Increased basal phosphorylation of detrusor smooth muscle myosin in alloxan-induced diabetic rabbit is mediated by upregulation of Rho-kinase β and CPI-17

Shaohua Chang, Joseph A. Hypolite, Michael E. DiSanto, Arun Changoikar, Alan J. Wein, and Samuel Chacko

Division of Urology and Department of Pathobiology, University of Pennsylvania, Philadelphia, Pennsylvania

Submitted 6 June 2005; accepted in final form 24 September 2005

Increased basal phosphorylation of detrusor smooth muscle myosin in alloxan-induced diabetic rabbit is mediated by upregulation of Rho-kinase β and CPI-17. Am J Physiol Renal Physiol 290: F650–F656, 2006. First published October 4, 2005; doi:10.1152/ajprenal.00235.2005.—Urinary bladder dysfunction caused by the alteration of detrusor smooth muscle (DSM) is one of the complications of diabetes. It is well established that smooth muscle contractility is regulated by an elevation of cytosolic Ca\(^{2+}\) via myosin light chain (MLC) phosphorylation. However, recent studies have shown the modulation of MLC phosphorylation without a rise in Ca\(^{2+}\) in smooth muscle and that two key molecules (Rho-kinase and CPI-17) are involved in the regulation of calcium sensitization. This study investigates the effect of diabetes on DSM calcium sensitization. Diabetes was induced by alloxan in New Zealand White rabbits, and age-matched rabbits given 5% sucrose in the drinking water served as control for diuresis. Two-dimensional gel electrophoresis showed that basal MLC phosphorylation level was significantly higher in diabetic animals than normal or diuretic controls, and Rho-kinase-specific inhibitor, Y-27632, decreased MLC phosphorylation level. Adding Y-27632 to bethanechol-precontracted DSM strips can induce muscle relaxation, but it occurred much more slowly in diabetic samples compared with controls. RT-PCR, Western blot analysis, and immunohistochemistry revealed the overexpression of Rho-kinase β and CPI-17 at both mRNA and protein levels in response to diabetes. In conclusion, our results demonstrate that Rho-kinase contributes to DSM MLC phosphorylation and there is a higher basal MLC phosphorylation level in diabetic DSM. Our results also suggest that this high basal MLC phosphorylation may be due to the upregulation of Rho-kinase and CPI-17. Thus Rho-kinase- and CPI-17-mediated Ca\(^{2+}\) sensitization might play a role in diabetes-induced alteration of the detrusor contractility and bladder dysfunction.

Urinary bladder dysfunction; calcium sensitization; hyperglycemia

Urinary bladder dysfunction is a common complication of diabetes mellitus. The effect of diabetes on the bladder is a delay in the first sensation to void during filling and increased bladder capacity, interpreted as sensory impairment. This altered urodynamic response then progresses with the development of poor contractility and leads to impaired bladder emptying and residual urine (7). These common diabetic complications of the urinary bladder function are thought to be due to the downstream effects of hyperglycemia on the nerve and muscle. However, the underlying mechanisms of diabetes-induced alteration in detrusor smooth muscle (DSM) contractility and bladder dysfunction are not well understood. The induction of experimental diabetes in the rat and rabbit with streptozotocin (STZ) and alloxan provides useful models with which to study various functional, biochemical, and pharmacological alterations that occur in the bladder (10, 18). There are several studies indicating that these diabetic complications may be due to neuronal changes (13–16, 28), downstream effects of oxidative stress (1, 5, 23), and bladder hypertrophy (17, 22).

Normal regulation of smooth muscle contractility is crucial for normal bladder function. Many investigators have shown diabetes-induced alteration in detrusor contractility, either decreased force generation (5, 10, 18, 25) or increased force generation (13, 27, 29) depending on agonists used and experimental conditions. These different contractile responses may be due to diabetes-induced alteration of certain specific receptors, which in turn alters the contractile characteristics. The information regarding the direct effects of diabetes on general smooth muscle contractility or the regulation of smooth muscle contractility is very limited. A recent study shows decreased bladder smooth muscle contraction in diabetes with higher myosin light chain (MLC) phosphorylation levels (25). Phosphorylation and dephosphorylation of MLC are the major regulatory mechanisms of smooth muscle contractility, which is modulated by MLC kinase and MLC phosphatase (MP). MLC kinase is a Ca\(^{2+}\)/calmodulin-dependent kinase, and its regulation is already well known. Recent studies have focused on the regulation of MP and discovered two important proteins that regulate MP activity, Rho-kinase and CPI-17. Rho-kinase is activated by the small GTPase RhoA and inhibits MP through phosphorylating its myosin-binding subunit (12). CPI-17 is a protein phosphatase 1 inhibitor, and its phosphorylated form has been shown to inhibit MP (6, 8). The inhibition of MP by Rho-kinase and CPI-17 decreases MP activity and raises the level of MLC phosphorylation without an increase in calcium concentration. This phenomenon is known as calcium sensitization of smooth muscle (3, 24). In this study, we investigate the effect of diabetes on the regulation of DSM calcium sensitization, especially on MLC phosphorylation, expression of Rho-kinase and CPI-17 in DSM.

Methods

Diabetic rabbit model. All animal studies were approved by the University of Pennsylvania Animal Care and Use Committee. Diabe-

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
tes was induced by injection of alloxan (100 mg/kg body wt) into the ear vein of 12- to 19-d-old male New Zealand White rabbits weighing 6.8 lbs. The blood samples were collected under normal conditions with food and water available for experimental animals. The blood glucose levels were checked 1 wk after the alloxan injection (using a glucometer) and again before euthanasia after 6 mo. Rabbits that maintained blood glucose levels of 300 mg/dl or higher over the 6-mo period were used for this study. Age-matched normal rabbits were given 5% sucrose in their drinking water to serve as diuretic controls.

**Force measurements.** Longitudinal strips of DSM (50 mg and 3 x 10 mm) were suspended in 15 ml of Tyrode’s buffer at 37°C as previously described (4). After a 30-min equilibration, the length of optimal force development (L0) was determined by increasing the length of each strip in 1.5-mm increments until maximal contractile force to electric field stimulation (80 V, 32 Hz, 1 ms) was achieved. After being washed three times with Tyrode’s buffer, the strips were equilibrated at L0 for an additional 15 min to allow stabilization of the muscle at the resting level. The detrusor muscle strips were then stimulated to contract by adding increasing concentrations of carbachol (0–250 μM). After maximal contraction was reached, the relaxation induced by 10 μM Y-27632, a highly selective Rho-kinase inhibitor, was determined.

**Two-dimensional gel electrophoresis.** The frozen bladder tissue was ground to a fine powder in a liquid nitrogen-cooled mortar. The frozen muscle powder was added into a tube containing isoelectric focusing (IEF) buffer (50 mg/ml) and then homogenized with a mini-electric homogenizer. The tissue homogenate was centrifuged at 15,000 g for 20 min. The supernatant was applied to mini-IEF cylindrical gels and electrophoresed at 350 V overnight in a Bio-Rad mini-IEF apparatus. The gels were then removed and subjected to second-dimension electrophoresis on 14% SDS-PAGE gels. The gels were then stained with Coomassie blue, and the spots corresponding to the standards were excised and subjected to protein sequencing using an automated protein sequencer (454, Roche). The spots were excised from the gels, and proteins were digested with trypsin. The resulting peptides were then subjected to mass spectrometry analysis.

**Force measurements.** Longitudinal strips of DSM (50 mg and 3 x 10 mm) were suspended in 15 ml of Tyrode’s buffer at 37°C as previously described (4). After a 30-min equilibration, the length of optimal force development (L0) was determined by increasing the length of each strip in 1.5-mm increments until maximal contractile force to electric field stimulation (80 V, 32 Hz, 1 ms) was achieved. After being washed three times with Tyrode’s buffer, the strips were equilibrated at L0 for an additional 15 min to allow stabilization of the muscle at the resting level. The detrusor muscle strips were then stimulated to contract by adding increasing concentrations of carbachol (0–250 μM). After maximal contraction was reached, the relaxation induced by 10 μM Y-27632, a highly selective Rho-kinase inhibitor, was determined.

**Protein extraction and Western blot analysis.** Total protein of each sample was separated by 12% SDS-PAGE on large-format (16 x 16 cm) gels and transferred to an Immobilon-P membrane (Millipore, Bedford, MA) overnight at 30 V (Bio-Rad mini-transfer unit) in buffer (25 mM Tris, 192 mM glycine, 20% methanol). After being blocked with 5% nonfat milk for 1 h in PBS containing 0.1% Tween 20 (PBST), the membrane was incubated with primary antibodies in PBS for 2 h at room temperature with a dilution of 1:1,000 for monoclonal Rho-kinase β antibody (Transduction Laboratories, Lexington, KY), 1:5,000 for monoclonal smooth muscle α-actin (Sigma, St. Louis, MO), and 1:2,000 for rabbit anti-CPI-17 antibody (Anti-CPI-17, Upstate, Charlotteville, VA). The membrane was then washed three times with PBST and further incubated with secondary horseradish peroxidase-linked antibody (1:3,000 dilution of anti-mouse IgG for Rho-kinase β, and 1:5,000 dilution of donkey anti-rabbit for anti-CPI-17; Amersham Biosciences, Piscataway, NJ) for 1 h at room temperature. Membranes were then washed five times with PBST, and protein expression was detected using an enhanced chemiluminescence kit (ECL) from Amersham Biosciences. The amount of Rho-kinase β and CPI-17 was determined by reflectance scanning. All reactions were kept in the linear range. Identical gels were run for all samples and stained with Coomassie blue to confirm that proteolytic breakdown of the samples had not occurred and also to confirm equal protein loading of gels. Smooth muscle α-actin was used as internal control to normalize Western blot data.

**Immunohistochemistry.** Cross-sections (5 μM) of bladder from diabetic and age-matched rabbits were made from the paraffin blocks. Tissue sections were deparaffinized and put into descending grades of alcohol and then blocked 30 min in 1% BSA solution. After blocking, sections were incubated for 2 h at room temperature with the antibodies specific for Rho-kinase β and CPI-17 (which are described above) at a 1:200 dilution. After washing three times in PBST, the sections were then treated with secondary antibody (anti-mouse Ig-FITC for Rho-kinase β and anti-rabbit IgG-FITC for CPI-17; Sigma) at a dilution of 1:400 for 1 h, washed again three times with PBST, and then mounted with a drop of mounting medium (Aqua-Mount, Lerner Labs, Pittsburgh, PA). Sections were viewed under a Nikon (Melville, NY) Eclipse E800 fluorescence microscope, and images were captured using a RT-Slider SPOT camera (Diagnostic Instruments, Sterling Heights, MI) and Image-Pro Plus software from Media Cybernetics (Silver Spring, MD). A negative control, in which only the secondary antibody was added, was performed for all samples.

**Statistical analysis.** All data are expressed as means ± SE with P < 0.05 considered statistically significant. ANOVA was applied using SigmaStat Version 2.03 (SPSS, Chicago, IL). Each n refers to a set of age-matched normal, diabetic control, and diabetic rabbits.

**RESULTS**

Blood glucose level in normal, diuretic, and diabetic animals. Alloxan treatment induced a significantly high level of blood glucose in the rabbits (Fig. 1). The average blood glucose level was...
glucose was $\sim 380 \pm 25.5$ mg/dl in diabetic animals, only $180 \pm 12.5$ mg/dl in diuretic controls, and $165 \pm 11.5$ mg/dl in normal animals. There was no significant difference in blood glucose levels between diuretic control and normal animals. This result indicated that only alloxan treatment induced higher blood glucose, whereas 5% sucrose in drinking water did not affect blood glucose levels. Alloxan treatment also altered animals’ body weight and bladder weight (see Table 1). There were a significant increase in bladder weight and a decrease in body weight in diabetic group compared with normal or diuretic controls. *Significant difference between samples ($n = 8$, $P < 0.01$).

**Expression of Rho-kinase β in normal, diuretic, and diabetic DSM.** We found that diabetes induced upregulation of Rho-kinase β at both mRNA and protein levels (Fig. 5). Real-time PCR is a very sensitive method to detect any change at mRNA level. A standard curve of target gene can be used to calculate its PCR efficiency and confirm the PCR amplification is in a linear range (Fig. 5A). A small PCR cycle number of crossing threshold means a high copy number of target transcript to start with. Our result showed the cycle number of crossing threshold was $\sim 27.3$ for normal sample, 26.9 for diuretic control, and 23.5 for diabetic sample (Fig. 5B). This significantly reduced cycle number revealed 10.3-fold higher expression of Rho-kinase β at the mRNA level in diabetic detrusor compared with normal and diuretic control. However, there was no significant difference between diuretic and normal detrusor. Western blot analysis confirmed the upregulation of Rho-kinase β in diabetic detrusor at the protein level. Smooth muscle α-actin was used as an internal control to normalize the Western blot. The Rho-kinase band was remarkably stronger in diabetic samples than in normal and diuretic controls (Fig. 5C). The overexpression of Rho-kinase β at the protein level revealed about a 2.1-fold increase in diabetic detrusor compared with normal and diuretic samples (Fig. 5D).

**Expression of CPI-17 in normal, diuretic, and diabetic DSM.** We also found that the expression of CPI-17 was significantly increased in diabetic detrusor at both mRNA and protein levels (Fig. 6). Real-time PCR showed that there was no significant difference in the required PCR cycle numbers between normal and diuretic controls, about 31.4 for normal samples and 31.6 for diuretic controls. However, it was significantly reduced to 26.1 cycles for diabetic samples, which meant $\sim 12.5$-fold more CPI-17 mRNA in diabetic DSM (Fig. 6B). Western blot also showed much stronger bands of CPI-17 for diabetic DSM samples compared with that of controls (Fig. 6C). Diabetes induced $\sim 2.5$-fold higher protein expression of CPI-17 in DSM (Fig. 6D).

**Immunohistochemical localization of Rho-kinase β and CPI-17 in bladder from diabetic and normal rabbits.** The representative immunostaining slides showed the localization of Rho-kinase β and CPI-17 in bladder tissue from normal and diabetic rabbits (Fig. 7). The intensity of immunofluorescent signals (FITC) indicated the expression of Rho-kinase β and CPI-17, which was much brighter in the bladder from diabetic rabbits (Fig. 7, A and C) compared with that from normal rabbits (Fig. 7, B and D). It can also be observed that both Rho-kinase β and CPI-17 are mainly expressed within smooth muscle bundles in the bladder. In conclusion, immunostaining confirmed that diabetes remarkably upregulated Rho-kinase β and CPI-17 in DSM.

### Table 1. Body weight and bladder weight from normal, diuretic, and diabetic animals

<table>
<thead>
<tr>
<th></th>
<th>Body Weight, kg</th>
<th>Bladder Weight, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>3.67±0.28</td>
<td>2.11±0.14</td>
</tr>
<tr>
<td>Diuretic control</td>
<td>3.88±0.31</td>
<td>2.19±0.22</td>
</tr>
<tr>
<td>Diabetic</td>
<td>2.83±0.15*</td>
<td>2.81±0.11*</td>
</tr>
</tbody>
</table>

Values are means ± SE. *$P < 0.01$. 

**Fig. 1. Blood glucose level in normal, diuretic control, and diabetic animals.** The average of blood glucose level was $163 \pm 11.5$ mg/dl in normal rabbits, $83 \pm 9.8$ mg/dl in diuretic controls, and $391 \pm 18.1$ mg/dl in alloxan-induced diabetic animals. There was a significant increase of blood glucose level in diabetic animals compared with normal or diuretic controls. *Significant difference between samples ($n = 8$, $P < 0.01$).
DISCUSSION

Urinary bladder dysfunction is a common complication of diabetes mellitus, and the mechanisms of diabetes-induced bladder dysfunctions are not well understood. Therefore, the treatment strategies for bladder dysfunction in diabetes are very limited. DSM contractility is crucial for normal bladder function. In this study, we examined the effects of diabetes on the regulation of MLC phosphorylation, which is a key factor for smooth muscle contraction. We demonstrated that MLC phosphorylation was higher in DSM from diabetic animals compared with normal and diuretic controls (Fig. 2). This result is consistent with a recent study on diabetes showing...

![Fig. 2](image-url)  
Selected areas from 2-dimensional (2D) gel showing basal MLC20 phosphorylation in normal, diuretic, and diabetic detrusor smooth muscle (DSM). A: normal. B: diuretic. C: diabetic. D: bar graph showing the average values of myosin light chain (MLC) phosphorylation. Phosphorylated MLC20 (P-MLC20) runs slightly higher and more toward the acidic side than unphosphorylated MLC20 (UP-MLC20) in the gel. The basal phosphorylation of MLC20 was ~18% in normal DSM. Diuretic control had a very similar level (19.2%) of MLC20 phosphorylation. However, the phosphorylation level was significantly increased to 28% in diabetic detrusor. *Significant difference between samples (n = 3, P < 0.05).

![Fig. 3](image-url)  
MLC20 dephosphorylation induced by selective Rho-kinase inhibitor Y-27632 in diabetic detrusor. A: 2D gel for diabetic detrusor. B: 2D gel for diabetic detrusor with Y-27632 incubation. C: bar graph showing the decreased MLC phosphorylation induced by Y-27632. The phosphorylation level of diabetic detrusor MLC20 was significantly decreased from 28 to 9.2% at 5 min after adding Y-27632. *Significant difference between samples (n = 3, P < 0.05).
decreased detrusor contraction with increasing levels of MLC phosphorylation (25). Moreover, we found that basal MLC phosphorylation can be reduced by incubation with Rho-kinase inhibitor Y-27632 (Fig. 3) and that DSM relaxation occurred more slowly in diabetic animals (Fig. 4). These data suggest that Rho-kinase is involved in the regulation of MLC phosphorylation and there is more Rho-kinase activity in diabetic DSM, which contributes to higher basal MLC phosphorylation and slower relaxation. We confirmed the upregulation of Rho-kinase at both mRNA and protein level (Figs. 5 and 7).

Rho-kinase is activated by a small GTPase RhoA and then activated Rho-kinase phosphorylates MP, which leads to an inhibition of MP activity (12). There are two isoforms of Rho-kinase, \( \alpha \) and \( \beta \), and our previous study showed the overexpression of Rho-kinase \( \beta \) in diabetic corpus cavernosum smooth muscle (4). Using the same experimental model for this study, we found that diabetic DSM also overexpressed Rho-kinase \( \beta \). Our findings reveal that diabetes induces upregulation of Rho-kinase in more than one type of urological smooth muscle. There are also reports on the upregulation of RhoA/Rho-kinase in cavernosal tissue isolated from the penis of STZ-diabetic rats (2), increased RhoA translocation in renal cortex of diabetic rats (20), and overexpression of RhoA in the basilar artery from diabetic rats (21). CPI-17 is a PKC-catalyzed phosphorylation-dependent inhibitory protein for MP, and it is mainly expressed in smooth muscle (8). It is well documented that diabetes induces overexpression of PKC (9, 11). We directly measured the effect of diabetes on CPI-17, the downstream substrate of PKC, and found overexpression of CPI-17 in detrusor from diabetic animals (Figs. 6 and 7). To our knowledge, this is the first report of upregulation of CPI-17 in DSM. The upregulation of CPI-17 and Rho-kinase provides a logical explanation for decreased MP activity without any change in MP content (25). Both CPI-17 and Rho-kinase play an important role in the calcium sensitization pathway by regulating DSM contractility through inhibition of MP activity (26). Therefore, the upregulation of Rho-kinase \( \beta \) and CPI-17 contributes to the high basal MLC phosphorylation level and slow relaxation in DSM from diabetic animals.

A recent study showed the overexpression of two thin filament-associated proteins, caldesmon and calponin, in DSM from diabetic rabbits (19). Both caldesmon and calponin suppress actin-myosin interaction and act as a brake for smooth muscle contraction. The overexpression of caldesmon and calponin might necessitate higher levels of MLC phosphorylation to overcome the effect of these inhibitory proteins on force generation. This might be one of the reasons why DSM from diabetic animals has impaired contraction, despite higher basal MLC phosphorylation.

Fig. 4. Relaxation of bethanechol-precontracted DSM strips from normal, diuretic, and diabetic animals by Y-27632. Muscle strips were stimulated to contract in response to 0 to 250 \( \mu \)M of bethanechol. After the muscle developed maximal force, Y-27632 was added to the muscle bath to obtain a final concentration of 10 \( \mu \)M and the relaxation of muscle strips was calculated.

Fig. 5. Expression of Rho-kinase \( \beta \) at both mRNA and protein level. A: real-time PCR standard curve for Rho-kinase \( \beta \). B: average of required PCR cycle numbers to reach crossing threshold. The required PCR cycle numbers was −27.3 for normal samples, 26.9 for diuretic controls, and 23.5 for diabetic samples. A significantly lower number of PCR cycles for the diabetic sample indicated that diabetic DSM sample had more copies of Rho-kinase \( \beta \) transcript. C: Western blot for Rho-kinase \( \beta \) and smooth muscle \( \alpha \)-actin. D: bar graph showing the average of relative protein expression level. There was almost a 2.1-fold higher protein expression of Rho-kinase \( \beta \) in diabetic detrusor compared with normal and diuretic samples. *Significant difference between samples (\( n = 4, P < 0.01 \)).
However, it is not clear whether this alteration is compensatory or pathological. The hyperglycemia-induced oxidative stress is also likely to alter the contractile protein by modification of the myosin active sites. Additional studies are required to evaluate the role of oxidative stress in reducing the DSM contractility in diabetes.

In summary, our results showed that the high basal MLC phosphorylation level, slow relaxation, and upregulation of Rho-kinase and CPI-17 only occurred in diabetic animals, not in diuretic controls. Thus the downstream effects of hyperglycemia might be the primary reason for all these changes. The upregulation of Rho-kinase and CPI-17 may play an important role in the adaptation of the smooth muscle to high blood glucose. Further studies on the pharmacological effects of Rho-kinase and CPI-17 may provide novel strategies for the treatment of diabetes-induced bladder dysfunction.

Fig. 6. Expression of CPI-17 at both mRNA and protein level. A: standard curve of real-time PCR for CPI-17. B: average of the PCR results. The required PCR cycle numbers was significantly decreased in diabetic DSM samples compared with normal or diuretic controls. It was $-31.4$ cycles for normal sample, $31.6$ cycles for diuretic controls, and $26.1$ cycles for diabetic samples. C: Western blot for CPI-17. D: bar graph showing the relative expression of CPI-17 at the protein level. There was almost a 2.5-fold higher expression of CPI-17 at the protein level in diabetic detrusor compared with normal and diuretic samples. *Significant difference between samples ($n = 4$, $P < 0.01$).

Fig. 7. Immunohistological localization of Rho-kinase $\beta$ and CPI-17. Representative bladder paraffin sections from age-matched normal and 6-mo diabetic rabbits were prepared for immunofluorescence microscopy. The immunofluorescent staining was remarkably brighter in the bladder from diabetic rabbits ($B$ and $D$) compared with the bladder from normal rabbits ($A$ and $C$), which indicated that both Rho-kinase and CPI-17 proteins were overexpressed in response to diabetes. It can also be concluded from $A-D$ that both Rho-kinase and CPI-17 are mainly expressed in the smooth muscle cells within DSM bundles (black arrowheads). The blood vessels (white arrows) also react with these antibodies as expected, but not the collagenous matrix ($*$).
REFERENCES


