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Effect of green tea on kidney tubules of diabetic rats

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It has been documented that green tea (GT) and its catechin components improve renal failure and inhibit the growth of mesangial cells. In the present study we examined the long-term effect of GT extract on streptozotocin (STZ)-induced diabetic nephropathy and on the glycogen accumulation in the kidney tubules. Male Sprague–Dawley rats were randomly assigned to normal control groups (2, 6, 8 and 12 weeks) and five diabetic groups (*n* 10) of comparable age. A GT diabetic group received 16 % concentration of GT for 12 weeks post-diabetes induction as their sole source of drinking water. GT treatment significantly ($P<0·01$) reduced the serum glucose, glycosylated protein, serum creatinine and blood urea N levels by 29·6 (SEM 3·7), 22·7 (SEM 5·2), 38·9 (SEM 10) and 41·7 (SEM 1·9) %, respectively, compared with the diabetic group of comparable age. In addition, the GT-treated group showed a significant 44 (SEM 10·8) % higher creatinine clearance (Ccr) compared with the untreated diabetic group. Likewise, GT reduced the urea N, creatinine, glucose and protein excretion rates by 30 (SEM 7·6), 35·4 (SEM 5·3), 34·0 (SEM 5·3) and 46·0 (SEM 13·0) % compared with the 12 weeks diabetic group. Administration of GT to 12 weeks diabetic rats significantly ($P<0·001$) prevented (99·98 (SEM 0·27) % less) the accumulation of glycogen in the kidney tubules. These results indicate that in STZ diabetes, kidney function appears to be improved with GT consumption which also prevents glycogen accumulation in the renal tubules, probably by lowering blood levels of glucose. Therefore, GT could be beneficial additional therapy in the management of diabetic nephropathy.

Green tea: Polyphenols: Diabetic nephropathy: Proximal tubules

Diabetes mellitus is characterised by hyperglycaemia, which has been strongly linked to diabetic complications such as neuropathy, retinopathy and nephropathy. Above all, diabetics are at augmented risk for end-stage renal disease consequent to diabetic nephropathy[1,2]. Stringent control of the hyperglycaemia by insulin treatment has been shown to avert hypertrophy and hyperfiltration and the subsequent rise in urinary protein excretion[3]. Clinical studies suggest that there is yet no completely effective treatment for diabetic nephropathy[4]. Hyperglycaemia is the principal factor responsible for structural alterations at the renal level and is directly linked to diabetic microvascular complications, particularly in the kidney[4]; therefore, glycaemic control remains the main target of treatment. Prevention of nephropathy is a very important concern and many studies have been focused on traditional and herbal medicines to find novel therapeutic agents for diabetic nephropathy.

Green tea (*Camellia sinensis*; GT) is a rich source of polyphenols, particularly flavonoids, which have been shown to have numerous pharmacological effects. Studies using animal models show that GT catechins could be beneficial in suppressing high-fat diet-induced obesity by modulating lipid metabolism and providing some protection against lipid and glucose metabolism disorders implicated in type 2 diabetes, and could reduce the risk of CVD[5–8]. Administration of GT catechins in streptozotocin (STZ) diabetic animals drastically improved kidney function as a result of its anti-thrombogenic action, which in turn controls the arachidonic acid cascade system[9]. These studies also demonstrated an improvement in the glomerular filtration rate[9–11]. Yokozawa *et al.* [12] examined variables of glomerular filtration in cisplatin (a nephropathy inducer)-treated rats and demonstrated that GT significantly decreased the blood N level, serum creatinine, serum malondialdehyde and kidney excretion of glucose and proteins and oxidative stress in the kidney[12]. Another study has shown that GT reduced serum glucose and creatinine levels and serum lipid peroxidation and increased serum superoxide dismutase, suggesting that catechins influence glucose metabolism and improve kidney function by reducing oxidative stress in alloxan-treated diabetic rats[13]. Moreover, GT catechins decreased plasma insulin levels but did not affect plasma glucose levels in an oral glucose tolerance test in normal rats[14]. In contrast, Mustata *et al.* have shown that GT drinking had a marginal effect on nephropathy

Abbreviations: Ccr, creatinine clearance; EGCG, (−)-epigallocatechin 3-*O*-gallate; GT, green tea; GTP, green tea polyphenols; PAS, periodic acid-Schiff; PHGG, partially hydrolysed guar gum; STZ, streptozotocin.

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parameters through improving renal mitochondrial defects; however, neither glycaemia nor urinary albumin were affected in GT-drinking diabetic animals[15]. These GT paradoxical effects on diabetic nephropathy animal models necessitate further studies to clarify the GT role on kidney function in the diabetic state. Accordingly, we tested the hypothesis that GT displays anti-diabetic properties on long-term follow up in the hypofiltration stage of STZ-treated diabetic animals. The effect of GT treatment on long-term (12 weeks) STZ-induced diabetic nephropathy was investigated by assessing serum and urine parameters indicative of nephropathy such as blood urea, N and serum creatinine, creatinine clearance (Ccr), urinary protein excretion and glycogen accumulation in kidney tubules.

Materials and methods

Animals

Male Sprague–Dawley rats (Kuwait Animal Laboratory Center Colony) weighing 200–230 g were cared for as outlined in the Guidelines for the Care and Use of Mammals in Neuroscience and Behavioural Research (Institute for Laboratory Animal Research 2003). Rats were housed (four or five animals per cage) in standard plastic cages with wood chip bedding. Bedding was changed daily for all animals to maintain sanitary conditions. The animals were kept in well-ventilated rooms with adjustable light–dark cycle and temperature regulation systems. The rooms and animal cages were cleaned daily, and all animals were provided with fresh food and water on a daily basis. They were also inspected daily for any possible signs of inflammation and respiratory or gastrointestinal infection. If such signs were present, the animal was excluded from the study.

Green tea extract preparation

GT extract was made as described previously[16]. Briefly, dried GT leaves were obtained from and packed in Sri Lanka (Swan brand, pure Ceylon tea; TC/E/PR/07/82; George Payne & Co. (Ceylon) Ltd, Colombo, Sri Lanka). The same quantity of GT was used in every preparation of the tea solution. Dried GT leaves (16 g) were added to 1 litre of deionised boiled water cooled to 80°C. The solution was kept to stand for 10 min before being filtered, cooled to room temperature, and dispensed in clean drinking bottles[17].

Experimental protocols and group treatments

Experimental rats (*n* 50) were injected intraperitoneally with STZ (75 mg/kg) (Sigma, St Louis, MO, USA) dissolved in 0·9 % saline[16]. STZ solutions were freshly prepared due to the limited stability of the compound[18]. Non-diabetic rats were studied of the same age as an onset control, to provide a starting value against which to judge any diabetes-induced damage.

Blood glucose levels were determined in all animals using an Encore Glucometer (Bayar, Elkhart, IN, USA) from blood samples obtained by tail vein bleeds. The presence of diabetes was verified at 24 h by the presence of hyperglycaemia and glucosuria (Visidex II and Diastix; Ames, Slough, Berks, UK). After 2 weeks of uncontrolled diabetes, rats with blood glucose levels ≥ 2500 mg/l (≥ 14 mM) were randomly divided into different diabetic groups as detailed in Table 1: diabetic groups (2 weeks, 6 weeks, 8 weeks and 12 weeks) (ten rats per group) were given water to drink; 12 weeks diabetic + GT group (ten rats) were given GT to drink for 12 weeks instead of water as described previously[16]; control normal groups (ten rats per group) were age-matched control animals and were injected (intraperitoneally) with an equal volume of 0·9 % saline (control vehicle) and given only water to drink. Water and GT bottles were made available to the animals *ad libitum*. The mean volume of GT extract intake was 122 (SEM 10·22) ml/d. At the end of the experiments, plasma glucose was estimated (GOD–Perid method; Boehringer Mannheim, Mannheim, Germany) on samples taken from the tail vein.

At the end of the experiments, blood samples were taken by cardiac puncture and used for the determination of blood urea N, serum creatinine levels and glucose (GOD–Perid method; Boehringer Mannheim). Serum glycosylated protein level was measured using the method of McFarland *et al.* [19]. The 24 h (before killing) urine was collected while rats were housed in metabolism cages and filtered for determination of urea N, glucose, protein and creatinine. Protein levels in freshly voided urine samples were assessed by the sulfosalicylic acid method[20]. Urea N and creatinine were determined

Table 1. Changes in body weight†
(Mean values with their standard errors)

		Final body weight (g)		Gain (g)	
Groups	No. of rats per group	Mean	SEM	Mean	SEM
Control 2 weeks	10	215·9	5·5	5·9	2·2
Diabetic 2 weeks	10	211·9	8·5	1·9	3·9
Control 6 weeks	10	287·5	6·5	77·5	4·5
Diabetic 6 weeks	10	239·5***	7	29·5***	4·9
Control 8 weeks	10	359·1	1·7	149·1	10·1
Diabetic 8 weeks	9	296·1***	13·5	86·1***	8·9
Control 12 weeks	10	544·5	26·3	334·5	20·1
Diabetic 12 weeks	8	331·2***	13·4	121·2***	9·5
Diabetic 12 weeks + green tea	10	343·9***	17·2	133·9***	14·2

*** Mean value was significantly different from that of normal control rats of comparable age ($P < 0·001$).
† Initial body weight for all animals was 210·0 (SEM 10·3) g.

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using the commercial test kits BUN Kainos and CRE-EN Kainos (Kainos Laboratory, Tokyo, Japan) and glucose by the Momose method[21]. The Ccr was calculated on the basis of urinary creatinine, serum creatinine, urine volume and body weight using the following equation as described previously[22]:

Ccr (ml/min per kg body weight) = (urinary creatinine (mg/l) × urinary volume (ml/d)/serum creatinine (mg/l) × (1000/body weight (g)) × (1/1440 (min)).

Specimen collection and histological staining

Respective groups (age-matched) of animals were killed after 2, 6, 8 and 12 weeks of the induction of diabetes[23]. The kidneys were gently removed after opening the abdominal cavity. The fresh kidneys were gently bisected longitudinally and immediately immersed (fixed) in labelled vials containing 10 % of buffered formalin and kept overnight. The segments were washed with distilled water. Then, the vials were filled with 70 % alcohol (Riedel-de Haen AG, Seelze, Germany) and kept at 4°C overnight. On the next day, the specimens were dehydrated by a graded series of alcohol and then treated with xylene (Univar; Ajax Chemicals, Auburn, NSW, Australia) for 1 h. The tissues were then placed in cassettes and placed in a hot paraffin wax container at 60°C overnight. On the next day, the tissues were embedded in paraffin using paraffin embedding apparatus (Jung Histoembedder; Leica, Wetzlar, Germany). The paraffin blocks were then sectioned transversely (4 μm thick) using a microtome (Jung Histocut; Leica). Sections were stained with haematoxylin and eosin stains. Some sections from diabetic animals were stained with periodic acid-Schiff (PAS) and PAS-diastase special stains in order to verify that the areas of the tubules that showed clear cytoplasm were due to the accumulation of glycogen. The PAS stain was strongly positive and the PAS-diastase was also positive for cells with clear cytoplasm.

Quantification of glycogen-filled proximal tubules

For morphometric analysis, ten sections from each block (two blocks (right and left kidneys) from each rat) were subjected to quantitative analysis. Sections from the eight to ten rats in each group were quantified. Random light microscopic fields were digitally photographed from the kidney tissues to count the clear tubules using objective lens power 40 × .

Data analysis

A one-way ANOVA was applied to assess significant differences between the mean values of the number of clear cytoplasm tubules found in controls, untreated and GT-treated diabetic rat groups. The *post hoc* Scheffe *F* and LSD tests were performed to determine individual probability values for comparisons between groups using SPSS software (SPSS, Inc., Chicago, IL, USA). The results are presented as mean values with their standard errors and the graph drawn using SPSS software. Data collected from the blood and urine samples were analysed by one-way ANOVA followed by the *post hoc* Scheffe *F* test using SPSS software to determine the significant differences between the groups. All data are presented as mean values with their standard errors. A difference among the means at $P<0{\cdot}05$ was considered statistically significant.

Results

Changes in body weight

The average body weight of animals with diabetes was significantly lower than that of the normal control rats of comparable age (Table 1). Likewise, the body weights of the diabetic rats treated with GT were significantly ($P<0{\cdot}001$) lower than the normal control group. There was no significant difference between the mean body weights of the untreated diabetic group compared with GT-treated groups. The average gains in body weight were similar in untreated and GT-treated animals after 12 weeks of diabetes. These weight gains were 36·2 (SEM 2·8) and 34·6 (SEM 4·93) %, respectively.

The effect of green tea on glucose and glycosylated protein levels in serum

Table 2 shows the effect of GT consumption on the levels of serum glucose and glycosylated protein. In all diabetic treated and untreated animals, the serum glucose and glycosylated protein levels were significantly ($P<0{\cdot}001$) elevated compared with normal control rats. However, diabetic rats treated with GT showed a significant reduction in both serum glucose ($P<0{\cdot}01$) and glycosylated protein ($P<0{\cdot}05$) when compared with other diabetic groups. The level of serum glucose was lower in the GT-treated rats. This reduction was approximately 29·6 (SEM 3·7) %. Likewise, serum glycosylated protein levels

Table 2. The effect of green tea (GT) on glucose and glycosylated protein in serum (Mean values with their standard errors)

	Glucose (mg/l)		Glycosylated protein (nmol/mg protein)	
Groups	Mean	SEM	Mean	SEM
Control 12 weeks (*n* 10)	908	149	17·8	1·13
Diabetic 2 weeks (*n* 10)	4958***	309	29·1***	0·98
Diabetic 6 weeks (*n* 10)	5176***	333	29·5***	1·9
Diabetic 8 weeks (*n* 9)	5905***	271	28·90***	2·1
Diabetic 12 weeks (*n* 8)	5736***	333	32·10***	2·9
Diabetic 12 weeks + GT (*n* 10)	4037***††	212	24·87†	1·67

*** Mean value was significantly different from that of the control group ($P<0{\cdot}001$).
Mean value was significantly different from those of the diabetic groups: † $P<0{\cdot}05$, †† $P<0{\cdot}01$.

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were lower in GT-treated rats. The serum glycosylated protein level was 22·7 (SEM 5·2) % lower than in the diabetic group of comparable age.

The effect of green tea on blood urea nitrogen, serum creatinine and creatinine clearance

Table 3 shows the effects of GT treatment on serum parameters under conditions of diabetes. The blood urea N level was significantly higher ($P<0·001$) in 12-week diabetic animals than control rats of the same age (148 (SEM 19) mg/l); whereas it was significantly lower ($P<0·01$) in the GT rats. This reduction was 41·7 (SEM 1·9) %. The serum creatinine level was significantly ($P<0·001$) higher in rats with diabetes in comparison with normal control rats of the same age (Table 3). Those diabetic animals given GT showed a non-significant difference in creatinine level compared with the 12-week diabetic rats ($P<0·10$). This reduction was 38·9 (SEM 10) %. On the other hand, all diabetic groups, treated or untreated, showed significantly ($P<0·001$) lower Ccr than the normal control animals. The GT-treated group showed a significant ($P<0·05$) higher Ccr than that in untreated diabetic rats. This increase was 44 (SEM 10·8) %.

The effect of green tea on glucose, protein, urea nitrogen and creatinine excreted in urine

Table 3 shows the effects of GT on the urinary function of diabetic animals. The glucose, protein, urea N and creatinine excretion rates were increased significantly ($P<0·001$) (1·70-, 3·29-, 1·95- and 1·59-fold, respectively) in 12-week diabetic compared with normal control rats. After oral administration of GT, urinary urea N excretion was significantly lower ($P<0·01$) compared with that in the 12-week diabetic group. Urea N decreased 30 (SEM 7·6) % in the 12 weeks diabetic rats compared with GT-treated animals. Likewise, creatinine, glucose and protein excretion declined 35·4 (SEM 5·3), 34·0 (SEM 5·3) and 46·0 (SEM 13·0) % in GT-treated animals compared with 12-week diabetic rats (Table 3).

Histopathological changes

Histological examination of the normal control kidney tissues showed normal kidney histology (Fig. 1 (A)). Haematoxylin and eosin sections examined under light microscopy showed that all the kidneys of the diabetic rats had multifocal areas of tubules with clear cytoplasm (Fig. 1 ((B)–(D)). Special PAS (Fig. 1 (E)) and PAS followed by diastase staining showed that the clear cytoplasm corresponded to glycogen accumulation. The PAS stain was strongly positive in 6-week- and 12-week-long diabetes and the PAS diastase effectively cleared the PAS stain indicating glycogen accumulation in the tubules of diabetic kidneys. Examples of 2, 6 and 12 weeks diabetic kidney tissues clearly show a gradual increase in the number of glycogen-filled tubules which was significantly decreased compared with normal control values in the GT-treated diabetic nephropathy group (Fig. 1). The number of tubules filled with glycogen per field in the diabetic kidneys was increased with time from zero to 25·5 (SEM 2·01) at 12 weeks (Fig. 2). This increase was significantly ($P<0·001$) higher compared with normal control animals. The number

Table 3. The effect of green tea (GT) on serum and urine kidney functional parameters (Mean values with their standard errors)

Groups	Serum urea N (mg/l)		Urine urea N (mg/d)		Serum creatinine (mg/d)		Urine creatinine (mg/d)		Urine glucose (mg/d)		Urine protein (mg/d)		Creatinine clearance (ml/kg BW per min)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Control 2 weeks (*n* 10)	148	19	261	45	0·33	0·13	7·34	0·50	3·49	0·71	20·9	2·1	7·04	0·47
Diabetic 2 weeks (*n* 10)	428***	36	474***	56	0·83***	0·19	8·69*	0·78	5·70***	0·50	69·40***	8·97	4·8***	0·26
Diabetic 6 weeks (*n* 10)	481***	25	496***	32	0·96***	0·29	10·30***	0·9	5·36***	0·59	85·62***	13·4	3·92***	0·40
Diabetic 8 weeks (*n* 9)	489***	39	515***	51	0·94***	0·10	10·89***	0·88	6·04***	0·64	82·90***	7·9	3·65***	0·22
Diabetic 2 weeks (*n* 8)	465***	41	510***	44	0·90***	0·19	11·60***	1·19	5·89***	0·53	89·60***	9·29	3·25***	0·39
Diabetic 12 weeks + GT (n 10)	270·9***††	19	360***†	39	0·55***‡	0·09	7·49††	0·61	3·89††	0·31	48·39***†	11·6	4·69***†	0·35

BW, body weight.
Mean value was significantly different from that of the control group: * $P<0·05$, *** $P<0·001$.
Mean value was significantly different from those of the diabetic groups: † $P<0·05$, †† $P<0·01$.
‡ Mean value was marginally significantly different from those of the diabetic groups ($P<0·10$).

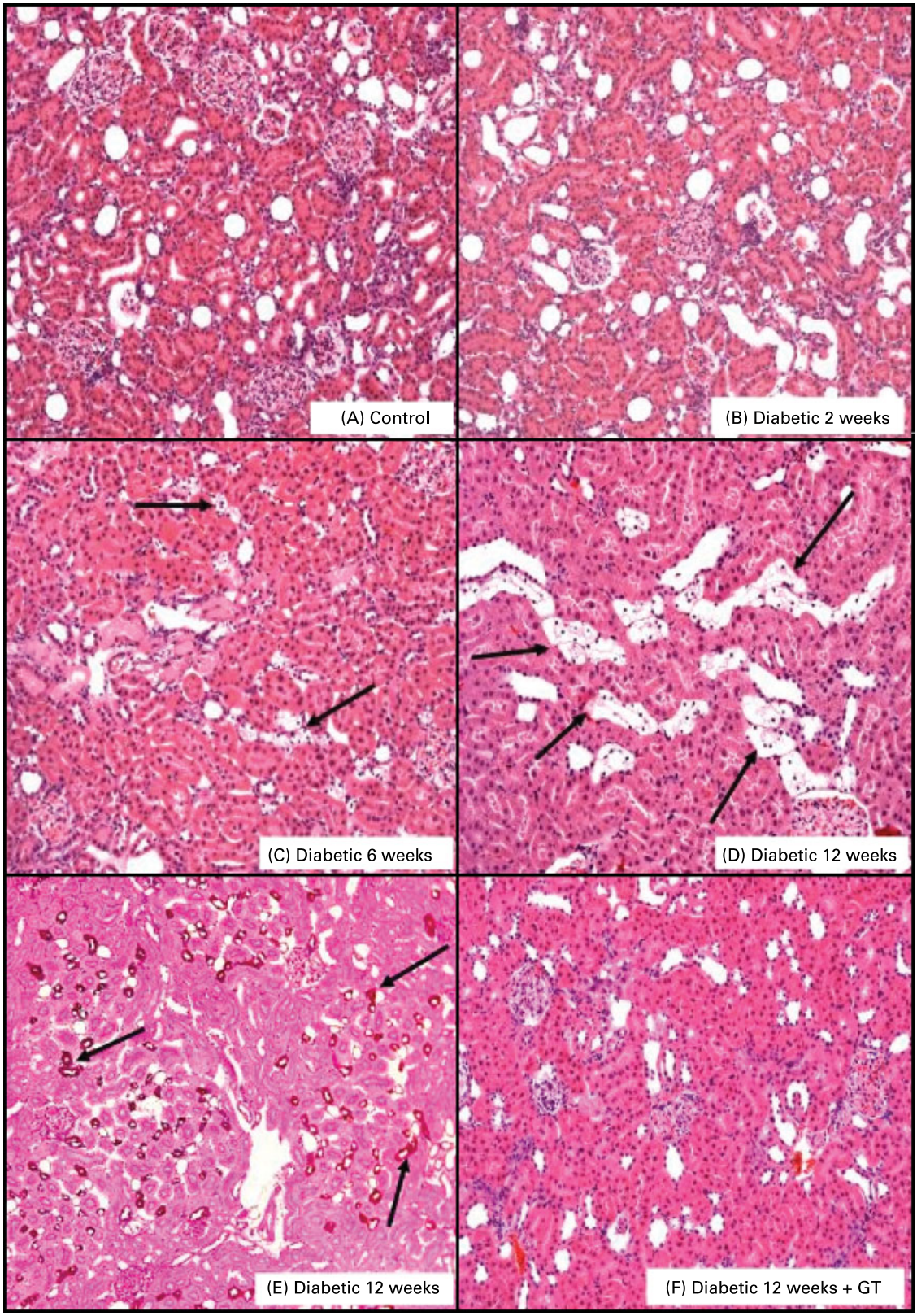

Fig. 1. Representative light microscopic photographs of proximal tubules showing the effect of green tea (GT) extract treatment on diabetic nephropathy. (A) Control normal kidney section showing normal proximal tubule epithelium with eosinophilic and granular cytoplasm (haematoxylin and eosin (H&E); × 100). (B), (C) and (D) Kidney sections from 2-, 6- and 12-week diabetic nephropathy rats showing a gradual increase in the number of glycogen-filled proximal tubules (→). The 12-week diabetic section shows the highest level of glycogen accumulation in the proximal tubules (H&E; B and C: × 100; D: × 200). (E) Tissue section from 12-week diabetic kidney stained by special periodic acid-Schiff stain for the glycoprotein showing strong positive staining (→) in the lining of epithelium of the proximal tubules (× 40). (F) GT extract treatment of diabetic animals for 12 weeks significantly decreased the number of glycogen-filled proximal tubules to zero level which was seen in the control normal animals of comparable age (H&E; × 100).

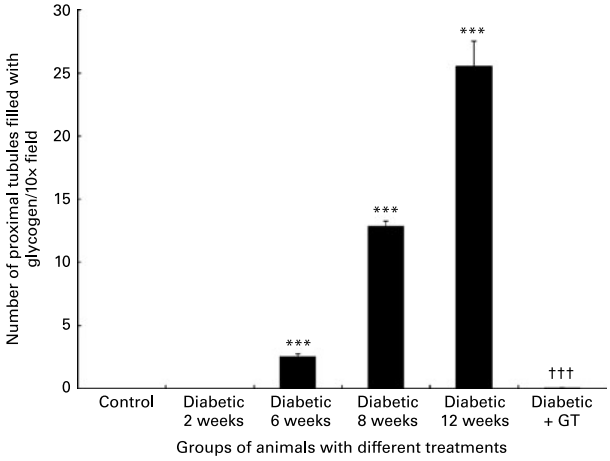

Fig. 2. Quantitative analysis of the number of proximal tubules filled with glycogen/field in the kidney sections. Note the significant steady increase in the number of the proximal tubules filled with glycogen in 6-, 8- and 12-week diabetic kidneys compared with the normal control group. The green tea (GT) treatment of diabetic rats significantly decreased the number of proximal tubules filled with glycogen to zero level compared with diabetic untreated animals. Values are means, with standard errors of difference indicated by vertical bars. *** Mean value was significantly different from that of normal control rats ($P<0{\cdot}001$). ††† Mean value was significantly different from that of 6-, 8- and 12-week diabetic groups ($P<0{\cdot}001$).

of glycogen-filled tubules ($P<0{\cdot}001$) decreased almost completely in GT-treated kidneys (Fig. 2). This decrease was 99·98 (SEM 0·27) %.

Discussion

The present results indicate that GT decreases glucose levels and renal injury associated with abnormal glucose-related oxidative stress in diabetic nephropathy. Furthermore, the present study shows a beneficial effect of GT on renal histochemical parameters, as it significantly prevented the accumulation of glycogen in the kidney tubules. It also reduced the serum levels of glucose, glycosylated proteins and creatinine and blood urea N levels compared with those in the untreated diabetic group of comparable age. In addition, the GT-treated group showed a significant increase in Ccr value and reduced creatinine and protein excretion. A progressive reduction in the glomerular filtration rate, reflected in increased serum creatinine and reduced Ccr levels, is the most common characteristic in the development of diabetic nephropathy, which in addition causes proteinuria and leads to histological changes in the kidney. This decrease in GFR is believed to be a result of changes in glomerular haemodynamic instigated by glomerulosclerosis[24,25]. The results of the present study demonstrate that rats with diabetic nephropathy showed significant increases in the blood urea N, serum creatinine, and urinary protein excretion rate, whereas the Ccr level decreased compared with that in normal rats, representing a decline in renal function. However, the GT treatment significantly improved these parameters.

Hyperglycaemia is the principal factor responsible for structural alterations at the renal level, and The Diabetes Control and Complications Trial Research Group[4] has made it clear that hyperglycaemia is directly associated with diabetic microvascular complications, particularly in the kidney. Consequently, glycaemic control remains one of the main targets of therapy. In the present study, the serum and urine glucose levels of diabetic rats showed approximately 3- and 1·6-fold increases, respectively, and GT consumption reduced these increases by 30 and 35 %, respectively. In support of the present results, recent reports have shown that (−)-epigallocatechin 3-*O*-gallate (EGCG) reduced the level of mRNA for gluconeogenesis enzymes[26] and caused many similar effects to insulin, including repression of glucose production and phosphoenolpyruvate carboxykinase and glucose-6-phosphatase gene expression in cells[27]. Likewise, Yokozowa *et al.* [22] have recently shown that GT polyphenols (GTP) and partially hydrolysed guar gum (PHGG) decreased blood glucose levels and attenuated the urinary protein excretion and morphological changes characteristic of diabetic nephropathy when renal dysfunction was already evident. Furthermore, the combination of GTP and PHGG reduced kidney weight, levels of blood urea N and serum creatinine and increased Ccr in diabetic animals. Hyperglycaemia, as assessed by blood glucose and glycosylated protein levels, was reduced by administration of GTP plus PHGG[22]. In line with the present study, several studies have also shown that the control of postprandial hyperglycaemia by GT can help reduce the risk of type 2 diabetes and provide evidence that GT promotes glucose metabolism in healthy humans, and produces an antihyperglycaemic effect in diabetic mice[28–30]. Indeed, Wu *et al.* [29] have shown that GT supplementation for 12 weeks improves insulin resistance and increases GLUT IV content in a fructose-fed rat model, resembling human type 2 diabetes mellitus[29]. In contrast, Mustata *et al.* [15] have recently shown that GT had marginal effects on nephropathy parameters but suppressed renal mitochondrial NADH-linked, ADP-dependent and dinitrophenol-dependent respiration and complex III activity in the STZ diabetic Lewis rat. In addition, GT did not induce any significant decrease in glomerular collagen IV, glomerular staining for redox active Fe and tubular Fe staining[15]. The failure to develop dramatic alterations in renal parameters may be related to the moderate hyperglycaemia and urinary albumin of these rats. These contradictory reports could result from differences in: (1) diabetic models, (2) animal strains, (3) STZ dosages resulting in mild *v.* severe hyperglycaemia and proteinuria and/or (4) insulin treatment used by different investigators.

Proteinuria is quantitatively related to the degree of nephropathy in patients with diabetes. The increased urinary protein excretion results from lesions in the glomerular filtration barrier. The present study shows that in comparison with normal rats, animals with diabetic nephropathy show increased urinary excretion of protein and that administration of GT reduced the degree of proteinuria which is in agreement with previously reported results that showed GTP, PHGG and GTP plus PHGG[22] and EGCG treatment[30] significantly reduced the extent of proteinuria. Likewise, the present study reveals that GT consumption significantly decreased the serum glycosylated protein levels in diabetic animals. These data also suggest that GT minimises the development of glomerular and tubulointerstitial injuries. In addition, diabetic animals used in the present study confirmed the presence of glomerular hypertrophy and diffuse and exudative lesions (data not

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shown) reported by Yamabe *et al.* [30] which also correlate with proteinuria. In addition, the decrease in total protein as a result of their excessive excretion via urine, and also an increase in lipids, whose abnormal metabolism has been proven to play a role in the pathogenesis of diabetic nephropathy and to enhance lipid peroxidation, were all improved by administration of the EGCG[30]. As a result, we contemplate that EGCG[30], GTP[22] or GT consumption (in the present study) has a positive effect on blood glucose and lipid metabolic abnormalities.

Recently, it has been shown that a key morphological change associated with sustained hyperglycaemia was accumulation of glycogen granules in about half of the distal tubules and thin segment, starting at 1 month after alloxan induction of diabetes in experimental rats, which was extended to about half of the proximal tubules at 6 months[31]. Abnormal glycogen deposits were first observed in the collecting ducts and the descending limb of Henle's loop in diabetic patients by Armanni and Ebstein[32], respectively. However, since then little attention has been paid to the accumulation of glycogen granules in renal tubules in humans with diabetes. In agreement with our observations, Nannipeiri *et al.* [33] observed glycogen granules in both proximal and distal renal tubules in 9-month diabetic rats. Glycogen accumulation in the distal renal tubules was also observed by means of PAS staining on paraffin sections, electron microscopy, biochemical assays or enzyme-gold cytochemistry[34–37]. It appears that in chronic untreated diabetes, prolonged hyperglycaemia is the sole driving force for glycogen accumulation. Thus we speculate that the longer diabetes is prolonged, the more glycogen might accumulate and spread into the renal tubules, and GT reverses this pathological phenomenon. Nevertheless, it is not yet clear whether glycogen accumulation in renal tubules is an inevitable change in the diabetic condition in humans, whether it is an early-phase pathogenesis that will contribute to the end-stage diabetic nephropathy, whether it is always associated with the end-stage nephropathy, or whether it plays a role in inducing a pathway leading to the pathophysiological changes of diabetic nephropathy[38,39].

Glucose is reabsorbed almost completely by the proximal tubules and begins to appear in the urine when the renal threshold is exceeded. The present study has shown that STZ-induced diabetic nephropathy leads to the accumulation of glycogen in the renal tubules indicating an abnormal reabsorption process of glucose or malfunctioning in transporting the reabsorbed glucose back into the blood capillaries which in turn leads to the appearance of glucose in the urine. However, GT treatment of diabetic rats prevented glucose accumulation to zero level, indicating that GT may be able to restore the normal function of the proximal tubules in reabsorbing glucose from the urine back into the blood circulation. Likewise, EGCG was shown to protect Madin–Darby canine kidney tubular cells from cellular injury and apoptosis caused by oxidative stress[40]. Recently, GT extract and its constituent polyphenols have also been shown to suppress cell death in a porcine renal proximal tubular cell line (LLC-PK1 cells) caused by the addition of nephrotoxic immunosuppressant FK506[41]. These results suggested that GT extract polyphenols and its constituents affect cell viability synergistically. It appears that the nephrotoxicity of drugs and their metabolites is often manifested as proximal tubule disorders, which result in the release of enzymes held in the proximal tubules. Moreover, GT reduced the urinary activity of renal tubular epithelial-cell enzymes, which are an index of renal tubular injury[42].

In conclusion, the present study demonstrated that GT extract provides a beneficial effect on long-term diabetic nephropathy via suppressing hyperglycaemia and preventing glycogen accumulation in the proximal tubules. The therapeutic property of GT seems propitious in improving kidney nephropathy by significantly improving serum and urine parameters. These findings support the importance of controlling blood glucose levels and maybe slowing or even reversing some of the early pathologies of diabetic nephropathy. However, further studies should be done in order to understand the exact cellular and molecular mechanisms which mediate such effects of GT action on proximal tubules and how GT reduces the accumulation of glycogen in the proximal tubules as well as its potential therapeutic implications against renal damage associated with diabetic nephropathy.

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References

1. Selby JV, FitzSimmons SC, Newman JM, Katz PP, Sepe S & Showstack J (1990) The natural history and epidemiology of diabetic nephropathy. Implications for prevention and control. *JAMA* **263**, 1954–1960.
2. Held PJ, Port FK, Webb RL, Wolfe RA, Garcia JR, Blagg CR & Agodoa LY (1991) The United States Renal Data System's 1991 annual data report: an introduction. *Am J Kidney Dis* **18**, 1–16.
3. Rasch R (1980) Prevention of diabetic glomerulopathy in streptozotocin diabetic rats by insulin treatment. Albumin excretion. *Diabetologia* **18**, 413–416.
4. Anonymous (1993) The effect of intensive treatment of diabetes on the development and progression of long-term complications in insulin-dependent diabetes mellitus. The Diabetes Control and Complications Trial Research Group. *N Engl J Med* **329**, 977–986.
5. Matsumoto N, Ishigaki F, Ishigaki A, *et al.* (1993) Reduction of blood glucose levels by tea catechin. *Biosci Biotechnol Biochem* **57**, 525–527.
6. Nakachi K, Matsuyama S, Miyake S, Suganuma M & Imai K (2000) Preventive effects of drinking green tea on cancer and cardiovascular disease: epidemiological evidence for multiple targeting prevention. *Biofactors* **13**, 49–54.

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7. Murase T, Nagasawa A, Suzuki J, Hase T & Tokimitsu I (2002) Beneficial effects of tea catechins on diet-induced obesity: stimulation of lipid catabolism in the liver. *Int J Obes Relat Metab Disord* **26**, 1459–1464.
8. Crespy V & Williamson G (2004) A review of the health effects of green tea catechins in *in vivo* animal models. *J Nutr* **134**, 3431S–3440S.
9. Yang JA, Choi JH & Rhee SJ (1999) Effects of green tea catechin on phospholipase A2 activity and antithrombus in streptozotocin diabetic rats. *J Nutr Sci Vitaminol* **45**, 337–346.
10. Rhee SJ, Kim MJ & Kwag OG (2002) Effects of green tea catechin on prostaglandin synthesis of renal glomerular and renal dysfunction in streptozotocin-induced diabetic rats. *Asia Pac J Clin Nutr* **11**, 232–236.
11. Rhee SJ, Choi JH & Park MR (2002) Green tea catechin improves microsomal phospholipase A2 activity and the arachidonic acid cascade system in the kidney of diabetic rats. *Asia Pac J Clin Nutr* **11**, 226–231.
12. Yokozawa T, Nakagawa T, Lee KI, Cho EJ, Terasawa K & Takeuchi S (1999) Effects of green tea tannin on cisplatin-induced nephropathy in LLC-PK1 cells and rats. *J Pharm Pharmacol* **51**, 1325–1331.
13. Sabu MC, Smitha K & Kuttan R (2002) Anti-diabetic activity of green tea polyphenols and their role in reducing oxidative stress in experimental diabetes. *J Ethnopharmacol* **83**, 109–116.
14. Wu LY, Juan CC, Ho LT, Hsu YP & Hwang LS (2004) Effect of green tea supplementation on insulin sensitivity in Sprague-Dawley rats. *J Agric Food Chem* **52**, 643–648.
15. Mustata GT, Rosca M, Biemel KM, *et al.* (2005) Paradoxical effects of green tea (*Camellia sinensis*) and antioxidant vitamins in diabetic rats: improved retinopathy and renal mitochondrial defects but deterioration of collagen matrix glycoxidation and cross-linking. *Diabetes* **54**, 517–526.
16. Renno WM, Saleh F, Klepacek I, Al-Khaledi G, Ismael H & Asfar S (2006) Green tea pain modulating effect in sciatic nerve chronic constriction injury rat model. *Nutr Neurosci* **9**, 41–47.
17. Jankun J, Selman SH, Swiercz R & Skrzypczak-Jankun E (1997) Why drinking green tea could prevent cancer. *Nature* **387**, 561.
18. Rakieten N, Rakieten ML & Moreshwar VN (1963) Studies on the diabetogenic action of streptozotocin (NSC-37917). *Cancer Chemother Rep* **29**, 91–98.
19. McFarland KF, Catalano EW, Day JF, Thorpe SR & Baynes JW (1979) Nonenzymatic glycosylation of serum proteins in diabetic mellitus. *Diabetes* **28**, 1011–1014.
20. Sakagishi Y (1968) Total protein. In *Rinsho Kagaku Bunseki II*, pp. 115–142 [M Saito, M Kitamura and M Niwa, editors]. Tokyo: Tokyo Kagaku Dojin.
21. Momose T, Yano Y & Ohashi K (1963) Organic analysis XLIV. A new deproteinizing agent for determination of blood sugar. *Chem Pharm Bull* **11**, 968–972.
22. Yokozawa T, Nakagawa T, Oya T, Okubo T & Juneja LR (2005) Green tea polyphenols and dietary fibre protect against kidney damage in rats with diabetic nephropathy. *J Pharm Pharmacol* **57**, 773–780.
23. Holson RR (1992) Euthanasia by decapitation: evidence that this technique produces prompt, painless unconsciousness in laboratory rodents. *Neurotoxicol Teratol* **14**, 253–257.
24. Yokozawa T, Nakagawa T, Wakaki K & Koizumi F (2001) Animal model of diabetic nephropathy. *Exp Toxicol Pathol* **53**, 359–363.
25. Brenner BM, Meyer TW & Hostetter TH (1982) Dietary protein intake and the progressive nature of kidney disease: the role of hemodynamically mediated glomerular injury in the pathogenesis of progressive glomerular sclerosis in aging, renal ablation, and intrinsic renal disease. *N Engl J Med* **307**, 652–659.
26. Koyama Y, Abe K, Sano Y, Ishizaki Y, Njelekela M, Shoji Y, Hara Y & Isemura M (2004) Effects of green tea on gene expression of hepatic gluconeogenic enzymes *in vivo*. *Planta Med* **70**, 1100–1102.
27. Waltner-Law ME, Wang XL, Law BK, Hall RK & Nawano M (2002) Epigallocatechin gallate, a constituent of green tea, represses hepatic glucose production. *J Biol Chem* **277**, 34933–34940.
28. Tsuneki H, Ishizuka M, Terasawa M, Wu JB, Sasaoka T & Kimura I (2004) Effect of green tea on blood glucose levels and serum proteomic patterns in diabetic (db/db) mice and on glucose metabolism in healthy humans. *BMC Pharm* **4**, 18.
29. Wu LY, Juan CC, Hwang LS, Hsu YP, Ho PH & Ho LT (2004) Green tea supplementation ameliorates insulin resistance and increases glucose transporter IV content in a fructose-fed rat model. *Eur J Nutr* **43**, 116–124.
30. Yamabe N, Yokozawa T, Oya T & Kim M (2006) Therapeutic potential of (−)-epigallocatechin 3-*O*-gallate on renal damage in diabetic nephropathy model rats. *J Pharm Exper Therap* **319**, 228–236.
31. Kang J, Dai XS, Yu TB, Wen B & Yang ZW (2005) Glycogen accumulation in renal tubules, a key morphological change in the diabetic rat kidney. *Acta Diabetol* **42**, 110–116.
32. Ebstein W (1882) Weiteres über Diabetes mellitus, insbesondere über die Complication desselben mit *Typhus abdominalis* (More about diabetes mellitus, in particular more about the complication of the same with *Typhus abdominalis*). *Deutsckes Arch Klin Med* **30**, 1–44.
33. Nannipeiri M, Lanfranchi A, Santerini D, Catalaneo C, Van de Wrve G & Ferrannini E (2001) Influence of long-term diabetes on renal glycogen metabolism in the rat. *Nephron* **87**, 50–57.
34. Rasch R & Gotzsche O (1988) Regression of glycogen nephrosis in experimental diabetes after pancreatic islet transplantation. *APMIS* **96**, 749–775.
35. Thomson KJ, Saunders NJ, Simpson JG & Whiting PH (1989) Renal structure and function in streptozotocin-diabetic rats treated with cyclosporine A. *Br J Exp Pathol* **70**, 405–414.
36. Holck P & Rasch R (1993) Structure and segmental localization of glycogen in the diabetic rat kidney. *Diabetes* **42**, 891–900.
37. Rasch R, Torffvit O, Bachmann S, Jensen PK & Jacobsen NO (1995) Tamm-Horsfall glycoprotein in streptozotocin diabetic rat: a study of kidney *in situ* hybridization, immunohistochemistry, and urinary excretion. *Diabetolgia* **38**, 525–535.
38. Raptis AE & Viberti G (2001) Pathogenesis of diabetic nephropathy. *Exp Clin Endocrinol Diabetes* **109**, Suppl. 2, S424–S437.
39. Caramori ML & Mauer M (2003) Diabetes and nephropathy. *Curr Opin Nephrol Hypertens* **12**, 273–282.
40. Itoh Y, Yasui T, Okada A, Tozawa K, Hayashi Y & Kohri K (2005) Examination of the anti-oxidative effect in renal tubular cells and apoptosis by oxidative stress. *Urol Res* **33**, 261–266.
41. Hisamura F, Kojima-Yuasa A, Kennedy DO & Matsui-Yuasa I (2006) Protective effect of green tea extract and tea polyphenols against FK506-induced cytotoxicity in renal cells. *Basic Clin Pharm Toxicol* **98**, 192–196.
42. Jeong BC, Kim BS, Kim JI & Kim HH (2006) Effects of green tea on urinary stone formation: an *in vivo* and *in vitro* study. *J Endourol* **20**, 356–361.

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