considered largely incurable, even when diagnosed at an early stage. Due to a lack of early symptoms and the aggressive nature of pancreatic tumors, pancreatic cancer patients are often diagnosed at a late stage, when metastasis has already occurred. The poor prognosis of pancreatic cancer has been mainly attributed to its aggressive local invasion and early metastasis (Niedergethmann et al., 2007; Rhim et al., 2012). Factors derived from both genetic and surrounding microenvironment may contribute to this aggressive nature. For example, genetic mutations in oncogene KRAS (Almoguera et al., 1988); tumor suppressor genes TP53, SMAD4, and BRCA2 (Hong et al., 2011); chromatin modification genes EPC1 and ARID2; and DNA damage repair gene ATM (Biankin et al., 2012) have been associated with pancreatic cancer progression. However, surrounding stromal cells also contribute to pancreatic cancer malignancy. It was reported that pancreatic stellate cells secrete growth factors and cytokines to promote cancer cell proliferation and migration (Erkan et al., 2012), facilitate tumor growth and metastasis (Hwang et al., 2008; Vonlaufen et al., 2008), and enhance pancreatic cancer stem cell phenotypes (Hamada et al., 2012; Lonardo et al., 2012). Chronic inflammation is also known to serve as a crucial driving force for pancreatic cancer progression (Farrow and Evers, 2002; Clark et al., 2007; Guerra et al., 2007; Rhim et al., 2012). Upon stimulation by inflammatory cytokines, cancer cells express chemokines to promote tumor growth, invasion,
metastasis, and angiogenesis via autocrine or paracrine loop (Coussens and Werb, 2002; Balkwill, 2004). Factors such as IL-1, IL-6, IL-8, and stromal cell-derived factor 1 (SDF1), and receptors such as C-X-C chemokine receptor type 4 (CXCR4) and epidermal growth factor receptor (EGFR), have all been shown to play crucial roles in tumorigenesis and chemoresistance in pancreatic or other cancers (Sawai et al., 2003; Mori et al., 2004; Li et al., 2005; Grandal and Madhous, 2008; Matsuo et al., 2009; Lesina et al., 2011). However, unlike other well-studied cytokines (McAllister et al., 2014), the importance of IL-17B–IL-17RB signaling in pancreatic cancer is unknown.

The IL-17 family consists of six cytokines, IL-17A to IL-17F, with 20–50% sequence homology. IL-17A and IL-17F are proinflammatory cytokines exclusively secreted by activated T cells (Fossiez et al., 1996). IL-17B, IL-17C, IL-17D, and IL-17E are expressed in various tissues in a low amount. The cognate receptors for the IL-17 family, IL-17RA to IL-17RE, have been identified, but the physiological roles of these receptors have yet to be fully characterized (Song and Qian, 2013).

IL-17RB has been detected in kidney, pancreas, liver, brain, and intestine (Kolls and Lindén, 2004), and up-regulation of IL-17RB expression was found in intestinal inflammation (Shi et al., 2000). We have previously shown that IL-17RB overexpression was associated with poor breast cancer prognosis (Furuta et al., 2011; Huang et al., 2013). Depletion of IL-17RB resulted in reduction of tumorigenic ability of breast cancer cells (Huang et al., 2013). It is likely that IL-17B–IL-17RB autocrine signaling may contribute to the malignant nature of pancreatic cancer.

In this study, we found that IL-17B/RB signaling is essential for pancreatic cancer malignancy. IL-17B–IL-17RB signal pathway enhanced tumor malignancy through two distinct pathways. One was to activate IL-8 expression via transcription factors nuclear factor κB (NF-κB) and activator protein-1 (AP-1) to promote invasion and vasculogenic endothelial cell recruitment. The other was to up-regulate chemokine (C-C motif) ligand 20 (CCL20), chemokine (C-X-C motif) ligand 1 (CXCL1) and trefoil factor 1 (TFF1) expression via transcription factors NF-κB, activating transcription factor 2 (ATF2) and acute myeloid leukemia 1 protein (AML1) to facilitate pancreatic cancer cell recruitment of macrophages (MQ) and enhance cancer cell survival in distant organs. Clinical evidence also indicated that IL-17B overexpression strongly correlated with postoperative metastasis and poor prognosis. Importantly, treatment with a newly developed monoclonal antibody against IL-17RB blocked tumor growth and metastasis, and also promoted survival in a mouse xenograft model. These findings shed light on the underlying mechanism of pancreatic cancer malignancy and provide a promising therapeutic target to inhibit pancreatic cancer progression.

RESULTS
Overexpression of IL-17RB associates with metastasis and poor clinical outcome in pancreatic cancer patients
To investigate whether IL-17RB is clinically important for pancreatic cancer, we performed immunohistochemistry (IHC) to analyze IL-17RB expression in 111 pancreatic cancer specimens (Fig. 1 A). The characteristics of these cases are given in Table 1. The specimens can be grouped into three categories based on the percentage of cancer cells expressing IL-17RB: negative (0%), low positive (<10%), and high positive (≥10%). High expression of IL-17RB was strongly correlated with poor differentiation (P = 0.046), metastasis (P = 0.009), and tumor stage using the TNM (tumor, node, metastasis) staging system (P < 0.001; Table 1). Moreover, high IL-17RB expression was associated with postoperative metastasis (P = 0.029, Fig. 1 B), marginally associated with recurrence (P = 0.057; Fig. 1 B), and correlated with poor prognosis (IL-17RB positive vs. negative: P = 0.035; IL-17RB high positive vs. negative: P = 0.007; Fig. 1 C). The hazard ratio of progression-free survival in patients with high IL-17RB expression was 1.53-fold (95% C.I. 1.03–2.27; P = 0.034) of those without detectable IL-17RB expression after being adjusted for age, gender, tumor location, differentiation status, pathological type, stage, and adjuvant therapy (Fig. 1 D).

Overall, patients with elevated IL-17RB expression had worse prognosis and enhanced tumor malignancy, indicating the importance of IL-17RB in pancreatic cancer progression.

IL-17RB has an essential role in pancreatic cancer growth, invasion, and metastasis
To evaluate the role of IL-17RB in pancreatic cancer, we first examined the expression of IL-17RB in a panel of human pancreatic cancer cell lines. High IL-17RB expression was detected in HPAF-II, BxPC3, Capan2, and CFPAC-1 cells (Fig. 2 A). In contrast, low expression was observed in HPAC, SU.86.86, and MiaPaCa-2 cells. We then performed a series of experiments using cells with perturbed IL-17RB expression (Fig. 2, B–G). Depletion of IL-17RB in CFPAC-1 and BxPC3 cells reduced soft agar colony formation and invasion abilities (Fig. 2, B–D). Conversely, colony formation and invasion ability were enhanced in SU.86.86 and HPAC cells when full-length IL-17RB was ectopically expressed (Fig. 2, E–G). In contrast, expression of IL-17RB lacking a ligand binding domain (ΔLBD) had no effect (Fig. 2, E–G). These results indicated that the IL-17B–IL-17RB signal is important for enhancing pancreatic malignancy.

To further substantiate its role in pancreatic cancer, we performed subcutaneous xenograft assays using IL-17RB-depleted CFPAC-1 cells (Fig. 2 H) and demonstrated that depletion of IL-17RB resulted in inhibition of tumor growth when compared with the control (shLacZ). Consistent with this observation, when we performed orthotopic xenografts with IL-17RB-depleted CFPAC-1 cells (Fig. 2 I), they formed smaller tumors. Expression of IL-17RB in these orthotopic tumors was confirmed by IHC (Fig. 2 J).

Notably, none of the IL-17RB-depleted xenograft mice developed metastasis. In contrast, four out of six mice implanted with the control CFPAC-1 cells (Fig. 2 K) developed lung metastasis and two of these also developed liver metastasis. Also, injection with IL-17RB-depleted cells through tail vein caused none or little lung metastasis, whereas injection with control cells led to severe lung tumor burden (Fig. 2 L).
IL-17B neutralizing antibody (Fig. 3, E–F) in these cells reduced colony formation (Fig. 3, C and E), invasion (Fig. 3, D and F), tumor growth (Fig. 3, G–H), and metastasis assayed by mouse xenograft models (Fig. 3 I), or by tail vein injection experiment (Fig. 3 J). Thus, similar to IL-17RB, expression of the ligand, IL-17B, also has a critical role in pancreatic cancer malignancy. Consistent with this notion, treating CFPAC-1 and BxPC3 cells with additional recombinant IL-17B (rIL17B) enhanced colony formation and invasion abilities (Fig. 3, A).

Similar results were observed using BxPC3 cells (unpublished data). Together, these data indicate that elevated IL-17RB expression is critical for pancreatic cancer malignancy.

IL-17B–IL-17RB signaling promotes pancreatic cancer malignancy

Interestingly, pancreatic tumor cells with high level of IL-17RB also expressed IL-17B, an IL-17RB ligand (Fig. 3 A). Depletion of IL-17B by shRNA (Fig. 3, B–D) or treatment with the IL-17B neutralizing antibody (Fig. 3, E–F) in these cells reduced colony formation (Fig. 3, C and E), invasion (Fig. 3, D and F), tumor growth (Fig. 3, G–H), and metastasis assayed by mouse xenograft models (Fig. 3 I), or by tail vein injection experiment (Fig. 3 J). Thus, similar to IL-17RB, expression of the ligand, IL-17B, also has a critical role in pancreatic cancer malignancy.

Consistent with this notion, treating CFPAC-1 and BxPC3 cells with additional recombinant IL-17B (rIL17B) enhanced colony formation and invasion abilities (Fig. 3, A).

Figure 1. Overexpression of IL-17RB is associated with metastasis and poor clinical outcome in pancreatic cancer patients. (A) Representative IHC results of patients with IL-17RB-negative (0%), low positive (< 10%), and high positive (>10%) expression in cancer cells. Bar, 50 µm. Boxes show the enlarged area. (B) Correlation of IL-17RB expression in cancer cells and clinical parameters (2 yr after operation) in 111 pancreatic cancer cases. χ² test was used. (C) Comparison of the progression free survival (PFS) of patients with different levels of IL-17RB expression using the Kaplan-Meier method. P = 0.035. (D) Univariate and multivariate Cox regression analysis of the influence of IL-17RB on the clinical outcome (progression free survival) of pancreatic cancer patients after surgical therapy.
Table 1. The correlation between IL-17RB expression and the clinical parameters in 111 pancreatic cancer cases

<table>
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<th>P-value&lt;sup&gt;a&lt;/sup&gt;</th>
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<td></td>
<td>Negative n (%)</td>
<td>Low n (%)</td>
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<tr>
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<td>23 (58)</td>
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<tr>
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<td>III and IV</td>
<td>16</td>
<td>6 (37)</td>
<td>3 (19)</td>
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<sup>a</sup><sup>x</sup><sup>2</sup> was used for statistical analysis.
<sup>b</sup>Median of Age = 67 yr old.
<sup>c</sup>Head including head, neck, and body.
<sup>d</sup>Including 3 mucinous adenocarcinoma, 4 mucinous cystadenocarcinoma, 3 adenosquamous cell carcinoma, 2 acinar cell adenocarcinoma, 1 pleomorphic carcinoma, and 1 undifferentiated carcinoma.
<sup>e</sup>Classified by AJCC staging system.

K–L). Moreover, adding rIL17B increased the colony formation and invasion of SU.86.86 and HPAC cells ectopically expressing IL-17RB, but not cells overexpressing ΔLBD (Fig. 3, M–N). These results suggest a critical role of IL-17B–IL-17RB signal in promoting pancreatic cancer malignancy.

IL-17B–IL-17RB signaling activates chemokines CCL20, CXCL1, IL-8, and TFF1 to enhance pancreatic cancer malignancy

To explore potential downstream targets of IL-17B–IL-17RB signaling, we compared the mRNA expression profiles between shLacZ-transduced and IL-17RB–depleted CFPAC-1 cells, and between lenti-neo and IL-17RB ectopically expressing HPAC cells. As shown in Fig. 4 A, 71 genes were down-regulated in IL-17RB–depleted CFPAC-1 cells but up-regulated in IL-17RB–expressing HPAC cells, indicating that these genes are potential targets of IL-17RB signaling. Among these, the four highest encoded chemokines CCL20, CXCL1, IL-8, and TFF1 were identified (Fig. 4 B). To further confirm this result, we performed qRT-PCR to measure each mRNA expression in those cells. As shown in Fig. 4 C, IL-17RB–depleted CFPAC-1 showed down-regulation of CCL20, CXCL1, IL-8, and TFF1 expression, whereas ectopic expression of IL-17RB, but not ΔLBD mutant, in HPAC1 cells resulted in up-regulation of these genes (Fig. 4 C). A similar expression pattern at the protein level was also observed (Fig. 4 D). Using TFF1 as an example of
Figure 2. IL-17RB expression has an essential role in tumorigenesis and metastasis of pancreatic tumor cells. (A) Immunoblot analysis of IL-17RB in pancreatic cancer cell lines. α-Tubulin was used as a loading control. (B) IB analysis of IL-17RB in CFPAC-1 and BxPC3 cell lines transduced with lentiviral-control shRNA (shLacZ) or shIL-17RB. Tubulin was used as a loading control. RE, relative expression. (C and D) Soft agar colony formation (SACF) assay (C) and invasion assay (D) using CFPAC-1 and BxPC3 cells infected with shLacZ or shIL-17RB. Tubulin was used as a loading control. RE, relative expression. (E and F) Assays for soft agar colony formation (SACF; F) and invasion (G) were performed using SU.86.86 and HPAC cells overexpressing full-length or ∆LBD IL-17RB. (H) Tumorigenesis assay of NOD/SCIDγ mice subcutaneously injected with shLacZ-transduced or IL-17RB–depleted CFPAC-1 cells. Cell dose: 1 × 10^6 cells per mouse. Six mice were used for each group. (I) Tumor weight of NOD/SCIDγ mice orthotopically implanted with shLacZ-transduced or IL-17RB–depleted CFPAC-1 cells. Cell dose: 2.5 × 10^5 cells per mouse. Six mice were used for each group. (J) IHC of IL-17RB in tumors derived from mice orthotopically implanted with shLacZ-transduced or IL-17RB–depleted CFPAC-1 cells. (K) Summary table of lung and liver metastasis derived from orthotopic xenograft. (L) Lung metastasis of NOD/SCIDγ mice intravenously injected with shLacZ-transduced or IL-17RB–depleted CFPAC-1 cells. Cell dose: 5 × 10^6 cells per mouse. Six mice were used for each group. Data shown are means ± SD. *, P < 0.05; **, P < 0.01 (Student’s t-test). All experimental data verified in at least two independent experiments.
Figure 3. The IL-17B–IL-17RB signaling pathway is essential for tumorigenic and metastatic abilities of pancreatic cancer cell lines. (A) RT-PCR analysis of IL-17B in pancreatic cancer cell lines. β-actin was used as a loading control. (B) mRNA expression of IL-17B determined by RT-qPCR in CFPAC1 and BxPC3 cells infected with shLacZ or shIL-17RB. (C and D) SACF assay (C) and invasion assay (D) using CFPAC-1 and BxPC3 cells infected with shLacZ or shIL-17B. (E and F) SACF assay (E) and invasion assay (F) using CFPAC-1 and BxPC3 cells supplemented with IgG control, anti–IL-17RB, or anti–IL-17B (1 µg/ml). (G) Tumorigenesis assay of NOD/SCIDγ mice subcutaneously injected with shLacZ-transduced or IL-17B–depleted CFPAC-1 cells. Cell
IL-17RB–regulated chemokines, a positive correlation was observed between IL-17RB and TFF1 expressions in the pancreatic cancer specimens by IHC (Fig. 4, E–F; P = 0.007). Consistent with these results, treating CFPAC-1 cells with rIL17B increased mRNA levels of these four chemokines within 3 h (Fig. 4 G). Similarly, increases of these four chemokines were also observed in those cells upon treatment with rIL17B in a dose-dependent manner after serum-starvation (Fig. 4 H). These results suggest that IL-17B–IL-17RB signal activates at least the expression of these four chemokines.

Because chemokines secreted from cancer cells frequently mediate recruitment of the myeloid cells to tumors to support cancer cell survival and to facilitate metastasis (Acharyya et al., 2012), we then examined whether CCL20, CXCL1, IL-8, and TFF1 are downstream factors mediating biological function of IL-17B–IL-17RB signal. First, we observed that depletion of the chemokine expression suppressed the invasion activity, but not the colony formation activity (Fig. 5, A and B). Second, MQ recruitment in mouse lungs invaded with the IL-17RB–depleted CFPAC-1 cells was significantly reduced (Fig. 5 C). Importantly, depletion of CCL20, CXCL1, or TFF1 also significantly decreased the percentage of CFPAC-1 cells interacting with MQ (Fig. 5 C); however, the effect was less dramatic than in IL-17RB–depleted cells. Consistent with these results, IL-17B, CCL20, CXCL1, and TFF1 were all required for pancreatic cancer cell survival in lung metastasis, as depletion of any of these genes significantly increased the proportion of apoptotic CFPAC-1 cells by TUNEL assay (Fig. 5 D). In contrast, IL-8 depletion did not affect cancer cell survival in lung (Fig. 5 D). Instead, depletion of IL-8 significantly decreased the recruitment of CD31+ vascologenic endothelial cells (Fig. 5 E), presuming that the recruitment is important for angiogenesis and a crucial step in metastasis (DeLisser et al., 1997). Similarly, depletion of IL-17RB, CCL20, CXCL1, or TFF1 also inhibited CD31+ cell recruitment (Fig. 5 E), whereas high IL-17RB expression was significantly correlated with CD31+ microvesSEL formation by IHC analysis of cancer specimens (Fig. 5, F and G; P < 0.001). Together, these results suggest that IL-17RB and its activated downstream chemokines have an important role in pancreatic cancer malignancy (Fig. 5 H).

**IL-17B–IL-17RB up-regulates CCL20, CXCL1, TFF1, and IL-8 via activation of ERK signal transducing pathway**

To elucidate mechanisms of IL-17B–IL-17RB–mediated chemokine up-regulation, we first compared kinase activation profiles of IL-17RB–depleted CFPAC-1 and IL-17RB–overexpressing HPAC cells using human phosphokinase arrays (Fig. 6, A and B). The analysis showed about a fourfold decrease in extracellular-signal-regulated-kinase (ERK)1/2 activation in IL-17RB–depleted CFPAC-1 cells, whereas there was a fivefold increase in IL-17RB–overexpressing HPAC cells (Fig. 6, C and D), indicating that ERK1/2 activity is positively regulated by IL-17RB. To further confirm this result, we performed direct Western blot analysis using two IL-17RB–depleted cell lines, CFPAC-1 and BxPC3, and two ectopically IL-17RB–overexpressing cell lines, HPAC and SU.86.86, and obtained a similar result (Fig. 6 E). To further test whether ERK1/2 mediates the activation of these chemokines, we added rIL17B to CFPAC-1 and HPAC-F-II cells and examined the potential signal cascade, including activations of ERK1/2 by phosphorylation, activation of IKK by phosphorylation, activation of NF-κB, and the expression of these chemokines (Fig. 6, F and G). As shown in Fig. 6 (F and G; #1 vs. #4), activation of IL-17B–IL-17RB signaling resulted in ERK1/2 and IKK phosphorylation (Fig. 6 F, #4), subsequent translocation of NF-κB into the nucleus (Fig. 6 H), and increased expressions of the chemokines identified above (Fig. 6 G). Consistent with this, phosphorylation of ERK1/2 and IKK and chemokine expression induced by rIL17B were abolished by the MEK/ERK inhibitor, U0126 (Fig. 6, F and G; #5). When cells were treated with the IKK/NF-κB inhibitor, BAY117082, the phosphorylation of IKK, but not ERK1/2, was diminished (Fig. 6 F, #6). However, chemokine gene expression was only moderately reduced (Fig. 6 G, #6), suggesting that additional factors downstream of IL-17B–IL-17RB–ERK signaling may also contribute to the up-regulation of CCL2, CXCL1, TFF1, and IL-8 in CFPAC-1 cells. Similar results were observed using HPAF-II cells (unpublished data).

To explore additional factors mediating IL-17B–IL-17RB/ERK signaling regulation of CCL20, CXCL1, TFF1, and IL-8 expression, we examined the promoter regulation of each of these chemokine genes by IL-17B–IL-17RB signaling. Within three hours of rIL17B treatment, the proximal promoter (~1,000 to +1 bp) activities of these chemokines were up-regulated in transient reporter assays (Fig. 6 I), suggesting that these proximal promoters may harbor IL-17B–IL-17RB–responsive elements. We next analyzed these promoters in silico (Heinemeyer et al., 1998; Messeguer et al., 2002; Farré et al., 2003; Karolchik et al., 2004; Fig. 6 J). In addition to the binding sites of NF-κB on the CCL20, CXCL1, TFF1, and IL-8 promoters, binding sites for two well-known ERK downstream effectors, ATF2 (Lopez-Bergami et al., 2010)
Figure 4. Chemokines CCL20, CXCL1, IL-8, and TFF1 are the downstream targets of the IL-17B–IL-17RB signaling. (A) Summary of cDNA microarray analyses. Total of 71 genes expressed at least 2-fold higher in IL-17RB–overexpressing HPAC cells and 2-fold lower in IL-17RB–depleted CFPAC-1 cells compared with the proper control were identified by Affymetrix microarray analyses. (B) Four chemokines, CCL20, CXCL1, IL-8, and TFF1, were identified among the 71 genes. (C) qRT-PCR analysis to reconfirm the expression profile of the four chemokines in IL-17RB–depleted CFPAC-1, IL-17RB–, and ΔLBD–overexpressing HPAC cells. β-actin was used as an internal control. (D) Immunoblot analysis of IL-17RB and the four chemokines in shLacZ-transduced or IL-17RB–depleted CFPAC-1 cells, and lenti-neo, IL-17RB, or ΔLBD–overexpressing HPAC cells. GAPDH was used as a loading control. RE, relative expression. (E) Representative pictures of the IHC analyses of IL-17RB and TFF1 in serial sections of a PDAC case. Boxes show the enlarged area of IL-17RB high (+++) and negative (−) regions. (F) Correlation between TFF1 and IL-17RB in 111 pancreatic cancer patients. (G) mRNA expression of the four chemokines were measured by RT-qPCR in CFPAC-1 cells treated with 50 ng/ml rIL17B for 0, 1, and 3 h after serum-starvation. β-actin was used as internal control. Data shown are means ± SD. *, P < 0.05; **, P < 0.01 (Student's t test). (H) Protein expression of IL-17RB and the four chemokines were measured by immunoblotting in CFPAC-1 cells treated with 0, 20, or 50 ng/ml rIL17B for 6 h after serum starvation, respectively. GAPDH were used as internal controls. RE, relative expression. All experimental data was verified in at least two independent experiments.
and AML1 (Tanaka et al., 1996), were found on the CCL20, CXCL1, and TFF1 promoters (Fig. 6 J). Binding sites for another ERK downstream transcription factor, AP1 (Whitmarsh and Davis, 1996), were found on TFF1 and IL-8 promoters (Fig. 6 J). Subsequently, we performed reporter activity analysis in response to rIL-17B treatment and found that the full activity responding to rIL17B of TFF1 was located on the −250 to +1 bp promoter region, which contains the binding sites for an other ERK downstream transcription factor, AP1 (Whitmarsh and Davis, 1996), were found on TFF1 and IL-8 promoters.
Figure 6. IL-17B–IL-17RB signaling modulates CCL20, CXCL1, TFF1, and IL-8 expression through transcription factors NF-κB, ATF2, AML1, and AP1 via the TRAF6–ACT1–TAK1–ERK1/2 pathway. (A–D) Phospho-kinase array detected ERK1/2 phosphorylation in shLacZ-transduced or IL-17RB–depleted CFPAC-1 cells (A), and lenti-neo or IL-17RB overexpressing HPAC cells (B). Relative phosphorylation level of ERK1/2 protein to reference (Ref) is indicated (C and D). (E) Immunoblot analysis of ERK1/2 phosphorylation in shLacZ-transduced or IL-17RB–depleted CFPAC-1 and BxPC3 cells, and lenti-neo or IL-17RB overexpressing HPAC and SU.86.86 cells. GAPDH was used as a loading control. Relative phosphorylation (RP) level of ERK1/2

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sites of ATF2 and AML1, in addition to NF-κB (Fig. 6 K). Also, upon rIL17B treatment, phosphorylation of ATF2, AML1, and c-Jun (the subunit of AP1) was detected (Fig. 6 L), reflecting a transcriptional activation of TFF1 gene (Tanaka et al., 1996; Whitmarsh and Davis, 1996; Lopez-Bergami et al., 2010). Similarly, the occupancy of NF-κB quantified by chromatin immunoprecipitation (ChIP) assay increased 4–6-fold in the IL-8 proximal promoter within 1 h after rIL17B treatment, although it was only slightly increased in CCL20, CXCL1, and TFF1 proximal promoters (Fig. 6 M). Interestingly, binding of AP1 and AML1 was detected in CCL20, CXCL1, and TFF1 but not IL-8 proximal promoters, and binding of ATF2 was detected in CCL20 and CXCL1 but not TFF1 or IL-8 proximal promoters (Fig. 6 M), suggesting that IL-8 may be modulated differently.

Because IL-17RB is known to interact with TNF receptor associated factor 6 (TRAF6) and ACT1 (also known as TRAF3IP2, TRAF3-interacting protein 2; Maezawa et al., 2006), and TRAF6–TAK1 is known to activate the ERK–MAPK signaling for cell survival (Nishimura et al., 2009), it is likely that IL-17B–IL-17RB signal may transduce through this path. To test this possibility, we performed the co-immunoprecipitation assay and found that the interactions of TRAF6, ACT1, and TAK1 (also known as NR2C2, nuclear receptor subfamily 2, group C, member 2) with IL-17RB were enhanced upon ectopic expression of IL-17RB in HPAC cells (Fig. 6 N). Treatment of rIL17B in both CFPAC-1 and HPAF-II cells also increased their interaction (not depicted), whereas the interactions were all diminished when the TRAF6 interaction domain of IL-17RB was deleted (Fig. 6 N). This suggested that the interaction between TRAF6 and IL-17RB was critical for the signal transduction. Collectively, these results suggest that IL-17B–IL-17RB signaling modulates transcriptional activation of CCL20, CXCL1, TFF1, and IL-8 chemokines via coordinated activation of ERK1/2 and its downstream transcription factors.

**Tissue culture:**

- CFPAC-1 and HPAF-II cells were maintained in DMEM (Invitrogen, Carlsbad, CA) supplemented with 10% fetal bovine serum (FBS; Invitrogen, Carlsbad, CA) and 1% streptomycin-penicillin (Invitrogen, Carlsbad, CA).
- All cultures were maintained at 37°C in a humidified incubator with 5% CO2.

**Stable cell lines:**

- CFPAC-1 and HPAF-II cells were transfected with IL-17RB expression vector pIRE-SCtrl (Invitrogen, Carlsbad, CA) using lipofectamine (Life Technologies, Carlsbad, CA).
- 48 h after transfection, cells were selected with G418 (Invitrogen, Carlsbad, CA) for 3 weeks.

**Western blot analysis:**

- Proteins were isolated from cell lysates and subjected to SDS-PAGE and transferred to PVDF membranes (Millipore, Billerica, MA).
- Membranes were probed with antibodies specific for IL-17RB (Invitrogen, Carlsbad, CA), GAPDH (Sigma-Aldrich, St. Louis, MO), and beta-actin (Sigma-Aldrich, St. Louis, MO).

**Immunohistochemistry (IHC):**

- For IHC, tissue sections were deparaffinized and rehydrated.
- Endogenous peroxidase was blocked with 3% hydrogen peroxide.
- Sections were incubated with primary antibodies overnight at 4°C.
- Secondary antibodies were applied for 2 h at room temperature.
- Images were captured using a microscope (Nikon, Melville, NY) equipped with a digital camera (Olympus, Center Valley, PA).

**Immunofluorescence (IF):**

- Cells were fixed with 4% paraformaldehyde and permeabilized with 0.1% Triton X-100.
- Primary antibodies were applied for 1 h at room temperature.
- Fluorescent secondary antibodies were applied for 1 h at room temperature.
- Images were captured using a confocal microscope (Leica, Wetzlar, Germany).

**Luciferase reporter assay:**

- Cells were transiently transfected with firefly luciferase reporter constructs using Lipofectamine 2000 (Invitrogen, Carlsbad, CA).
- After 24 h, cells were treated with rIL17B for 12 h.
- Luciferase activity was measured using a luminometer (PerkinElmer, Waltham, MA).

**Chromatin immunoprecipitation (ChIP):**

- Cells were cross-linked with 1% formaldehyde.
- Chromatin was sheared to a size of 200–500 bp by sonication.
- Immunoprecipitation was performed using antibodies against specific transcription factors.
- Enriched DNA was analyzed by qPCR using primers specific for the promoter region of interest.

**In vitro invasion assay:**

- Cells were seeded into the top chamber of a 24-well transwell plate (Costar, Corning, NY) coated with Matrigel.
- The lower chamber contained SFM.
- Cells were incubated for 24 h at 37°C.
- Invasion was determined by staining and counting the cells that had migrated through the membrane.

**In vivo metastasis assay:**

- CFPAC-1 cells were orthotopically implanted into the pancreas of severe combined immunodeficient (SCID) mice (n = 10).
- Treatment with D9 or control IgG was initiated 1 week after implantation.
- Mice were euthanized 8 weeks after treatment.
- Lungs and liver were harvested and examined for metastases.

**Tumor growth assay:**

- CFPAC-1 cells were orthotopically implanted into the pancreas of nonobese diabetic/severe combined immunodeficient (NOD/SCIDγ) mice (n = 10).
- Treatment with D9 or control IgG was initiated 1 week after implantation.
- Tumor growth was measured by bioluminescence imaging.

**Statistical analysis:**

- Data were analyzed using GraphPad Prism 6.0 (GraphPad Software, La Jolla, CA).
- P values were calculated using Student’s t-test or one-way ANOVA followed by Tukey’s multiple comparisons test.
- Differences were considered significant at *P* < 0.05, **P** < 0.01, and ***P*** < 0.001.
Figure 7. Treatment with a neutralizing monoclonal antibody against IL-17RB blocks tumor growth and metastasis, and extends survivals in a mouse orthotopic xenografted model. (A and B) Soft agar colony formation (A) and invasion (B) assays using CFPAC-1 and BxPC3 cells treated with control IgG or D9 antibody. All experimental data were verified in at least two independent experiments. (C) Relative sensitivity of both control and IL-17RB–KD clones to IgG and anti–IL-17RB in colony formation activities. (D) Schematic diagram of antibody treatment in orthotopically xenografted mice. (E and F) IVIS image (E) and tumor weight (F) of antibody-treated NOD/SCID+ mice orthotopically implanted with CFPAC-1 cells on day 28. Cell dose:
factors NF-κB, ATF2, AML1, and API via the TRAF6– ACT1–TAK1–ERK1/2 pathway to induce expression of CCL20, CXCL1, TFF1, and IL-8. Even though there was only an association between IL-17RB expression and MQ recruitment observed in our animal model, these chemokines may contribute to the recruitment of MQ to promote cancer cell local invasion and survival in lung, as well as vasculogenic endothelial cells to facilitate angiogenesis. Clinical evidence suggested that high expression of IL-17RB strongly correlated with advanced pancreatic cancer, postoperative recurrence, and metastasis. Importantly, treatment of a monoclonal antibody recognizing the native form of IL-17RB successfully delayed the malignancy of pancreatic cancer cells expressing IL-17RB and significantly extended animal survival.

Autocrine stimulation of cancer cells and reciprocal paracrine stimulation between cancer cells and stromal cells have been suggested to play crucial roles in tumorigenesis and disease progression (Ben-Baruch, 2006; Raman et al., 2007). The amount of secreted chemokines in the microenvironment and the expression level of the chemokine receptors on cancer cells contribute to the extent of cancer malignancy. In pancreatic cancer, severe desmoplastic response is usually observed around the primary tumor (Olive et al., 2009; Rhim et al., 2014). These stromal cells secrete cytokines, growth factors, and angiogenic factors to promote tumor growth (McCawley and Matrisian, 2001) and metastasis (Farrow and Evers, 2002; Ben-Baruch, 2006). Likewise, chemokines induced by IL-17B–IL-17RB as described in this study may also be secreted from stromal cells and participate in MQ and endothelial cell recruitment to promote pancreatic cancer progression. Indeed, we observed that, except for TFF1, which was predominantly expressed in cancer cells, CCL20, CXCL1, and IL-8 were detected in both pancreatic cancer cells and the surrounding stroma, especially in inflammatory cells (unpublished data). TFF1 overexpression in pancreatic cancer cells has been observed to greatly enhance metastasis but not affect primary tumor growth (Arunagam et al., 2011). Increased levels of three other chemokines in the tumor microenvironment have been shown to stimulate tumor growth, migration, invasion, angiogenesis, metastasis, and chemoresistance (Li et al., 2003; Campbell et al., 2005; Fernando et al., 2011; Acharaya et al., 2012). The dynamic interaction between cancer cells and the microenvironment is complicated. Based on our observations, we hypothesize that IL-17B–IL-17RB signaling increases the tumorigenic and metastatic potential in the cancer cell itself first, and then facilitates the reconstitution of its microenvironment (i.e., MQ and vasculogenic endothelial cell recruitment) to be prone to metastasis, in part, by secreting these chemokines. Thus, the IL-17B–IL-17RB signaling emerges as an important regulator of pancreatic cancer growth and metastasis and may serve as an effective immunotherapeutic target (Laheru and Jaffee, 2005).

Up-regulation of chemokines in cancer cells has been attributed to constitutively activated NF-κB in many cancers, including pancreatic cancer (Rayet and Gélinas, 1999; Farrow and Evers, 2002). Besides chemokines, numerous target genes of NF-κB, which promote cell cycle activity, angiogenesis, anti-apoptosis, metastasis, and tumor progression, have been identified (Baldwin, 2001; Tak and Firestein, 2001; Yamamoto and Gaynor, 2001; Karin, 2006). Our study indicated that IL-17B–IL-17RB signaling not only activated transcriptional activity of NF-κB but also induced the expression of three oncogenic transcription factors: ATF2, AML1, and API via ERK1/2 to modulate chemokine expression (Fig. 6). This coordinated regulation of the expression of multiple chemokines places the IL-17B–IL-17RB signaling in the key position of a multifaceted regulatory network for pancreatic cancer progression.

There has been a long-running debate about whether chronic pancreatitis leads to pancreatic cancer because most pancreatic cancer develops spontaneously in the absence of apparent inflammation (Algul et al., 2007). Recently, McAllister et al. (2014) used a murine model of pancreatic intraepithelial neoplasia (PanIN) to demonstrate such an association. They found that recruitment of IL-17A–secretion CD4+ and γδ T cell to the pancreatic microenvironment is required for pancreatic cancer initiation and progression in mice with activated Kras and chronic pancreatitis. In parallel, our study found that IL-17RB expression and IL-17B–IL-17RB signaling is critical for 40–50% of pancreatic tumor growth, invasion, and metastasis. Our data also showed that autocrine/paracrine IL-17B–IL-17RB signaling stimulates at least three chemokines, including IL-8, CXCL1, and CCL20, known to enhance inflammation by recruiting neutrophils, MQ, and lymphocytes (Onishi and Gaffen, 2010), suggesting a similar proinflammatory effect as IL-17A–IL-17RA.
signaling in pancreas. Interestingly, whether oncogenic KRAS modulates the expression of IL-17B in pancreatic cancer cells in a manner similar to IL-17RA (McCAllister et al., 2014) is unclear. Because KRAS is mutated and activated in 80–95% of pancreatic cancer, whereas only 40% of the patients are IL-17RB+ (Fig. 1), KRAS may not be the sole pathway regulating IL-17RB expression. This is consistent with the observation that KRAS in most of the pancreatic cancer cell lines is activated, but not every cell line expresses high levels of IL-17RB. It is also noted that BxPC3, one cell line used in this study, expresses wild-type KRAS and still has relatively high expression of IL-17RB. Genetic amplification of IL-17RB was not detected in cancer cells with IL-17RB overexpression. It is likely that other epigenetic factors and posttranslational mechanisms may contribute to IL-17RB up-regulation, which is currently under investigation.

Overall, the data presented here define a novel regulatory pathway mediated by IL-17B–IL-17RB in pancreatic cancer cells. Our findings show that IL-17RB plays a critical role in pancreatic cancer malignancy, especially metastasis, and that the treatment with D9 monoclonal antibody effectively prolongs diseased animal lifespan. This suggests that targeting IL-17RB may be an effective adjuvant treatment. Determining how IL-17RB is up-regulated in pancreatic cancer cells, identifying additional downstream targets involved in metastasis, and pinpointing how IL-17B–IL-17RB participates in pancreatic cancer microenvironment remodeling will help provide a complete picture of this IL-17B–IL-17RB-centered regulatory network. Such information will be essential to further develop therapeutic strategies for treating pancreatic cancers.

MATERIALS AND METHODS

Ethics statement. All pancreatic cancer tissue specimens are from the National Taiwan University Hospital, Taipei, Taiwan. All patients were given informed consent, which was approved by the institutional review board of the NTUH (2013/03/29, INC). Animal care and experiments were approved by the Institutional Animal Care and Utilization Committee of Academia Sinica (IACUC#10-04-065). All data points of cell line experiments were performed in at least triplicate, and all experiments were approved by the Institutional Animal Care and Utilization Committee of Academia Sinica (IACUC#10-04-065). All data points of cell line experiments were performed in at least triplicate, and all experiments were performed at least two times with similar results. One representative result is shown.

Cell culture. Human pancreatic cancer cell lines HPAF-II, BxPC3, Capan2, CFPCA-1, HPAC, SU.86.86, and MIA PaCa-2 cells were obtained from the American Type Culture Collection (ATCC) and cultured in ATCC-suggested complete growth medium in a humidified 37°C incubator supplemented with 5% CO₂. To assess the effect of IL-17B on IL-17RB signaling, cells were serum starved before rIL17B treatment to remove the endogenous IL-17B.

Plasmids and reagents. Lentivirus control, IL-17RB, ΔILBD, and ΔTRAF6 were cloned as previously described (Hwang-Verslues et al., 2009). In brief, 2,500 cells were seeded in a layer of 0.35% agar complete growth medium over a layer of 0.5% agar complete growth medium in a well of a 12-well plate. Additional 50 µl of serum-free media containing 50 ng rIL17B or 1 µg anti–IL-17RB antibody was added weekly. On day 14 or 28 after seeding, crystal violet–stained colonies were counted.

Invasion assay. Cells (10⁴) were seeded in the top chamber with Matrigel-coated membrane (24-well Falcon HTS Fluoro Block insert; pore size, 8 µm; BD) in serum-free media containing 50 ng/ml rIL17B or 1 µg/ml anti–IL-17RB antibody. Medium supplemented with serum was used as a chemotactant in the lower chamber. After 48h incubation, the invaded cells were fixed with methanol, stained with 4,6-diamidino-2-phenylindole (DAPI) and counted with fluorescence microscopy.

IL-17RB antibody production. Recombinant IL-17RB extracellular domain that carried only a single N-linked GlcNAc at each glycosylation sites was generated by ectopic overexpression in a suspension cell culture of N-acetylglucosaminyltransferase I-deficient (GnTI−) strain HEK293 cells (Reeves et al., 2002). The resulting N-glycan, GlcNAc2Man3, was then treated with endoglycosidase Hendo H to remove residual glycans. Polyclonal antibody (FGSRB for Co-IP) and monoclonal antibody (A68 for IB and IHC; D9 for IF and functional analysis) generated through this immunogen displayed a high specificity against endogenous IL-17RB.

Immunoblotting. Immunoblot analysis was performed after 8 or 12% SDS-PAGE, with overnight incubation with a 1:1,000 dilution of primary antibody and followed by a 1:5,000 dilution of horseradish peroxidase–conjugated anti–rabbit, anti–mouse, or anti–goat antibody (GeneTex). Signals were detected using Immobilon Western Chemiluminescent HRP Substrate (Millipore). The homemade antibody against IL-17RB (A68) was used. Antibodies against CCL20 (67310), CXCL1 (20326), and IL-8 (6217) anti–IL-17RB antibody. Medium supplemented with serum was used as a chemotactant in the lower chamber. After 48h incubation, the invaded cells were fixed with methanol, stained with 4,6-diamidino-2-phenylindole (DAPI) and counted with fluorescence microscopy.

RNA isolation, reverse-transcription, (real-time) PCR assay, and gene expression analysis by microarray analysis. Total RNA from cell culture and tumor tissue was isolated using TRIzol reagent (Invitrogen) and reverse-transcribed with Transcriptor First Strand cDNA Synthesis kit (Roche) for gene expression analysis according to instructions from the manufacturers. Quantitative real-time RT–PCR was performed using KAPA SYBR FAST qPCR kit (KAPA Biosystems) for gene expression according to the manufacturer’s instruction and analyzed on a StepOnePlus Real-Time PCR system (Applied Biosystems). β-actin mRNA was used as an internal control for mRNA expression. Expression levels were calculated according to the relative ΔC, method. All primers are listed in Table S2. Affymetrix U133 Plus 2.0 human oligonucleotide microarrays (Phalan Biotech Group) were used to detect gene expression in IL-17RB–depleted CFPCAC-1– and IL-17RB–overexpressing HPAC cells.

Soft agar colony formation assay. Soft agar colony formation assay was performed as previously described (Hwang-Verslues et al., 2009). In brief, 2,500 cells were seeded in a layer of 0.35% agar complete growth medium over a layer of 0.5% agar complete growth medium in a well of a 12-well plate. Additional 50 µl of serum-free media containing 50 ng rIL17B or 1 µg/ml anti–IL-17RB antibody was added weekly. On day 14 or 28 after seeding, crystal violet–stained colonies were counted.

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IHC. Formalin-fixed paraffin embedded primary tumor tissue sections were used for IHC. Heat-induced antigen retrieval was performed using 0.1 M citrate buffer, pH 6.0, and autoclaved for 20 min. Endogenous peroxidase was eliminated with 3% H$_2$O$_2$. Slides were blocked with a homemade anti-IL-17RB antibody [A68; 1:100] in PBS/10% FBS and anti-TFF1 antibody (1:100, EPR3972; Genetex) or anti-CD31 rabbit polyclonal antibody (1:50, GTX81432) in PBS/5% FBS overnight at 4°C. After washing, slides were incubated with HRP rabbit/mouse polymer before visualization with liquid diaminobenzidine tetrahydrochloride plus substrate DAB chromogen from Dako REAL EnVision. All slides were counterstained with hematoxylin. The images were captured by an Aperio Digital Pathology system. For CD31+ endothelial cell counting in mice, 1 tumor section per mouse ($n = 6$) was used and 4 fields (400×) of each section were examined. 111 pancreatic cancer specimens were used for CD31 and IL-17RB double staining. Four fields (400×) of each case, with IL-17RB negative or high expression were evaluated.

Transient reporter assay. CFPAC-1 cells of 80% confluence were transfected using Lipofectamine 2000 (Invitrogen). Luciferase reporter gene construct (1.6 µg) and 10 ng pGL4-74 Renilla luciferase construct (for normalization) were co-transfected per well of a 12-well plate. Six hours after transfection, cells were treated with rIL17B (range from 50 to 200 ng/ml) for 16h. Cell extracts were prepared at 24h after transfection, and the luciferase activity was measured using the Dual-Glo Luciferase Assay System (Promega).

ChIP assay. Chromatin immunoprecipitation assay was performed as previously reported (Hwang-Verslues et al., 2013). Immunoprecipitations were performed with anti-NF-kB (GTX1020790; GeneTex), anti-ATF2 (E242; GeneTex), anti-AML1 (N20; Santa Cruz Biotechnology), anti–JUN (H79; Santa Cruz Biotechnology), and corresponding control immunoglobulin G antibodies and protein A/G plus-agarose (Santa Cruz Biotechnology). qPCR was performed to detect protein associated promoter regions using primers listed in Table S3.

Co-immunoprecipitation (Co-IP) assays. Whole-cell lysates were prepared using a lysis buffer containing 10 mM Tris–Cl (pH 7.5), 1% Triton X-100, 150 mM NaCl, 2 mM MgCl$_2$, protease and phosphatase inhibitors cocktail (Roche) followed by 30 min end-to-end rotation and centrifugation at 12,000 g at 4°C. For Co-IP, 500 µg of the crude whole-cell extract was incubated with 5 µg anti-IL-17RB (FGRB, homemade, polyclonal) or control IgG antibodies at 4°C overnight. Then, 50 µl prewashed protein A/G agarose (Santa Cruz Biotechnology) qPCR was performed to detect protein associated promoter regions using primers listed in Table S3.

Tumorigenicity and metastasis assays in mice. For tumorigenicity assay, NOD/SCIDγ mice were injected with 2.5 × 10$^6$ GFP-LUC-tagged CFPAC-1 cells orthotopically. IVIS kinetics imaging system (Caliper Life Sciences) was used to monitor tumor growth and metastasis. For subcutaneous implantation, 10$^6$ GFP-LUC-tagged CFPAC-1 cells were injected. Tumor volumes were evaluated every 7 d. Mice were sacrificed and lungs were examined for metastatic cancer cells. For in vivo metastasis assay, 5 × 10$^6$ GFP-LUC-tagged CFPAC-1 cells were injected intravenously. The lungs were inspected for tumor burden 70 d after injection.

Immunofluorescence microscopy for paraffin sections. 5 × 10$^6$ GFP-LUC-tagged CFPAC-1 cells were injected intravenously per mouse. Six mice for each time point were used. Mice were sacrificed and the lungs were obtained for formalin fixation and paraffin embed for immunofluorescence 8 or 24 h after injection for MQ counting or TUNEL assay, respectively. Heat-induced antigen retrieval was performed using Triony, pH 6.0, and heated at 95°C for 10 min. Slides were blocked with rat anti-mouse F4/80 monoclonal antibody (1:100, Cia-A3-11, Genetex), anti-MUC1 mouse monoclonal antibody (1:200; MA1-38211; Thermo Fisher Scientific), or rabbit anti-GFP (1:100; GTX113617) monoclonal antibody in antibody diluent (Dako) overnight at 4°C. After washing, slides were incubated with an appropriate fluorochrome-conjugated secondary antibody (1:100; Alexa Fluor 488 goat-α-rat or Alexa Fluor 647 goat-α-rabbit; Invitrogen). For TUNEL staining, DeadEnd Fluorometric TUNEL System (Promega) was used. Coverslips with stained tissues were then washed with PBS twice, stained with DAPI (1:2,000), and mounted onto glass slides with Dako fluorescent mounting medium and examined with a Leica TCS-SP5-MP-SMD confocal microscope (100× objective) fitted with appropriate fluorescence filters. To determine the numbers of cancer cells directly contacting MQ, 5–8 fields of each slide (×40 objective) and a total of two slides of each mouse were evaluated. For TUNEL assay, two slides of each mouse were used for staining, and 100 cancer cells of each slide were examined. All localization experiments were performed at least twice independently.

Statistical analysis. Except for the clinical correlation and quantification for specific immunomobuls, all data are presented as means ± SD, and Student’s t test was used to compare control and treatment groups. * and ** indicate statistical significance with P < 0.05 and < 0.01, respectively. The following analyses were performed using SPSS statistics software: an χ$^2$ (χ$^2$) test was used to examine the correlation between IL-17RB expression and the clinical parameters in 111 pancreatic cancer cases. The Kaplan–Meier estimation method was used for overall progression free survival analysis, and a log-rank test was used to compare differences. Univariate and multivariate Cox regression analyses were performed to evaluate the influence of IL-17RB expression on the clinical outcome of pancreatic cancer patients after surgery.

Online supplemental material. Table S1 shows primer sequence and restriction enzyme for cloning. Table S2 shows primer sequence for RT–qPCR. Table S3 shows primer sequence for ChIP. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20141702/DC1.

We thank Dr. L.J. Juan for her critical reading of the manuscript and Meng-Han Wang, Liu-Chen Lin, and Pei-Hsun Chiang for their kind assistance throughout this study. This work was supported by the Academia Sinica, and Ministry of Science and Technology (MOST-103-2321), Taiwan. The authors declare no competing financial interests.


Submitted: 3 September 2014
Accepted: 3 February 2015

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