Distinct Actions of Endothelin A-Selective Versus Combined Endothelin A/B Receptor Antagonists in Early Diabetic Kidney Disease

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ABSTRACT

Selective endothelin A (ET<sub>A</sub>) and combined ET<sub>A</sub> and ET<sub>B</sub> receptor antagonists are being investigated for use in treating diabetic nephropathy. However, the receptor-specific mechanisms responsible for producing the potential benefits have not been discerned. Thus, we determined the actions of ET<sub>A</sub> and ET<sub>B</sub> receptors on measures of glomerular function and renal inflammation in the early stages of diabetic renal injury in rats through the use of selective and combined antagonists. Six weeks after streptozotocin (STZ)-induced hyperglycemia, rats were given 2R-(4-methoxyphenyl)-4S-(1,3-benzodioxol-5-yl)-1-[(N,N-di(n-butyl)aminocarbonyl)-methyl]-pyrrolidine-3-carboxylic acid (ABT-627) (5 mg/kg/day), a selective ET<sub>B</sub> antagonist; [2R,3R,4S]-4-(benzo[d][1,3]dioxol-5-yl)-2-(3-fluoro-4-methoxyphenyl)-1-[2-(N-propyl)pentylsulfonamido)ethyl]pyrrolidine-3-carboxylic acid hydrochloride (A-182086) (10 mg/kg/day), a combined ET<sub>A/B</sub> antagonist; or vehicle for 1 week. Sham controls received STZ vehicle (saline). Hyperglycemia led to significant proteinuria, increased glomerular permeability to albumin (P<sub>abl</sub>), nephrinuria, and an increase in total matrix metalloproteinase (MMP) and transforming growth factor-β1 (TGF-β1) activities in glomeruli. Plasma and glomerular soluble intercellular adhesion molecule-1 (sICAM-1) and monocyte chemoattractant protein-1 (MCP-1) were elevated after 7 weeks of hyperglycemia. Daily administration of both ABT-627 and A-182086 for 1 week significantly attenuated proteinuria, the increase in P<sub>abl</sub>, nephrinuria, and total MMP and TGF-β1 activity. However, glomerular sICAM-1 and MCP-1 expression was attenuated with ABT-627, but not A-182086, treatment. In summary, both selective ET<sub>A</sub> and combined ET<sub>A/B</sub> antagonists reduced proteinuria and glomerular permeability and restored glomerular filtration barrier component integrity, but only ET<sub>A</sub>-selective blockade had anti-inflammatory and antifibrotic effects. We conclude that selective ET<sub>A</sub> antagonists are more likely to be preferred for the treatment of diabetic kidney disease.

Introduction

Diabetic nephropathy is the most common cause of end-stage renal disease in patients with diabetes mellitus. An early marker for diabetic nephropathy is the occurrence of microalbuminuria (Rosenstock and Raskin, 1986). Defects in the glomerular filtration barrier including the podocytes result in both functional and histopathological changes observed in the glomerulus of diabetic kidneys. Podocytes attach to the glomerular basement membrane (GBM) through adhesion proteins, mainly α<sub>3</sub>β<sub>1</sub> integrins and the dystroglycan complex. The filtration slit between adjacent podocytes includes a number of cell-surface proteins including nephrin, podocalyxin, and P-cadherin, which ensure retaining of large macromolecules, such as serum albumin. In diabetic nephropathy, the etiology of podocyte injury and subsequent proteinuria is via two primary mechanisms: podocyte apoptosis and/or reduced podocyte adhesion to the GBM (Shankland, 2006). Detached cells are shed in the urine as live podocytes (Pettermann et al., 2005). Loss of cell anchorage to the GBM may result from down-regulation of the α<sub>3</sub>β<sub>1</sub> integrins.

ABBREVIATIONS: GBM, glomerular basement membrane; ET, endothelin; HG, hyperglycemic; MCP-1, monocyte chemoattractant protein-1; MMP, matrix metalloproteinase; NO, nitric oxide; P<sub>abl</sub>, permeability to albumin; ICAM-1, intercellular adhesion molecule-1; sICAM-1, soluble ICAM-1; STZ, streptozotocin; TGF-β, transforming growth factor β; ZO-1, zonula occludens-1; S, sham; PBS, phosphate-buffered saline; PMSF, phenylmethylsulfonyl fluoride; RT-PCR, real-time polymerase chain reaction; GAPDH, glyceraldehyde-3-phosphate dehydrogenase; ABT-627, 2R-(4-methoxyphenyl)-4S-(1,3-benzodioxol-5-yl)-1-[(N,N-di(n-butyl)aminocarbonyl)-methyl]-pyrrolidine-3R-carboxylic acid, LU 135252, (2S)-(2-(4,6-dimethoxypyrimidin-2-yl)oxy-3-methoxy-3,3-di-(phenyl)propanoic acid; A-182086, (2R,3R,4S)-4-(benzo[d][1,3]dioxol-5-yl)-2-(3-fluoro-4-methoxyphenyl)-1-[2-(N-propyl)pentylsulfonamido)ethyl]pyrrolidine-3-carboxylic acid hydrochloride.
The endothelin (ET) system plays an important role in the development of diabetic nephropathy. ET\textsubscript{A} receptors account for the majority of the vasoconstrictor and proliferative effects of ET-1 (Benigni and Remuzzi, 1995) as well as the promotion of mononuclear cell infiltration (Suzuki et al., 2001) and production of matrix proteins (Gómez-Garré et al., 1996). In contrast, ET\textsubscript{B} receptors mediate endothelial-dependent nitric oxide (NO) release (Tack et al., 1997), contribute to ET-1 clearance from plasma (Fukuroda et al., 1994), and regulate renal sodium (Na\textsuperscript{+}) and water excretion in the collecting duct and other tubular segments (Kohan et al., 1992). Our laboratory recently reported that glomerular and plasma serum levels of interstitial adhesion molecule 1 (ICAM-1) and monocyte chemoattractant protein 1 (MCP-1) were increased after 6 weeks of STZ-induced diabetes (Saleh et al., 2011) with subsequent increase in macrophage infiltration into renal cortices after 10 weeks (Sasser et al., 2007). These effects were shown to be ET\textsubscript{A} receptor-dependent. Several studies have noted that ET\textsubscript{A}-selective or combined ET\textsubscript{A/B} antagonists prevent the development of diabetic nephropathy (Hocher et al., 2001). However, given the contrasting actions of these receptor subtypes in the vasculature and kidney, it remains obscure as to whether blockade of the ET\textsubscript{B} receptor in conjunction with ET\textsubscript{A} antagonism would be harmful, beneficial, or neutral for the treatment of patients with diabetic nephropathy.

Previous animal studies have examined treatment with antagonists at the time of STZ administration, thus we wanted to elucidate the effects of ET antagonist treatment after establishing diabetic nephropathy. This study addressed two basic questions. First, does administration of an ET\textsubscript{A} or combined ET\textsubscript{A/B} antagonist reverse proteinuria and the glomerular permeability defect in STZ-induced hyperglycemic (HG) rats? And second, do ET\textsubscript{A}-selective antagonists have an advantage over combined ET\textsubscript{A/B} antagonists with regard to attenuating glomerular injury and inflammatory mediators?

Materials and Methods

STZ-Induced Hyperglycemia. Experiments used male Sprague-Dawley rats (250–275 g) from Harlan (Indianapolis, IN). All protocols were approved by the Institutional Animal Care and Use Committee of the Medical College of Georgia and followed the American Physiological Society Guidelines for the Care and Use of Laboratory Animals. Rats were housed under conditions of constant temperature and humidity and exposed to a 12:12-h light/dark cycle. Hyperglycemia was induced by injection of STZ (65 mg/kg; Sigma-Aldrich, St. Louis, MO), dissolved in sterile saline in the penile vein (n = 30). Onset of diabetes was confirmed by the presence of glycosuria 48 h after injection. To check the hyperglycemic state of the rats, the glucose concentrations in tail blood samples were measured with an Accu-Chek glucometer (Roche Diagnostics, Indianapolis, IN). All rats with blood glucose levels 400 mg/dl or higher were considered hyperglycemic. A group of control rats (sham) were injected with the sterile saline (n = 18) and kept under identical housing conditions with free access to water and food ad libitum. After induction of hyperglycemia, both groups of rats were kept under observation for 6 weeks before the start of 1-week treatment with endothelin antagonists. During this period, body weight, nonfasting blood glucose, and severity of diabetic-related symptoms were monitored once a week. To prevent hyperglycemic rats from dying during the observation period, those animals were treated with a low level of insulin by using time-release implants (Linplant, Scarborough, ON, Canada), whereas sham rats received the implant excipient, palmitic acid. The implants were sterilized in 2% poviodone-iodine solution and inserted by a 16-gauge hypodermic needle under the dorsal skin of the neck. Every implant gradually released the insulin at a dose of approximately 1 unit per day.

Experimental Protocol. Six weeks after induction of hyperglycemia, rats were randomly allocated to the following six experimental groups: 1) untreated nonhyperglycemic sham rats (S; n = 6), 2) sham rats treated with ET\textsubscript{A} antagonist, 2R-(4-methoxyphenyl)-4S-(1,3-benzodioxol-5-yl)-1-(N-N-dimethylaminocarbonyl-methyl)-pyrrolidine-3F-carboxylic acid (ABT-627) (atrasentan); 5 mg/kg/day (S + ABT-627; n = 6), 3) sham rats treated with mixed ET\textsubscript{A/B} receptor antagonist, A-182066; 10 mg/kg/day (S + A-182066; n = 6), 4) untreated HG rats (n = 10), 5) hyperglycemic rats treated with ABT-627; 5 mg/kg/day (HG + ABT-627; n = 10), and 6) hyperglycemic rats treated with A-182066, 10 mg/kg/d (HG + A-182066; n = 10). ABT-627 and A-182066 were kindly provided by Abbott Laboratories (Abbott Park, IL). Both drugs have been shown to produce near maximum inhibition of the pressor response to ET-1 or the precursor ET-1 (Wessale et al., 2002; Wu-Wong et al., 2002). Oral administration of A-182066 at 10 mg/kg completely abolished the vasodilator response to sarafotoxin 6c and significantly inhibited the pressor response as well (Wessale et al., 2002). ABT-627 and A-182066 had very high binding affinity (K\textsubscript{d}) in Chinese hamster ovary cell preparations expressing ET\textsubscript{A} receptors at 0.034 and 0.20 nM, respectively, whereas the K\textsubscript{d} values for ET\textsubscript{B} binding were 63.3 and 1.23 nM, respectively (Wu-Wong et al., 2002). The drugs were administered in the drinking fluid at concentrations calculated to deliver the above-mentioned doses. Because of poor water solubility of the antagonists, dilute solutions of sodium hydroxide were used to prepare a concentrated stock solution (1 g/l of 0.1 M NaOH) before being diluted into the drinking water. Daily food and water consumption were monitored, and the concentrations of drugs in the drinking water were adjusted to maintain appropriate dosing. All rats were kept in metabolic cages during the 1-week treatment for urine collection and proteinuria analysis. On the seventh day after treatment had been started, rats were anesthetized with sodium pentobarbital (50 mg/kg). Plasma samples were collected from arterial blood drawn from the abdominal aorta. The kidneys were removed for further evaluation.

Isolation of Glomeruli. Kidneys were decapsulated and placed in phosphate-buffered saline (PBS; pH 7.4, 4°C) containing phenylmethylsulfonyl fluoride (PMSF, 1 mM). Glomeruli were isolated as described previously (Saleh et al., 2010, 2011). In brief, cortical tissue was minced and then passed through a 180-μm stainless-steel sieve to separate glomeruli from tubular fragments and vasculature. The material was again filtered through a 200-μm microlute filter. The filtrate was passed through a smaller pore size microlute filter (70 μm) with glomeruli being retained on the top. Glomeruli were then washed with ice-cold PBS/PMSF, and decapsulated glomeruli were resuspended in ice-cold PBS buffer. Tubular contamination was always confirmed at less than 5% of total tissue under light microscopy. The glomeruli were washed two more times and resuspended in PBS before the final pellet was snap-frozen in liquid nitrogen and stored at −80°C.

For immunoassays and Western blotting, the glomeruli were resuspended in lysis buffer (20 mM HEPES, pH 7.4, 10 mM NaCl, 5 mM EDTA, 0.2% Triton X-100, 10 mM sodium fluoride, 1 mM sodium ortho-vanadate, 1 mM PMSF, 1 μg/ml leupeptin, and 1 μg/ml pepstatin) and homogenized by using an ultrasonic homogenizer (20 s). This suspension was centrifuged at 10,000g for 10 min, and the supernatant was used for immunoassays and Western blotting as well as protein determination by the Bradford method (Bio-Rad Laboratories, Hercules, CA).

For analysis of mRNA expression, quantitative real-time polymerase chain reaction (RT-PCR) was conducted using frozen glomeruli that were first processed for RNA extraction using a QIAGEN
RNasey RNA isolation kit and QIAshredder homogenizer columns (QIAGEN, Valencia, CA).

**Measurements and Calculation of Glomerular Permeability.** $P_{\text{abl}}$ was determined in isolated glomeruli without freezing. Glomeruli were resuspended at room temperature in 5% bovine serum albumin containing 115 mM NaCl, 5 mM KCl, 10 mM sodium acetate, 1.2 mM dibasic sodium phosphate, 25 mM sodium bicarbonate, 1.2 mM magnesium sulfate, 1 mM calcium chloride, and 3.5 mM glucose, pH 7.4.

The theory and detailed method for determining albumin permeability has been described previously (Saleh et al., 2010, 2011). In brief, images of individual glomeruli (usually 5–10 glomeruli per rat) were taken through an inverted microscope equipped with a digital camera before and after changing the standard media (described above) to one containing 1% bovine serum albumin. The change in volume ($\Delta V$) was used to calculate the albumin reflection coefficient ($P_{\text{abl}}$) using the following equation: $P_{\text{abl}} = \frac{\Delta V}{V_{\text{final}} - V_{\text{initial}}}$, which was analyzed off-line (Digimizer; MedCalc Software, Mariakerke, Belgium). The program calculated the average glomerular radius to then calculate glomerular volume ($V = 4/3 \pi r^3$). The change in volume ($\Delta V$) was used to calculate the albumin reflection coefficient ($P_{\text{abl}}$) by the following equation: $(\Delta V)_{\text{experimental}} = (\Delta V)_{\text{control}}$.

The $P_{\text{abl}}$ of the control glomeruli was set at 1.0. $P_{\text{abl}}$ is defined as ($1 - P_{\text{abl}}$) and is an index of albumin movement across the filtration barrier relative to water. A $P_{\text{abl}}$ of zero indicates albumin movement at the same velocity as water such that $P_{\text{abl}}$ is 1.0. When $P_{\text{abl}}$ is 1.0, albumin cannot cross the filtration barrier down its concentration gradient, so $P_{\text{abl}}$ is zero.

**Biochemical Analyses.** Commercially available kits for sICAM-1 (Quantikine, R&D Systems, Minneapolis, MN) and MCP-1 (RayBioTech, Inc., Norcross, GA) were used for determining (Quantikine, sICAM-1 Immunoassay; R&D Systems, Minneapolis, MN) at the same velocity as water such that $P_{\text{abl}}$ is used to calculate the albumin reflection gradient, so $P_{\text{abl}}$ is zero.

**Data are means ± S.E.M. ($n$ = 6 in sham and sham-treated groups and $n$ = 10 in HG and HG-treated groups).** Urine flow data were derived from 24-h urine collections in metabolic cages.

**Results**

**Metabolic Characteristics.** As depicted in Table 1, after 6 weeks of hyperglycemia (referred to as pretreatment), rats had significant lower body weights and elevated nonfasting glucose levels, food consumption, water intake, and urine flow compared with sham groups. One-week treatment with either ABT-627 or A-182086 did not change any of these characteristics.

**Proteinuria.** To investigate the pathophysiological relevance of endothelin in incipient diabetic nephropathy, we examined the effects of relatively short-term (1 week)
treatment with ET antagonists on urinary protein excretion in rats with established hyperglycemia. As illustrated in Fig. 1A, after 6 weeks of hyperglycemia, rats had very high protein excretion rates (≈530 mg/day) compared with sham groups (≈15 mg/day). Figure 1A depicts protein excretion over the course of the 1-week treatment period (weeks 6–7) in untreated/treated sham and hyperglycemic groups. ET antagonists had no effect on proteinuria in sham groups. After only 1 day of treatment, ABT-627 produced a significant decrease in proteinuria compared with the corresponding values in untreated hyperglycemic rats (426 ± 13 versus 512 ± 15 mg/day). In contrast, A-182086 had no effect on proteinuria at day 1 (521 ± 15 mg/day). During the 1-week treatment, ABT-627 did not produce any additional decrease in proteinuria compared with day 1. However, A-182086 produced a gradual decrease in protein excretion level in hyperglycemic rats. On day 7, both ABT-627- and A-182086-treated hyperglycemic groups had similar decreases in proteinuria compared with the hyperglycemic untreated group (HG + ABT-627, 384 ± 12; HG + A-182086, 416 ± 20 versus HG, 546 ± 22 mg/day).

\( P_{alb} \) Ex Vivo and In Vitro. \( P_{alb} \) was increased to 0.83 after 7 weeks of hyperglycemia (Fig. 1B). One-week treatment with both ABT-627 and A-182086 markedly reduced \( P_{alb} \) in hyperglycemic rats. Neither antagonist had any effect on \( P_{alb} \) in sham-treated rats. \( P_{alb} \) was closely correlated to proteinuria \((r = 0.9959, p < 0.0001)\).

**Podocyte Markers.** Nephrin, ZO-1, and podocin gene expression in isolated glomeruli was significantly decreased at 7 weeks in hyperglycemic rats compared with sham as quantified by RT-PCR. Treatment of hyperglycemic rats with ABT-627 significantly increased the expression of all of these podocyte-marker genes. We were surprised to find that ABT-627 also increased the gene expression of nephrin in sham rats. A-182086 significantly increased ZO-1 gene in the HG + A-182086 group without any effect on the other two podocyte-marker genes (Fig. 2A). Figure 2B illustrates the 24-h nephrin excretion rate at the 7-week time point, which was significantly increased in hyperglycemic rats compared with shams (61.7 ± 9.7 versus 11.6 ± 6.0 ng/day; \( p < 0.05 \)). Rats treated for 1 week with either ABT-627 or A-182086 restored urinary nephrin levels to sham levels (19.8 ± 5.0 and 18.6 ± 5.6 ng/day, respectively).

**\( \alpha_3 \beta_1 \) Integrin Expression.** Under baseline conditions, a single band (132 kDa) was detected for both \( \alpha_3 \) and \( \beta_1 \) integrins (Fig. 3). Both \( \alpha_3 \) and \( \beta_1 \) integrins expression was significantly
down-regulated as a result of hyperglycemia ($p < 0.05$). Treatment with ABT-627 or A-182086 resulted in a significant increase in the $\alpha_3$ integrin compared with hyperglycemic controls.

However, neither ET antagonist affected the glomerular expression of $\beta_1$ integrin.

**MMP Activity and Active TGF-$\beta_1$ Content.** Hyperglycemic rats displayed 122 and 207% increases in total glomerular MMPs (Fig. 4A) and active TGF-$\beta_1$ (Fig. 4B) content compared with sham rats. Both ABT-627 and A-182086 significantly reduced total MMP activity and restored them to sham levels. ABT-627, but not A-182086, prevented the increase in active TGF-$\beta_1$ content; however, the levels of active TGF-$\beta_1$ remained significantly higher in HG + A-182086 compared with levels from both sham and HG + ABT-627 rats.

**Glomerular and Systemic Inflammation.** ICAM-1 and MCP-1 are an important adhesion molecule and inflammatory chemokine, respectively, that have been documented to participate in the onset and development of diabetic nephropathy (Wu et al., 2006). Glomerular content (Fig. 5A) and plasma concentrations (Fig. 5B) of ICAM-1 and MCP-1 were increased significantly after 7 weeks of established hyperglycemia. Treatment of hyperglycemic rats for 1 week with ABT-627 completely abolished the increase in glomerular sICAM-1 and MCP-1 and plasma sICAM-1 concentration. A-182086 had no effect on the elevated levels of glomerular sICAM-1 and MCP-1 and plasma sICAM-1 concentration in hyperglycemic rats. Neither antagonist produced any change in plasma MCP-1 concentrations.

**Glomerular Expression of ET Pathway Genes.** Seven weeks of hyperglycemia did not evoke any change in glomerular prepro-ET-1, ETA, or ETB mRNA levels compared with their corresponding shams. However, 1-week treatment with ETA or ET$_{A/B}$ antagonist produced a significant reduction in glomerular expression of all ET pathway genes in hyperglycemic rats. In sham groups, treatment with A-182086, but not ABT-627, resulted in a significant decrease in prepro-ET-1 and ET$_A$ gene expression with no effect on ET$_B$ expression (Fig. 6).

**Discussion**

This study provides further evidence that the endothelin pathway initiates a functional glomerular defect and injury in a type 1 diabetes animal model. An important new finding is that ET$_A$-selective or mixed ET$_{A/B}$ antagonists can produce rapid reversal of established hyperglycemia-induced changes in the glomerular filtration barrier. Our experimental protocol was designed to provide clinical relevance by determining whether proteinuria and increased...
glomerular $P_{\text{alb}}$ could be reversed even after diabetes was established. Using an ex vivo method that eliminates the influence of glomerular capillary pressure and flow dynamics, we demonstrated that the ability of ETA or ETA/B antagonists to improve glomerular permeability to albumin after hyperglycemia was similar. These data suggest that the ETA receptor contributes to the glomerular defect seen in diabetes, whereas the ETB receptor has little role, if any. These findings are consistent with direct in vitro measurements that ETA, but not ETB, receptor antagonists improve $P_{\text{alb}}$ in this model (Saleh et al., 2010). We also observed that ETA-selective antagonism had a profound anti-inflammatory effect on the diabetic kidney in contrast to the combined ETA/ETB antagonist. Together, these findings support the potential therapeutic advantage of selective ETA versus combined ETA/ETB antagonists.

We observed a difference in the rate of proteinuria reduction between the two antagonists. In a preclinical study conducted by our group, Sasser et al. (2007) showed that albuminuria increases during the first 10 weeks of STZ-induced hyperglycemia and the ETA antagonist, ABT-627, completely ameliorated albuminuria. These data are consistent with those of Hocher et al. (2001) who investigated both a selective ETA antagonist [(2S)-2-(4,6-dimethoxypyrimidin-2-yl)oxy-3-methoxy-3,3-di(phenyl)propanoic acid (LU 135252)] and a mixed ETA/B (LU 224332) antagonist (Hocher et al., 2001). In contrast, Gross et al. (2003) observed that the ETA-selective antagonist, LU 135252 (darusentan), prevented renal histological alterations in STZ-diabetic rats and significantly decreased urinary ET-1 excretion, but had no effect on albuminuria, although the reason for these different findings is unclear. Nonetheless, our current findings demonstrating a differential effect of the selective versus combined antagonists would suggest that a lack of selectivity could reduce efficacy in terms of reducing proteinuria.

In previous studies using selective ETA antagonists, blood pressure was significantly reduced along with albuminuria (Sasser et al., 2007; Gagliardini et al., 2009); so, it has been impossible to distinguish the benefits of reduced glomerular capillary pressure versus direct effects on permeability. Preclinical studies in subjects with nondiabetic chronic kidney disease showed a blood pressure-independent reduction in proteinuria in response to acute selective ETA receptor administration (Dhaun et al., 2009). These studies support the hypothesis that ETA antagonism can reverse renal dysfunction independent of blood pressure and renal hemodynamics and suggest a direct effect on the glomerular filtration barrier structure.

The specific independent role of ETB receptors in modulating proteinuria and glomerular permeability cannot be identified using ETB-selective antagonists in vivo because pharmacological blockade of ETB receptors results in hypertension via increased ETA activity by reduced ET-1 clearance (Pollock and Pollock, 2001). The current study demonstrated a more rapid and efficient level of reduction in proteinuria with the ETA-selective blocker compared with the mixed antagonist. This is consistent with the hypothesis...
that the ETβ receptor functions to oppose the direct role of the ETα receptor in terms of influencing the integrity of glomerular permeability and proteinuria.

The significant improvement of proteinuria progression produced by both types of antagonists was accompanied by marked restoration of glomerular filtration barrier components and function. One of the molecular mechanisms that leads to proteinuria in diabetic nephropathy is the down-regulation of podocyte- and filtration-slit molecule expression. We observed that hyperglycemia was associated with reduced expression of podocyte foot-process proteins, namely nephrin, ZO-1, and podocin in isolated glomeruli, with an increase in nephrin urinary excretion rate. We have shown previously that chronic ET-1 infusion in normoglycemic rats resulted in an ETA-dependent increase in nephrin excretion rate (Saleh et al., 2010b). In addition, serum from pre-eclamptic women contains a factor or a group of factors that stimulate the production of ET-1 from glomerular endothelial cells triggering nephrin loss from podocytes (Collino et al., 2008). Loss of podocyte attachment to glomerular basement membrane and subsequent podocyturia may result from down-regulation of the glomerular basement membrane integrin, α5β1 (Korhonen et al., 1990; Adler, 1992). Our data showed that both ABT-627 and A-182086 restore integrin α5 protein but not the β1 subunit.

We observed that both ABT-627 and A-182086 significantly reduced the diabetes-induced increases in active glomerular TGF-β, but the mixed antagonist was less effective. We have reported previously that this model of hyperglycemia does not have any overt fibrosis as detected by histological staining (Sasser et al., 2007); so, we have relied on early markers of fibrosis such as TGF-β. Inhibition of TGF-β prevents fibrosis under experimental diabetic conditions (Sharma et al., 1996; Chen et al., 2003). Several previous studies reported antifibrotic properties of long-term treatment with either selective ETα or nonselective ETαβ antagonists (Nakamura et al., 1995; Hocher et al., 2001). We reported previously that ABT-627 prevents increases in TGF-β in this model (Sasser et al., 2007). Prior evidence also suggests that ETβ receptors may possess antifibrotic action via endothelial NO synthase-derived NO signaling after inhibition of TGF-β (Dreieicher et al., 2009); so, the observation that the combined ETαβ antagonist was less effective was perhaps predictable. However, comparison of the two types of antagonists on measures of glomerular fibrosis in our studies was somewhat inconclusive because both ETα and ETαβ antagonists normalized activity of glomerular MMPs. Overexpression of glomerular TGF-β1 in diabetes is associated with increased activity of MMPs, mainly gelatinases (MMP-2 and MMP-9) that contribute to glomerular basement membrane thickening (Krag et al., 2007).

We recently reported that chronic ET-1 infusion in the rat increases glomerular and renal inflammation independent of hypertension (Saleh et al., 2010). Furthermore, we have also reported that selective ETα blockade in the STZ-diabetic rat prevents the increase in early markers of inflammation, ICAM-1 and MCP-1 (Saleh et al., 2011). The current study extends these findings to demonstrate that we could reverse the diabetes-induced increase in inflammation, but only with an ETα-selective antagonist and not the combined blocker. These findings suggest that the ETβ receptor functions as an anti-inflammatory factor and that targeting the endothelin pathway for treatment of diabetes should be restricted to ETα-selective compounds.

The general beneficial effects of both ETα-selective and combined receptor antagonism have been demonstrated in a wide variety of studies including our own. However, in terms of systemic and glomerular inflammation, ETβ receptor antagonism seems to counteract the benefit of ETα blockade. ETβ receptors are involved in the synthesis of the vasodilator NO by endothelial cells, through activation by either ET-1 or ET-3 (Namiki et al., 1992). Inhibition of NO has also been associated with an increase in leukocyte adhesion to mesenteric venules, reflecting that the increases in monocyte/macrophage infiltration are caused by decreases in NO production (Dubey et al., 1996). Another possible explanation for the nonbeneficial effect of ETαβ blockade is the involvement of the ETβ receptor in the clearance of ET (Fukuroda et al., 1994). The nonselective NOS inhibitor, Nω-nitro-l-arginine methyl ester, exacerbates liver and kidney injury accompanied with increased leukocyte infiltration in animal models of endotoxemia (Saetre et al., 2001). Part of these effects has been attributed to increased adhesion molecule expression (ICAM-1, P-selectin) after inhibition of endogenous NO production. In addition, mice lacking endothelial NO synthase aggravate anti-GBM glomerulonephritis, indicating a protective role of endogenous NO during renal inflammation (Heeringa et al., 2000).

We did not observe any changes in mRNA expression of glomerular ET-1, ETα, and ETβ receptors after 7 weeks of hyperglycemia; however, treatment with an ETα or ETαβ antagonist produced marked decreases in glomerular expression of each of these genes. A previous study from another lab reported that glomerular ET-1 mRNA levels were increased in kidneys from STZ-treated rats, whereas the mRNA levels for ETα and ETβ receptors remained unchanged (Fukui et al., 1993). Of course, mRNA levels do not always reflect protein expression and function. On the contrary, Shin et al. (1995) reported that moderate hyperglycemia in diabetic rats is associated with a reduction in renal ET-1 mRNA levels early after the induction of diabetes; however, plasma ET-1 levels were not affected. These data demonstrated that the intrarenal ET-1 system may be affected independently of the systemic ET-1 system.

Factors such as hyperglycemia (Yamauchi et al., 1990), shear stress (Hocher et al., 1997) caused by glomerular hyperfiltration, and urine flow (Hocher et al., 1998) have been shown to stimulate ET-1 synthesis or release. Glucose stimulates also ET-1 synthesis in vitro. Studies examining systemic and intrarenal ET-1 in diabetes have yielded conflicting results. Plasma ET-1 levels have been described as either undetectable (Takahashi et al., 1991), unchanged (Shin et al., 1995), enhanced (Nakamura et al., 1995; Hocher et al., 1998), or suppressed (Hu et al., 1993), and renal ET-1 levels have been shown to be unchanged (Takahashi et al., 1991), enhanced (Fukui et al., 1993), or reduced (Shin et al., 1995). Accordingly, it is suggested that these changes are caused by differences in the diabetic state, and these differences may be caused by the degree of hyperglycemia, renal localization, or varying duration of diabetes. Glomerular ET-1 mRNA levels have been reported to increase with progression of diabetic nephropathy in STZ-diabetic rats, whereas the mRNA levels for ETα and ETβ do not
change in diabetes (Fukui et al., 1993). Of course, mRNA levels do not always reflect protein expression and function. On the contrary, early after the induction of diabetes, renal ET-1 mRNA and protein expression have been reported to be reduced and plasma ET-1 levels were unchanged, implying that the intrarenal ET-1 system may be affected independently of the systemic ET-1 system (Shin et al., 1995).

From a clinical perspective, both ET\textsubscript{A} and ET\textsubscript{B} antagonists would seem to have beneficial effects for reducing proteinuria in the long term. However, the ET\textsubscript{A}-selective antagonist was significantly more effective than the combined antagonist at reducing TGF-\(\beta\) and inflammatory mediators in the model of type 1 diabetes. Our data suggest an antiinfective and anti-inflammatory role for the ET\textsubscript{B} receptor, thus providing rationale for use of ET\textsubscript{A}-selective rather than mixed ET\textsubscript{A/B} antagonists for treatment of diabetic nephropathy and perhaps other forms of proinflammatory disease and inflammation.

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Authorship Contributions

Participated in research design: Saleh, J. S. Pollock, and D. M. Pollock.

Conducted experiments: Saleh.

Performed data analysis: Saleh and D. M. Pollock.

Wrote or contributed to the writing of the manuscript: Saleh, J. S. Pollock, and D. M. Pollock.

Other: J. S. Pollock and D. M. Pollock acquired funding for the research.

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