European Review for Medical and Pharmacological Sciences 2016; 20: 2680-2688

Nigella sativa oil and thymoquinone ameliorate albuminuria and renal extracellular matrix accumulation in the experimental diabetic rats

B. AL-TRAD[1,2], K. AL-BATAYNEH[2], S. EL-METWALLY[1,3], A. ALHAZIMI[1,4], I. GINAWI[1], M. ALARAJ[1], E. ALKOFAHI[2], O. ALJUMAILI[2], A. KOSBA[1]

[1]College of medicine, University of Ha'il, Ha'il, Saudi Arabia
[2]Department of Biological Sciences, Yarmouk University, Irbid, Jordan
[3]Physiology Department, College of Medicine, Al-Azhar University, Cairo, Egypt
[4]College of Medicine, King Abdulaziz University, Jeddah, Saudi Arabia

Abstract. – OBJECTIVE: Increasing evidence suggests that *Nigella sativa* oil (NSO) and its principal bioactive constituents, thymoquinone (TQ), exhibit antioxidant, antihyperglycemic and renoprotective effects in streptozotocin (STZ)-induced diabetes in rats. However, the potential molecular mechanisms by which NSO and TQ may exert their actions in the diabetic kidney are still poorly characterized. This study was designed to investigate the effect of NSO and TQ treatment on the albuminuria, podocyte injury and the complex systems controlling the extracellular matrix proteins accumulation and angiogenesis in the STZ-induced model of diabetic nephropathy.

MATERIALS AND METHODS: Adult female Wistar rats were divided into four experimental groups (control, untreated STZ-diabetic, and NSO or TQ treated STZ-diabetic rats). The treated rats received 2 mL/kg NSO or 50 mg/kg TQ via oral gavage once a day for 10 weeks.

RESULTS: The results showed that the albuminuria and the kidney weight/body weight ratio were increased in the diabetic rats compared with the control animals and they were significantly ameliorated by the treatment with NSO or TQ. The real-time PCR showed that the NSO and TQ treatment prevented diabetes-induced down-regulation of mRNA expression of the podocyte-specific marker (podocin) as well as the mRNA overexpressions of collagen IV, transforming growth factor-β_1 (TGF-β_1) and vascular endothelial growth factor-A (VEGF-A) in the diabetic kidney. These results were also confirmed by immunohistochemistry.

CONCLUSIONS: NSO and TQ treatment decreased albuminuria in the experimental models of the diabetic nephropathy by the preservation of the podocyte function; along with the suppression of enhanced extracellular matrix gene expression through interfering with TGF-β_1 production and angiogenesis.

Key Words:
Nigella sativa oil, Thymoquinone, Diabetic nephropathy, Albuminuria.

Introduction

Among all diabetes mellitus complications, the diabetic nephropathy is a common microvascular complication estimated to affect 40% of patients with diabetes[1]. Microalbuminuria and a decrease in creatinine clearance and glomerular filtration rate are the early clinical signs of the diabetic nephropathy[1,2]. A variety of structural alterations is involved in the progression of the diabetic nephropathy, including glomerular and tubular hypertrophy, thickening of basement membranes, and progressive mesangial expansion[2]. End-stage diabetic kidneys are commonly characterized by irreversible structural renal changes such as, glomerulosclerosis and tubulointerstitial fibrosis[2].

Nigella sativa (plant family of Ranunculaceae), is ripe fruit that contains minute black seeds, known as black seed or black cumin[3,4]. *Nigella sativa* seeds contain an essential oil (0.4-2.5%), fixed oil (36-48%), alkaloids, saponin and proteins[4]. *Nigella sativa* oil (NSO) was shown to contain thymoquinone (TQ) which is the main bioactive component (27.8-57.0%) of the essential oil of the black seed[3]. Toxicity studies on laboratory animals have reported that NSO and TQ are quite safe, mainly when given orally[3,4]. Consequently, NSO and TQ have been used as anti-inflammatory, antioxidant and anticancer therapeutic agents[4-6].

Corresponding Author: Bahaa Al-Trad, Ph.D; e-mail: bahaa.tr@yu.edu.jo

It has been shown that TQ protects the proximal tubular epithelial cells against tubular injury induced by angiotensin II[7]. In the gentamicin-induced nephrotoxicity, *Nigella sativa* and TQ supplementation prevent the development of gentamicin-induced acute renal toxicity failure[8,9]. Furthermore, NSO improved renal function and attenuated oxidative stress induced by chronic cyclosporine A treatment[10]. Recent studies suggest that TQ treatment exerts a therapeutic renoprotective effect in streptozotocin (STZ) induced diabetes in rats by decreasing oxidative stress and the improvement of renal morphology and function[11,12,13]. Findings from those studies support the concept that NSO and TQ exerted a renal protective effect in renal disease models. However, further preclinical research regarding the beneficial effect of NSO and TQ treatment on the molecular mechanisms accounts for diabetic nephropathy is required to specify their usefulness as an effective therapy in this disease. Therefore, the aim of this report was to investigate the effects of NSO and TQ treatment on the albuminuria, podocyte injury and the complex systems controlling the extracellular matrix proteins accumulation and angiogenesis in the STZ-induced model of the diabetic nephropathy.

Materials and Methods

Animals

All experimental procedures were approved by the Committee of Animal Ethics at Yarmouk University; Irbid-Jordan. Female adult Wistar rats, 55-60 days old and weighing approximately 200 g were maintained in the animal house of Yarmouk University under the standard conditions of a 12-light-dark cycle, temperature at 23 ± 1°C. The animals were fed a standard rodent chow and tap water ad libitum.

Induction of Diabetes and Experimental Protocols

After an overnight fast, diabetes mellitus was induced in rats by intra-peritoneal injecting a freshly prepared STZ (Sigma-Aldrich, St Louis, MO, USA; 55 mg/kg; dissolved in 0.1 M acetate buffer; pH 4.5). A control group of rats received citrate buffer only. Once serum glucose is higher than 300 mg/dl, the rats were randomly divided into four treatment groups (n = 5-6 per group): (1) control (non-diabetic, ND), (2) diabetic (D), (3) diabetic treated with 50 mg/kg TQ (D+TQ, Sigma-Aldrich, St Louis, MO, USA), administered orally and (4) diabetic which were treated orally with 2 mL/kg NSO (D+NSO). The dosage of TQ (50 mg/kg) and NSO (2 mL/kg) based on previous studies[11,14]. The ND group received the vehicle only (2 mL/kg corn oil). Body weight was recorded weekly and the dose of administration was adjusted according to the recorded body weight measurements.

After being treated for 10 weeks and one day before sacrifice, the rats were placed in metabolic cages and urine was collected for 24 hrs for the analysis of urine albumin concentration and the urine volume. Then, the animals were weighed and anesthetized with ether. Blood samples were collected and the right kidney was removed and then transferred into RNAlater solution (Sigma-Aldrich, St Louis, MO, USA) for real-time PCR analysis. The left kidney was fixed with 4% paraformaldehyde for immunohistochemical analysis.

Measurements of Blood Glucose and Urinary Albumin Excretion

The blood glucose level was determined by glucometer (Accu-Chek Performa, Roche Diagnostics, Indianapolis, IN, USA). Urine samples were centrifuged at 4°C and 2,000 rpm for 10 min and the supernatant was used to measure the urinary albumin excretion rate (UAE) using albumin rat ELISA kit (Abcam, Cambridge, UK).

Immunohistochemistry

Immunostaining for podocin, transforming growth factor-β1 (TGF-β_1), collagen IV and vascular endothelial growth factor-A (VEGF-A) was performed using 1:100 dilution of primary antibodies against podocin (Abcam, Cambridge, UK; Cat.No. ab50339), TGF-β_1 (Santa Cruz Biotechnology, Santa Cruz, CA, USA; Cat.No.sc-146), collagen IV (Abcam, Cambridge, UK; Cat.No. ab6586) and VEGF-A (Santa Cruz Biotechnology, Santa Cruz, CA, USA; Cat.No. sc-7269) as previously described[15].

Real-time RT-PCR Analysis

RNAlater conserved kidney tissues were homogenized and the total RNA was extracted using RNeasy mini tissue kit (Qiagen, Valencia, CA, USA) following the manufacturer instructions. cDNA was synthesized from the total RNA (0.5 µg) using oligo-(dT)15 primer in a 20-µl reaction according to the manufacturer's instructions (iNtRON, Biotechnology, Sungnam, South Korea).

Table I. Sequences of primers used for quantitative real time RT-PCR.

Gene	GenBank accession	Forward (5-3)	Reverse (5-3)
β-Actin	NM_031144	CCTAGACTTCGAGCAAGAGA	TCCATACCCAGGAAGGAAG
podocin	NM_130828.2	ATTCCGACTGGGACATCT	GTTACCACCTCATGGAAAGG
TGF-β_1	NM_021578	CGTACACAGCAGTTCTTCTCT	ATGACATGAACCGACCCTTC
Collagen IV	NM_001135759	AGCACCCTTTTCTGATCCATAG	TTTACACTCCGACACCCATAC
VEGF-A	NM_031836	TTTCCCTTTCCTCGAACTGAT	ACGTCACTATGCAGATCATGC

Abbreviations: TGF-β_1: transforming growth factor-β_1; VEGF-A: vascular endothelial growth factor-A.

The real-time RT-PCR was performed on LineGene 9600 Real-Time PCR system (Bioer Technology Co, Bingjiang, China), using the KAPA SYBR® FAST Universal 2X qPCR master mix (KAPA Biosystem, Boston, MA, USA). Primers were designed and synthesized by IDT (Integrated DNA Technologies, INC., IA; Table I). The cycling parameters were: 95°C for 3 min and 45 cycles of 95°C for 3 s and 60°C for 20 s. The relative gene expression levels were determined by the CT method as described by Livak and Schmittgen[16]. The levels of genes expression were expressed as the normalized ratio of gene expression relative to β-actin mRNA.

Statistical Analysis

Statistical analyses of data were performed using the SPSS version 14.0 for Windows (SPSS Inc., Chicago, IL, USA). All data will be expressed as means ± SEM. One-way analysis of variance (ANOVA) was used to identify differences between the groups followed by LSD post-hoc test analysis. p-value < 0.05 was considered as statistically significant difference.

Results

Blood glucose level was elevated in all of the diabetic rats compared with the control rats (Figure 1; $p < 0.05$). Treatment of diabetic rats with NSO or TQ significantly reduced blood glucose level compared with that in untreated diabetic rats. To evaluate the renal hypertrophy and renal functional parameters, ratio of kidney weight/body weight and UAE were measured, respectively (Figure 2). Kidney weight/body weight ratio was increased in the untreated diabetic rats compared with the control rats (Figure 2A; $p < 0.05$). The treatment of diabetic rats with NSO or TQ reduced significantly the kidney weight/body weight ratio compared with the diabetic rats. Diabetes was associated with an increase in UAE compared to the diabetic control rats. However, UAE was significantly lower in diabetic rats treated with NSO or TQ (Figure 2B; $p < 0.05$).

In attempt to clarify the mechanism of the beneficial effect of NSO and TQ treatment on diabetes-induced proteinuria in the present study, we assessed the extent of podocyte damage by monitoring the protein expression of slit diaphragm protein (podocin). The mRNA expression and the immunostaining intensity of podocin were lower in the glomeruli of the D group when compared to the control ND group (Figures 3A and 3B; $p < 0.05$). In the NSO and TQ treatment groups, however; the expression and distribution of podocin were completely (D+TQ group) and partially (D+NSO group) recovered (Figures 3A and 3B). Collectively, these results strongly suggest that restoration of podocin expression mediated the reno-protective effect of NSO and TQ.

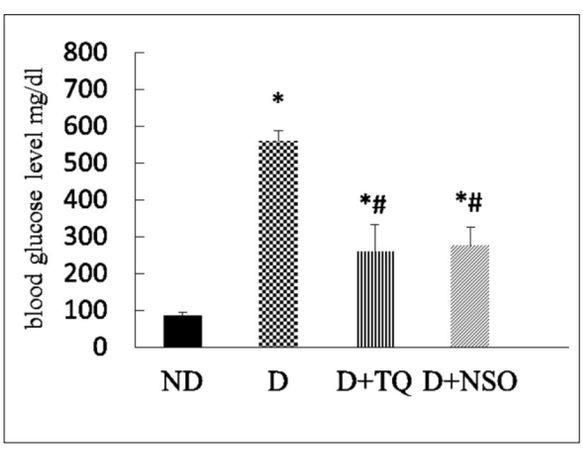

Figure 1. Effect of NSO and TQ treatment on blood glucose level in control and diabetic rats. Data represent the mean ± SEM. *$p < 0.05$ compared to the ND group. #$p < 0.05$ compared to D group. *Abbreviations:* NSO, *Nigella sativa* oil; TQ, thymoquinone; ND, non-diabetic; D, diabetic.

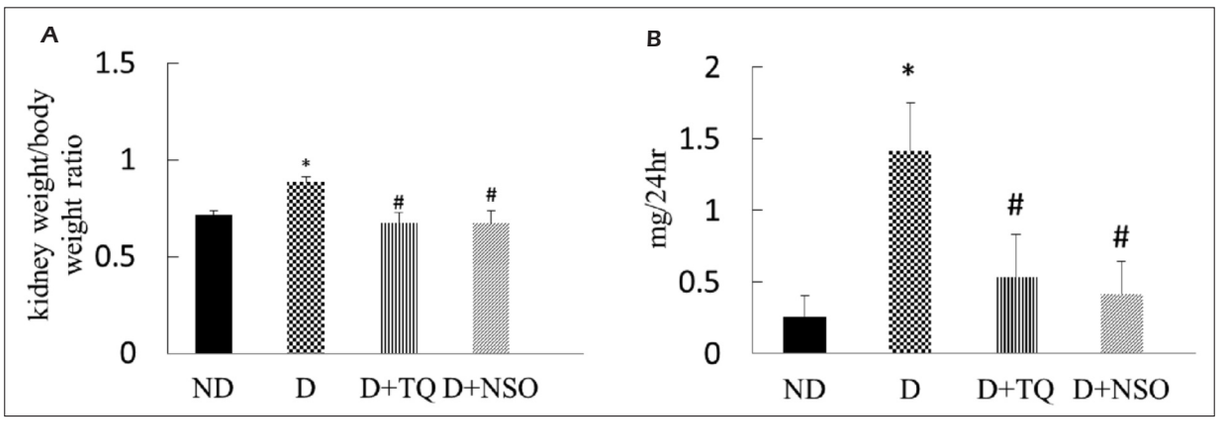

Figure 2. Effect of NSO and TQ treatment on ***(A)***, kidney weight/body weight ratio and ***(B)***, urinary albumin excretion in control and diabetic rats. Data represent the mean ± SEM. $^{*}p < 0.05$ compared to the ND group. $^{\#}p < 0.05$ compared to D group. *Abbreviations:* NSO, *Nigella sativa* oil; TQ, thymoquinone; ND, non-diabetic; D, diabetic.

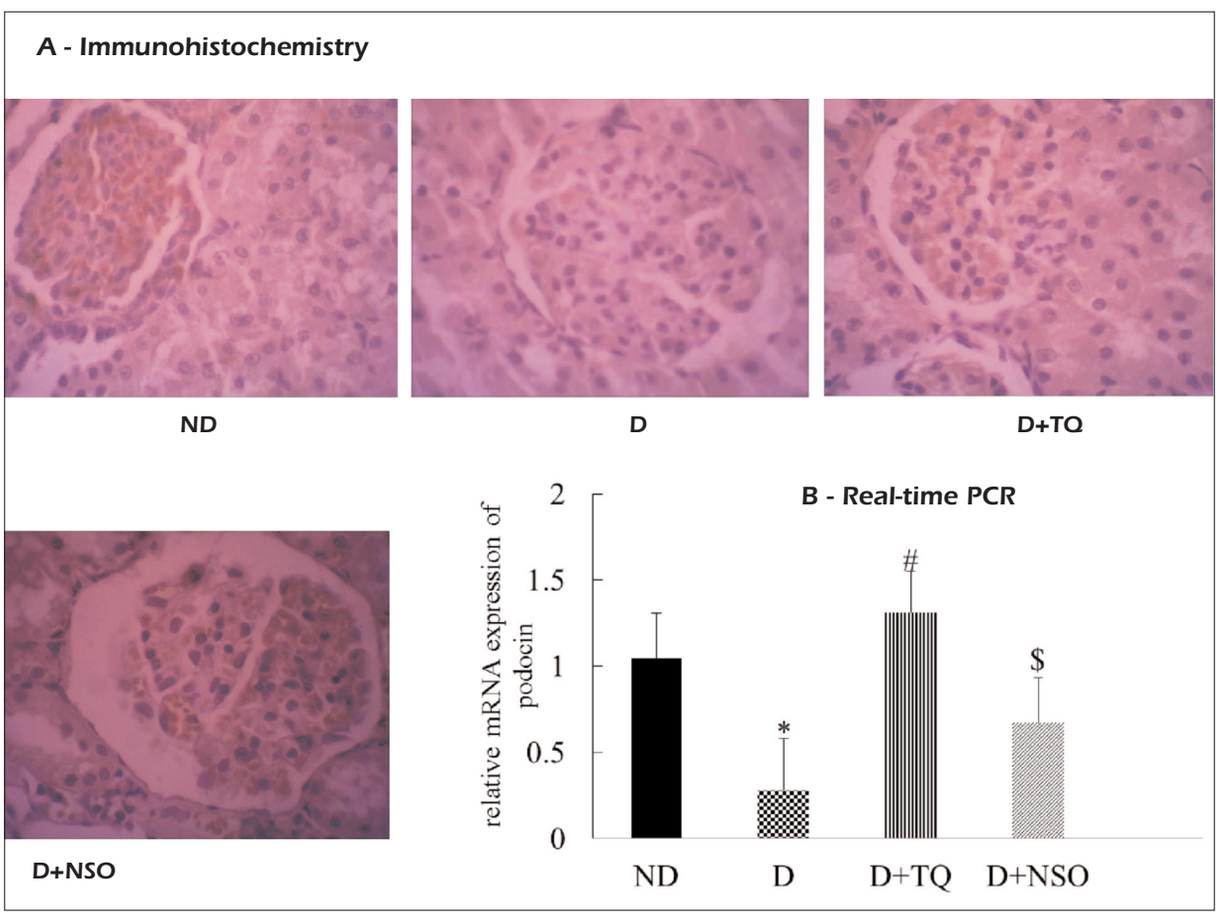

Figure 3. Immunohistochemistry and real-time PCR detect that NSO and TQ treatment restores the podocin expression in the diabetic kidney. ***A,*** Immunohistochemical stain of the kidney sections (hematoxylin staining; magnification, ×400) shows that the podocin immunostaining (*brown staining*) in the glomeruli was much stronger in the ND group compared with the D group. NSO and TQ treatment inhibited the decrease in the podocin immunostaining in the NSO and TQ groups. ***B,*** Podocin mRNA expression by real-time PCR. Data represent the mean ± SEM.$^{*}p < 0.05$ compared to the ND group. $^{\#}p < 0.05$ compared to the D group. $^{\$}p < 0.10$ compared to the D group. *Abbreviations:* NSO, *Nigella sativa* oil; TQ, thymoquinone; ND, non-diabetic; D, diabetic.

To determine the effect of NSO and TQ treatment on extracellular matrix proteins accumulation and deposition in the diabetic kidney, we analyzed the TGF-β_1 and collagen IV expression in the renal glomeruli. Diabetes was associated with an increase in the intensity of immunostaining for TGF-β_1 and collagen IV in the D rats compared to the ND rats (Figures 4A and 5A). The levels of mRNA for TGF-β_1 and collagen IV were significantly greater in the D group than in the ND group (Figures 4B and 5B; $p < 0.05$). Compared with diabetic rats without treatment, the immunostaining intensity and the mRNA of TGF-β_1 and collagen IV were decreased in the NSO and TQ treatment groups; however, the effect was more obvious in the NSO treated rats.

Angiogenesis plays an important role in the development and progression of the diabetic nephropathy. VEGF-A was used in this research as a biomarker of angiogenesis. The immunostaining intensity and the mRNA of VEGF-A were significantly increased in the D group compared to the ND group, and these changes were significantly attenuated by the TQ treatment or tended to be attenuated in the NSO group (Figures 6A and 6B).

Discussion

A treatment that can delay the onset of diabetic nephropathy, the most common cause of the end-stage renal failure worldwide, and slow its progression is instantly needed to improve the survival in patients with diabetes. Medicinal plants may provide an alternative for new drugs.

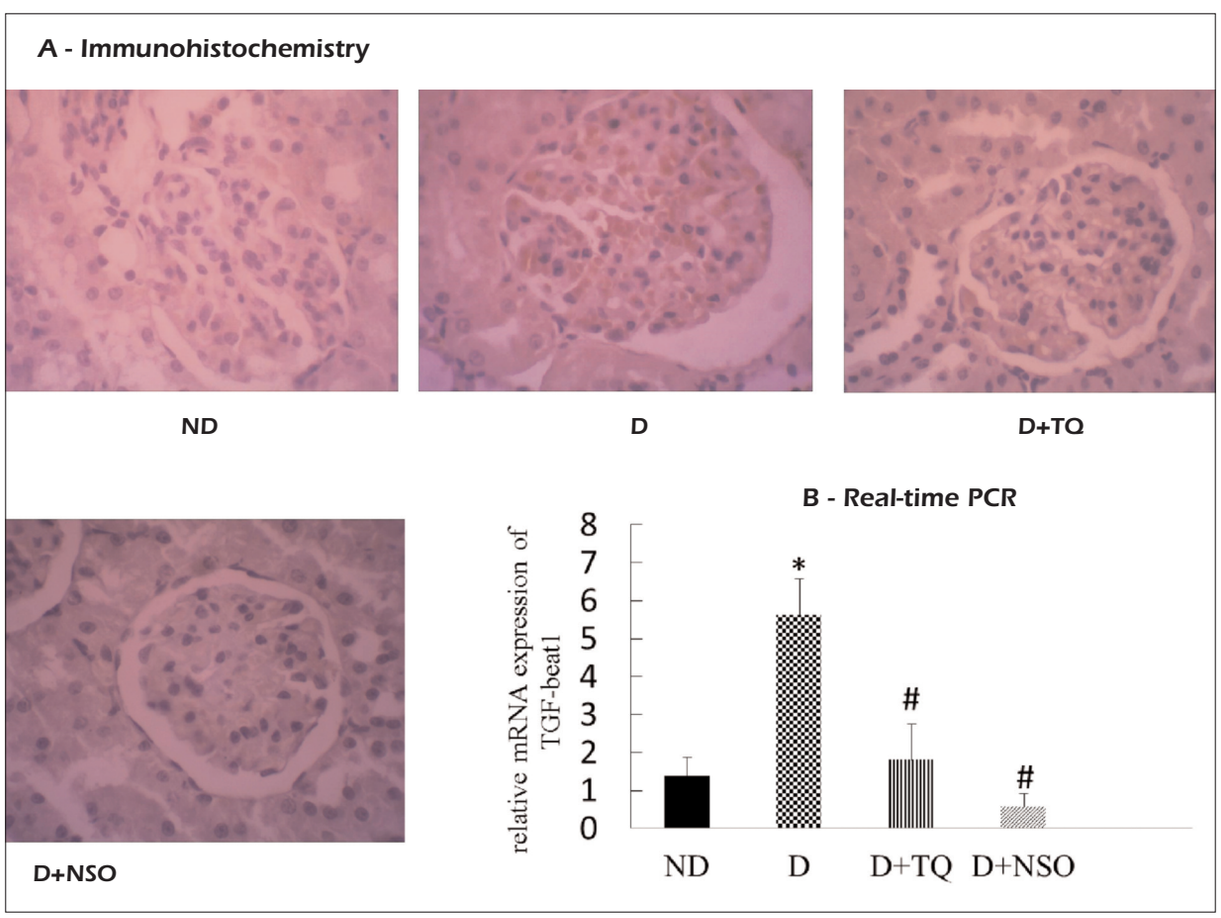

Figure 4. Immunohistochemistry and real-time PCR detect that NSO and TQ treatment inhibit the TGF-β1 expression in the diabetic kidney. ***A,*** Immunohistochemical stain of the kidney sections (hematoxylin staining; magnification, ×400) show that the TGF-β_1 immunostaining (*brown staining*) in the glomeruli was much stronger in the D group compared with the ND group. NSO and TQ treatment inhibited the increase in the TGF-β_1 immunostaining in the NSO and TQ groups. ***B,*** TGF-β_1 mRNA expression by real-time PCR. Data represent the mean ± SEM.*$p < 0.05$ compared to the ND group. #$p < 0.05$ compared to D group. *Abbreviations:* NSO, *Nigella sativa* oil; TQ, thymoquinone; ND, non-diabetic; D, diabetic.

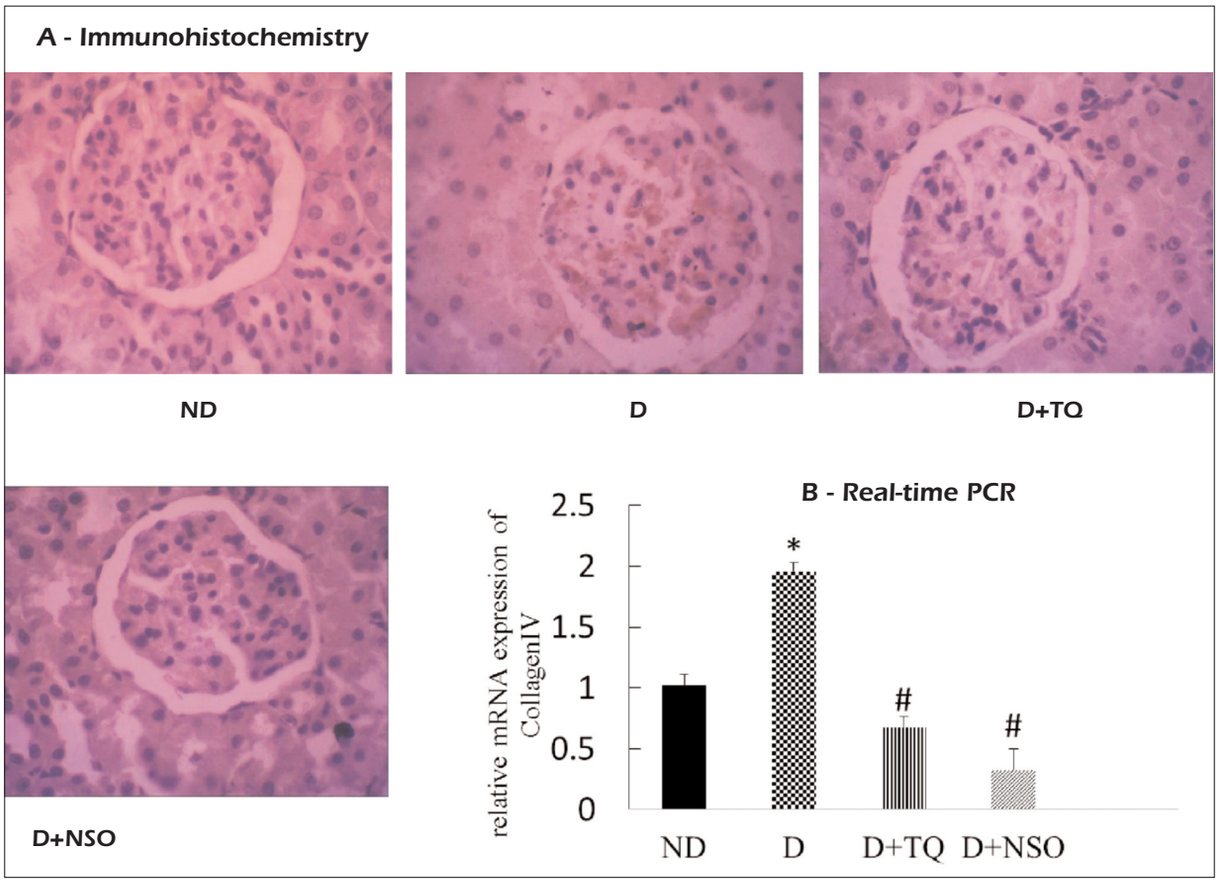

Figure 5. Immunohistochemistry and real-time PCR detect that NSO and TQ treatment inhibit the collagen IV expression in the diabetic kidney. ***A,*** Immunohistochemical stain of the kidney sections (hematoxylin staining; magnification, ×400) shows that the collagen IV immunostaining (*brown staining*) in the glomeruli was much stronger in the D group compared with the ND group. NSO and TQ treatment inhibited the increase in the collagen IV immunostaining in the NSO and TQ groups. ***B,*** Collagen IV mRNA expression by real-time PCR. Data represent the mean ± SEM.*$p < 0.05$ compared to the ND group. #$p < 0.05$ compared to the D group. *Abbreviations:* NSO, *Nigella sativa oil*; TQ, thymoquinone; ND, non-diabetic; D, diabetic.

Recent studies reported that TQ, a component derived from the medical plant *Nigella sativa*, improved the renal morphology in STZ-induced diabetic rats[11,12,13], mainly through the antioxidative/anti-inflammatory effects[12]. Our current study provided further evidence that NSO and TQ treatment ameliorate diabetic nephropathy in experimental diabetic rats with a decrease in albuminuria, podocyte injury, and extracellular matrix proteins accumulation.

Podocytes are specialized glomerular epithelial cells that are responsible for preserving the glomerular filtration barrier. In diabetes-induced kidney injury, podocytes loss and injury are associated with marked proteinuria, a hallmark of diabetic nephropathy[17]. Previous studies demonstrated that the down regulation in the podocin, a key podocyte slit diaphragm protein, is involved in the development of proteinuria in the diabetic nephropathy[15,17]. Our results indicated that podocyte injuries in diabetic kidney could be reversed after treatment with NSO or TQ through the restoration of the expression patterns of podocin. In line with that, a recent immunohistochemical study has shown evidence that administration of TQ decrease the expression of the desmin, an early podocyte injury marker, in STZ-induced diabetic nephropathy[13], which further provide evidence for the protective effect of TQ on podocytes. Taken together, we assumed that NSO and TQ treatment may exert renoprotective effect via lowering proteinuria, which may be mediated, at least in part, by upregulation of podocin expression in the glomeruli of diabetic rat.

Excessive extracellular matrix proteins accumulations in the mesangium and tubulointersti-

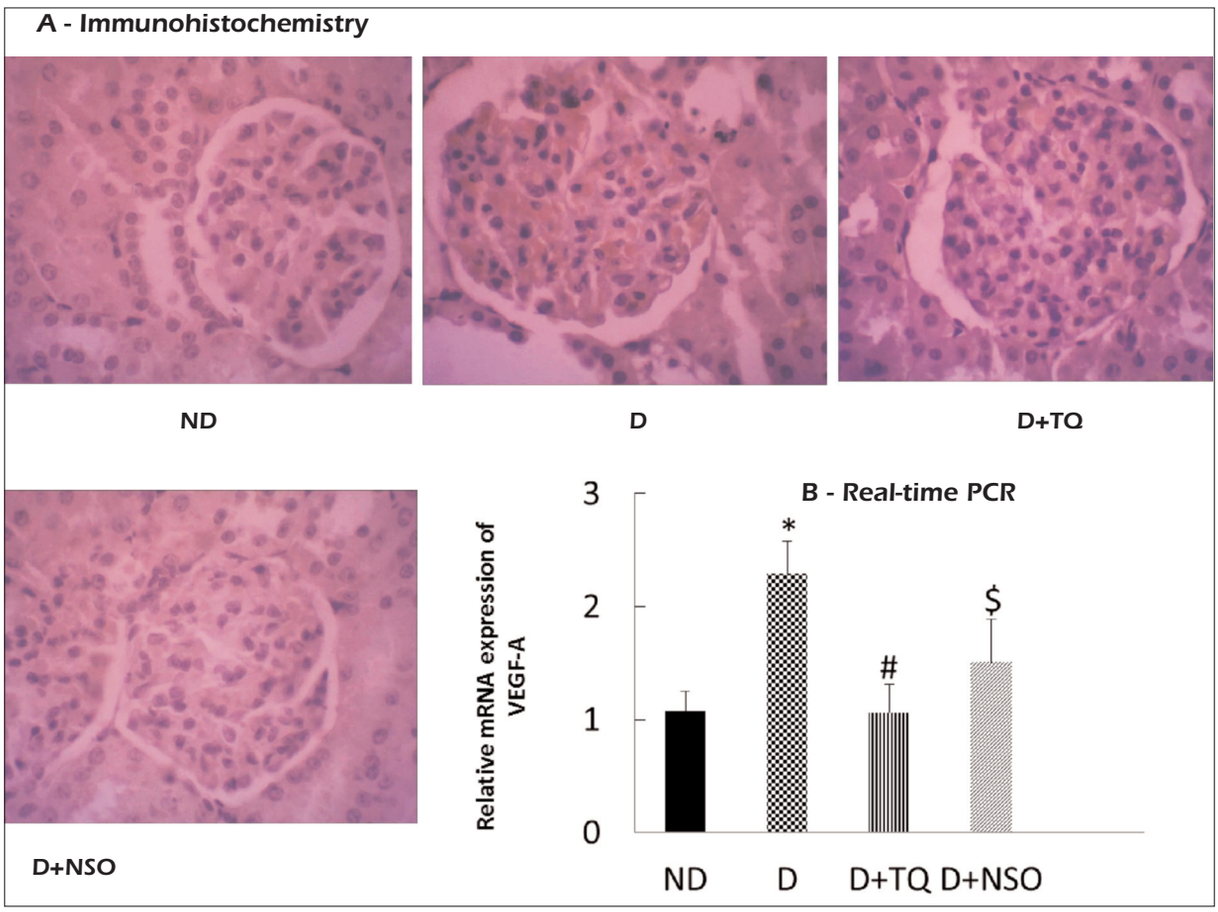

Figure 6. Immunohistochemistry and real-time PCR detect that NSO and TQ treatment inhibits the VEGF-A expression in the diabetic kidney. ***A,*** immunohistochemical stain of the kidney sections (hematoxylin staining; magnification, ×400) shows that the VEGF-A immunostaining (*brown staining*) in the glomeruli was much stronger in the D group compared with the ND group. NSO and TQ treatment inhibited the increase in the VEGF-A immunostaining in the NSO and TQ groups. ***B,*** VEGF-A mRNA expression by real-time PCR. Data represent the mean ± SEM.*$p < 0.05$ compared to the ND group. $^{\#}p < 0.05$ compared to the D group. $^{\$}p < 0.10$ compared to the D group. *Abbreviations:* NSO, *Nigella sativa* oil; TQ, thymoquinone; ND, non-diabetic; D, diabetic.

tium are important components of the pathophysiological changes in various glomerular diseases, including the diabetic nephropathy[18]. TGF-β is the key cytokine known to stimulate the biosynthesis of collagen and other matrix components. It was shown that TGF-β inhibits the cell cycle in most types of cells, leading to an increase in volume and DNA and protein content; i.e. hypertrophy[19]. In the kidney, TGF-β stimulates renal cell growth and extracellular matrix proteins accumulation, the two hallmarks of the diabetic nephropathy[20]. Moreover, it was shown that treatment of diabetic mice with anti-TGF-β antibodies improved renal function and prevented renal hypertrophy and mesangial matrix expansion[2,21]. Given the central role of TGF-β system in diabetic nephropathy, the suppression of TGF-β should be a therapeutic target in the diabetic kidney disease. In the present study, the NSO and TQ treated diabetic rat showed less TGF-β_1 and collagen IV expression than the non-treated diabetic rat did, suggesting a protective effect for NSO and TQ with respect to the extracellular matrix proteins deposition in the diabetic kidney.

Recent evidence has indicated that blocking angiogenesis, the formation of new blood vessels from pre-existing vasculature, attenuated abnormal renal structural changes and transforming growth factor TGF-β expression in diabetic animals[22,23]. The expression of VEGF-A, a key mediator of angiogenesis, is induced by hyperglycaemia and was reported to be upregulated in the experimental diabetic nephropathy[15,23,24], and in human kidney specimens at early stages of dia-

betic nephropathy[25]. Given the evidence above, targeting angiogenic pathways may prevent the progression of the diabetic nephropathy. In the present study, we demonstrated that NSO and TQ treatment could attenuate the diabetic nephropathy via inhibiting the angiogenesis related factor VEGF-A.

Finally and as expected, the observed renoprotection effect of NSO and TQ treatment was associated with a decrease in glycemic levels that could be explained by beta-pancreatic islet regeneration[26,27]. Hyperglycemia is a key factor in inducing TGF-β in the diabetic kidney[19]. In addition, high glucose treated podocyte cells exhibit reductions in podocin and nephrin expression indicating podocytes damage[28]. Therefore, the reno-protective effect of NSO and TQ treatment in the current study could be mediated, at least in part, by lowering the blood glucose level in the diabetic rats.

Conclusions

This study demonstrated that NSO and TQ treatment decreased albuminuria in the experimental models of diabetic nephropathy by the preservation of podocyte function; along with the suppression of enhanced extracellular matrix gene expression through interfering with TGF-β_1 production and angiogenesis. Although our report is an experimental study of diabetic nephropathy in rats, we provide a proof of concept evidence that NSO and TQ may be effective in controlling the diabetic nephropathy in humans.

Acknowledgements

This work was financially supported by grants from his excellency Professor Dr. Nasser Elrasheed Chair for Renal Diseases Research. Several persons have contributed to the experimental procedure and samples analysis; they warmly thanked.

Conflict of Interest

The Authors declare that there are no conflicts of interest.

References

1) Tuttle KR, Bakris GL, Bilous RW, Chiang JL, de Boer IH, Goldstein-Fuchs J, Hirsch IB, Kalantar-Zadeh K, Narva AS, Navaneethan SD, Neumiller JJ, Patel UD, Ratner RE, Whaley-Connell AT, Molitch ME. Diabetic kidney disease: a report from an ADA Consensus Conference. Diabetes Care 2014; 37: 2864-2883.
2) Kanwar YS, Wada J, Sun L, Xie P, Wallner EI, Chen S, Chugh S, Danesh FR. Diabetic nephropathy: mechanisms of renal disease progression. Exp Biol Med (Maywood) 2008; 233: 4-11.
3) Randhawa MA, Alghamdi MS. Anticancer activity of Nigella sativa (black seed) - a review.Am J Chin Med 2011; 39: 1075-1091.
4) Ali BH, Blunden G. Pharmacological and toxicological properties of Nigella sativa. Phytother Res 2003; 17: 299-305.
5) Ragheb A, Attia A, Eldin WS, Elbarbry F, Gazarin S, Shoker A. The protective effect of thymoquinone, an anti-oxidant and anti-inflammatory agent, against renal injury: a review. Saudi J Kidney Dis Transpl 2009; 20: 741-752.
6) Yi T, Cho SG, Yi Z, Pang X, Rodriguez M, Wang Y, Sethi G, Aggarwal BB, Liu M. Thymoquinone inhibits tumor angiogenesis and tumor growth through suppressing AKT and extracellular signal-regulated kinase signaling pathways. Mol Cancer Ther 2008; 77: 1789-96.
7) Sayed AA. Thymoquinone protects renal tubular cells against tubular injury. Cell Biochem Funct 2008; 26: 374-380.
8) Yaman I, Balikci E. Protective effects of Nigella sativa against gentamicin-induced nephrotoxicity in rats. Exp Toxicol Pathol 2010; 62: 183-190.
9) Sayed-Ahmed MM, Nagi MN. Thymoquinone supplementation prevents the development of gentamicin-induced acute renal toxicity in rats. Clin Exp Pharmacol Physiol 2007; 34: 399-405.
10) Uz E, Bayrak O, Uz E, Kaya A, Bayrak R, Uz B, Turgut FH, Bavbek N, Kanbay M, Akcay A. Nigella sativa oil for prevention of chronic cyclosporine nephrotoxicity: an experimental model. Am J Nephrol 2008; 28: 517-522.
11) Kanter M. Protective effects of thymoquinone on streptozotocin-induced diabetic nephropathy. J Mol Histol 2009; 40: 107-115.
12) Sayed AA. Thymoquinone and proanthocyanidin attenuation of diabetic nephropathy in rats. Eur Rev Med Pharmacol Sci 2012; 16: 808-815.
13) Omran OM. Effects of thymoquinone on STZ-induced diabetic nephropathy: an immunohistochemical study. Ultrastruct Pathol 2014; 38: 26-33.
14) Zaoui A, Cherrah Y, Mahassini N, Alaoui K, Amarouch H, Hassar M. Acute and chronic toxicity of Nigella sativa fixed oil. Phytomedicine 2002; 9: 69-74.
15) Al-Trad B, Ashankyty IM, Alaraj M. Progesterone ameliorates diabetic nephropathy in streptozotocin-induced diabetic rats. Diabetol Metab Syndr 2015; 7: 97.
16) Livak KJ, Schmittgen TD. Analysis of relative gene expression data using real-time quantitative PCR and the 2(-Delta DeltaC(T)) method. Methods 2001; 25: 40-408.

17) Qi XM, Wang J, Xu XX, Li YY, Wu YG. FK506 reduces albuminuria through improving podocyte nephrin and podocin expression in diabetic rats. Inflamm Res 2016; 65: 103-114.

18) Mason RM, Wahab NA. Extracellular matrix metabolism in diabetic nephropathy. J Am Soc Nephrol 2003; 14: 1358-1373.

19) Border WA, Noble NA. Evidence that TGF-beta should be a therapeutic target in diabetic nephropathy. Kidney Int 1998; 54: 1390-1391.

20) Chen S, Jim B, Ziyadeh FN. Diabetic nephropathy and transforming growth factor-β: transforming our view of glomerulosclerosis and fibrosis build-up. Semin Nephrol 2003; 23: 532-543.

21) Ziyadeh FN. Mediators of diabetic renal disease: The case for TGF-Beta as the major mediator. J Am Soc Nephrol 2004; 15: S55-S57.

22) Zent R, Pozzi A. Angiogenesis in diabetic nephropathy. Semin Nephrol 2007; 27: 161-171.

23) Nakagawa T, Sato W, Kosugi T, Johnson RJ. Uncoupling of VEGF with endothelial NO as a potential mechanism for abnormal angiogenesis in the diabetic nephropathy J Diabetes Res 2013; 2013: 184539.

24) Cooper ME, Vranes D, Youssef S, Stacker SA, Cox AJ, Rizkalla B, Casley DJ, Bach LA, Kelly DJ, Gilbert RE. Increased renal expression of vascular endothelial growth factor (VEGF) and its receptor VEGFR-2 in experimental diabetes. Diabetes 1999; 48: 2229-2239.

25) Kanesaki Y, Suzuki D, Uehara G, Toyoda M, Katoh T, Sakai H, Watanabe T. Vascular endothelial growth factor gene expression is correlated with glomerular neovascularization in human diabetic nephropathy. Am J Kidney Dis 2005; 45: 288-294.

26) Alimohammadi S, Hobbenaghi R, Javanbakht J, Kheradmand D, Mortezaee R, Tavakoli M, Khadivar F, Akbari H. Protective and antidiabetic effects of extract from Nigella sativa on blood glucose concentrations against streptozotocin (STZ)-induced diabetic in rats: an experimental study with histopathological evaluation. Diagn Pathol 2013; 8: 137.

27) Abdelmeguid NE, Fakhoury R, Kamal SM, Al Wafai RJ. Effects of Nigella sativa and thymoquinone on biochemical and subcellular changes in pancreatic β-cells of streptozotocin-induced diabetic rats. J Diabetes 2010; 4: 256-266.

28) Li C, Siragy HM. High glucose induces podocyte injury via enhanced (pro)renin receptor-Wnt-β-catenin-Snail signaling pathway. PLoS One 2014; 9: e89233.