Vascular Reactivity in Heart Failure
Role of Myosin Light Chain Phosphatase

Syed M. Karim, Albert Y. Rhee, Allison M. Given, Michael D. Faulx, Brian D. Hoit, Frank V. Brozovich

Abstract—Congestive heart failure (CHF) is a clinical syndrome, which is the result of systolic or diastolic ventricular dysfunction. During CHF, vascular tone is regulated by the interplay of neurohormonal mechanisms and endothelial-dependent factors and is characterized by both central and peripheral vasoconstriction as well as a resistance to nitric oxide (NO)–mediated vasodilation. At the molecular level, vascular tone depends on the level of regulatory myosin light chain phosphorylation, which is determined by the relative activities of myosin light chain kinase and myosin light chain phosphatase (MLCP). The MLCP is a trimeric enzyme with a catalytic, a 20-kDa and a myosin targeting (MYPT1) subunit. Alternative splicing of a 3′ exon produces leucine zipper positive and negative (LZ+/−) MYPT1 isoforms. Expression of a LZ+ MYPT1 has been suggested to be required for NO-mediated smooth muscle relaxation. Thus, we hypothesized that the resistance to NO-mediated vasodilatation in CHF could be attributable to a change in the relative expression of LZ+ MYPT1 isoforms. To test this hypothesis, left coronary artery ligation was used to induce CHF in rats, and both the dose response relationship of relaxation to 8-Br-cGMP in skinned smooth muscle and the relative expression of LZ+ MYPT1 isoforms were determined. In control animals, the expression of the LZ+ MYPT1 isoform predominated in both the aorta and iliac artery. In CHF rats, LVEF was reduced to 30±5% and there was a significant decrease in both the sensitivity to 8-Br-cGMP and expression of the LZ+ MYPT1 isoform. These results indicate that CHF is associated with a decrease in the relative expression of the LZ+ MYPT1 isoform and the sensitivity to 8-Br-cGMP–mediated smooth muscle relaxation. The data suggest that the resistance to NO-mediated relaxation observed during CHF lies at least in part at the level of the smooth muscle and is a consequence of the decrease in the expression of the LZ+ MYPT1 isoform. (Circ Res. 2004;95:000-000.)

Key Words: cGMP □ vascular function □ nitric oxide □ congestive heart failure

Congestive heart failure (CHF) is a clinical syndrome, which is the result of systolic or diastolic ventricular dysfunction. It is associated with vascular abnormalities including a resting vasoconstriction1–8 and resistance to nitric oxide (NO)–mediated vasodilatation.1–3 Previous studies have demonstrated impairment in NO-mediated vasodilatation in renal and cerebral arteries in rat models of heart failure,4,5 and similar attenuated responses to nitrates have been demonstrated in the peripheral vasculature in humans with heart failure.1 The decrease in the sensitivity to NO has been attributed to both endothelial dysfunction6–8 and abnormalities at the level of smooth muscle.2 Nonetheless because nitrates decrease both preload and afterload, nitrates are beneficial in both the acute treatment of decompensated CHF as well as the chronic treatment of patients with CHF.9,10 Thus understanding the mechanism for both the regulation of vascular tone and the resistance to NO-mediated vasodilatation is critical for the management of congestive heart failure.

The level of regulatory myosin light chain 20 (MLC20) phosphorylation has been shown to determine the force of smooth muscle contraction11 and thus vascular tone. Therefore, vascular tone is critically dependent on the activities of myosin light chain kinase (MLCK) and myosin light chain phosphatase (MLCP), and steady state MLC20 phosphorylation can be computed12 as the activities of (MLCK/MLCK + MLCP). MLCK is a Ca2+/calmodulin dependent enzyme,13,14 whereas the activity of MLCP can be both inhibited to produce Ca2+ sensitization (see review15), or stimulated to produce Ca2+ desensitization.15,16 MLCP is a heterotrimeric enzyme (see review17) consisting of a 37-kDa catalytic subunit, a 20-kDa subunit of unknown function, and a 130/133-kDa myosin targeting subunit (MYPT1). Alternative splicing of a central and 3′ exon generates four isoforms of MYPT1.17–19 Specifically, exclusion of a 31-bp 3′ exon results in a shift of the reading frame of the MYPT1 transcript to encode a C-terminal LZ motif.19 Additionally, both the activity20 and regulation21 of MLCP has been suggested to be isoform specific.

NO-mediated vasodilatation is one of the fundamental vascular responses.16,22 NO is known to activate the soluble...
pool of guanylate cyclase and result in an increase in cGMP, which in turn activates type IIA protein kinase G (PKGIIA). The activation of PKGIIA results in vesicle calcium release and a vasodilatation attributable to hyperpolarization,23 a decrease in Ca\(^{2+}\) flux,24,25 and an activation of MLCP.26 The importance of cGMP-mediated activation of MLCP in smooth muscle relaxation is underscored by recent results that have demonstrated that the sensitivity of smooth muscle relaxation to cGMP is regulated by the level of expression, relative to total MYPT1 expression, of the LZ\(^{+}\) MYPT1 isoform19 and PKGIIA activation of MLCP requires a LZ\(^{+}\) MYPT1.27

We have previously shown for MYPT1 that alternative mRNA splicing is both developmentally regulated and tissue specific, and thus is MYPT1 isoform specific.18,19 This could suggest that MYPT1 splicing is modulated during disease states. In this study, we determined if the resistance to cGMP-mediated vasodilatation during CHF is attributable to a change in the relative expression of LZ\(^{+}\) MYPT1 isoforms, an abnormality at the level of the smooth muscle.

Materials and Methods

Animal Model of Congestive Heart Failure

We used a well-accepted and studied model of CHF, the rat infarct model, which many others have demonstrated has signs of CHF including a decrease in left ventricular function (LVF), dilatation of the LV, hypervolemia, pleural effusions, and ascites.26–31 Briefly, using a surgical protocol approved by the IACUC of Case Western Reserve University, Sprague Dawley rats were placed under general anesthesia using a combination of IP ketamine, xylazine, and acepromazine, and then intubated and placed on a mechanical ventilator (Harvard Apparatus). A left thoracotomy was performed, and the heart was exposed before the chest was closed. In control and postmyocardial infarction rats, left ventricular function was assessed by echocardiography at 2-week intervals. Images were collected using a cardiac ultrasound system (Acuson Sequoia) equipped with a 13-MHz linear array transducer. Two-dimensional digital image processing was performed using an automated unit consisting of the intensities of the bands using an automated unit consisting of a flat bed scanner and analysis software (Amersham).

Statistics

All values reported in the text are mean±SEM and a total of n=6 to 10 animals are included in each experimental group. Differences between means were determined using an ANOVA and P<0.05 was taken as significant. There was no difference between the data for control and sham surgical animals, and the data are labeled as control.

Results

Left Ventricular Function

Two-dimensional echocardiography was performed on both control and CHF rats. The control animals had LVEF of 65±5%. After ligation of the LAD, the anterior wall and septum became hypokinetic to akinetic, the left ventricular end diastolic dimension increased, and the LVEF fell to 30±5% (n=20, Figure 2, Table 1). Further, the CHF animals would stand in their cage with their noses elevated, which is
suggestion of orthopnea, and at the time of euthanasia had pleural effusions. These findings are consistent with the development of the clinical syndrome of CHF in the rats 8 weeks after an anterior myocardial infarction (MI).

Mechanical Studies
After Ca²⁺ activation of permeabilized smooth muscle strips, force rose to a steady state in both control and CHF animals. There was no significant difference in the maximum force per cross-section between the control and the CHF rats (Table 2), suggesting that tissues were permeabilized to similar extents. In both controls and CHF animals, the aorta generated the highest force, whereas the iliac artery developed the lowest force.

Overall, the smooth muscles from the control animals, compared with CHF animals, were significantly more sensitive to 8-Br-cGMP (Figure 3). In skinned control aortic strips, 1 nmol/L 8-Br-cGMP produced a 58±14% (n=6) relaxation compared with only 8±3% (n=5, P<0.05) in the CHF animals; in control aorta complete relaxation was produced by 10 μmol/L 8-Br-cGMP, whereas in CHF aortic strips only 47±19% relaxation. Similarly for the iliac artery, 10 nmol/L 8-Br-cGMP completely relaxed control strips (n=6), compared with a 30±6% (n=5) relaxation in the CHF rats. Further, 10 nmol/L 8-Br-cGMP only produced a 66±12% relaxation iliac artery strips from CHF rats (Figure 3). The portal vein was relatively insensitive to 8-Br-cGMP in both control and CHF rats; 1 nmol/L 8-Br-cGMP produced a 3±1% relaxation for both the control (n=5) and CHF (n=5) animals, whereas 100 μmol/L 8-Br-cGMP produced a 52±9% relaxation in the portal vein from control rats compared with a 37±12% relaxation in CHF rats (Figure 3). Although the relaxation response of the portal vein to higher concentrations of 8-Br-cGMP was decreased in the CHF rats, these differences were not statistically significant.

Protein Expression and Message
To determine whether CHF was associated in a change in protein expression of MYPT1 isoforms, we performed Western blots using both a polyclonal MYPT1 antibody and a monoclonal antibody selective for only LZ⁺ MYPT1 isoforms. As can be seen (Figure 4A), in smooth muscle from

### TABLE 1. Left Ventricular Function

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<thead>
<tr>
<th></th>
<th>Controls</th>
<th>CHF</th>
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<tbody>
<tr>
<td>End diastolic dimension</td>
<td>0.87±0.04</td>
<td>1.04±0.10</td>
</tr>
<tr>
<td>End systolic dimension</td>
<td>0.59±0.04</td>
<td>0.77±0.04</td>
</tr>
<tr>
<td>Fractional shortening</td>
<td>36.0±2.9</td>
<td>25.8±2.7</td>
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End diastolic dimension, end systolic dimension, and fractional shortening were all significantly (P<0.01) different in the CHF rats compared to controls.

### TABLE 2. Maximal Ca²⁺ Activated Force

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th>CHF</th>
</tr>
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<tbody>
<tr>
<td>Aorta</td>
<td>16.0±2.2</td>
<td>15.1±0.7</td>
</tr>
<tr>
<td>Portal vein</td>
<td>10.9±0.8</td>
<td>12.4±2.6</td>
</tr>
<tr>
<td>Iliac artery</td>
<td>7.2±0.9</td>
<td>9.8±3.4</td>
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There was no significant difference between the maximal Ca²⁺ activated force (mN/mm²) in smooth muscle from control or CHF animals (n=5–6 in each group).
the CHF rats compared with control tissues for the same level of total MYPT1, the expression of the LZ+/H11001 MYPT1 isoform decreased markedly in the iliac artery and modestly in the aorta. The ratio of the density of LZ+/H11001 band/total MYPT1 band was calculated to quantify the relative expression of the LZ+/H11001 MYPT1 isoform. However, this quantification uses two antibodies with different affinities, and thus this ratio is only a relative measure of protein expression. In control tissues, the relative expression of the LZ+/H11001 MYPT1 isoform was highest in the iliac artery (Figure 4B). Compared with the control tissues, in the CHF animals, the expression of the LZ+/H11001 MYPT1 isoform significantly decreased (P<0.05) in both the aorta and iliac artery, but the decrease was more pronounced (P<0.05) in the iliac artery compared with the aorta (30% versus 20%, respectively). The expression of the LZ+/H11001 MYPT1 isoform in the portal vein was low, and did not change after the development of CHF.

To confirm that this decrease in protein expression in the aorta and iliac artery was accompanied by a change in the relative mRNA levels, we used RT-PCR to determine the relative mRNA levels for LZ- and LZ+ MYPT1 transcripts (Figure 5). In control animals, the expression of the LZ+ MYPT1 transcript predominated in aorta (94±6%) and iliac artery (67±4%). Eight weeks after ligation of the anterior coronary artery in the CHF animals there was a decrease (P<0.05) in the expression of the LZ+ MYPT1 transcript to 79±6% in aorta and 37±5% in the iliac artery (Figure 5). Thus for both the aorta and iliac artery, CHF was associated with a significant decrease in the expression of both MYPT1 LZ+ transcript and protein.

We also used Western blots to determine whether a change in the expression of PKGI or a switch in PKGI isoform expression, from PKGIα to PKGIβ, accompanied CHF. Western blots using a nonspecific PKGIα/β antibody showed the presence of only a single protein band at 78 kDa in smooth muscle from both control and CHF rats (Figure 6). The intensity of this band was similar (P>0.05) in control and CHF tissues, suggesting that CHF is not accompanied by a change in total PKGI expression. In addition in both control and CHF smooth muscle, a PKGIβ-specific antibody did not detect protein, which suggests that PKGI expression is exclusively PKGIα.

**Discussion**

NO-mediated vasodilatation is a fundamental response of the vasculature.\(^{16,22}\) The basic mechanism governing NO-
mediated smooth muscle relaxation has been delineated. NO is known to stimulate guanylate cyclase to increase cGMP which in turn activates PKGI. PKGI has multiple targets in smooth muscle, which all result in smooth muscle relaxation by different mechanisms including phosphorylation of the maxi K⁺ channel to produce hyperpolarization, both Ca²⁺ channels and the SR to decrease intracellular Ca²⁺, and an activation of MLCP.

However, there is diversity in the response of smooth muscle to NO in normal tissues, as well as a blunted response in CHF. The mechanism responsible for differential sensitivity to NO has been suggested to be attributable to changes in the relative expression of LZ/MYPT1 isoforms. Surks et al. have demonstrated that compared with control tissue, CHF was associated with a change in the relative expression of LZ/MYPT1 isoforms with a significant decrease in the expression of the LZ⁺ MYPT1 isoform in both the aorta and the iliac artery (Figure 4). The decrease in LZ⁺ MYPT1 isoform expression was more prominent in the more distal vessel (iliac artery), compared with a conduit vessel (aorta), and could suggest that the modulation of LZ⁺ MYPT1 isoform expression in resistance vessels could be even more dramatic. Furthermore, the sensitivity to cGMP-mediated smooth muscle relaxation (Figure 3) scaled with the relative expression of the LZ⁺ MYPT1 isoform (Figure 4). The expression of the LZ⁺ MYPT1 isoform and sensitivity to cGMP-mediated relaxation listed from highest to lowest is control iliac artery, control aorta, CHF iliac artery, CHF aorta, and portal vein. Further the decrease in LZ⁺ MYPT1 isoform expression in both the aorta and iliac artery correlates with the decrease in the sensitivity to cGMP mediated smooth muscle relaxation. Thus, similar to normal tissues, the sensitivity to cGMP-mediated relaxation is determined, at least in part, by the expression of the LZ⁺ MYPT1 isoform. The sensitivity to cGMP-mediated smooth muscle relaxation was low in the portal vein consistent with the expression of the LZ⁺ MYPT1 isoform, but similar to that observed in the CHF aorta. These data could suggest that there could be a threshold level of LZ⁺ expression before a tissue is sensitive to cGMP.

PKGI is expressed in three different isoforms (PKGIα, PKGIβ, and PKGII) in mammalian smooth muscles, and this group has suggested that only PKGIα, but not PKGIβ, dimerizes with the MYPT1 to activate MLCP activity. We demonstrated that compared with control tissue, CHF was neither associated with a change in the total PKGI expression nor a change in PKGI isoform expression, which is exclusively PKGIα in both control and CHF smooth muscle (Figure 6). These data rule out the possibility that the isoforms could explain a decrease in sensitivity to NO-mediated vasodilation in CHF.

In our animals 8 weeks after anterior coronary artery ligation, echocardiography (Figure 2) demonstrated a significant impairment of LV systolic function and dilatation of the left ventricle (Table 1). Ligation of the LAD to produce an anterior myocardial infarction is well accepted to produce a model of CHF and LV remodeling in rats. The alterations in LVF observed in our CHF animals is similar to that demonstrated by others.

In the rats used in this study, CHF was associated with a change in the relative expression of LZ⁺/LZ⁻ MYPT1 isoforms with a significant decrease in the expression of the protein level of the LZ⁺ MYPT1 isoform in both the aorta and the iliac artery (Figure 4). The decrease in LZ⁺ MYPT1 isoform expression was more prominent in the more distal vessel (iliac artery), compared with a conduit vessel (aorta), and could suggest that the modulation of LZ⁺ MYPT1 isoform expression in resistance vessels could be even more dramatic. Furthermore, the sensitivity to cGMP-mediated smooth muscle relaxation (Figure 3) scaled with the relative expression of the LZ⁺ MYPT1 isoform (Figure 4). The expression of the LZ⁺ MYPT1 isoform and sensitivity to cGMP-mediated relaxation listed from highest to lowest is control iliac artery, control aorta, CHF iliac artery, CHF aorta, and portal vein. Further the decrease in LZ⁺ MYPT1 isoform expression in both the aorta and iliac artery correlates with the decrease in the sensitivity to cGMP mediated smooth muscle relaxation. Thus, similar to normal tissues, the sensitivity to cGMP-mediated relaxation is determined, at least in part, by the expression of the LZ⁺ MYPT1 isoform. The sensitivity to cGMP-mediated smooth muscle relaxation was low in the portal vein consistent with the expression of the LZ⁺ MYPT1 isoform, but similar to that observed in the CHF aorta. These data could suggest that there could be a threshold level of LZ⁺ expression before a tissue is sensitive to cGMP.
observed decrease in sensitivity to cGMP-mediated smooth muscle relaxation in the present study was attributable to a change in PKGI expression. In addition, our experiments were performed in skinned smooth muscle, and thus we can also rule out neurohormonal activation, differences in resting membrane potential or differences in Ca\(^{2+}\) flux as contributors to the decrease in sensitivity to cGMP.

Using short GST fusion proteins, Surks et al\(^{11}\) have shown that MYPT1 is able to dimerize with PKGI\(\alpha\), only if both MYPT1 and PKGI express a LZ. However, we have recently shown that both full-length avian LZ\(^{-}\) and LZ\(^{+}\) MYPT1 isoforms will bind PKGI\(\alpha\),\(^27\) suggesting that the PKGI-MYPT1 interaction is not mediated by the C-terminal LZ domain of MYPT1, but rather, possibly mediated by a MYPT1 coiled-coil domain present at aa 888–928.\(^{43}\) Although the LZ is not required for the interaction of MYPT1 with PKGI\(\alpha\), we did demonstrate that a LZ\(^{-}\) MYPT1 isoform is required for PKGI\(\alpha\) to activate MLCP activity.\(^27\) Although the exact mechanism by which PKGI\(\alpha\) activates MLCP activity has yet to be elucidated, it could be attributable to coiled-coil interaction of PKGI\(\alpha\) with MYPT1\(^{27,43}\) and subsequent MYPT1 phosphorylation.\(^{26,27,41}\) Nonetheless, the decrease in LZ\(^{-}\) MYPT1 expression observed during CHF in the present study would suggest that the decrease in sensitivity to NO-mediated vasodilation observed in this clinical syndrome lie at least partially at the level of the smooth muscle, and is a consequence of the decrease in LZ\(^{+}\) MYPT1 expression.

Most effective therapies that result in a decrease in mortality in patients with CHF are aimed at the vasculature,\(^{1,10}\) which suggests that there is an underlying abnormality of vascular function associated with this clinical syndrome. However until the present study, no data existed to suggest a possible molecular mechanism for the abnormality of vascular function. Others\(^5\) have demonstrated a decrease in the sensitivity of smooth muscle relaxation to nitroprusside in the rat infarct model of CHF, suggesting that in this model there is an abnormality in NO signaling at the level of the smooth muscle, independent of endothelial function. Additionally, the skinned smooth muscle strips used in the present study lack an endothelium and thus the decrease in sensitivity to cGMP mediated relaxation in the present study, reflects the abnormality in NO signaling in this animal model of CHF. Further, we have previously shown that cGMP/PKGI\(\alpha\)-mediated activation of MLCP activity requires the expression of a LZ\(^{-}\) MYPT1 subunit.\(^{27}\) Thus during the clinical syndrome of CHF, the data in the present article suggest that the resistance to NO-mediated vasodilation lie at least in part at the level of the smooth muscle and is a consequence of a modulation of MYPT1 LZ\(^{+}\) isoform expression, and specifically attributable to a decrease in the expression of LZ\(^{-}\) MYPT1 isoform.

An increase in blood flow is known to increase the shear stress on the endothelial cells and stimulate the production of NO, which stimulates PKGI and a resulting increase in cGMP, which activates PKGI and results in vasodilatation. Our results demonstrate that the vessel’s sensitivity to NO-mediated vasodilation is determined, in part, by the relative expression of the LZ\(^{-}\) MYPT1 isoform. Thus, the decrease in LZ\(^{-}\) MYPT1 expression observed in our animal model of CHF would thus result in a decrease in the sensitivity to NO, and would be expected to blunt flow-mediated vasodilatation. This would increase vascular tone and thus could produce a resting vasoconstriction, another vascular abnormality associated with the clinical syndrome of CHF.

The signaling pathway to explain a change in LZ\(^{-}\) MYPT1 isoform expression both during development\(^9\) and CHF (present study) is unknown. However, pharmacologically targeting this pathway with small molecule inhibitors or other therapeutic agents aimed at blocking MYPT1 isoform switching or directly activating the MLCP, could potentially open a new, and possibly more effective avenue for treating patients with CHF.

**Acknowledgments**

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**References**

15. Somlyo AP, Somlyo AV. Ca\(^{2+}\) sensitivity of smooth muscle and non-
muscle myosin II. Modulated by G proteins, kinases, and myosin phos-


17. Hartshorne DJ, Ito M, Erdi F. Myosin light chain phosphatase: subunit

18. Dirksen WP, Vladic F, Fisher SA. A myosin phosphatase targeting subunit
isoform transition defines a smooth muscle developmental pheno-

19. Khatri JJ, Joyce KM, Brozovich FV, Fisher SA. Role of myosin phos-
phatase isoforms in cGMP-mediated smooth muscle relaxation. *J Biol

20. Ogut O, Brozovich FV. Determinants of the contractile properties in the
embryonic chicken gizzard and aorta. *Am J Physiol.* 2000;279:
C1722–C1732.

21. Richards CT, Ogut O, Brozovich FV. Agonist-induced force
enhancement. The role of isoforms and phosphorylation of the myosin-
2002;277:4422–4427.

22. Furchgott RF. Endothelium-derived relaxing factor: discovery, early

The large conductance, voltage-dependent, and calcium-sensitive K+
channel, Hslo, is a target of cGMP-dependent protein kinase phospor-

24. Schmidt HH, Lohmann SM, Walter U. The nitric oxide and cGMP signal
transduction system: Regulation and mechanism of action. *Biochim

25. Fukao M, Mason HS, Britton FC, Kenyon JL, Horowitz B, Keef KD.
Cyclic GMP-dependent protein kinase activates cloned BKCa channels
expressed in mammalian cells by direct phosphorylation at serine 1072.

26. Surks HK, Mochizuki N, Kasai Y, Georgescu SP, Tang KM, Ito M, Lincoln TM, Mendelsohn ME. Regulation of myosin phosphatase by a
specific interaction with cGMP-dependent protein kinase 1er. *Science.*

27. Huang QQ, Fisher SA, Brozovich FV. Unzipping the role of myosin light

28. Geenen DL, Malhotra A, Scheuer J. Regional variation in rat cardiac

29. Geenen DL, Malhotra A, Liang D, Scheuer J. Ventricular function and
contractile proteins in the infarcted overloaded rat heart. *Cardiovasc.

30. Delp MD, Duan C, Mattson JP, Musch TI. Changes in skeletal muscle
biochemistry and histology relative to fiber type in rats with heart failure.

31. Symons JD, Stebbins CL, Musch TI. Interactions between angiotensin II
and nitric oxide during exercise in normal and heart failure rats. *J Appl

32. Hoit BD, Castro C, Bultron G, Knight S, Matlib MA. Noninvasive
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33. Rhee AY, Brozovich FV. The smooth muscle cross-bridge cycle studied

34. Karagiannis P, Babu GJ, Periasamy M, Brozovich FV. The smooth
muscle myosin seven amino acid heavy chain insert’s kinetic role in the

35. Fisher SA, Ikebe M, Brozovich F. Endothelin-1 alters the contractile
80:885–893.

36. Huang QQ, Fisher SA, Brozovich FV. Forced expression of essential
myosin light chain isoforms demonstrates their role in smooth muscle

37. Lincoln TM, Dey N, Sellak H. Invited review: cGMP-dependent protein
kinase signaling mechanisms in smooth muscle: From the regulation of

38. Furchgott RF, Zawadzka Jv. The obligatory role of endothelial cells in
the relaxation of arterial smooth muscle by acetylcholine. *Nature.* 1980;288:
373–376.

39. Sagawa T, Ilissano S, Vanhoutte PM. Heterogeneous distribution of endo-
thelium-dependent relaxations resistant to NG-nitro-L-arginine in rats.

40. Pfitzer G, Merkel L, Ruegg JC, Hofmann F. Cyclic GMP-dependent
protein kinase relaxes skinned fibers from guinea pig taenia coli but not
endothelium-dependent relaxations resistant to NG-nitro-L-arginine in rats.

41. Surks HK, Mendelsohn ME. Dimerization of cGMP-dependent protein

42. Langsetmo K, Stafford WF III, Mabuchi K, Tao T. Recombinant small
smooth muscle myosin isoforms in cGMP-mediated smooth muscle relaxation.

43. Rhee AY, Brozovich FV. The smooth muscle cross-bridge cycle studied

44. Surks HK, Mendelsohn ME. Regulation of myosin phosphatase by a
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