Inhibitory Effect of NH₄Cl Treatment on Renal Tgfβ1 Signaling Following Unilateral Ureteral Obstruction

Martina Feger  Ioana Alesutan  Tatsiana Castor  Sobuj Mia  Katharina Musculus  Jakob Voelkl  Florian Lang

Department of Physiology, University of Tuebingen, Tuebingen, Germany

Key Words
Unilateral ureteral obstruction • NH₄Cl • Tgfβ1 • Sox9 • Renal fibrosis

Abstract
Background/Aims: Consequences of obstructive nephropathy include tissue fibrosis, a major pathophysiological mechanism contributing to development of end-stage renal disease. Transforming growth factor β 1 (Tgfβ1) is involved in the progression of renal fibrosis. According to recent observations, ammonium chloride (NH₄Cl) prevented phosphate-induced vascular remodeling, effects involving decrease of Tgfβ1 expression and inhibition of Tgfβ1-dependent signaling. The present study, thus, explored whether NH₄Cl influences renal Tgfβ1-induced pro-fibrotic signaling in obstructive nephropathy induced by unilateral ureteral obstruction (UUO).

Methods: UUO was induced for seven days in C57Bl6 mice with or without additional treatment with NH₄Cl (0.28 M in drinking water). Transcript levels were determined by RT-PCR as well as protein abundance by Western blotting, blood pH was determined utilizing a blood gas and chemistry analyser. Results: UUO increased renal mRNA expression of Tgfb1, Tgfβ-activated kinase 1 (Tak1) protein abundance and Smad2 phosphorylation in the nuclear fraction of the obstructed kidney tissues, effects blunted in NH₄Cl treated mice as compared to control treated mice. The mRNA levels of the transcription factors nuclear factor of activated T cells 5 (Nfat5) and SRY (sex determining region Y)-box 9 (Sox9) as well as of tumor necrosis factor α (Tnfa), interleukin 6 (Il6), plasminogen activator inhibitor 1 (Pai1) and SnaI were up-regulated in the obstructed kidney tissues following UUO, effects again significantly ameliorated following NH₄Cl treatment. Furthermore, the increased protein and mRNA expression of α-smooth muscle actin (α-Sma), fibronectin and collagen type I in the obstructed kidney tissues following UUO were significantly attenuated following NH₄Cl treatment. Conclusion: NH₄Cl treatment ameliorates Tgfβ1-dependent pro-fibrotic signaling and renal tissue fibrosis markers following obstructive nephropathy.
Introduction

Renal fibrosis, particularly tubulointerstitial fibrosis, is a common pathophysiological pathway of several renal diseases leading to end-stage renal failure [1-3]. Renal fibrosis contributes to the pathophysiology of chronic kidney disease [1, 3]. Tubulointerstitial fibrosis is characterized by excessive accumulation of extracellular matrix (ECM) proteins, such as α-smooth muscle actin (α-Sma), collagen type I and fibronectin, leading to destruction of the functional tissue [1, 3, 4]. The increased production and deposition of ECM is mainly caused by myofibroblasts [5], which may be recruited from resident fibroblasts, bone marrow-derived cells or from epithelial to mesenchymal transition (EMT) [5, 6].

Mechanisms involved in the regulation of ECM protein expression leading finally to ECM deposition include transforming growth factor β 1 (Tgfβ1) [1, 3, 4]. Tgfβ1 signaling seems to be a major pathway inducing fibroblast activation and proliferation [7]. In renal fibrosis, Tgfβ1-induced EMT is mediated via Smad2/3 phosphorylation and subsequent nuclear translocation [3]. Activation of the Tgfβ1/Smad pathway up-regulates plasminogen activator inhibitor 1 (Pai1) which is closely linked to the development of EMT and ECM deposition [3]. In addition to activation of Smad-dependent signaling pathways, Tgfβ1 activates various Smad-independent pathways to induce its pro-fibrotic effects [7]. Tgfβ-activated kinase 1 (Tak1) has been identified as a major non-canonical signaling molecule in Tgfβ1-mediated fibrosis [7]. Moreover, Tak1 participates in the regulation of Tgfβ1-induced activation of Smads [7].

Tgfβ1, tumor necrosis factor α (Tnfα) and Pai1 are further implicated in excessive vascular remodeling, osteoinductive signaling and subsequent vascular calcification in klotho deficiency [8, 9]. According to recent observations, ammonium chloride (NH₄Cl) treatment prevented tissue calcification and reduced vascular senescence in klotho-hypomorphic mice [8]. In those mice, the excessive expression of Tgfb1, transcription factor nuclear factor of activated T cells 5 (Nfat5), Nfat5-downstream mediator SRY (sex determining region Y)-box 9 (Sox9) and Pai1 was reversed following NH₄Cl treatment. NH₄Cl has previously been shown to interfere with Tgfβ1 [10]. Moreover, the expression of Sox9, a transcriptional regulator in the development of tissue fibrosis [11] was shown to be regulated by Tgfβ1 [12] and Tak1 [13].

The present study thus explored the effect of NH₄Cl treatment on renal Tgfβ1-dependent signaling and markers of fibrosis following obstructive nephropathy. To this end, mice were subjected to unilateral ureteral obstruction (UUO), a well established model to induce tubulointerstitial fibrosis [2, 14], with or without NH₄Cl treatment added to the drinking water [8].

Materials and Methods

Animals

All animal experiments were conducted according to the German law for the welfare of animals and were approved by local authorities. Experiments have been performed in male mice (C57Bl6) at the age of 8 weeks. Mice had free access to food (Sniff) and tap drinking water. Where indicated, NH₄Cl (0.28 M) was added to the drinking water 3 days before the surgical intervention and for the duration of the UUO treatment.

Unilateral ureteral obstruction

Renal fibrosis was induced by unilateral ureteral obstruction (UUO) [2]. Following surgical incision of the skin and abdominal wall, the left ureter was exposed and ligated twice with a non-resorbable 7-0 filament. Following ligation the surgical wound was closed by sutures. Mice were treated with metamizole for analgesia (200 mg/kg body weight) after the procedure and for the duration of the UUO experiment in drinking water. The mice were sacrificed 7 days after the ligation procedure and the obstructed as well as the non-obstructed kidney were rapidly removed and kidney tissues snap frozen in liquid nitrogen.
Blood pH analysis

For blood pH analysis, the retro-orbital plexus was punctured with a heparinized capillary. The blood samples were injected directly from the capillary into a blood gas analyzer (i15 blood gas and chemistry analyzer, Edan) to determine blood pH.

Quantitative RT-PCR

Total RNA was isolated from murine kidney tissues using Trifast Reagent (Peqlab) according to the manufacturer’s instructions. Reverse transcription of 2 µg RNA was performed using oligo(dT) 

Primer (Invitrogen) and SuperScript III Reverse Transcriptase (Invitrogen). Quantitative real-time PCR was performed with the iCycler IQ™ Real-Time PCR Detection System (Bio-Rad Laboratories) and iQSybr Green Supermix (Bio-Rad Laboratories) according to the manufacturer’s instructions. The following primers were used (5’→3’ orientation):

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\begin{align*}
\text{a-Sma fw:} & \quad \text{CCCAGACATCAGGGAGTAATGG;} \\
\text{a-Sma rev:} & \quad \text{CTATCGGATACTTCAGTGCTG;} \\
\text{Col1a1 fw:} & \quad \text{ACCCGAGGTAGTGCTGGATCTG;} \\
\text{Col1a1 rev:} & \quad \text{CATTGCAGCTATCGCACAC;} \\
\text{Fbn fw:} & \quad \text{GTGACACTTATGAGCGCCCTA;} \\
\text{Fbn rev:} & \quad \text{CCAATCTTTGTGATCACAGAG;} \\
\text{Gapdh fw:} & \quad \text{AGGTGCCTGGTGAAGAAAGTT;} \\
\text{Gapdh rev:} & \quad \text{TGTAGACCATGTAGTGGAGTCA;} \\
\text{Il6 fw:} & \quad \text{TCTATACCACTTGATGCTGTG;} \\
\text{Il6 rev:} & \quad \text{GAATTGCCATTGCACAACTCTTT;} \\
\text{Nfat5 fw:} & \quad \text{GAGGGGTGTGGATTGGAATCT;} \\
\text{Nfat5 rev:} & \quad \text{CTGGTGCTGACTGTTACTGAGTT;} \\
\text{Pai1 fw:} & \quad \text{TTCAGCCCTTGTCCTGCCCT;} \\
\text{Pai1 rev:} & \quad \text{ACACTTTTACCTCGGAAGTT;} \\
\text{Snai1 fw:} & \quad \text{CAGAGCCTGCTCTTGCT;} \\
\text{Snai1 rev:} & \quad \text{GGTCAGCAAAGACAGCGTT;} \\
\text{Sox9 fw:} & \quad \text{AGTACCCGCATCTGGACACAC;} \\
\text{Sox9 rev:} & \quad \text{AGGAGAGTCCTCTTCTGGCT;} \\
\text{Tgfb1 fw:} & \quad \text{CTCCCGGGCTCTTGAGTGC;} \\
\text{Tgfb1 rev:} & \quad \text{GCCCTAGCTTGAGCGACAGATCTG;} \\
\text{Tnfa fw:} & \quad \text{CTGAACCTCAGGGGTGATCC;} \\
\text{Tnfa rev:} & \quad \text{GGTTGGTCACTGGAATACTTGAGA.}
\end{align*}
\]

The specificity of the PCR products was confirmed by analysis of the melting curves. All PCRs were performed in duplicate and relative mRNA fold changes were calculated by the 2^{−ΔΔCt} method using Gapdh as internal reference. Results are shown normalized to the mRNA expression in obstructed kidney tissues of control treated mice.

Extraction of nuclear and cytoplasmic proteins

Cytoplasmic and nuclear extracts were prepared using the NE-PER nuclear and cytoplasmic extraction reagents (Thermo Fisher Scientific) according to the manufacturer’s instructions. Protein concentration was determined by Bradford assay (BioRad Laboratories) and 20 µg of protein were boiled in Roti-Load1 Buffer (Carl Roth) at 100°C for 5 min. Smad2 phosphorylation in the nuclear and cytoplasmic fractions were further determined by Western blot analysis.

Western blot analysis

Murine kidney tissues were lysed with ice-cold lysis buffer (Thermo Fisher Scientific) supplemented with complete protease and phosphatase inhibitor cocktail (Thermo Fisher Scientific). After centrifugation at 10000 rpm for 5 min, proteins were boiled in Roti-Load1 Buffer (Carl Roth) at 100°C for 5 min. Proteins were separated on SDS-polyacrylamide gels and transferred to PVDF membranes. The membranes were incubated overnight at 4°C with the following primary antibodies: rabbit anti-α-smooth muscle actin, rabbit anti-collagen I (diluted 1:1000, Abcam), mouse anti-fibronectin (diluted 1:1000, BD Biosciences), rabbit anti-Tak1, rabbit anti-Smad2, rabbit anti-phosphorylated Smad2 (Ser^{465/467}, diluted 1:1000, Cell Signaling),...
rabbit anti-α-tubulin and rabbit anti-Gapdh antibody (diluted 1:2000, Cell Signaling) and then with secondary goat anti-rabbit HRP-conjugated antibody (diluted 1:2000, Cell Signaling) or goat anti-mouse HRP-conjugated antibody (diluted 1:2000, Cell Signaling) for 1 hour at room temperature. For loading controls, the membranes were stripped with stripping buffer (Carl Roth) at 60°C for 10 min. Antibody binding was detected with the ECL detection reagent (Thermo Fisher Scientific). Bands were quantified with Quantity One Software (Bio-Rad Laboratories) and results are shown as the ratio of total protein to Gapdh. For cytoplasmic and nuclear phosphorylated Smad2, results are shown as the ratio of phosphorylated to total Smad2 to Hdac2 or α-tubulin protein for the nuclear fraction or the cytoplasmic fraction, respectively.

**Statistics**

Data are provided as means ± SEM, n represents the number of independent experiments. All data were tested for significance between control and NH₄Cl treated mice using unpaired Student t-test (normal distributed data) or Mann-Whitney test (non-normal distributed data) according to Shapiro-Wilk test. Only results with p< 0.05 were considered statistically significant.

**Results**

To explore whether NH₄Cl treatment influences renal pro-fibrotic signaling following obstructive nephropathy, UUO was performed in C57Bl6 mice with or without additional treatment with NH₄Cl. The mice were treated with 0.28 M NH₄Cl in the drinking water 3 days before the obstructive injury and for the duration of the UUO treatment. Seven days after the obstructive injury, the animals were sacrificed and the obstructed kidney tissues were compared between the treatment groups. NH₄Cl treatment significantly (p<0.01) decreased blood pH from 7.37 ± 0.03 to 7.20 ± 0.04 (n=5).

**Fig. 1.** Effect of NH₄Cl treatment on UUO-induced Tgfβ1 and Tgfb1-activated kinase 1 (Tak1) expression in renal tissue. (A) Arithmetic means ± SEM (n = 6) of transforming growth factor β 1 (Tgfb1) relative mRNA expression (arbitrary units, a.u.) in renal tissue from non-obstructed control kidney (CTR) and obstructed kidney (UUO) following 7 days of unilateral ureteral obstruction (UUO) in control treated mice (ctr; white bars) and in mice treated with NH₄Cl (0.28 M NH₄Cl added to the drinking water; black bars). (B) Representative original western blots and arithmetic means ± SEM (n = 9) showing Tgfb1-activated kinase 1 (Tak1)/Gapdh protein ratio in renal tissue from non-obstructed control kidney (CTR) and obstructed kidney (UUO) following 7 days of unilateral ureteral obstruction (UUO) in control treated mice (ctr; white bars) and in mice treated with NH₄Cl (0.28 M NH₄Cl added to the drinking water; black bars). *(p<0.05) statistically significant vs respective kidney tissues of control treated mice.
Based on previous observations, Tgfβ1 signaling was investigated in renal obstructive injury. As shown in Fig. 1A, Tgfβ1 mRNA expression was higher in the obstructed kidney tissues than in non-obstructed control kidney tissues following UUO. The increased Tgfβ1 mRNA levels were significantly decreased in the obstructed kidney tissues from NH₄Cl treated mice as compared to control treated mice (Fig. 1A). The effects of NH₄Cl treatment on renal Tgfβ1 expression were paralleled by a significant reduction of the increased Tak1 protein levels in the obstructed kidney tissues (Fig. 1B). Moreover, the increased Smad2 phosphorylation at Ser⁴⁶⁵/⁴⁶⁷ in the nuclear fraction isolated from obstructed kidney tissues following UUO was significantly decreased in NH₄Cl treated mice as compared to control treated mice (Fig. 1B). No significant effects of NH₄Cl treatment on Smad2 phosphorylation in the cytoplasmic fraction isolated from the obstructed kidney tissues were observed (Fig. 1B). In non-obstructed control kidney tissues, NH₄Cl treatment did not significantly modify Tgfβ1 and Tak1 expression (Fig. 1) or Smad2 phosphorylation (Fig. 2).

To further define the effects of NH₄Cl on Tgfβ1-mediated pro-fibrotic signaling following UUO, the mRNA expression of the transcription factors Nfat5 and Sox9 was determined. Following UUO, Nfat5 and Sox9 mRNA levels were increased in the obstructed kidney tissues as compared to non-obstructed control kidney tissues, effects significantly suppressed following treatment with NH₄Cl (Fig. 3A, B). NH₄Cl treatment did not significantly modify Nfat5 and Sox9 mRNA levels in the non-obstructed control kidney tissues (Fig. 3A, B).

**Fig. 2.** Impact of NH₄Cl treatment on nuclear and cytoplasmic Smad2 phosphorylation in renal tissue following unilateral ureteral obstruction. (A) Representative original western blots showing phospho-Smad2 (Ser⁴⁶⁵/⁴⁶⁷), Smad2, Hdac2 and α-tubulin protein abundance in nuclear and cytoplasmic fractions of renal tissue from non-obstructed control kidney (CTR) and obstructed kidney (UUO) following 7 days of unilateral ureteral obstruction (UUO) in control treated mice (ctr) and in mice treated with NH₄Cl (0.28 M NH₄Cl added to the drinking water). (B, C) Arithmetic means ± SEM (n = 7) of nuclear (Nuc, B) and cytoplasmic (Cyt, C) phospho-Smad2 (Ser⁴⁶⁵/⁴⁶⁷)/Smad2 to Hdac2 or α-tubulin protein ratio in the nuclear fraction and cytoplasmic fraction respectively, in renal tissue from non-obstructed control kidney (CTR) and obstructed kidney (UUO) following 7 days of unilateral ureteral obstruction (UUO) in control treated mice (ctr; white bars) and in mice treated with NH₄Cl (0.28 M NH₄Cl added to the drinking water; black bars). *(p<0.05) statistically significant vs respective kidney tissues of control treated mice.
Further experiments addressed the transcript levels of Tgfβ1 target genes: Tnfa, the cytokine Il6, Pai1 and Snai1. As shown in Fig. 4, the increased mRNA expression of Tnfa, Il6, Pai1 and Snai1 in obstructed kidney tissues following UUO were all significantly reduced in NH4Cl treated mice as compared to control treated mice. NH4Cl treatment did not
significantly modify Tnfα, Il6, Pai1 and Snai1 mRNA expression in the non-obstructed control kidney tissues (Fig. 4).

In order to quantify the effect of NH₄Cl treatment on markers of the fibrotic response following UUO, the expression of α-Sma, fibronectin and collagen type I was determined. As a result, the increased α-Sma (Fig. 5A), fibronectin (Fig. 5B) and collagen type I (Fig. 5C) protein expression in obstructed kidney tissues following UUO were significantly reduced in NH₄Cl treated mice as compared to control treated mice. Accordingly, NH₄Cl treatment significantly blunted the increased renal mRNA expression of α-Sma (Fig. 5D), fibronectin (Fbn) (Fig. 5E) and collagen type I (Col1a1) (Fig. 5F) in obstructed kidney tissues following UUO. In non-obstructed control kidney tissues, NH₄Cl treatment did not significantly affect renal α-Sma, fibronectin and collagen type I protein expression and Fbn and Col1a1 mRNA levels but significantly increased renal α-Sma mRNA expression (Fig. 5).

Discussion

The present study reveals a suppressive effect of NH₄Cl treatment on the signaling of renal interstitial fibrosis following UUO. NH₄Cl treatment significantly blunted the increase of renal
α-Sma, a mesenchymal marker mainly expressed by activated fibroblasts and myofibroblasts [5]. Consistent with reduced α-Sma abundance following obstructive injury, renal expression of ECM proteins such as fibronectin and collagen type 1 were mitigated in the mice treated with NH₄Cl.

In the development of renal fibrosis, Tgfβ1 is regarded as the most relevant pro-fibrotic cytokine [7]. Similar to previous findings [8], NH₄Cl treatment inhibited UUO-induced upregulation of Tgfb1 mRNA expression in the obstructed kidney tissues. Dietary treatment with NH₄Cl leads to acidosis [15]. Moreover, NH₄⁺ may further dissociate to H⁺ and NH₃, which permeates membranes and thus enters cells and cellular compartments [16]. NH₃ may bind H⁺ and may thus be trapped as NH₄⁺ within acidic cellular compartments [17]. The binding of H⁺ alkalinizes those compartments [17]. By alkalinizing lysosomes, NH₄Cl has previously been shown to interfere with Tgfβ1 maturation [10].

The effects of NH₄Cl on Tgfb1 expression were paralleled by inhibition of increased Tak1 protein levels and of increased nuclear phosphorylated Smad2, downstream signaling mediators of the pro-fibrotic Tgfβ1 target genes: Tnfa, Il6, Pai1 and Snai1 following obstructive injury. Beyond that, the cellular accumulation of NH₄⁺ with Cl⁻ may lead to cell swelling [19] which suppresses expression of the cell volume sensitive transcription factor TONEBP (Tonicity-Responsive Enhancer Binding Protein) or Nfat5 [20]. Accordingly, NH₄Cl treatment significantly blunted UUO-induced renal Nfat5 expression. Tgfb1 up-regulates Nfat5 expression [21]. Nfat5 was in turn shown to up-regulate Tnfr and Il6 in immune cells [22]. On the other hand, Nfat5 was shown to regulate the expression of several collagen subtypes [23] and chondrogenic differentiation dependent on Sox9 [23], a key transcription factor also in the development of fibrosis [11]. Previous studies show that Sox9 expression is up-regulated by Tgfb1 [12] and Tak1 [13].

Tgfβ is decisive in the triggering of fibrosis of the kidney [3]. Tgfβ may be effective through serum- and glucocorticoid-inducible kinase 1 (Sgk1) and Akt [24]. Sgk1 expression is sharply up-regulated by cell shrinkage [24]. Tgfb1 significantly contributes to the stimulation of renal fibrosis following UUO [4]. Sgk1 is at least in part effective by phosphorylating glycogen synthase kinase 3 (Gsk-3) [14], which is accomplished by Sgk and Akt isoforms [25].

NH₄Cl similarly interferes with Tgfb1 signaling in vascular tissue during hyperphosphatemia [8]. Moreover, renal dysfunction following 5/6 nephrectomy is ameliorated by NH₄Cl treatment [26]. The renoprotective effects of NH₄Cl drinking solution were independent of phosphate [27]. According to these observations, NH₄Cl may have beneficial properties in renal disease. On the other hand acidosis has been shown to aggravate and alkali treatment to delay progression of chronic kidney disease [28, 29].

Conclusion

Tgfb1 signaling leading to renal tissue fibrosis may be counteracted by NH₄Cl treatment, an observation possibly opening novel therapeutic opportunities.

Abbreviations

Col1a1 (collagen type I); ECM (extracellular matrix); EMT (epithelial to mesenchymal transition); Fbn (fibronectin); Gapdh (glyceraldehyde 3-phosphate dehydrogenase); Gsk-3 (glycogen synthase kinase 3); Hdac2 (histone deacetylase 2); Il6 (interleukin 6); Nfat5 (nuclear factor of activated T-cells); NH₄Cl (ammonium chloride); Pai1 (plasminogen activator inhibitor 1); Sgk1 (serum- and glucocorticoid-inducible kinase 1); Smad2 (Sma and Mad (Mothers against decapentaplegic) 2); Sox9 (SRY (sex determining region Y)-box 9); Tak1 (Tgfβ-activated kinase 1); Tgfb1 (transforming growth factor β 1); Tnfr (tumor necrosis factor α); TONEBP (Tonicity-Responsive Enhancer Binding Protein); UUO (unilateral ureteral obstruction); α-Sma (α-smooth muscle actin).
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Disclosure Statement

All authors disclose that they have no potential conflict of interest.

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