Involvement of RhoA/Rho Kinase Pathway in Myogenic Tone in the Rabbit Facial Vein

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Abstract—Myogenic tone (MT), a fundamental stretch-sensitive vasoconstrictor property of resistance arteries and veins, is a key determinant of local blood flow regulation. We evaluated the pathways involved in MT development. The role of the RhoA/Rho kinase, p38 MAP kinase, and HSP27 in MT was investigated in the rabbit facial vein (RFV), previously shown to possess MT at a pressure level equivalent to 20 mm Hg. Venous MT is poorly understood, although venous diseases affect a large proportion of the population. Stretched RFV are characterized by a temperature-sensitive MT, which is normal at 39°C but fails to develop at 33°C. This allows for the discrimination of the pathways involved in MT from the multiple pathways activated by stretch. Isolated RFV segments were mounted in organ baths and stretched. Temperature was then set at 33°C or 39°C. MT was associated to the translocation of RhoA to the plasma membrane and the Rho kinase inhibitor Y27632 decreased stretch-induced MT by $93.1 \pm 4.9\%$. MT was also associated to an increase in p38 ($131.0 \pm 12.5\%$ at 39°C versus 100% at 33°C) and HSP27 phosphorylation ($196.1 \pm 13.3\%$ versus 100%), and the p38 MAP kinase inhibitor SB203580 decreased MT by $36.5 \pm 8.1\%$. (39°C, compared with RFV stretched at 33°C). Finally, phosphorylation of p38 was blocked by Y27632 and HSP27 phosphorylation was inhibited by SB203580 and Y27632. Thus, MT and the associated p38 and HSP27 phosphorylation seem to depend on RhoA/Rho kinase activation in stretch RFV. (*Hypertension*. 2005;45:974-979.)

Key Words: signal transduction ■ kinase ■ heat shock proteins

The process of matching blood flow to metabolic demand through changes in perfusion pressure is determined to a large extent by myogenic tone (MT). Myogenic properties of vessels include 2 processes: basal MT and myogenic response. Basal MT is a constant vasoconstriction caused by the transmural pressure or stretch applied to the arterial wall. Myogenic response is characterized by a smooth muscle cells contraction in response to increase in pressure or stretch.[1] The myogenic response participates in the local regulation of blood flow and protects downstream capillary beds from large increases in hydrostatic pressure, such as that induced by postural changes, and an increase in the amplitude of MT is associated with hypertension[2] and diabetes mellitus.[3] Signaling mechanisms that contribute to MT require calcium entry, protein kinase C,[4] and phospholipase C activation,[5] as well as calcium-sensitization of the contractile apparatus.[1,6–9] There is also growing evidence that actin polymerization and the dynamic remodeling of the actin cytoskeleton play an important role in MT.[10] In addition, Ca^{2+} and myosin light chain (MLC) phosphorylation are key regulators of the dynamic reorganization of actin filaments. In recent years, evidence has accumulated that the ras-related small GTP-binding protein Rho is another important signaling element that mediates various actin-dependent cytoskeletal functions, including smooth muscle contraction. However, its roles in

different signal transduction cascades may vary depending on the cell type.[11]

The role of mitogen-activated protein (MAP) kinases, which may also affect smooth muscle contractility,[12] in pressure myogenic contraction have not been fully explored.[8] Using the rabbit facial vein (RFV), we have previously shown that ERK1/2 activation, although stimulated by stretch, is not linked to MT.[13] In another study, in resistance arteries, we found that activation of p38 MAP kinase contributes to vascular smooth muscle contraction induced by agonists such as thromboxane A2.[14] Furthermore, it has been shown that endothelin-1 activates p38 MAP kinase pathways and heat shock protein (HSP) 27, and that p38 could regulate phosphorylation of HSP27.[15] A specific role has been found for HSP27 in the regulation of actin cytoskeletal dynamics, based on the ability of HSP27 to modulate phosphorylation-dependent actin polymerization.[16–18] Thus, we hypothesized that RhoA/Rho kinase and p38–HSP27 might play a role in myogenic contraction.

Nevertheless, a main difficulty in studying MT is that stretch per se activates multiple pathways not necessarily involved in MT. Stretch and MT cannot easily be dissociated; classically, arteries submitted to pressure (thus developing MT because of stretch) are compared with unstretched arteries (absence of pressure).[8] To bypass this difficulty, we used the RFV that develops MT to a degree similar to that

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observed in resistance arteries but that is temperature-sensitive.[19] At equal stretch, MT that is observed in the RFV at 39°C is absent at 33°C.[19] Using the RFV is also opening an important perspective in the understanding of vein pathophysiology. The control of venous tone is poorly understood and sparsely studied. Venous tone changes with aging,[20] hypertension,[21,22] or diabetes.[23,24] MT occurs in the RFV with a stretch level (5 mN in a 3- to 4-mm-long segment) corresponding to a blood pressure ≈20 mm Hg, which is within the normal range in veins. Thus, MT may play a role in venous tone regulation even though the system is operating at low pressures.

Therefore, we used the RFV model allowing the comparison of stretched vessels with (39°C) or without (33°C) MT to test the hypothesis that p38, HSP27, or RhoA activation could be involved in or affected by the development of MT in RFV.

Materials and Methods

RFV
Buccal segments of the facial vein were isolated as previously described[19,7] from male New Zealand White rabbits (2.5 to 2.7 kg). The procedure used was in accordance with the European Community standards on the care and use of laboratory animals (authorization 00577); 3-mm-long ring segments of RFV were mounted between parallel stainless steel wires in 5-mL organ baths. One wire was attached to a fixed support, whereas the other was connected to a moveable holder supporting a tension transducer, so that isometric force could be recorded and data were collected (Biopac MP 100). Vein segments were maintained at 33°C in a physiological salt solution (PSS) of the following composition (mmol/L): 135 NaCl, 15 NaHCO$_3$, 4.6 KCl, 1.5 CaCl$_2$, 1.2 MgSO$_4$, 11 glucose, 10 N-2-hydroxy-ethylpiperazine-N-2-ethylsulfonic acid (pH 7.4), Po$_2$ 160 mm Hg, and Pco$_2$ 37 mm Hg.

Each segment was submitted to one of the following protocols: (1) RFV segments were subjected to a 5.0-mN force (stretch), which is optimal for the development of MT[7,13] and allow to stabilize for 30 minutes, in the absence (33°C) of MT; (2) RFV segments, after stabilization at 33°C, were maintained at 33°C or warmed to 39°C and exposed or not (time control group) to (10 nmol/L to 10 μmol/L) the Rho kinase inhibitor Y27632 or the p38 MAP kinase inhibitor SB203580; and (3) RFV were just bathed in PSS, without stretch, at 33°C or 39°C.

P38 MAP Kinase and HSP27 Activation
Phosphorylation p38 (phospho-p38) and HSP27 (phospho-HSP27) were quantified in RFV segments using Western blot analysis. Tissue extraction was performed as previously described:[13,12] frozen vessel segments were pulverized in liquid nitrogen (LN$_2$). The powders were resuspended in lysis buffer (500 mmol/L Tris-HCl pH 7.4, 20% sodium dodecyl sulfate, 100 mmol/L sodium orthovanadate, and protease inhibitors [Boehringer Mannheim]). For Western blot analysis, lysates containing 15 μg of protein were electrophoresed on polyacrylamide gels and transferred to nitrocellulose membranes (Amersham ECL). Membranes were incubated overnight at 4°C with primary antibody against phospho-p38 or phospho HSP27 (New England Biolabs) and incubated with horseradish peroxidase-conjugated secondary antibodies (Amersham). Phospho-p38 and phospho-HSP27 bands were visualized using the ECL-Plus Chemiluminescence kit (Amersham) and expressed as a percentage of the activity measured in parallel-processed control vessels. Staining membranes with Ponceau red was used to normalize for loading variations.

Rho A Activation
Activation of Rho A is characterized by its translocation to plasma membrane. Frozen vascular segments were pulverized in LN$_2$. The powders were resuspended in ice-cold homogenization buffer of the following composition: 300 mmol/L sucrose, 1 mmol/L NaN3, 20 mmol/L N-2-hydroxy-ethylpiperazine-N-2-ethylsulfonic acid pH 7.4, and protease inhibitors (Boehringer Mannheim) and centrifuged at 31 000g for 30 minutes (ultracentrifuge; Beckman). The supernatant was collected as the cytosolic fraction. Pellets were resuspended, and the membrane proteins were extracted by incubation in homogenization buffer (0.1 mol/L NaCl, 30 mmol/L imidazole, 8% sucrose, 1 mmol/L NaN3, pH 6.8, and protease inhibitors [Boehringer Mannheim]). The extract was centrifuged at 10 000g at 4°C. The supernatant was collected as the membrane fraction. Immunoreactive bands for Rho A in cytosolic and membrane fractions were processed as described for Western blots with anti-Rho A (Santa Cruz) as primary antibody.

Drugs
SB203580 and Y27632 were purchased from Calbiochem (La Jolla, Calif); all other reagents were purchased from Sigma (St Louis, Mo). SB203580 and Y27632 were dissolved in water.

Statistical Analysis
Results are expressed as mean±SEM. The significance of the different treatments was determined by ANOVA or 2-tailed Student paired t test. $P<0.05$ were considered to be significant.

Results
In RFV segments, MT develops at 39°C, whereas it is absent when the temperature is maintained at 33°C (Figure 1). As previously shown,[7,25] after reducing temperature to 33°C, the addition of papaverine (10 μmol/L) does not further relax the vein (not shown).

In RFV at 39°C exposed to stretch, the Rho kinase inhibitor Y27632 induced a concentration-dependent reduction of MT (Figure 1, lower panel, and Figure 2). The p38 MAP kinase inhibitor SB203580 attenuated MT in a dose-dependent way but to a lesser extent than Y27632 (Figure 2): Y27632 (10 μmol/L) reduced MT to 6.9±5.0% of control (stretched
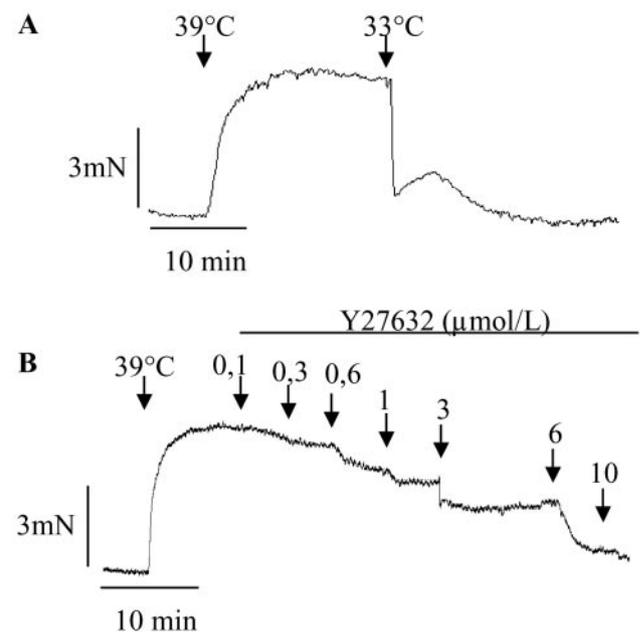

Figure 1. Typical recordings showing wall tension in a rabbit facial vein segment mounted in a myograph. A, myogenic tone fully developed at 39°C and is absent when bath temperature is 33°C. B, the inhibitory effect of cumulative concentration (0.1 to 10 μmol/L) of the Rho kinase inhibitor Y27632.
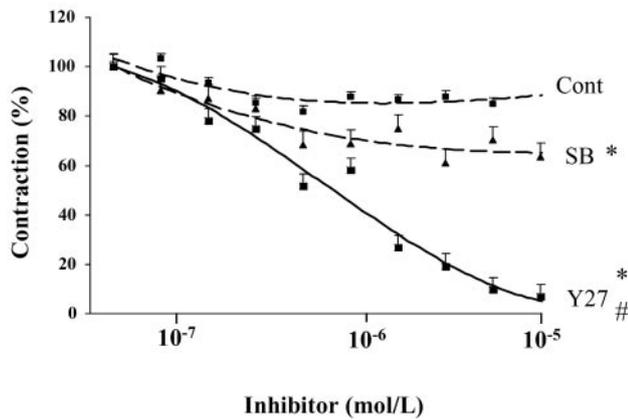
Figure 2. Effect of the Rho kinase inhibitor Y27632 (Y27) and of the p38 MAP kinase inhibitor SB203580 (SB) on myogenic tone in rabbit facial vein segments mounted in a myograph. Data are expressed as percent of control. Myogenic tone in the presence of the Y27632 or SB203580 was compared with a time–control experiment (Cont). Mean±SEM is presented (n=6 per group). *$P<0.05$, 2-factor ANOVA, vs control. #$P<0.05$, 2-factor ANOVA, Y27632 vs SB203580.

RFV at 39°C) and SB230580 (10 μmol/L) to 63.5±8.1% of control.

As suggested by the contraction experiment (Figure 3A), RhoA/Rho kinase could be involved in stretch-induced MT. This is confirmed by the blot (Figure 3B) showing that in absence of MT (33°C), RhoA is more concentrated in the cytosol fraction, whereas in the presence of MT (39°C) RhoA is translocated from the cytoplasm to the plasma membrane.

The phosphorylation of p38–MAP kinase was determined in RFV segments submitted to stretch in the absence (33°C) or in the presence (39°C) of MT, with or without Y27632 (10 μmol/L). The effect of temperature was also evaluated and basal p38 phosphorylation was considered to be 100% in unstretched RFV segments at 33°C. Figure 4A shows that p38 phosphorylation was not affected by temperature in unstretched veins. At 33°C, stretch induced a significant increase of p38 phosphorylation (141.0±11.0%) compared with unstretched veins. This activation of p38 was not significantly affected by Y27632 (Figure 4A).

Then, we measured p38 activation in the presence of stretch at 33°C (without MT) and at 39°C (with MT). Basal p38 phosphorylation was considered to be 100% in vein segments stretched at 33°C. Stretch at 39°C was also associated with an increased in p38 phosphorylation (131.0±12.5%) and Y27632 completely blocked p38 phosphorylation associated with MT (Figure 4B).

In another series of experiments, HSP27 phosphorylation was determined in RFV segments submitted or not to stretch at 33°C or 39°C and in the presence or absence of Y27632 (10 μmol/L) or SB203480 (10 μmol/L). In unstretched RFV segments, the temperature had no significant effect on HSP27 phosphorylation (Figure 5A). In stretched RFV segments maintained at 33°C, HSP27 phosphorylation was not different from that measured in unstretched segments at 33°C, and neither Y27632 nor SB239580 had an effect on HSP27 phosphorylation. Compared with stretched vein segments at 33°C, HSP27 phosphorylation was higher in stretched vein
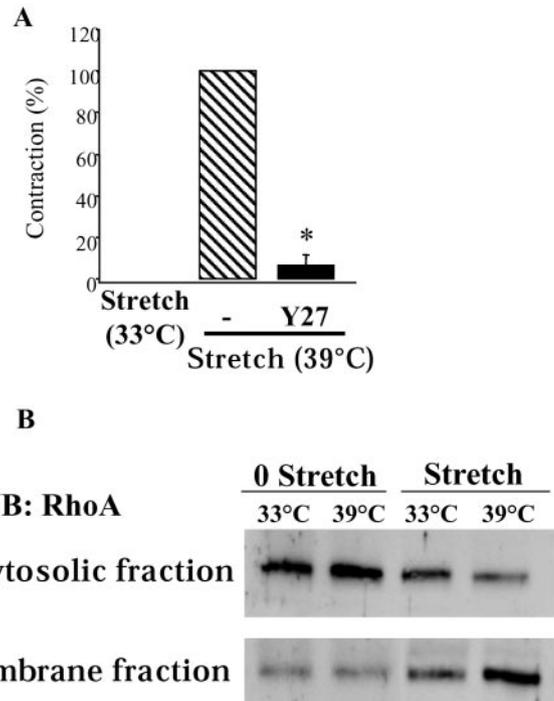

Figure 3. Inhibition of myogenic tone by Y27632 (10 μmpl/L), in rabbit facial vein segments mounted in a myograph (A). Data are presented as percentage (%) of myogenic tone. 100% is corresponding to myogenic tone in the absence of inhibitor and control is corresponding to the vein segments stretched at 33°C, thus not developing myogenic tone. Mean±SEM is presented (n=7 per group). *$P<0.05$, 2-factor ANOVA, vs control. The low panel (B) represents a Western blot analysis of Rho in control conditions (vein segments stretched at 33°C) or in the presence of myogenic tone (stretched segments at 39°. Cytosolic (C) and membrane (M) fractions were separated before migration so that the translocation of Rho to the membrane could be visualized as a change in the ratio of the cytosolic to the membrane fraction.

segments at 39°C and thus developing MT (196.1±13.3% of control) (Figure 5B). Both SB203580 and Y27632 significantly inhibited HSP27 phosphorylation associated with MT.

Ponceau red staining, measured in each group, was not significantly affected in the different experimental condition, suggesting that the blots were loading with similar amounts of proteins. Thus, the amounts of phosphorylated p38 and HSP27 were similar.

Discussion

In this study, we found that Rho kinase inhibition suppressed MT in the rabbit facial vein. Furthermore, MT was associated to RhoA translocation from the cytosol to the plasma membrane. These results suggest that the RhoA/Rho kinase pathway plays a major role in MT. These results are consistent with a previous work showing that Y27632 caused a dose-dependent inhibition of basal tone in cannulated rat mesenteric resistance arteries, with almost total inhibition at 3 μmol/L.[26] They differ from another study showing that Y27632 only partly attenuated MT in rat tail small arteries.[1] This discrepancy may reflect a difference in the degree of participation of Rho kinase in MT in different vessels and/or a difference in its interaction with other kinases.[1] It has been
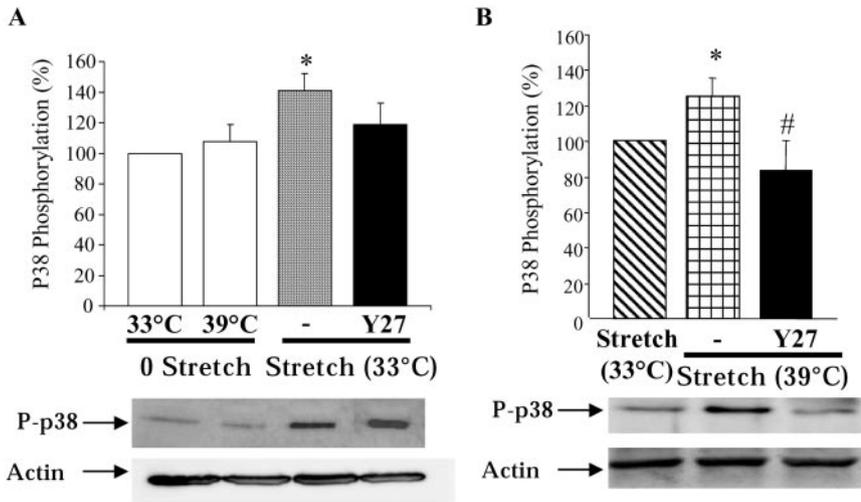
A

B

Figure 4. A, Phosphorylation of p38 MAP kinase was measured in rabbit facial vein segments unstretched at 33°C and 39°C and stretched at 33°C (stretch) with or without Y27632 (10 μmol/L). Data are presented as percentage (%) of control (33°C without stretch). Mean±SEM is presented (n=6 per group). *$P<0.05$, 2-factor ANOVA, vs control. B, Phosphorylation of p38 MAP kinase was also measured in vein segments stretched at 39°C in the presence of Y27632 (10 μmol/L). Data are presented as percentage (%) of control (stretch 33°C). Mean±SEM is presented (n=6 per group). *$P<0.05$, 2-factor ANOVA (stretch 39°C) vs control (stretch 33°C); #$P<0.05$, 2-factor ANOVA, vessels stretched at 39°C with Y27632 versus stretch 39°C.

shown that a Ca^{2+} sensitization may contribute to MT,[27] and recent evidence for the involvement of the small GTPase RhoA in Ca^{2+} sensitization in smooth muscle contraction has been reported by several laboratories.[28–30] Rho kinase, the RhoA effector, can directly modulate smooth muscle contraction through MLC phosphorylation, independently of the Ca^{2+}-calmodulin–dependent myosin light chain kinase pathway.[31] Rho kinase is able to regulate MLC phosphorylation by the direct phosphorylation of MLC and by the inactivation of myosin phosphatase through phosphorylation of the myosin binding subunit.[32] Therefore, Rho kinase and myosin phosphatase coordinately regulate the phosphorylation state of MLC and, as a result, induce smooth muscle contraction.

Our results also indicate that SB203580, the specific p38 MAP kinase inhibitor, attenuated MT in a concentration-dependent manner. In addition, p38 phosphorylation was significantly higher in RFV segments stretched at 39°C, thus developing MT, than in vein segments stretched at 33°C. Furthermore, our findings show that Y27632 inhibited contraction-induced p38 phosphorylation, suggesting that RhoA/Rho kinase activation was upstream of p38 and induced its activation. Our findings are consistent with a previous study suggesting that p38 MAP kinase activation could be involved in the mechanotransduction of wall tension in gracilis muscle arterioles.[8] Studies in large vessels and isolated smooth muscle cells suggested that MAP kinase activation contributes to vascular smooth muscle contraction induced by endothelin-1[33–35] and angiotensin II.[36] In the rat thoracic aorta, p38 may partly regulate enothlin-1–induced contraction through a MLC phosphorylation-independent pathway.[33] Recently, the p38 MAPK/HSP27 pathway has been suggested to be involved in the generation of maximal force development. Some of the important downstream events coupled with p38 MAP kinase activation include phosphorylation of MAPK-activated protein kinases 2 and 3, which in turn phosphorylate HSP27.[37,38] Phosphorylation of HSP27 is another MAP kinase-mediated mechanism that has been proposed to modulate the maintenance of the contractile response of vascular smooth muscle.[39,40,15] In this study, we found that HSP27 was activated in conditions of MT development and that RhoA and p38 were needed for this activa-

tion. Nevertheless, that HSP27 is phosphorylated does not necessarily imply that it is directly involved in MT. Several reports suggest that HSP27 might modulate actin filament dynamics and be involved in contraction of smooth muscle cells. HSP27, in its nonphosphorylated state, behaves as a phosphorylation-regulated F-actin capping protein capable of inhibiting actin polymerization.[41,16] Phosphorylation of HSP27, via activation of p38, might markedly modify the equilibrium in favor of polymerized actin, thereby contributing to the maintenance of the microfilament network.[42] Studies in cells transiently transfected with dominant-negative RhoA suggest that RhoA might exert its effects on cytoskeleton reorganization through HSP27 and that cytoskeletal proteins might interact to induce sustained smooth muscle contraction.[11] It is still unclear whether RhoA interacts with HSP27, but our work suggests that RhoA via the activation of Rho kinase stimulated p38, leading to HSP27 phosphorylation.

It should be noted that we used a vein that may not be representative of resistance arteries, most usually used in the study of MT. Nevertheless, the RFV shares several common features with arteries, including histological features and a strong capacity to contract.[43] Nevertheless, each specific blood vessel (and this applies to arteries) has specific features and extrapolation must always be considered carefully. The RFV has this unique feature allowing comparison of stretched vessels with or without MT. This is a key issue of the present study because stretch per se activates many pathways not necessarily involved in MT, as we have previously shown with ERK1/2.[13] In addition, because the RFV is a vein, our study opens an important perspective in the study of venous tone. It is estimated that 75% of the total blood volume in the resting state is contained within venules and veins. Therefore, constriction or dilation of veins would have a greater effect on changing blood volume distribution than any other part of the vasculature.[44,45] The factors controlling venoconstriction are complex and include neural and humoral mechanisms. The increased sympathetic nerve activity results in augmented venoconstriction, which predominates in the development of spontaneous hypertension.[46]
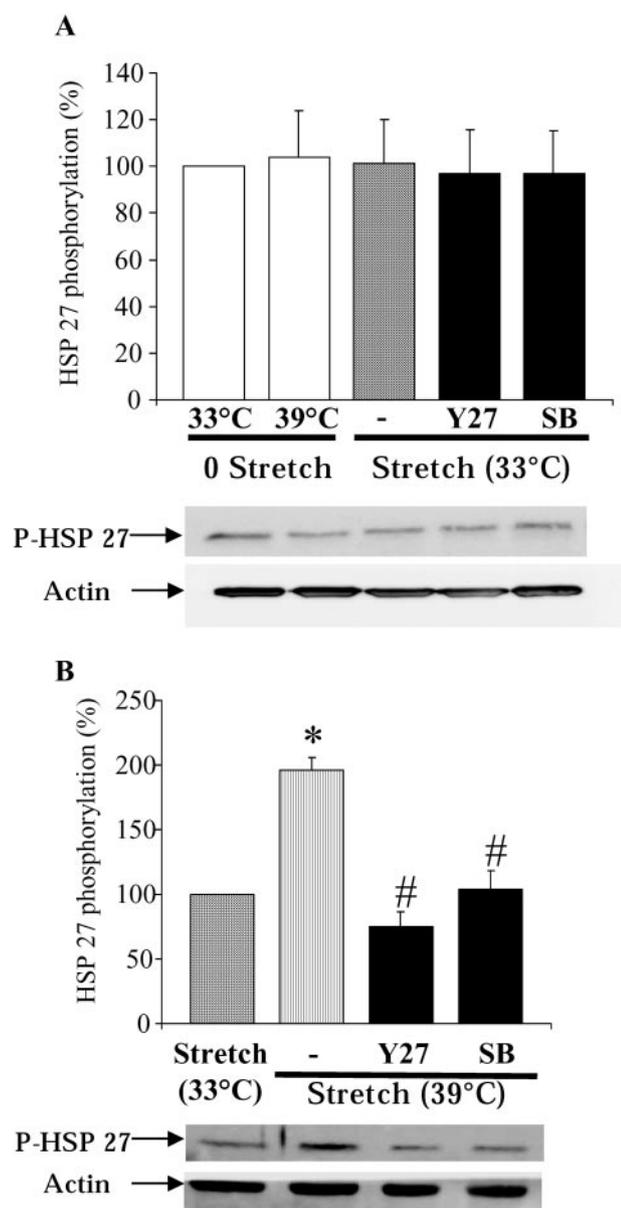
Figure 5. Panel A: Phosphorylation of HSP27 was measured in rabbit facial vein segments unstretched at 33°C and 39°C and stretched at 33°C (stretch) with or without Y27632 (10μmol/L) or SB203580 (10μmol/L). Data are presented as percentage (%) of control (33°C without stretch). Mean ± sem is presented (n=6 per group). B, Phosphorylation of HSP27 was also measured in vein segments stretched at 39°C in the presence of SB203580 (10 μmol/L) or Y27632 (10 μopl/L). Data are presented as per-centage (%) of control (stretch 33°C). Mean±SEM is presented (n=6 per group). *$P<0.05$, 2-factor ANOVA (stretch 39°C) vs control (stretch 33°C); #$P<0.05$, 2-factor ANOVA, vessels stretched at 39°C with Y27632 or SB203580 vs vessels stretched at 39°C.

In conclusion, this study brings new insights in the under-standing of venous myogenic contraction showing a complete involvement of RhoA/Rho kinase and a partial involvement of p38 MAP kinase, and it might provide a novel mechanism insight on increased venoconstriction in hypertension. In conditions of MT development, pressure might activate RhoA, which plays a major role in the development of MT through sensitization of the contractile apparatus to calcium.

In parallel, RhoA/Rho kinase would also activate p38 MAP kinase, which would then activate HSP27 phosphorylation, possibly inducing cytoskeletal rearrangement by facilitating thin-filament regulation of smooth muscle contraction.

References

1. Schubert R, Kalentchuk VU, Krien U. Rho kinase inhibition partly weakens myogenic reactivity in rat small arteries by changing calcium sensitivity. *Am J Physiol Heart Circ Physiol*. 2002;283:H2288–H2295.
2. Hughes JM, Bund SJ. Arterial myogenic properties of the spontaneously hypertensive rat. *Exp Physiol*. 2002;87:527–534.
3. Ungvari Z, Pacher P, Kecskemeti V, Papp G, Szollar L, Koller A. Increased myogenic tone in skeletal muscle arterioles of diabetic rats. Possible role of increased activity of smooth muscle Ca2+ channels and protein kinase C. *Cardiovasc Res*. 1999;43:1018–1028.
4. Laher I, Vorkapic P, Dowd AL, Bevan JA. Protein kinase C potentiates stretch-induced cerebral artery tone by increasing intracellular sensitivity to Ca2+. *Biochem Biophys Res Commun*. 1989;165:312–318.
5. Osol G, Laher I, Kelley M. Myogenic tone is coupled to phospholipase C and G protein activation in small cerebral arteries. *Am J Physiol*. 1993; 265:H415–H420.
6. Davis MJ, Wu X, Nurkiewicz TR, Kawasaki J, Davis GE, Hill MA, Meininger GA. Integrins and mechanotransduction of the vascular myogenic response. *Am J Physiol Heart Circ Physiol*. 2001;280: H1427–1433.
7. Henrion D, Laher I, Bevan JA. Intraluminal flow increases vascular tone and 45Ca2+ influx in the rabbit facial vein. *Circ Res*. 1992;71:339–345.
8. Massett MP, Ungvari Z, Csiszar A, Kaley G, Koller A. Different roles of PKC and MAP kinases in arteriolar constrictions to pressure and agonists. *Am J Physiol Heart Circ Physiol*. 2002;283:H2282–H2287.
9. Matchkov VV, Tarasova OS, Mulvany MJ, Nilsson H. Myogenic response of rat femoral small arteries in relation to wall structure and [Ca(2+)](i). *Am J Physiol Heart Circ Physiol*. 2002;283:H118–H125.
10. Cipolla MJ, Gokina NI, Osol G. Pressure-induced actin polymerization in vascular smooth muscle as a mechanism underlying myogenic behavior. *FASEB J*. 2002;16(1):72–76.
11. Wang P, Bitar KN. Rho A regulates sustained smooth muscle contraction through cytoskeletal reorganization of HSP27. *Am J Physiol*. 1998;275: G1454–G1462.
12. Matrougui K, Eskildsen-Helmond YE, Fiebeler A, Henrion D, Levy BI, Tedgui A, Mulvany MJ. Angiotensin II stimulates extracellular signal-regulated kinase activity in intact pressurized rat mesenteric resistance arteries. *Hypertension*. 2000;36:617–621.
13. Loufrani L, Lehoux S, Tedgui A, Levy BI, Henrion D. Stretch induces mitogen-activated protein kinase activation and myogenic tone through 2 distinct pathways. *Arterioscler Thromb Vasc Biol*. 1999;19:2878–2883.
14. Bolla M, Matrougui K, Loufrani L, Maclouf J, Levy B, Levy-Toledano S, Habib A, Henrion D. p38 mitogen-activated protein kinase activation is required for thromboxane-induced contraction in perfused and pres-surized rat mesenteric resistance arteries. *J Vasc Res*. 2002;39:353–360.
15. Yamboliev IA, Hedges JC, Mutnick JL, Adam LP, Gerthoffer WT. Evidence for modulation of smooth muscle force by the p38 MAP kinase/HSP27 pathway. *Am J Physiol Heart Circ Physiol*. 2000;278: H1899–H1907.
16. Benndorf R, Hayess K, Ryazantsev S, Wieske M, Behlke J, Lutsch G. Phosphorylation and supramolecular organization of murine small heat shock protein HSP25 abolish its actin polymerization-inhibiting activity. *J Biol Chem*. 1994;269:20780–20784.
17. Landry J, Huot J. Modulation of actin dynamics during stress and phys-iological stimulation by a signaling pathway involving p38 MAP kinase and heat-shock protein 27. *Biochem Cell Biol*. 1995;73:703–707.
18. Ibitayo AI, Sladick J, Tuteja S, Louis-Jacques O, Yamada H, Groblewski G, Welsh M, Bitar KN. HSP27 in signal transduction and association with contractile proteins in smooth muscle cells. *Am J Physiol*. 1999;277: G445–G454.

19. Winquist RJ, Bevan JA. Temperature sensitivity of tone in the rabbit facial vein: myogenic mechanism for cranial thermoregulation. *Science*. 1980;207:1001–1002.

20. Moore A, Mangoni AA, Lyons D, Jackson SH. The cardiovascular system. *Br J Clin Pharmacol*. 2003;56:254–260.

21. Hayasashi K, Mori K, Miyazaki H. Biomechanical response of femoral vein to chronic elevation of blood pressure in rabbits. *Am J Physiol Heart Circ Physiol*. 2003;284:H511–H518.

22. Martin DS, Rodrigo MC, Appelt CW. Venous tone in the developmental stages of spontaneous hypertension. *Hypertension*. 1998;31:139–144.

23. Cheng X, Leung SW, Lim SL, Pang CC. Attenuated arterial and venous constriction in conscious rats with streptozotocin-induced diabetes. *Eur J Pharmacol*. 2003;458:299–304.

24. Pang CC. Autonomic control of the venous system in health and disease: effects of drugs. *Pharmacol Ther*. 2001;90:179–230.

25. Henrion D, Laher I, Klaasen A, Bevan JA. Myogenic tone of rabbit facial vein and posterior cerebral artery is influenced by changes in extracellular sodium. *Am J Physiol*. 1994;266:H377–H383.

26. VanBavel E, van der Meulen ET, Spaan JA. Role of Rho-associated protein kinase in tone and calcium sensitivity of cannulated rat mesenteric small arteries. *Exp Physiol*. 2001;86:585–592.

27. Yeon DS, Kim JS, Ahn DS, Kwon SC, Kang BS, Morgan KG, Lee YH. Role of protein kinase C- or RhoA-induced Ca(2+) sensitization in stretch-induced myogenic tone. *Cardiovasc Res*. 2002;53:431–438.

28. Jensen PE, Gong MC, Somlyo AV, Somlyo AP. Separate upstream and convergent downstream pathways of G-protein- and phorbol ester-mediated Ca2+ sensitization of myosin light chain phosphorylation in smooth muscle. *Biochem J*. 1996;318:469–475.

29. Uehata M, Ishizaki T, Satoh H, Ono T, Kawahara T, Morishita T, Tamakawa H, Yamagami K, Inui J, Maekawa M, Narumiya S. Calcium sensitization of smooth muscle mediated by a Rho-associated protein kinase in hypertension. *Nature*. 1997;389:990–994.

30. Taggart MJ, Lee YH, Morgan KG. Cellular redistribution of PKCalpha, rhoA, and ROKalpha following smooth muscle agonist stimulation. *Exp Cell Res*. 1999;251:92–101.

31. Kureishi Y, Kobayashi S, Amano M, Kimura K, Kanaide H, Nakano T, Kaibuchi K, Ito M. Rho-associated kinase directly induces smooth muscle contraction through myosin light chain phosphorylation. *J Biol Chem*. 1997;272:12257–12260.

32. Amano M, Fukata Y, Kaibuchi K. Regulation and functions of Rho-associated kinase. *Exp Cell Res*. 2000;261:44–51.

33. Kwon S, Lee WJ, Fang LH, Kim B, Ahn HY. Mitogen-activated protein kinases partially regulate endothelin-1-induced contractions through a myosin light chain phosphorylation-independent pathway. *J Vet Med Sci*. 2003;65:225–230.

34. Cain AE, Tanner DM, Khalil RA. Endothelin-1–induced enhancement of coronary smooth muscle contraction via MAPK-dependent and MAPK-independent [Ca(2+)](i) sensitization pathways. *Hypertension*. 2002;39:543–549.

35. Ohanian J, Cunliffe P, Ceppi E, Alder A, Heerkens E, Ohanian V. Activation of p38 mitogen-activated protein kinases by endothelin and noradrenaline in small arteries, regulation by calcium influx and tyrosine kinases, and their role in contraction. *Arterioscler Thromb Vasc Biol*. 2001;21:1921–1927.

36. Meloche S, Landry J, Huot J, Houle F, Marceau F, Giasson E. p38 MAP kinase pathway regulates angiotensin II-induced contraction of rat vascular smooth muscle. *Am J Physiol Heart Circ Physiol*. 2000;279:H741–H751.

37. Hedges JC, Yamboliev IA, Ngo M, Horowitz B, Adam LP, Gerthoffer WT. p38 mitogen-activated protein kinase expression and activation in smooth muscle. *Am J Physiol*. 1998;275:C527–534.

38. Larsen JK, Yamboliev IA, Weber LA, Gerthoffer WT. Phosphorylation of the 27-kDa heat shock protein via p38 MAP kinase and MAPKAP kinase in smooth muscle. *Am J Physiol*. 1997;273:L930–L940.

39. Beall A, Epstein A, Woodrum D, Brophy CM. Cyclosporine-induced renal artery smooth muscle contraction is associated with increases in the phosphorylation of specific contractile regulatory proteins. *Biochim Biophys Acta*. 1999;1449:41–49.

40. Bitar KN, Kaminski MS, Hailat N, Cease KB, Strahler JR. HSP27 is a mediator of sustained smooth muscle contraction in response to bombesin. *Biochem Biophys Res Commun*. 1991;181:1192–1200.

41. Miron T, Vancompernolle K, Vandekerckhove J, Wilchek M, Geiger B. A 25-kD inhibitor of actin polymerization is a low molecular mass heat shock protein. *J Cell Biol*. 1991;114:255–261.

42. Guay J, Lambert H, Gingras-Breton G, Lavoie JN, Huot J, Landry J. Regulation of actin filament dynamics by p38 map kinase-mediated phosphorylation of heat shock protein 27. *J Cell Sci*. 1997;110:357–368.

43. Winquist RJ, Bevan JA. In vitro model of maintained myogenic vascular tone. *Blood Vessels*. 1981;18:134–138.

44. Monos E, Berczi V, Nadasy G. Local control of veins: biomechanical, metabolic, and humoral aspects. *Physiol Rev*. 1995;75:611–666.

45. Freis ED. Studies in Hemodynamics and Hypertension. *Hypertension*. 2001;38:1–5.

46. Li L, Watts SW, Banes AK, Galligan JJ, Fink GD, Chen AF. NADPH oxidase—derived superoxide augments endothelin-1–induced venoconstriction in mineralocorticoid hypertension. *Hypertension*. 2003;42:316–321.

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