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## Relationship between PPAR $\alpha$ activation and NO on proximal tubular Na<sup>+</sup> transport in the rat

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### Abstract

**Background:** Nitric oxide (NO) regulates renal proximal tubular (PT) Na<sup>+</sup> handling through modulation of Na<sup>+</sup>-K<sup>+</sup> ATPase. Peroxisome Proliferator Activated Receptor $\alpha$  (PPAR $\alpha$ ), a nuclear transcription factor, is expressed in PTs and has been reported to influence NO generation/activity in renal tissues. This study tested the hypothesis that PPAR $\alpha$  interacts with NO and thereby affects renal tubular Na<sup>+</sup> transport. Urinary excretion of nitrite (UNO<sub>x</sub>V) and Na<sup>+</sup> (U<sub>Na</sub>V) and PT Na<sup>+</sup> transport (Na<sup>+</sup>-K<sup>+</sup> ATPase activity) were determined in rats treated with clofibrate (250 mg/kg i.p) or WY14643 (45 mg/kg; i.p.), a PPAR $\alpha$  ligand, 2% NaCl (orally), clofibrate/NaCl, L-NAME, an inhibitor of NO production (100 mg/kg; orally), L-NAME/Clofibrate.

**Results:** Clofibrate or WY14643 increased PPAR $\alpha$  expression by 106  $\pm$  7% ( $p < 0.05$ ) and 113  $\pm$  8% ( $p < 0.05$ ), respectively. Similarly, clofibrate and WY14643 increased expression of MCAD, a downstream target protein of PPAR $\alpha$  by 123  $\pm$  8% ( $p < 0.05$ ) and 143  $\pm$  8% ( $p < 0.05$ ), respectively. L-NAME attenuated clofibrate-induced increase in PPAR $\alpha$  expression by 27  $\pm$  2% ( $p < 0.05$ ) but did not affect MCAD expression. UNO<sub>x</sub>V excretion increased 3–4 fold in rats treated with clofibrate, WY14643 or NaCl from 44  $\pm$  7 to 170  $\pm$  15, 144  $\pm$  18 or 132  $\pm$  11 nmol/24 hr, respectively ( $p < 0.05$ ). Similarly, clofibrate, WY14643 or NaCl elicited a 2–5 fold increase in U<sub>Na</sub>V. L-NAME significantly reduced basal UNO<sub>x</sub>V and U<sub>Na</sub>V and abolished the clofibrate-induced increase. Clofibrate, WY14643, NaCl or clofibrate + NaCl treatment reduced Na<sup>+</sup>-K<sup>+</sup>-ATPase activity in the PT by 89  $\pm$  23, 62  $\pm$  10, 43  $\pm$  9 and 82  $\pm$  15% ( $p < 0.05$ ), respectively. On the contrary, L-NAME or ODQ, inhibitor of sGC, abolished the inhibition of Na<sup>+</sup>-K<sup>+</sup>-ATPase activity by clofibrate ( $p < 0.05$ ). Clofibrate either alone or with NaCl elicited ~2-fold increase in the expression of the  $\alpha$ 1 subunit of Na<sup>+</sup>-K<sup>+</sup> ATPase in the PT while L-NAME abolished clofibrate-induced increase in Na<sup>+</sup>-K<sup>+</sup> ATPase expression.

**Conclusion:** These data suggest that PPAR $\alpha$  activation, through increased NO generation promotes renal excretion of Na<sup>+</sup> through reduced Na<sup>+</sup>-K<sup>+</sup> ATPase activity in the PT probably via post translational modification of Na<sup>+</sup>-K<sup>+</sup>-ATPase.

### Background

The proximal tubule (PT) is a major player in the maintenance of salt and water hemostasis as it accounts for the

absorption of approximately 70% Na<sup>+</sup> and water-filtered load [1]. The PT epithelial cells are highly enriched in Na<sup>+</sup>-K<sup>+</sup> ATPase that is located at the basolateral domain of

epithelial cells and provides the driving force for active sodium and potassium translocation and for the secondary active transport of other solutes across the renal tubules. It consists of  $\alpha$  ( $\alpha_1$ - $\alpha_4$ ),  $\beta$  ( $\beta_1$ - $\beta_3$ ) and  $\gamma$  ( $\gamma_1$  &  $\gamma_2$ ) subunits of which the  $\alpha_1$  isoform represents the major  $\text{Na}^+$ -transporting system [2]. In different species and tissues, the renal  $\text{Na}^+$ - $\text{K}^+$  ATPase activity is regulated tightly by complex multi hormonal mechanisms and intracellular second messengers to maintain plasma electrolytes during dietary and pathological fluctuation of electrolytes and pH [1,3]. Such regulation involves the activation of distinct hormone- and tissue-specific intracellular signaling molecules such as protein kinase C (PKC) and protein kinase A (PKA) [4,5].

Nitric oxide (NO) is a key paracrine and autocrine regulator of physiological function in a number of organs including the kidney and NO has been reported to inhibit the  $\alpha_1$  isoform of  $\text{Na}^+$ - $\text{K}^+$  ATPase in the PT probably via activation of PKC, or by inhibition of PKA [6-8]. The three isoforms of NO synthase (NOS) enzyme are differentially expressed throughout the kidney with the iNOS isoform expressed in the PT accounting for NO production in this segment [9-11].

Peroxisome Proliferator Activated Receptors (PPARs) constitute a subfamily of the nuclear receptor super-family which are activated by natural ligands such as fatty acids and eicosanoids [12-14]. PPARs regulate gene expression through binding with retinoic acid receptor (RXR) to specific DNA sequence elements termed PPAR response elements (PPREs) or by interfering with other transcription factor pathways in a DNA binding-independent manner [15,16]. Of the three PPARs, namely PPAR $\alpha$ ,  $\beta$  and  $\gamma$ , only the PPAR $\alpha$  stimulates the  $\beta$ -oxidative degradation of fatty acids, resulting in high yield of ATP production and playing an essential role in supporting kidney reabsorptive functions [17,18]. Fatty acid  $\beta$ -oxidation occurs in the kidney peroxisomes which are found exclusively in the PT of the nephron and ranks among the largest peroxisomes known in different cell types [19,20]. PPAR $\alpha$  is highly expressed in the rat kidney PT as well as in other nephron segments but its functional role remains unclear [21,22]. Based on the co-expression of PPAR $\alpha$  and iNOS in the PT and the fact that PPAR $\alpha$  activation modulates the production of NO in non renal cells, we tested the hypothesis that PPAR $\alpha$  activators regulate renal tubular  $\text{Na}^+$  transport by modulating PT  $\text{Na}^+$ - $\text{K}^+$ -ATPase activity via NO production [23].

In this study, we employed NaCl loading as a stimulant for NO production [24] and investigated the effect of clofibrate and WY14643, PPAR $\alpha$  activators, on renal NO production and  $\text{Na}^+$ - $\text{K}^+$  ATPase activity in the freshly isolated renal proximal tubular cells of the rat.

## Results

Fifty five age and weight-matched male Sprague-Dawley rats were used in this study. Initial body weights of the animals were  $194 \pm 6$ ,  $191 \pm 3$ ,  $198 \pm 4$ ,  $195 \pm 3$ ,  $201 \pm 3$ ,  $199 \pm 4$ , and  $199 \pm 6$  g for the control, clofibrate, NaCl, clofibrate/NaCl, L-NAME, Clofibrate/L-NAME and WY14643 groups, respectively. After the treatment, body weights were unchanged except in the control group where the weight slightly increased by  $12 \pm 1$  % ( $p < 0.05$ ) to  $218 \pm 6$  g.

### PPAR $\alpha$ and MCAD protein expression

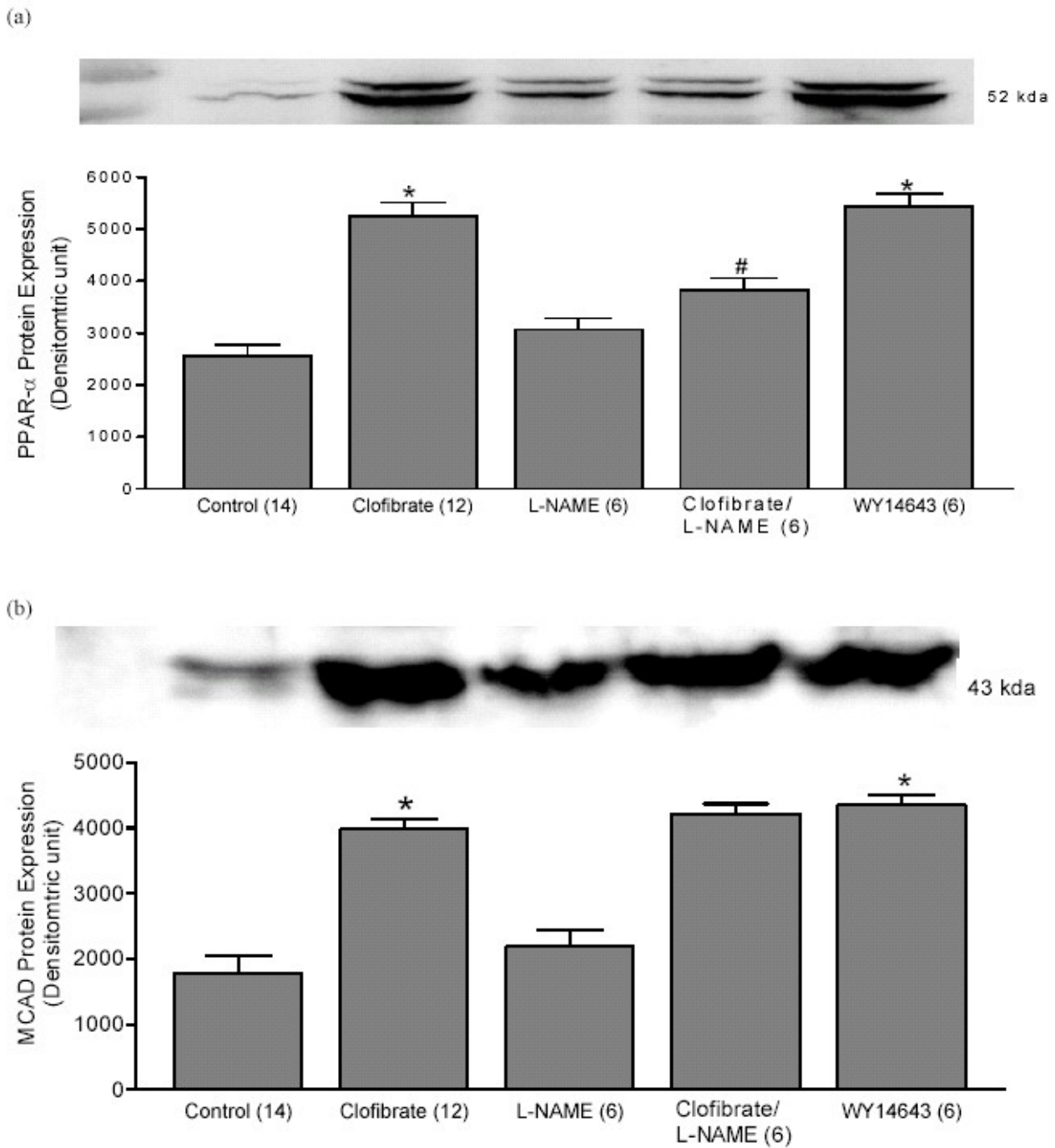
The effects of treatment with different agents on PPAR $\alpha$  and MCAD protein expression are illustrated in Fig. 1. Fig. 1a shows that, treatment with clofibrate or WY14643 for 7 days increased PPAR $\alpha$  expression by  $106 \pm 7$  % ( $p < 0.05$ ) or  $113 \pm 8$  % ( $p < 0.05$ ), respectively. L-NAME did not affect basal expression of PPAR $\alpha$  but it attenuated clofibrate-induced increase in PPAR $\alpha$  expression ( $27 \pm 2$  %;  $p < 0.05$ ). However, PPAR $\alpha$  expression in groups treated with NaCl alone or in combination with clofibrate was not significantly altered (data not shown). Fig. 1b shows that clofibrate or WY14643 increased MCAD protein expression by  $123 \pm 8$  % ( $p < 0.05$ ) or  $143 \pm 8$  % ( $p < 0.05$ ), respectively. Unlike the data obtained with PPAR $\alpha$ , L-NAME was without effect on basal or clofibrate-induced MCAD expression.

### Urinary excretion of Nitrite and $\text{Na}^+$

Compared to the control rats, treatment with clofibrate, WY14643 or NaCl elicited a 3-4 fold increase ( $p < 0.01$ ) in 24 hr urinary nitrite excretion rats (Fig. 2a). Combined administration of clofibrate and NaCl produced an increase in nitrite excretion that was not greater than that produced by clofibrate alone. On the other hand, L-NAME reduced basal nitrite excretion by  $46 \pm 7$  % ( $p < 0.05$ ) and abolished clofibrate-induced increase in nitrite excretion ( $p < 0.05$ ). Accompanying these changes was a 2-5-fold increase in urinary  $\text{Na}^+$  excretion (Fig. 2b) following treatment with WY14643, clofibrate or NaCl. L-NAME reduced 24 hr  $\text{Na}^+$  excretion by  $80 \pm 14$  % ( $p < 0.05$ ) and abolished clofibrate-induced increase in  $\text{Na}^+$  excretion ( $p < 0.05$ ).

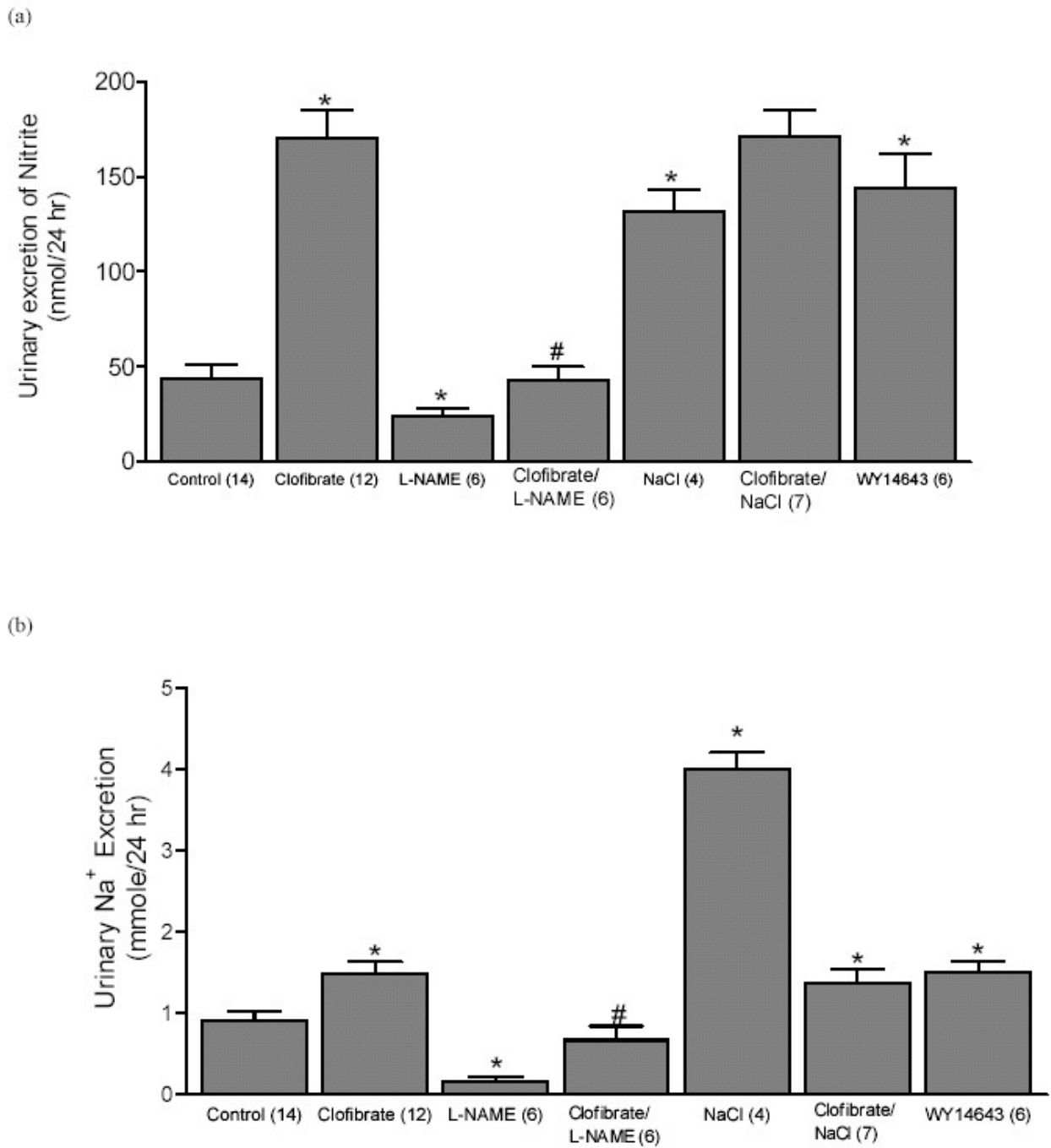
### $\text{Na}^+$ - $\text{K}^+$ ATPase activity and the expression of $\text{Na}^+$ - $\text{K}^+$ ATPase $\alpha_1$ protein

The effects of these treatments on  $\text{Na}^+$ - $\text{K}^+$ ATPase activity and expression are illustrated in Fig. 3. Basal  $\text{Na}^+$ - $\text{K}^+$ ATPase activity in these experiments was  $226 \pm 28$  nmol/mg protein/min. Clofibrate, NaCl or WY14643 caused a significant reduction in  $\text{Na}^+$ - $\text{K}^+$  ATPase activity in the PT by  $89 \pm 33$  % ( $p < 0.05$ ),  $43 \pm 4$  % ( $p < 0.05$ ) or  $63 \pm 23$  % ( $p < 0.05$ ), respectively (Fig. 3a). Combined administration of clofibrate and NaCl elicited a greater reduction in  $\text{Na}^+$ - $\text{K}^+$ -ATPase activity ( $81 \pm 14$  %,  $p < 0.05$ ), that was higher than that produced by NaCl alone but not



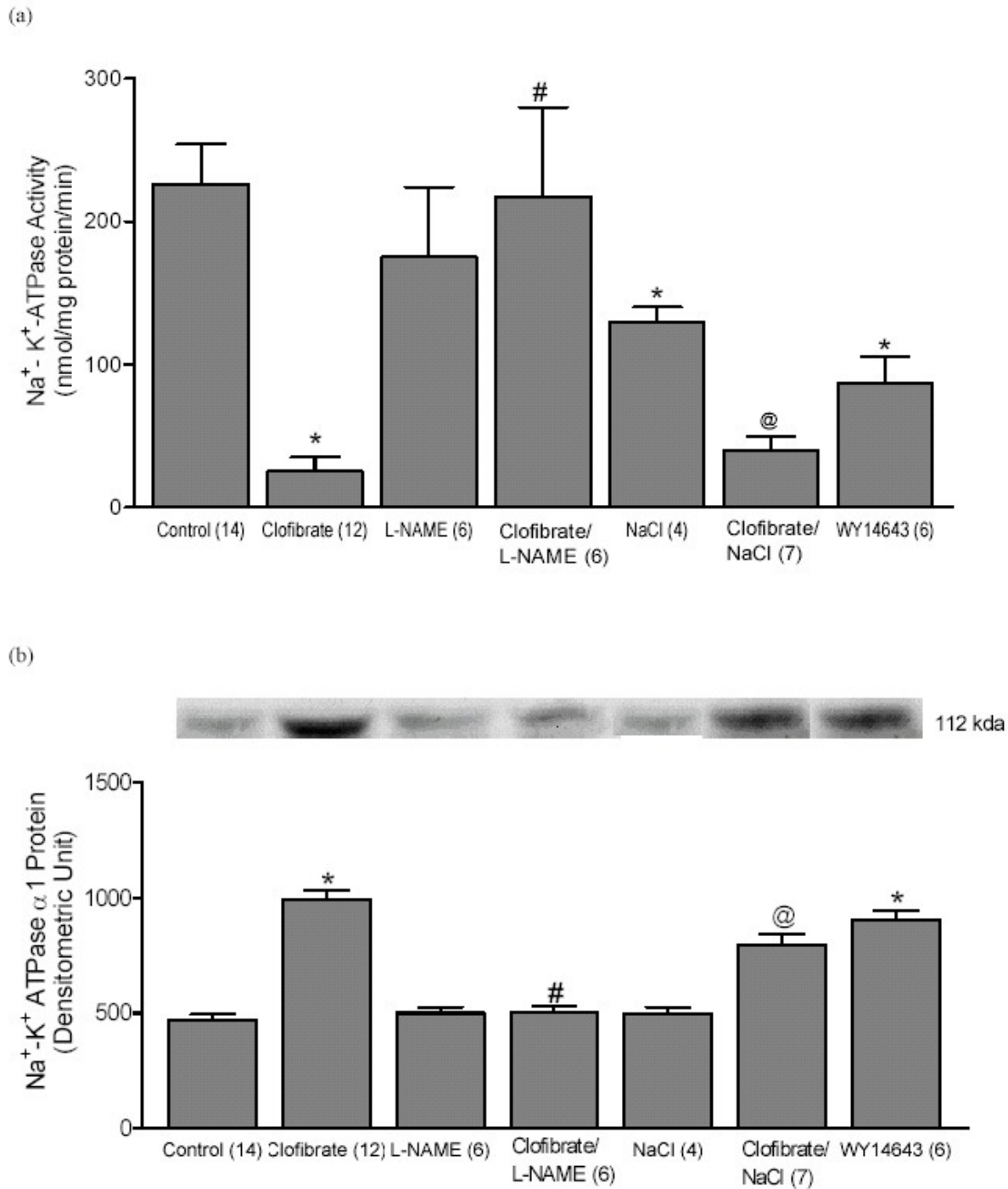
**Figure 1**

Changes in PPAR $\alpha$  and MCAD protein expression. Expression of PPAR $\alpha$  (a) and MCAD (b) proteins in vehicle-treated (Control) rats, or rats treated for 7 days with clofibrate (Clofibrate; 250 mg/kg; i.p.), L-NAME (L-NAME; 100 mg/kg; p.o.), WY14643 (WY14643; 45 mg/kg; i.p.), or clofibrate and L-NAME (Clofibrate/L-NAME). The upper tracing in each figure shows a typical immunoblot for PPAR $\alpha$  (a) or MCAD (b) proteins. Values are mean  $\pm$  SEM. Values in parentheses are the number of experiments. \*  $p < 0.05$  versus Control. #  $p < 0.05$  versus Clofibrate.



**Figure 2**

Urinary excretion of nitrite and Na<sup>+</sup>. 24 hr urinary excretion of nitrite (a) and Na<sup>+</sup> (b) after 7 days of treatment with vehicle (Control), clofibrate (Clofibrate; 250 mg/kg; i.p.), L-NAME (L-NAME; 100 mg/kg; p.o.), 2 % NaCl in drinking water (NaCl), WY14643 (WY14643; 45 mg/kg; i.p.), clofibrate and NaCl (Clofibrate/NaCl) or clofibrate and L-NAME (Clofibrate/L-NAME). Values in parentheses are the number of animals. Values are mean ± SEM. \*-p < 0.05 versus Control. #-p < 0.05 versus Clofibrate.



**Figure 3**

Na<sup>+</sup>-K<sup>+</sup>-ATPase activity and Expression of Na<sup>+</sup>-K<sup>+</sup>-ATPase α1 protein. Na<sup>+</sup>-K<sup>+</sup>-ATPase activity (a) and expression of Na<sup>+</sup>-K<sup>+</sup>-ATPase α1 protein (b) in the renal proximal tubules of different experimental groups: Control (vehicle-treated), clofibrate (clofibrate 250 mg/kg; i.p.), L-NAME (L-NAME; 100 mg/kg; p.o.), Clofibrate/L-NAME (Clofibrate and L-NAME), NaCl (2% NaCl in drinking water), Clofibrate/NaCl (clofibrate and NaCl) or WY14643 (WY14643; 45 mg/kg; i.p.). Values are mean ± SEM. Values in parentheses are the number of animals. \*-p < 0.05 versus Ccontrol. #-p < 0.05 versus Clofibrate. @-p < 0.05 versus NaCl.

greater than that produced by clofibrate alone. On the other hand, L-NAME did not affect basal Na<sup>+</sup>-K<sup>+</sup>-ATPase activity but abolished clofibrate-induced reduction in Na<sup>+</sup>-K<sup>+</sup>-ATPase activity. The role of cGMP in clofibrate-induced reduction in Na<sup>+</sup>-K<sup>+</sup>-ATPase activity was evaluated by measuring the Na<sup>+</sup>-K<sup>+</sup>-ATPase activity in the presence of ODQ (10<sup>-6</sup>M), an inhibitor of sGC. ODQ reversed clofibrate-induced reduction in Na<sup>+</sup>-K<sup>+</sup>-ATPase activity from 25 ± 10 to 58 ± 7 nmol/mg protein/min (data not shown).

Figure 3b illustrates that treatment with WY14643 or clofibrate elicited a significant increase in the expression of the  $\alpha 1$  subunit of the Na<sup>+</sup>-K<sup>+</sup>-ATPase protein, the major Na<sup>+</sup> transporting isoform and this remained elevated even during combined administration of NaCl and clofibrate. However, though NaCl its own inhibited Na<sup>+</sup>-K<sup>+</sup>-ATPase activity, it did not affect the expression of Na<sup>+</sup>-K<sup>+</sup>-ATPase  $\alpha 1$  protein. Similarly, L-NAME alone did not alter Na<sup>+</sup>-K<sup>+</sup>-ATPase  $\alpha 1$  expression but abolished clofibrate-induced increase in Na<sup>+</sup>-K<sup>+</sup>-ATPase expression.

## Discussion

The main highlight of this study is that activation of PPAR $\alpha$  increased renal NO production and inhibited Na<sup>+</sup> transport in freshly isolated PT of the rat. These results therefore add to a growing list of actions of PPAR $\alpha$  which had until recently being thought were limited to specific tissue types. The biologic function of PPAR $\alpha$  was initially limited to lipid catabolism and peroxisome proliferation in the liver [17]. However, with the discovery that PPAR $\alpha$  is present in a variety of different cell types and a growing list of their activities, their functions and biological effects have grown tremendously [25].

PPAR $\alpha$  is highly expressed in the kidney especially in the PT cells. Indeed, PPAR $\alpha$ -mediated  $\beta$ -oxidation of long chain fatty acids occurs predominantly in the S3 segment of the PT and represents an important mechanism for energy production in the kidney cortex. In addition, fatty acid  $\beta$ -oxidation enzymes which exist in the mitochondria, peroxisomes and microsomes of this nephron segment are very important in the preservation of renal function following damage to the kidney [26-29]. The importance of fatty acid  $\beta$ -oxidation and PPAR $\alpha$  is also underscored by the recognition that the kidney is the only other organ in addition to the liver in which fatty acid  $\beta$ -oxidation occurs in the peroxisomes which are found exclusively in the PT of the nephron, and rank among the largest peroxisomes known in different cell types [20].

The association of PPAR $\alpha$  with PT drew us to this nephron segment with a view to evaluating its effect on ion transport. PT cells possesses an abundance of Na<sup>+</sup>-K<sup>+</sup> ATPase that regulates transepithelial Na<sup>+</sup> movement and a

number of agents, endogenous and exogenous, and disease conditions can modulate the activity of the enzyme. Prominent amongst the endogenous regulators of Na<sup>+</sup>-K<sup>+</sup>-ATPase activity in the PT is NO. However, the effects of NO on PT are controversial as increase as well as inhibition of Na<sup>+</sup> transport have been reported [6,30,31].

Following the demonstration in some recent reports that PPAR $\alpha$  ligands modulate NO production in vascular tissues and macrophages, we wondered whether PPAR $\alpha$  activators affect NO production in the kidney and if so, whether NO plays a role in the effect of PPAR $\alpha$  on sodium excretion and renal Na<sup>+</sup> transport in the PT. We first established that clofibrate and WY14643 are PPAR $\alpha$  ligands based on their capacity to increase PPAR $\alpha$  expression and its downstream target protein MCAD. These effects were accompanied by increased nitrite excretion. However, L-NAME inhibited PPAR $\alpha$  but not MCAD expression (Fig. 1). Using NaCl loading as a stimulus for NO production we observed that NaCl caused a 3–4 fold increase in urinary excretion of nitrite as did clofibrate and WY14643, prototype PPAR $\alpha$  activators [24]. The increase in urinary nitrite excretion is indicative of the ability to stimulate renal NO production. In parallel to this, clofibrate, WY14643 and NaCl decreased Na<sup>+</sup>-K<sup>+</sup>-ATPase activity and the combined administration of clofibrate and NaCl further enhanced this reduction. In addition, ODQ, an inhibitor of sGC, or L-NAME attenuated the effects of clofibrate on Na<sup>+</sup>-K<sup>+</sup>-ATPase activity. The decrease in Na<sup>+</sup>-K<sup>+</sup>-ATPase activity following sodium loading is in agreement with studies that demonstrated increased level of endogenous digitalis-like factor and is consistent with the known capacity of the PT Na<sup>+</sup>-K<sup>+</sup>-ATPase to participate in promoting Na<sup>+</sup> excretion [32]. Taken together, these data suggest that PPAR $\alpha$  activation affects Na<sup>+</sup> transport and that this effect may involve NO production. This being the case, it is expected that Na<sup>+</sup> and water excretion should increase when NO production increased. This was indeed the case as we observed a marked increase in urinary Na<sup>+</sup> excretion following administration of WY14643, clofibrate or NaCl alone or in combination with each other. Though NO production was of similar magnitude in the groups treated with clofibrate, WY14643 or NaCl, the corresponding effect on U<sub>Na</sub>V and urine output is greatest for the NaCl group. We interpret these data to mean that salt loading promotes natriuretic and diuretic effects that are not exclusively linked to NO production in the PT. It thus appears that high salt concentration may increase the osmolar gradient in the medulla and countercurrent multiplier system therein and thereby elicit a strong natriuretic effect that involves additional mechanism apart from NO production. The lower effect on PT Na<sup>+</sup>-K<sup>+</sup>-ATPase activity in NaCl-treated group despite the strong natriuresis suggests additional effects on other nephron segments possibly in the loop of Henle where inhibition of Na<sup>+</sup>, K<sup>+</sup>

or Cl<sup>-</sup> transport can produce strong natriuretic effect as seen with the loop diuretics.

Though there are many isoforms of Na<sup>+</sup>-K<sup>+</sup>-ATPase, the  $\alpha$ -1 isoform represents the main sodium transporter in the basolateral membrane and is the target of many hormones that regulate PT sodium reabsorption [2,32]. In these experiments, it is note worthy that reduction in Na<sup>+</sup>-K<sup>+</sup>-ATPase activity by clofibrate, clofibrate and NaCl, and WY14643 but not that by NaCl alone was accompanied by increased expression of  $\alpha$ 1 subunit of Na<sup>+</sup>-K<sup>+</sup>-ATPase protein. Similarly, L-NAME abolished clofibrate-induced increase in Na<sup>+</sup>-K<sup>+</sup>-ATPase expression but not its activity. We interpret the incongruence in activity and expression of Na<sup>+</sup>-K<sup>+</sup>-ATPase to post translational modifications of the enzyme by NaCl and L-NAME. The reason for this is not clear but it is not surprising considering that dissociation has also been observed between PKC-inhibitable inhibition by dopamine of Na<sup>+</sup>-K<sup>+</sup>-ATPase activity and phosphorylation of the  $\alpha$  subunit of the enzyme [33].

## Conclusion

Data presented in this study suggest that PPAR $\alpha$  activators increase NO generation and promote ion transport in the PT through a reduction in Na<sup>+</sup>-K<sup>+</sup> ATPase activity. The effects produced by NaCl or L-NAME may involve a post translational modification of Na<sup>+</sup>-K<sup>+</sup> ATPase.

## Methods

This study was approved by the Institutional Animal Care and Use Committee (IACUC) of Texas Southern University following the National Institutes of Health (NIH) guidelines for laboratory animal use.

## Materials

All chemicals were purchased from Sigma-Aldrich (St. Louis, MO) unless specified otherwise. Rabbit polyclonal antibody against Na<sup>+</sup>-K<sup>+</sup> ATPase  $\alpha$ 1 and PPAR $\alpha$  were purchased from Santa Cruz (Santa Cruz Biotechnology, Inc. Santa Cruz, CA). Antibody to MCAD (medium chain acyl-dehydrogenase) and 1H-[1,2,4] oxadiazolo [4,3- $\alpha$ ] quinoxalin-1-one (ODQ) were obtained from Cayman (Cayman Chemicals, Ann Arbor, MI)

Adult male Sprague-Dawley rats (Harlan, Houston TX), 150–200 g were randomly allocated to 4 treatment groups as follows: Control (mineral oil, 50  $\mu$ l i.p.; n = 8), clofibrate (250 mg/kg; i.p.; n = 6), NaCl (2% in drinking water; n = 4), and clofibrate/NaCl (n = 7). The NaCl group was included since salt loading is a known activator of NO production [24]. In another set of experiments 30 rats were randomly divided into five treatment groups (n = 6 in each group): control, clofibrate (250 mg/kg; i.p.), L-NAME (100 mg/kg; orally) clofibrate/L-NAME and WY14643 (45 mg/kg; i.p.) a synthetic PPAR $\alpha$  ligand. Ani-

mals were maintained on the treatments for 7 days before they were sacrificed. They were kept in metabolic cages for collection of 24 hr urine output on days 1 and 7 of the study period. At the end of the treatment period, animals were anesthetized with pentobarbital sodium (50 mg/kg; i.p.) and the kidneys were perfused with 20 ml of Krebs buffer containing iron oxide particles (100  $\mu$ l/10 ml buffer).

## Isolation of proximal tubule

PT from the rat kidney were isolated following the procedure described by Chibalin et al with little modification. Kidneys were isolated, cut longitudinally, and the cortex was separated from the medulla and the papilla [33]. Cortical tissues were minced and placed in scintillation vials containing 10 ml fresh ice-cold digestion solution (collagenase 230 u/ml, hyaluronidase 250 u/ml, trypsin inhibitor 10  $\mu$ g/ml, sucrose 320 mM, and EDTA 0.1 mM). Using a plastic pipette, the samples were titrated for about 20 sec to loosen up tissue and to expose more tubules for digestion. These samples were then incubated in a shaking water bath for 15–20 min at 37°C while continuously bubbling with 95% O<sub>2</sub> and 5% CO<sub>2</sub>. After a complete digestion, samples were placed in a 50 ml centrifuge tube which was placed on a BioMag magnetic separator (Polyscience Inc, PA). Vascular tissue and glomeruli containing iron were separated by magnetic attraction and tubular fraction carefully transferred to another tube. Proximal tubular fraction was further enriched by percoll density-gradient centrifugation in which samples were layered in between 5 ml of 35% percoll and 5 ml of 100% percoll solution and centrifuged at 13000 g for 15 min. Proximal tubular fraction was carefully collected. Viability of the tubules (95%) was confirmed by microscopy and trypan blue exclusion test.

## Na<sup>+</sup>-K<sup>+</sup> ATPase activity assay

Na<sup>+</sup>-K<sup>+</sup> ATPase activity was determined in the proximal tubular fraction as the rate of inorganic phosphate released in the presence or absence of ouabain [6,34]. Tubular suspension was washed three times with phosphate-free buffer (NaCl 2.36 M, NaHCO<sub>3</sub> 0.54 M, KCl 0.4 M, MgCl<sub>2</sub> 0.12 M) and the final proximal tubule suspension was adjusted to 1 mg protein/ml. Aliquots of tubular suspension (100  $\mu$ l) were pipetted into 800  $\mu$ l reaction mixture (NaCl 75 mM, KCl 5 mM, MgCl<sub>2</sub> 5 mM, NaN<sub>2</sub> 6 mM, Na EGTA 1 mM, imidazole 37.5 mM, Tris HCl 75 mM and histidine 30 mM; pH 7.4) with or without ouabain (1 mM) in a final volume of 1 ml and pre-incubated for 5 min in a water bath at 37°C. Reaction was initiated by adding Tris ATP (4 mM) and was stopped after 15 min of incubation at 37°C by adding 50  $\mu$ l of 50% TCA. For determination of ouabain-insensitive ATPase activity, NaCl and KCl were omitted from the reaction mixture where ouabain was added. To quantify the amount of

phosphate produced, 1 ml of coloring reagent (10% ammonium molybdate in 10 N sulfuric acid + ferrous sulfate) was added to the reaction mixture, mixed thoroughly and centrifuged at 3000 g for 10 min. Formation of phosphomolybdate was determined spectrophotometrically at 740 nm against a standard curve prepared from  $K_2HPO_4$ .  $Na^+$ - $K^+$  ATPase activity was estimated as the difference between total ATPase activity and the ouabain-insensitive ATPase activity and expressed as nmol phosphate produced per mg protein per min. In another set of experiments, proximal tubules isolated from clofibrate-treated rats were incubated with ODQ ( $10^{-6}$  M), an inhibitor of soluble guanylyl cyclase (sGC) for 30 mins before measurement of  $Na^+$ - $K^+$  ATPase activity.

#### **Immunoblotting of $Na^+$ - $K^+$ ATPase $\alpha 1$ protein**

Solubilized protein collected from the PT of the rat kidney was separated in 10% SDS-PAGE gel and transferred to a PVDF membrane (Amersham Pharmacia, NJ). Blots were blocked with 5% non-fat dried milk (wt/vol) and 0.1% Tween 20 in TBS (50 mM Tris Base, 137 mM NaCl, 1 M HCl; pH 7.4) overnight at 4°C and incubated for 1 hr with isoform-specific anti  $\alpha$ -1 mouse monoclonal antibody (1:500). After washing in TBST (TBS + 0.1% Tween 20), blots were incubated with corresponding peroxidase-conjugated affinity purified anti-mouse anti serum at 1:1000 dilution for 1 hr. Immunoreactivity was detected by enhanced chemiluminescence (Hyperfilm ECL, Amersham Pharmacia, NJ).

#### **Immunoblotting of PPAR $\alpha$ and MCAD protein**

40  $\mu$ g of protein from PT homogenate was electrophoresed on 12% polyacrylamide gels and transferred to PVDF membrane (Amersham Pharmacia, NJ). Blots were probed with rabbit polyclonal anti PPAR $\alpha$  antibody and anti MCAD antibody at 1:1000 and 1: 500 dilutions, respectively, followed by addition of secondary antibody at 1:5000 dilution. Immunocomplexes were visualized using an enhanced chemiluminescence (ECL-Plus) detection system from Amersham Pharmacia, NJ.

The intensity of the bands was scanned and quantified using Personal Densitometer SI scanner and ImageQuant analysis software (Molecular Dynamics, Sunnyvale, CA).

#### **Biochemical Analysis**

Protein concentration in the tissue preparation was determined by the BCA protein assay kit from Pierce (Rockford, IL). Urine  $Na^+$  was determined by flame photometer (PFP7. Genway Ltd, Essex, UK) and urinary excretion of nitrite was determined colorimetrically by Griess Assay.

#### **Statistical Analysis**

Data were presented as mean  $\pm$  SEM and compared between groups for significance using students 't' test. In all cases,  $p < 0.05$  was considered as significant.

#### **List of abbreviations**

MCAD: Medium chain acyldehydrogenase

NO: Nitric Oxide

ODQ: 1H-[1,2,4]oxadiazolo [4,3- $\alpha$ ]quinoxalin-1-one

PKA: Protein Kinase A

PKC: Protein kinase C

PPAR: Peroxisome Proliferator Activated Receptor

PT: Proximal Tubule

sGC: Soluble guanylyl cyclase

$U_{NaV}$ : Urinary sodium

UV: Urine volume

$UNO_xV$ : Urinary Nitrite

#### **Authors' contributions**

MAN carried out biochemical and molecular biology experiments, participated in the design of the study and drafted the manuscript. KR participated in western blot experiments. AOO conceived of the study, and participated in its design, redaction and coordination.

#### **Acknowledgment**

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#### **References**

1. Feraille E, Carranza ML, Gonin S *et al.*: **Insulin-induced stimulation of  $Na^+$ - $K^+$ -ATPase activity in kidney proximal tubule cells depends on phosphorylation of the alpha-subunit of Tyr-10.** *Mol Biol Cell* 1999, **10**(9):2847-2859.
2. Herrera VLM, Cova T, Sassoon D *et al.*: **Developmental cell specific regulation of  $Na^+$ - $K^+$ -ATPase  $\alpha 1$ -,  $\alpha 2$ -, and  $\alpha 3$ -isoform gene expression.** *Am J Physiol* 1994, **266**:C1301-1312.
3. Fisone G, Cheng SX, Nairn AC *et al.*: **Identification of the phosphorylation site for cAMP-dependent protein kinase on  $Na^+$ - $K^+$ -ATPase and effects of site-directed mutagenesis.** *J Biol Chem* 1994, **269**(12):9368-9373.
4. Pedemonte CH, Bertorello AM: **Short-term regulation of the proximal tubule  $Na^+$ - $K^+$ -ATPase: increased/decreased  $Na^+$ - $K^+$ -ATPase activity mediated by protein kinase C isoforms.** *J Bioenerg Biomembr* 2001, **33**(5):439-447.
5. Feraille E, Doucet A: **Sodium-potassium-adenosine triphosphate-dependent sodium transport in the kidney: hormonal control.** *Physiol Rev* 2001, **81**(1):345-418.

6. Ellis DZ, Nathanson JA, Sweadner KJ: **Carbachol inhibits Na<sup>+</sup>-K<sup>+</sup>-ATPase activity in choroid plexus via stimulation of the NO/cGMP pathways.** *Am J Physiol Cell Physiol* 2000, **279**:C1685-C1693.
7. Fisone G, Snyder GL, Fryckstedt J, Caplan MJ, Aperia A, Grengard P: **Na<sup>+</sup>-K<sup>+</sup>-ATPase in the choroid plexus. Regulation by serotonin/protein kinase C pathway.** *J Biol Chem* 1995, **270**(6):2427-2430.
8. Fisone G, Snyder GL, Aperia A, Grengard P: **Na<sup>+</sup>-K<sup>+</sup>-ATPase phosphorylation in the choroid plexus: synergistic regulation by serotonin/protein kinase C and isoproterenol/cAMP-PK/PP-1 pathways.** *Mol Med* 1998, **4**(4):258-265.
9. Morrisey JJ, McCracken R, Kaneto H, Vehaskari M, Montani D, Klahr S: **Location of an inducible nitric oxide synthase mRNA in the normal kidney.** *Kidney Int* 1994, **45**:998-1005.
10. Wilcox C: **L-arginine-nitric oxide pathway.** In *The kidney: Physiology and Pathophysiology* Edited by: Seldin D, Giebisch G. Philadelphia: Lippincott Raven; 2000:849-871.
11. Ahn KY, Mohaupt MG, Madsen KM, Kone BC: **In situ hybridization localization of mRNA encoding inducible nitric oxide synthase in rat kidney.** *Am J Physiol* 1994, **36**:F748-F757.
12. Forman BM, Chen J, Evans RM: **Hypolipidemic drugs, polyunsaturated fatty acids, and eicosanoids are ligands for peroxisome proliferator-activated receptors alpha and delta.** *Proc Natl Acad Sci USA* 1997, **94**(9):4312-4317.
13. Devchand PR, Keller H, Peters JM, Vazquez M, Gonzalez FJ, Wahli W: **The PPARalpha-leukotriene B4 pathway to inflammation control.** *Nature* 1996, **384**(6604):39-43.
14. Kliewer SA, Lenhard JM, Wilson TM, Patel I, Morris DC, Lehmann JM: **A prostaglandin J2 metabolite binds peroxisome proliferator-activated receptor gamma and promotes adipocyte differentiation.** *Cell* 1995, **83**(5):813-819.
15. Tugwood JD, Issemann I, Anderson RG, Bundell KR, McPheat WL, Green S: **The mouse peroxisome proliferator activated receptor recognizes a response element in the 5' flanking sequence of the rat acyl CoA oxidase gene.** *EMBO J* 1992, **11**(2):433-439.
16. Delerive P, Martin-Nizard F, Chinetti G et al.: **Peroxisome proliferator activated receptor activators inhibit thrombin-induced endothelin-1 production in human vascular endothelial cells by inhibiting the activator protein-1 signaling pathway.** *Circ Res* 1999, **85**(5):394-402.
17. Issemann I, Green S: **Activation of a member of the steroid hormone receptor superfamily by peroxisome proliferator.** *Nature* 1990, **347**(6294):645-650.
18. Schoonjans K, Staels B, Auwerx J: **The peroxisome proliferator activated receptors (PPARs) and their effects on lipid metabolism and adipocyte differentiation.** *Biochim Biophys Acta* 1996, **1302**(2):93-109.
19. Osmundsen H, Bremer J, Pedersen I: **Metabolic aspects of peroxisomal beta-oxidation.** *Biochim Biophys Acta* 1991, **1085**:141-158.
20. Zaar K: **Structure and function of peroxisome in the mammalian kidney.** *Eur J Cell Biol* 1992, **59**:233-254.
21. Braissant O, Foufelle F, Scotto C, Dauca M, Wahli W: **Differential expression of peroxisome proliferator-activated receptors (PPARs): tissue distribution of PPAR-alpha, -beta, and -gamma in the adult rat.** *Endocrinology* 1996, **137**(1):354-366.
22. Kliewer SA, Forman BM, Blumberg B et al.: **Differential expression and activation of a family of murine peroxisome proliferator-activated receptors.** *Proc Natl Acad Sci USA* 1994, **91**(15):7355-7359.
23. McKee M, Scavone C, Nathanson JA: **Nitric Oxide, cGMP, and hormone regulation of active sodium transport.** *Proc Natl Acad Sci USA* 1994, **91**(25):12056-12060.
24. Mattson DL, Higgins DJ: **Influence of dietary sodium intake on renal medullary nitric oxide synthase.** *Hypertension* 1996, **27**:688-92.
25. Bishop-Bailey D: **Peroxisome proliferator-activated receptors in the cardiovascular system.** *Br J Pharmacol* 2000, **129**(5):823-834.
26. Bell DR, Bars RG, Elcombe CR: **Differential tissue specific expression and induction of cytochrome P450IVA1 and acyl-CoA oxidase.** *Eur J Biochem* 1992, **206**:979-986.
27. Dreyer C, Krey G, Keller H, Givel F, Helftenbein G, Wahli W: **Control of the peroxisomal beta-oxidation pathway by a novel family of nuclear hormone receptors.** *Cell* 1992, **68**:879-887.
28. Lehir M, Dubach UC: **Peroxisomal and mitochondrial beta-oxidation in the rat kidney: Distribution of fatty acyl-coenzyme A oxidase and 3-hydroxyacyl-coenzyme A dehydrogenase activities along the nephron.** *J Histochem Cytochem* 1982, **30**:441-444.
29. Portilla D, Dai G, Peters JM, Gonzalez FJ, Crew MD, Proia AD: **Eto-moxir-induced PPARalpha-modulated enzymes protect during acute renal failure.** *Am J Physiol Renal Physiol* 2000, **278**(4):F667-675.
30. Wang T: **Role of iNOS and eNOS in modulating proximal tubule transport and acid-base balance.** *Am J Physiol Renal Physiol* 2002, **283**:F658-F662.
31. Wu XC, Harris PJ, Johann EJ: **Nitric oxide and renal nerve-mediated proximal tubular reabsorption in normotensive and hypertensive rats.** *Am J Physiol Renal Physiol* 1999, **277**:F560-F566.
32. Fedorova OV, Lakatta EG, Bagrov AV: **Endogenous Na, K pump ligands are differentially regulated during acute NaCl loading of Dahl rats.** *Circulation* 2000, **102**:3009-3014.
33. Chibalin AV, Pedemonte CH, Katz AI, Feraille E, Berggren PO, Bertorello AM: **Phosphorylation of the catalytic alpha-subunit constitutes a triggering signal for Na<sup>+</sup>-K<sup>+</sup>-ATPase endocytosis.** *Biol Chem* 1998, **273**(15):8814-8819.
34. Esmann M: **ATPase and phosphatase activity of Na<sup>+</sup>-K<sup>+</sup>-ATPase: Molar and specific activity, protein determination.** *Methods Enzymol* 1988, **156**:105-115.

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