Inhibition of VEGFR-2 Reverses Type 1 Diabetes in NOD Mice by Abrogating Insulitis and Restoring Islet Function

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The dysregulation of receptor tyrosine kinases (RTKs) in multiple cell types during chronic inflammation is indicative of their pathogenic role in autoimmune diseases. Among the many RTKs, vascular endothelial growth factor receptor (VEGFR) stands out for its multiple effects on immunity, vascularization, and cell migration. Herein, we examined whether VEGFR participated in the pathogenesis of type 1 diabetes (TID) in nonobese diabetic (NOD) mice. We found that RTK inhibitors (RTKIs) and VEGF or VEGFR-2 antibodies reversed diabetes when administered at the onset of hyperglycemia. Increased VEGF expression promoted islet vascular remodeling in NOD mice, and inhibition of VEGFR activity with RTKIs abrogated the increase in islet vascularity, impairing T-cell migration into the islet and improving glucose control. Metabolic studies confirmed that RTKIs worked by preserving islet function as treated mice had improved glucose tolerance without affecting insulin sensitivity. Finally, examination of human pancreata from patients with T1D revealed that VEGFR-2 was confined to the islet vascularity, which was increased in inflamed islets. Collectively, this work reveals a previously unappreciated role for VEGF-2 signaling in the pathogenesis of T1D by controlling T-cell accessibility to the pancreatic islets and highlights a novel application of VEGFR-2 antagonists for the therapeutic treatment of T1D.
our findings suggest that VEGF/VEGFR-2 signaling serves a critical gatekeeper function by controlling essential remodeling of the vasculature that is necessary for T cells to gain access to tissues.

**RESULTS**

**Inhibition of VEGFR-2 reverses T1D in NOD mice.** To delineate the specific contributions of PDGFR and VEGFR activity in the reversal of diabetes after RTKI treatment (14), we treated diabetic NOD mice at the onset of diabetes with oral doses of SU-9518 (40 mg/kg) and PF-337210 (10 mg/kg), RTKIs with varying affinity for VEGFRs (Supplementary Table 1). SU-9518, a strong PDGFR inhibitor with weak affinity for VEGFR-2, was ineffective at reversing hyperglycemia (Fig. 1A), suggesting a lack of efficacy in compounds that ineffectively block VEGFR activity. However, daily dosing of diabetic mice with the potent VEGFR inhibitor PF-337210 (5 mg/kg) reversed diabetes and reduced blood glucose levels in all mice by the first week of treatment (Fig. 1A and B). Despite 10 weeks of continuous dosing, all mice became diabetic within 3–5 weeks after drug administration was discontinued (Fig. 1C). All RTKI-mediated reversal of diabetes was dependent on viable islet mass, as we found no drug efficacy when treating mice that had no or very few remaining islets by dosing with STZ or using long-standing diabetic mice (Supplementary Fig. 1A and B).

We tested whether an anti–VEGF–2 Blocking antibody, DC101, could also reverse diabetes (27–29). DC101 efficiently reversed diabetes in all mice treated for 3 weeks (Fig. 1D and E). Moreover, indirect blockade of VEGFR-2 activity through the use of a neutralizing anti–VEGF-A antibody (clone r84) (30) reversed diabetes in 70% of mice (Supplementary Fig. 1C). However, treatment of diabetic NOD mice with blocking antibodies against PDGFRβ-specific ligands (PDGF-BB and PDGF-DD) or PDGFRβ did not reverse diabetes (Fig. 1F). Although these data contrast those made previously that soluble PDGFRβ receptor can reverse disease (14), this antagonist can also block elements of the VEGF pathway (31). Taken together, these data suggest that VEGFR-2 is a central target in the RTKI-mediated reversal of diabetes and reveals a previously unappreciated role for VEGFR-2 signaling in the pathogenesis of T1D.

VEGFR-2 expression in islets is confined to the vasculature of new-onset, diabetic NOD mice. We next examined which cell types in the pancreas expressed VEGFR-2 to identify the key cellular target of RTKIs. Using immunofluorescence staining for CD45, a pan leukocyte marker, and VEGFR-2, we found that leukocytes did not express VEGFR-2 (Supplementary Fig. 2A). Flow cytometric analysis of CD11b+, CD8+, and naive or activated CD31+ vessels distributed within the islets of new-onset diabetic NOD mice confirmed our histological findings (Supplementary Fig. 2B). We also found that insulin-producing β-cells or CK19+ duct cells do not express VEGFR-2 (Supplementary Fig. 3). However, examination of the islet vasculature using immunofluorescence for CD31 (Fig. 2A and Supplementary Fig. 3E and F) and VEGFR-2 (Fig. 2B and Supplementary Fig. 3C and D) showed that CD31+ vessels distributed within the islets express significant levels of VEGFR-2 (overlay, Fig. 2C and Supplementary Fig. 3G and H). Quantitative PCR revealed that VEGFR-2 levels were not differentially regulated across the conditions we tested (Fig. 2D). Together, these results suggested that RTKI-mediated reversal of diabetes was not likely due to a direct effect on leukocytes or insulin-producing β-cells but rather through a direct action on endothelial cells.

Next, we tested the hypothesis that receptor activity may be controlled by regulated expression of VEGF-A in the islets of new-onset diabetic NOD mice by immunohistochemistry and found increased VEGF-A expression in the islets (Fig. 2E). Similarly, we found increased VEGF-A staining in islets of prediabetic mice (Fig. 2F), whereas a low immune reactivity for VEGF-A was detected in β-cells of islets from NOD-RagKO mice that are devoid of inflammation (Fig. 2G). Western analysis of whole-islet

**RESEARCH DESIGN AND METHODS**

**Animals.** Female NOD mice were purchased from Taconic. NOD.GREAT mice were derived in our laboratory (21). All mice were housed in a pathogen-free facility at the University of California San Francisco. All animal experiments were approved by the Institutional Animal Care and Use Committee of the University of California San Francisco.

**Compounds and treatments.** Survante (22), SU-9518 (23), and PF-337210 (24), provided by Pfizer, were resuspended in methylcellulose (MC) at 10 mg/mL. Inhibitory profiles and structure data are provided in Supplementary Tables 1 and 2. Female, new-onset diabetic NOD mice were treated with RTKI or MC only immediately on the day blood glucose levels were >250 but not greater than 400 mg/dL. In some experiments, treatment was initiated 3 weeks after the onset of hyperglycemia (long-term diabetic mice). Diabetes reversal is defined as mice whose blood glucose levels declined to <250 mg/dL. New-onset diabetic NOD mice were treated intraperitoneally three times per week for 3 weeks with 800 μg of DC101 (anti–VEGF–2 antibody; BioXcell). Diabetic NOD mice were also treated with weekly intraperitoneal injection of 1 mg anti-PDGFR-BB, anti–PDGFR-DD mAb (provided by P

**Histological staining of pancreatic tissue.** Mouse pancreas were analyzed using standard immunofluorescence staining procedures. The following antibodies were used: guinea pig anti-insulin (Biodata), guinea pig anti-glucagon (Biodata), mouse anti-human CD31 and CD45 (Biolegend), and rat anti-mouse CD31 and CD45 (Southern Biotech). Sections were subsequently washed and incubated with the species-appropriate, Alexa-conjugated secondary antibodies (Invitrogen). Sections were stained with DAPI for 5 min to stain nuclei and mounted with FluorSave reagent (Calbiochem).

**Flow cytometry analysis.** Single-cell suspensions were prepared from the lymph nodes and murine islets using standard procedures, followed by Fc receptor blocking with anti–CD16/32 (clone 2.4G2) prior to staining. Single-cell suspensions were stained with antibodies against the following cell surface antigens: CD4 and Thy1.2 or Thy1.1 (Biolegend); CD62L, CD8, CD11c, CD11b, CD25, CD44, and CD69 (BD Biosciences); and DAPI (Inviogen Life Technologies) to assess cell viability. Analysis was performed on live cells (DAPI−) on a BD LSRII flow cytometer with FACS Diva software (BD Pharmingen). Postacquisition analysis was performed with Flowjo software version 9.1.

**Metabolic studies.** Intraperitoneal insulin (IPITT) and glucose tolerance test (IGITT) were performed on prediabetic NOD mice as described previously (35). In brief, NOD mice were treated with MC or PF-337210 (5–10 mg/kg) by gavage for 3 weeks, and IPITT or IGITT were performed weekly. For IPITT, mice were intraperitoneally injected with sterile 30% glucose solution (Sigma-Aldrich) at 1.5 g/kg after a 10-h fast. For IGITT, mice were intraperitoneally injected with sterile 30% glucose solution (Sigma-Aldrich) at 1.5 g/kg after a 17-h fast. Blood glucose levels were sampled at the indicated time points after insulin or glucose administration. Insulin was measured by insulin ELISA (Exocell). Statistical and graphical analyses were performed using GraphPad Prism version 5.01 or Microsoft Office Excel 2007. Statistical comparisons between two groups were performed using an unpaired two-tailed Student t test or a nonparametric Mann-Whitney test. Comparisons between multiple groups were performed by one-way or two-way ANOVA, followed by a post hoc Bonferroni test to determine significance of differences between two groups. Values of P ≤ 0.05 were considered significant.
homogenates substantiated these histological observations (Fig. 2H), suggesting that increased expression of VEGF-A is linked to inflammation rather than a secondary response to hyperglycemia.

We performed coimmunofluorescence for VEGF-A, immune cell markers, and insulin to determine the identity of the VEGF-A–expressing cells in the inflamed pancreas. We found that insulin+ β-cells expressed detectable levels of VEGF-A (Fig. 2I–K, red arrows) as well as multiple immune cell subsets, including CD4+ (Fig. 2Iii, white arrows), CD8+ (Fig. 2Jii, white arrows), and CD11c+ (Fig. 2Kii, white arrows) cells. Collectively, these results indicated that VEGFR activity in endothelial cells is regulated by a multicellular source of VEGF that is increased in inflamed islets and highlight a role for VEGF-A–expressing cell and islet endothelium interactions in the pathogenesis of T1D.

RTKIs prevent increases in islet vascular density associated with insulin. We next tested the hypothesis that the elevated expression of VEGF-A induces islet vascular remodeling, subsequently enhancing leukocyte migration and insulitis. Immunofluorescent staining of purified islets from new-onset diabetic NOD mice revealed a more extensive and branched vascular network with an increased number of dilated vessels, compared with islets isolated at an age (4 weeks) preceding invasive insulitis (Fig. 3A and B). Islets of 18-week-old NOD mice were stained with anti-CD31 and anti-Thy1.2 antibodies to visualize the islet endothelium and infiltrating T cells, respectively. Linear regression analysis revealed a positive correlation between the CD31+ and Thy1.2+ islet area, indicating that increases in islet vascular area were partly attributed to increased insulitis (Fig. 3C). Moreover, the CD31+ islet area was increased by threefold in islets isolated from 18-week-old NOD mice compared with islets isolated at 4 weeks of age (Fig. 3D). Treatment of new-onset diabetic NOD mice with PF-337210 significantly decreased islet vascular density compared with control-treated mice (Fig. 3E).

RTKI-mediated inhibition of VEGFR signaling impairs T-cell trafficking. We next examined the effects of VEGFR inhibition on T-cell migration. To minimize variability in the absolute number and frequency of T cells isolated from purified islets of prediabetic NOD mice treated with PF-337210 (data not shown), we took advantage of an islet antigen–specific T-cell transgenic model (BDC2.5 T cells congenically marked with Thy1.1+) to synchronize the migration and tracking of T cells into the islet in an in vivo migration assay (32). A 2-week pre-treatment of NOD-RagKO mice with PF-337210 resulted in a significant reduction in the proportion of islets infiltrated with Thy1.1+ T cells 48 h after transfer (Fig. 4A). The enumeration of Thy1.1+ T cells by immunofluorescence revealed that T cells in islets were reduced by twofold in...
PF-337210–treated animals compared with control-treated mice (Fig. 4B–D, red). The impaired T-cell migration was associated with a reduced vascularity in NOD-RagKO mice that received activated BDC2.5 T cells and were treated with PF-337210 (Fig. 4E).

The impairment in T-cell trafficking was not restricted to islets, as we noted reduced spleen mass, total splenocyte counts, and numbers of transferred Thy1.1+ T cells in the spleen (Supplementary Fig. 4A–C). However, the number of PBMCs or Thy1.1+ T cells in the blood was not affected by PF-337210 administration (Supplementary Fig. 4D and E), suggesting that VEGFR inhibition did not lead to T-cell toxicity or altered proliferation that could account for the reduced number of transferred BDC2.5 T cells in the tissues of PF-337210–treated mice. The expression of T-cell activation markers on transferred T cells in the blood and spleen was not affected by PF-337210 (Supplementary Fig. 5). Taken together, these data are consistent with our observations that leukocytes in NOD mice express insignificant levels of VEGFR-2 and confirm that PF-337210 does not directly affect T cells.

**VEGFR-2 inhibition reduces insulitis and preserves islet function.** We next examined whether RTKI or the anti-VEGFR antibody (DC101) led to reduced insulitis and improved islet function in NOD mice. Examination of islet infiltration after drug administration showed that the percentage of severely infiltrated islets (score = 3) in diabetic mice treated for 3 weeks with RTKI or DC101 was significantly reduced compared with vehicle-treated (MC) mice (Fig. 5A–E). Furthermore, the decrease in severely infiltrated islets was accompanied by an increased proportion of immunologically spared islets (score = 0) and islets with noninvasive insulitis (score = 1). Similar to the transfer setting, inhibition of VEGFR-2 with PF-337210 had no effect on islet function.

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**FIG. 2.** Insulitis promotes overexpression of VEGF-A. Immunofluorescence staining of CD31 (A, red), VEGFR-2 (B, green), and overlay (C). 

**D:** Quantification of VEGFR-2 transcripts from islet RNA at different stages of diabetes progression (n = 5 per group). GAPDH, glyceraldehyde-3-phosphate dehydrogenase; NO-Db, new-onset diabetic; Pre-Db, prediabetic; RagKO, NOD RAG-deficient mice. Immunohistochemistry for VEGF-A performed on pancreatic sections from new-onset (E), prediabetic NOD (F), or NOD-RagKO female mice (G). 

**H:** Western analysis of whole-islet homogenates for VEGF-A from two mice per group. 

**I–K:** Representative coimmunofluorescence staining of pancreata from diabetic NOD mice for insulin (white), VEGF-A (green), CD4 (I, red), CD8 (J, red), CD11c (K, red), and DAPI (blue). White arrows highlight examples of CD4+, CD8+, and CD11c+ cells that express VEGF-A. Red arrows indicate β-cells that express VEGF-A. Images i and ii for I–K are the same section with different signals depicted to highlight the islet area (white, II–KII) and the VEGF-A+ cells (green, II–KII).
on the expression of activation markers or interferon-γ (IFN-γ) by T cells in the islets (Fig. 5F). The reduced insulin improved islet function based on an IPGTT assay in prediabetic mice, after a 3-week PF-337210 treatment. The RTKI treatment improved glucose tolerance, suggesting preservation of islet function and improved insulin sensitivity in peripheral tissues. Instead, the data support our hypothesis that the RTKI-mediated reversal of diabetes in NOD mice is not attributed to differences in food consumption (Supplementary Fig. 6C) or weight loss (Supplementary Fig. 6D). These findings suggest that the enhanced glucose tolerance observed in PF-337210–treated mice is not attributed to improved insulin sensitivity in peripheral tissues. Instead, the data support our hypothesis that the RTKI-mediated improvement in glucose tolerance is due to impaired T-cell trafficking, which reduces insulitis and leads to improved islet function and glucose control.

**An increase in islet vascularity in TID patients is associated with increased insulitis.** To gain insight into the potential translation of our preclinical findings, we examined the vasculature features of islets from T1D patients and controls. The islet boundary was first approximated by insulin and DAPI staining (Fig. 6A, B, E, and F; white line). Concurrent staining of tissues with anti-CD31 and anti-CD45 antibodies to allow visualization of blood vessels and leukocytes, respectively, revealed that all CD31+ vessels in the islets of both T1D patients and controls were VEGFR-2+ (Fig. 6C and D). VEGFR-2 expression was not detected in CD45+ leukocytes in either normal or T1D patients, similar to what was observed in the mouse studies (Fig. 6G and H). In addition, we did not detect expression of VEGFR-2 in β-cells, unlike previous studies showing VEGFR expression in human islets (34). The images in Fig. 6I and J (which are from the same section shown in C and D, respectively) reveal that VEGFR-2+ cells (white arrows) are not β-cells. Instead these are the CD31+ cells in Fig. 6C and D (white arrows). Notably, the quantification of the CD45+ (insulitis, Fig. 6K) and VEGFR-2+ (vascularity, Fig. 6L) islet areas revealed that both are increased in T1D patients relative to controls. Collectively, our results suggest that inflammation and islet vascular remodeling are linked processes that are associated with the pathogenesis of T1D in humans.

**DISCUSSION**

Herein, we demonstrate that VEGFR-2 is a central target in the RTKI-mediated reversal of diabetes in NOD mice. The pathogenesis of TID requires infiltration of immune cells into the pancreatic islets, and this is dependent upon VEGF-mediated activation of VEGFR-2 within the islet endothelium. Inhibition of VEGFR-2 signaling impairs T-cell migration and reduces insulitis, restoring islet function and glucose control. Histological studies of human pancreata indicate that a similar pathogenic process occurs in T1D patients and suggests that activation of the VEGF/VEGFR-2 signaling axis is a key molecular event linking vascular remodeling and insulitis, processes that contribute to loss of glucose control and onset of hyperglycemia.
RTK RESTORES ISLET FUNCTION BY REDUCING INSULITIS

VEGF-A is a master regulator of angiogenesis and vascular permeability and contributes to the establishment of chronic inflammation in various pathological settings (35–37). We show that VEGF-A abrogates increases in islet vascular density and subsequently impede the development of insulitis. Similar observations have been reported in streptozotocin-induced diabetes (38) and other inflammatory settings in which inhibition of VEGF-2 signaling impairs vascular remodeling and reduces inflammation (19,28,39,40). In addition to promoting increased vascularity, VEGF-A contributes to inflammation and leukocyte recruitment by inducing the expression of adhesion molecules and chemokines by endothelial cells (19,41–43). Our findings support the conclusion that reduced insulitis is due to decreased islet vascularity. However, there is also the possibility that VEGF-2 antagonists repress the expression of molecules that promote leukocyte trafficking/homing to the islet vasculature. Future studies will require the characterization of potential molecular changes in activated islet endothelial cells to fully understand the role of islet vascular remodeling in the pathogenesis of T1D.

Our results suggest that there may be distinct molecular and functional properties of islet endothelial cells in a pathogenic state versus those in homeostasis, rendering them more sensitive to RTKI treatment. We found that the islet vascularity showed obvious morphological changes indicative of pathological angiogenesis, which is induced by elevated expression of VEGF-A (36). Although Akirav et al. (44) previously reported that VEGF-A is increased in the inflamed islets of prediabetic NOD mice, they found that islet vascularity decreases with the progression of diabetes. The discrepancies between these studies may reflect a difference in the assays used to measure islet vascularity.

A pathogenic role for VEGF-A is supported by the observation that the overexpression of VEGF-A in β-cells led to increased islet vascularity, inflammation, and disruption in islet architecture, resulting in impaired glucose homeostasis and insulin secretion during a high-fat diet (45). However, a complete loss of VEGF signaling in islets is also detrimental. For instance, β-cell–specific ablation of VEGF-A resulted in reduced islet vascularity and endothelial cell fenestration, culminating in impaired insulin secretion and glucose intolerance. However, in the setting of autoimmune diabetes, this potential impairment in function is outweighed by the protection offered by preventing diabetogenic leukocytes from entering the islet and destroying β-cells. Collectively, our data and the altered islet function after perturbations in β-cell–specific VEGF-A expression indicate that VEGF-A functions in a narrow physiological range to maintain islet homeostasis and function.

We propose a model in which reversal of diabetes is delineated in three distinct stages, including 1) acute reversal, 2) maintenance of euglycemia, and 3) long-term remission of diabetes in the absence of continued drug dosing. The acute reversal and maintenance of euglycemia of diabetes is dependent on the inhibition of VEGFR-2. However, the lack of complete diabetes reversal in mice treated with anti–VEGF-A antibody indicates that other VEGFRs may also mediate the islet vascular remodeling. In this regard, inhibition of VEGFR-3 was shown to reduce insulitis in NOD mice (38). Alternatively, it is very likely that small molecule antagonists, such as the RTKIs used in this study, are able to penetrate the target tissue more effectively than mAbs such as r84. We cannot exclude the effect of RTKIs on other physiological systems that control glucose metabolism (e.g., liver or adipose tissue). For instance, RTKI treatment also enhances insulin-independent glucose metabolism in peripheral tissues. In this regard, recent studies have shown that JAK-STAT inhibitors increased peroxisome proliferator–activated receptor-γ (PPAR-γ), a critical regulator of fatty acid storage and glucose metabolism, expression in adipocytes and immune cells (46).

The discrepancy between the lack of reversal of diabetes with the PDGFR antagonists used in this study and the previously reported reversal using a soluble PDGFRβ-Ig fusion protein (14) may be explained by functional differences between the reagents used to inhibit PDGFR. Kielty and colleagues (31) recently demonstrated that PDGFR is able to functionally bind VEGF ligand, leading to PDGFR activation. Therefore, it is possible that the acute reversal of diabetes after soluble PDGFRβ-Ig may be attributed to the binding and neutralization of VEGF ligands in addition to PDGFR ligands. The studies using Gleevec suggest that c-Abl also participates in reversal of hyperglycemia and long-term remission, but through a distinct mechanism that likely involves the inhibition of proapoptotic pathways in β-cells (15,47) and altered T-cell immunity (48), leading to islet mass preservation. Similarly, the current study suggests that RTKIs function by preserving islet mass. Although we cannot rule out the possibility of β-cell
regeneration, previous studies have shown that the most likely effect of drugs on the islets is to reverse the metabolic stress caused by the immune response, leading to recovery of the insulin production by the remaining β-cells (49,50).

In summary, our findings that VEGFR-specific RTKIs and blocking anti–VEGFR-2 antibodies reverse diabetes by preserving islet function suggest that therapeutic modalities aimed at preventing islet vasculature activation may provide an alternative treatment strategy for T1D.
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S.A.V. designed and performed research, analyzed data, and wrote the manuscript. J.L., S.K., B.K., G.L.S., and C.W. performed research. B.C. assisted in designing the in vivo migration assay used in this study. M.A.A. designed research. R.A.B. and N.P. contributed data as well as new reagents/analytic tools. R.H.A. designed research and contributed data as well as new reagents/analytic tools. J.A.B. designed research, analyzed data, and wrote the manuscript. J.A.B. is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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