**Rho/Rho Kinase Signal Transduction Pathway in Cardiovascular Disease and Cardiovascular Remodeling**

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The small guanosine triphosphatase Rho and its target, Rho kinase, play important roles in both blood pressure regulation and vascular smooth muscle contraction. Rho is activated by agonists of receptors coupled to cell membrane G protein, such as angiotensin II and phenylephrine. Once Rho is activated, it translocates to the cell membrane where it, in turn, activates Rho kinase. Activated Rho kinase phosphorylates myosin light chain phosphatase, which is then inhibited. This sequence stimulates vascular smooth muscle contraction, stress fiber formation, and cell migration. In this way, Rho and Rho kinase activation have important effects on several cardiovascular diseases. Currently available substances that specifically inhibit this signaling pathway could offer clinical benefits in several cardiovascular, as well as non-cardiovascular, diseases, such as arterial hypertension, pulmonary hypertension, cerebral or coronary spasm, post-angioplasty restenosis, and erectile dysfunction.

**Key words:** Rho, Rho kinase, Small G proteins, Arterial hypertension, Cardiovascular remodeling.

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**INTRODUCTION**

Arterial hypertension is a cardiovascular disorder characterized by altered vascular tone and increased vascular contractility. It is accompanied by proliferation and migration of vascular smooth muscle cells and differing degrees of inflammation of the arterial wall, processes that together constitute vascular remodeling. Proliferation, migration of vascular smooth muscle cells from the media to the intima, and inflammation of the arterial wall participate in a number of vascular disorders, including for example, the progression of atherosclerosis, restenosis, rejection of bypass grafts, and renal failure. In addition to cardiac remodeling, arterial hypertension is accompanied by hypertrophy of cardiac myocytes, hyper-
plasia of fibroblasts, and alterations of the extracellular matrix.

Of the main complications of arterial hypertension, those associated with the development of atherosclerosis are the least affected by current antihypertensive treatment. A metaanalysis of the effects of antihypertensive treatment revealed a 48% reduction in the incidence of cerebrovascular accidents compared with only a 16% reduction in the incidence of heart disease, figures that are markedly lower than would have been predicted from available epidemiological studies. This finding can be interpreted in a number of ways. One of these is that development of atherosclerosis and the associated complications are not effectively prevented by current antihypertensive treatment. These findings are consistent with the lack of evidence to support lowering of arterial blood pressure as an effective mean of reducing atherosclerosis or proliferation of vascular smooth muscle cells, and provide a strong incentive to investigate other mechanisms of vascular damage and remodeling with greater potential for treatment and prevention.

It has recently been shown that activation of the Rho/Rho kinase signal transduction pathway is one of the principal mechanisms of vasoconstriction in arterial hypertension and that this pathway has novel therapeutic potential. Studies have suggested that the small guanosine triphosphatase (GTPase) Rho and its target Rho kinase play a crucial role in the regulation of arterial blood pressure. In vitro studies have demonstrated that the activated form of Rho kinase regulates vascular smooth muscle contraction via phosphorylation of the myosin light chain, sensitization of contractile proteins to Ca++, and the formation of stress fibers. Furthermore, Rho kinase may also be regulated by various components of the cytoskeleton that play an essential role in the mechanotransduction of flow and pressure in the blood vessels. In addition to a role in the pathogenesis of atherosclerosis, Rho kinase participates in the processes of cell adhesion and mobility, in cytokinesis, and in gene expression. Prolonged treatment with fasudil (a specific inhibitor of Rho kinase) has been shown to reduce the development of coronary vascular lesions such as medial thickening and perivascular fibrosis in spontaneously hypertensive rats.

**THE RHO/RHO KINASE SIGNAL TRANSDUCTION PATHWAY**

The small GTPase superfamily contains more than 100 structurally related proteins that undergo conformational changes and alter their subcellular localization in a manner that is dependent on guanine nucleotides. Small GTPases are active when bound to GTP and inactive when bound to GDP. In their activated state, they bind effectors that, in turn, regulate a large number of biological processes. They are controlled by various classes of regulatory proteins. Figure 1 shows the cycle of activation and inactivation of the small GTPases. With few exceptions, their activation is mediated by guanine nucleotide exchange factors (GEFs). These factors displace the GDP dissociation inhibitor (GDI) from the GDP-bound GTPase, allowing it to bind GTP. GTP binding induces a conformational change in the GTPase that allows it to bind effectors.

**Figure 1.** Activation-inactivation cycle of the small GTPases. External factors activate guanine nucleotide exchange factor (GEF). This factor displaces GDP dissociation inhibitor (GDI), releasing the isoprenylated residue that anchors the small GTPase to the plasma membrane, and catalyzes the exchange of GDP for GTP. GTP binding induces a conformational change in the small GTPase that activates it and allows it to bind effectors. GTPase activating protein (GAP) stimulates the intrinsic GTPase activity of the small GTPase. GTP hydrolysis returns the small GTPase to its inactive state bound to GDP and GDI.
tion inhibitor (GDI) and unmask the isoprene group that anchors the small GTPase to the plasma membrane, as well as catalyzing the exchange of GDP for GTP. GTP binding induces a conformational change in the small GTPase that activates it and allows it to bind effectors. GTPase activating proteins (GAP) stimulate the intrinsic hydrolysis of GTP and lead to the rapid conversion of small GTPases to their inactive state bound to GDP and GDI.

Based on structural and functional relationships, the small GTPase superfamily is subdivided into 5 families: Ras, Rho, Rab, Arf, and Ran (Figure 2). Members of the Ras family include the 3 classical isoforms H-Ras, K-Ras, and N-Ras, and are primarily involved in the regulation of cell proliferation and differentiation. The classical isoforms of Ras also regulate apoptosis. As shown in Figure 2, all of these effects are likely to be regulated by the extracellular regulated kinases (ERK), a subfamily of the mitogen-activated protein kinases (MAPK), or phosphatidylinositol-3-kinase (PI3K). Members of the Rho family (Rap, Ral, and the Rho subfamily that includes RhoA, RhoB, Rac1, and Cdc42) are unique in controlling the formation of the different conformational forms of the actin cytoskeleton. In addition, Rho proteins regulate a large number of other processes, including gene transcription and lipid metabolism. RhoB has opposing actions to RhoA and inhibits RhoA-mediated gene expression. The effects of Rho A on the cellular architecture are mediated by Rho-dependent serine/threonine kinases that fall into 2 subgroups: the related protein kinases protein kinase C (PKC) and protein kinase N, and the Rho kinases. The latter group, with a mass of approximately 160 kDa, includes ROKα (or ROCK2) and ROKβ (or ROCK 1). ROKα can stimulate LIM-kinase, an enzyme that phosphorylates and inactivates cofilin, thereby inhibiting and favoring the contraction of vascular smooth muscle cells, the formation of stress fibers, and cell migration. The availability of Y-27632, a selective inhibitor of Rho kinase, as well as dominant negative forms of the enzyme, has been useful in elucidating the roles of this pathway.
The processes regulated by the different families of small GTPases are extremely diverse. In fact, there is almost no area of cell biology or biomedical science in which a role for these proteins has not been identified. Furthermore, there are a large number of interactions between members of the Ras and Rho families. The signal transduction pathways regulated by members of the Rho family play an important role in a number of pathologic conditions, including cancer, inflammation, bacterial infection, and arterial hypertension. Rac also controls the generation of reactive oxygen species (ROS), both in leukocytes and nonhematopoietic cells. In the latter cell type, Rac stimulates the production of ROS by activating a protein complex similar to NADPH-oxidase, which has mainly been characterized in neutrophils.

These GTPases act as molecular controls in a wide variety of cell processes, among which the best characterized is the regulation of the actin cytoskeleton. Some actions of G-protein-coupled receptors are mediated by small GTPases like Rho. It has been demonstrated that agonists of G-protein-coupled receptors such as angiotensin II, lysophosphatidic acid, carbachol, and phenylephrine increase the concentration of Rho at the membrane and reduce its levels in the cytosol, indicating translocation and activation of Rho. The Rho signal transduction pathway participates in various pathophysiologic processes in the cardiovascular system. The majority of these processes are directly or indirectly associated with arterial hypertension and its associated complications (Table 1).

**INTERACTION BETWEEN ANGIOTENSIN II AND RHO IN THE CARDIOVASCULAR SYSTEM**

Vascular remodeling occurs during normal development and participates in various physiologic processes. However, structural changes to the vasculature can be pathologic as well as adaptive and can lead to the development of arterial hypertension, atherosclerosis, and diseased venous bypass grafts. Angiotensin II contributes to vascular remodeling through the activation of signaling cascades that promote vasoconstriction, cell proliferation, and inflammation. The cytoskeleton also participates in adaptive structural responses of the vasculature. The cytoskeleton mediates vasoactive responses and transduces both mechanical stimuli and pharmacologic signals. Some of the cytoskeletal changes that occur in vascular remodeling, specifically in vascular smooth muscle cells, are induced by angiotensin II. In fact, Rho has been directly linked to pathologic vascular remodeling through a series of lines of evidence that demonstrate that angiotensin II activates the Rho/Rho kinase pathway and regulates the cytoskeleton. Figure 2 summarizes the angiotensin II-mediated regulation of vascular smooth muscle cell contraction by Rho kinase. Regulators of muscle cell contraction activate 3 independent processes.
Early inflammation of the coronary arterial wall and late coronary
Mediation of the effects of thrombin on the proliferation
Contribution to cerebral arterial tone in chronic arterial
which occurs in striated muscle.
response in a process that appears to differ from that
Activation of genes associated with the hypertrophic
ding to the formation of premyofibrils and the induc-
Expression of plasminogen activator-1 mRNA, and perivascular
Vascular sensitization to calcium through phosphorylation
TABLE 1. Cardiovascular Processes Involving Rho and Rho Kinase
Vascular sensitization to calcium through phosphorylation
of the myosin light chain, causing arterial vasoconstriction,
increased vascular resistance, and arterial hypertension.20,21
Activation of ERK protein kinases and arterial contraction
induced by angiotensin II in resistance vessels.22,23
Mediation of the effects of thrombin on the proliferation
Expression of plasminogen activator-1 mRNA and perivascular
Angiotensin II evokes a variety of hypertrophic re-
sponses in cardiac myocytes, including activation of
various protein kinases, reexpression of fetal genes,
and increased protein synthesis. In cultured rat car-
diac myocytes, angiotensin II activates RhoA, lea-
ding to the formation of premyofibrils and the induc-
tion of genes associated with the hypertrophic response in a process that appears to differ from that
which occurs in striated muscle.24 In these same
cells, angiotensin II is a potent activator of ERK pro-
teins. This activation is blocked by the administration
of an antagonist of the type I angiotensin II receptor,
an effect which is prevented by pretreatment of the
cardiac myocytes with exoenzyme C3. Angiotensin II
was found to increase incorporation of tritiated
α-actin and c-fos promoters is upregulated by an-
giotensin II, and that this effect is partially inhibited
by pretreatment with exoenzyme C3. Angiotensin II
was found to increase incorporation of tritiated
phenylalanine in cardiac myocytes, an effect that was
also suppressed by pretreatment with exoenzyme C3.
These observations indicate that the Rho family of
small GTPases regulates the hypertrophic response of
cardiac myocytes to angiotensin II.25

Hyper trophy and Hyperplasia of Vascular Smooth Muscle Cells
Rho and Rho kinase, as well as c-fos, play a key
role in the hypertrophic changes induced in vascular
smooth muscle cells by angiotensin II.26 In this cell
type, Y-27632 abolishes both mRNA and protein ex-
pression of c-fos in response to angiotensin II.27
Mechanotransduction in vascular smooth muscle cells
depends on the presence of intact actin filaments.
Furthermore, Rho is activated by stretching, and the
Rho/Rho kinase pathway mediates stretch-induced
ERK activation and vascular hyperplasia.28

Angiotensin II, Vascular Inflammation,
and RhoA
It has been postulated that Rho kinase could partici-
perate in atherogenesis, based on studies of the role
of this pathway in vascular inflammation. Monocyte
chemoattractant protein-1 (MCP-1) is a chemokine
that regulates monocyte recruitment and participates
in atherogenesis. Rho kinase regulates the an-
giotensin-induced production of MCP-1, indepen-
dently of ERK activation. In vascular smooth muscle
cells, this MCP-1 production is blocked by botulinum
exotoxin C3.28 Overexpression of a dominant-nega-
tive Rho kinase or the use of Y-27632 significantly
inhibit the angiotensin II-dependent expression of
MCP-1.28

Bradykinins and the Rho Signal Transduction
Pathway
Few studies have assessed the possible interaction
of bradykinins with the Rho signaling pathway, and
even fewer in relation to cardiovascular remodeling. It
has been shown in A549 epithelial cells that
bradykinin stimulates the activation of NFκB and the
synthesis of interleukin-1β, and that RhoA is both ne-
necessary and sufficient to mediate this effect.29

RHO SIGNALING AND ARTERIAL
HYPERTENSION
The role of Rho signaling in arterial hypertension
was first recognized in 1997. In that study, a specific
inhibitor of Rho kinase was observed to reduce arterial
blood pressure in 3 experimental models of arterial hy-
pertension. However, the relationship between Rho
signaling and pathologic cardiovascular remodeling,
or with the vasoactive molecules angiotensin II and the
bradykinins, was not studied.
Increases in the expression and activity of RhoA are
associated with an increase in DNA synthesis and a re-
duction in the expression of the cell cycle protein
p27Kip1 in the aorta and tail artery of spontaneously
hypertensive and L-NAME-treated rats.30 In the aorta,
nitric oxide inhibits the activity of Rho kinase and the
sensitization of the tissue to calcium, leading to the
hypothesis that nitric oxide-mediated vasodilatation oc-
curs through inhibition of the vasoconstrictor activity
of Rho kinase. Nitric oxide induces vasodilation through cyclic GMP. A recent study demonstrated that protein kinase G phosphorylates RhoA and inhibits its activity. In addition, sodium nitroprusside reverses the RhoA translocation induced by phenylephrine, indicating inhibition of RhoA activity. Figure 3 summarizes the mechanisms through which RhoA has been observed to cause vasoconstriction in arterial hypertension.

Few studies have addressed the role played by this signal transduction pathway in arterial hypertension in humans. In a recent study in hypertensive patients, fasudil, a specific inhibitor of Rho kinase used in the treatment of cerebrovascular spasm in subarachnoid hemorrhage, was seen to induce a stronger vasodilatory response in the forearm of hypertensive than control subjects, while the response to sodium nitroprusside was similar in both patient groups. This result constitutes the first evidence that the Rho/Rho kinase pathway participates in the pathogenesis of increased systemic vascular resistance in hypertensive patients.

THE RELATIONSHIP BETWEEN RHO SIGNALING AND ATHEROGENESIS

The Role of Rho in the Endothelium

There are various interactions between Rho signaling and the structure and function of the endothelium in both normal and pathologic conditions. These interactions play a role in the development of arterial hypertension and are associated with the progression of atherosclerosis in various arteries. The integrity of the endothelium depends on intercellular adhesions mediated by vascular-endothelial (VE) cadherin that, in turn, depend on connections to the actin cytoskeleton. Rho controls cytoskeletal dynamics and cadherin function in epithelial and endothelial cells. The function of these cadherins is also regulated by ROS, which control the pathophysiologic changes associated with inflammation and endothelial damage, and with migration of endothelial cells and angiogenesis. Endothelial dysfunction is characterized by an altered endothelial response that favors the processes of vasoconstriction, cell adhesion, and coagulation. The statins, inhibitors of HMG-CoA reductase, are useful for reversing endothelial dysfunction, an effect that appears to be independent of the reduction of serum cholesterol concentration. Rho-dependent activation of preproendothelin-1 expression is inhibited by statins. Thus, control of vascular tone and proliferation mediated by endothelin-1 is regulated at multiple levels, and Rho signaling may play a significant role.

Rho modulates the permeability of endothelial monolayers and regulates actin filament assembly, contractile activity due to myosin, and the distribution of the calcium dependent cell adhesion molecule VE cadherin. Rho and the contractile processes mediated by RhoA do not participate in the increased permeability induced by bradykinin and platelet activating factor in intact microvessels. The regulation of the endothelial cell barrier is absolutely dependent on components of the cytoskeleton. Factors that cause edema induce contraction of this barrier through actomyosin, associated with phosphorylation of myosin light chain and reorganization of filaments. Alteration of this structural assembly increases dysfunction of the endothelial barrier by activating specific signaling pathways that “talk” to networks of microfilaments and increase the Rho-mediated contractility of the endothelial barrier. The migration of endothelial cells induced by vascular endothelial growth factor (VEGF) is a critical step in angiogenesis, and requires the participation of Rac, another small GTPase.

THE RELATIONSHIP BETWEEN RHO SIGNALING AND VASCULAR INFLAMMATION, ADHESION MOLECULES, AND PROCOAGULATION IN ARTERIAL HYPERTENSION

Inflammation is crucial to the pathogenesis of atherosclerosis and plays an important role in the vascular complications associated with arterial hypertension. Transmigration of monocytes into the subendothelial space, via integrin activation and chemotaxis, is the initial step in atherosclerotic plaque formation and inflammation. Integrins are activated by ERK, while p38-MAPK and Rho control chemotaxis mediated by MCP-1. Rho and Rho kinase are upstream of p38-MAPK in MCP-1 signaling. Thus, ERK and p38-MAPK regulate distinct signal cascades that lead to integrin activation and chemotaxis induced by MCP-1. In addition to regulating fibrinolytic activity, plasminogen activator inhibitor type 1 (PAI-1) also plays a role in the pathogenesis of atherosclerosis and arterial hypertension. Angiotensin II, acting through the type 1 angiotensin II receptor, upregulates protein and mRNA expression of PAI-1 in vascular smooth muscle cells. Overexpression of a dominant-negative Rho kinase or the use of Y-27632 completely blocks the induction of PAI-1 expression by angiotensin II, without affecting ERK activation. These observations indicate that activation of the ERK and Rho kinase pathways is necessary for the induction of PAI-1 expression by angiotensin II. Rho kinase could be a novel target through which to inhibit the effects of angiotensin II in the treatment of arterial hypertension and atherosclerosis.

In rat fibroblasts, inhibition of PKC or RhoA selectively inhibits induction of c-fos by transforming
growth factor β1 (TGF-β1), indicating possible roles for both PKC and RhoA in the induction of c-fos by TGF-β1.

Rho participates in signaling through chemotrac- tant receptors that initiates rapid adhesion in leukocytes.23 The interactions of endothelial ICAM-1 and VCAM-1 with their ligands are involved in the differ- ential regulation of distinct steps in diapedesis by modulating the balance of active and inactive forms of small GTPases.24 In endothelial cells of the aorta, the statin cerivastatin blocks lipopolysaccharide-induced expression of ICAM-1 mRNA. Cotreatment with ge- ranylgeranyl pyrophosphate reverses the effect of the statin, indicating that this effect is caused by inhibition of Rho activity.25

Rho mediates the assembly of focal adhesions through integrins and actin stress fibers. Genetic inhibi- tion of RhoA in human endothelial cells has demons- trated a requirement for Rho in the assembly of stable adhesions with monocytes through clustering of the receptors E-selectin, ICAM-1, and VCAM-1, which recognize ligands present on monocytes.26

The endothelium of the cerebral blood vessels, which constitutes the blood-brain barrier, controls the adhesion and migration of lymphocytes into the brain. The cell adhesion molecule ICAM-1 participates in the extravasation, morphological changes, and gene regulation associated with the migration of lymphocytes across the blood-brain barrier through activation of Rho and phosphorylation of the endothelial actin cytoskeleton.27,28 In the brain, the signaling pathway mediated by ICAM-1 in the endothelial cells is a cen- tral element in facilitating lymphocyte migration. Rho proteins, which require posttranslational prenylation to be functionally active, are essential components of this signaling cascade. It has been suggested that the signal transduction systems of cerebral endothelial cells, par- ticularly Rho proteins, could be attractive pharmaco- logical targets through which to recruit leukocytes to the central nervous system.29

It has been observed in experiments with human T lymphocytes that Rho and Rho kinase regulate the ty- rosine kinase PYK2 by controlling F-actin-mediated control of the integrin lymphocyte function-associated antigen-1, highlighting a novel form of modulating the activity of this cytoplasmic tyrosine kinase. In addi- tion, Rho regulates the chemokine-induced polariza- tion and migration of lymphocytes, in which cdc42 plays a key role.30 Antithrombin directly inhibits chemokine-induced migration of monocytes and lymphocytes via the effects of its heparin binding site by activating PKC and Rho.31

Disequilbrium between nitric oxide and endothe- lin-1 plays an important role in cardiovascular dis- eases. Thrombin exerts powerful effects on endothe- lial function. A study has addressed the molecular mechanisms through which thrombin regulates the ex- pression of endothelial nitric oxide synthase (eNOS) and endothelin converting enzyme-1 (ECE-1) in hu- man endothelial cells. Incubation of human umbilical cord endothelial cells with thrombin caused a marked downregulation of eNOS expression and increased the levels of ECE-1 protein in a concentration dependent manner. Thrombin also downregulated and upregulated mRNA expression of eNOS and ECE-1, respect- ively. The effects of thrombin on eNOS and ECE-1 were found to be mediated by the Rho and ERK path- ways, respectively.30

NADH/NADP(+) Oxidases, Reactive Oxygen Species, and Rho

The NADH/NADP(+) oxidase pathway is one of the main producers of ROS in the vascular system. Superoxide (O2-) anions are generated that can react with nitric oxide to form the peroxynitrite anion, which lacks the relaxant activity of nitric oxide on the smooth muscle. Angiotensin II induces activation of NADH/NADP(+) oxidases in vascular smooth muscle cells, leading to increased production of O2- and inac- tivation of nitric oxide. In phagocytes, the NADP(+) oxidase system that generates O2- is regulated by small G proteins related to Rac.31

In the vascular smooth muscle cells of the rat aorta, inhibition of Gβi with pertussis toxin and inhibition of NADH/NADP(+) oxidase reduces stimulation of p21- activated kinase (PAK) induced by lysosphosphatic acid (LPA). Thus, in these cells, LPA activation of PAK is mediated by Gβi and is dependent on Src. In addition, activation of PAK by LPA requires genera- tion of ROS.31

Tissue factor activates the extrinsic pathway of coagulation, which leads to thrombin formation. Throm- bin induces expression of tissue factor mRNA in vascular smooth muscle cells and, consequently, con- tributes to prolonged procoagulant activity and in- increased thrombogenicity at sites of vascular lesion. NADP(+) oxidase participates in the redox-sensitive induction of tissue factor mRNA expression and the surface procoagulant activity activated by thrombin. This response is mediated by the NADP(+) oxidase- dependent activation of MAPK and by the P3K/pro- tein kinase B pathway. Given that active tissue factor promotes the formation of thrombin, NADP(+) oxy- dase could play a crucial role in perpetuating thrombo- genic effects in lesioned vessel walls.32

Phagocytes produce O2- through the reduction of molecular oxygen by the NADP(+) oxidase complex. This complex is formed from a membrane-bound flavocytochrome and 3 cytosolic proteins, one of which is a dimer of Rac1 p21 or Rac2 p21 and the Rho-gua- nine nucleotide dissociation inhibitor (RhoGDI). It has been proposed that, following dissociation of RhoGDI, Rac1 p21 bound to GDP is the physiologic activator of

NAD(P)H-oxidase in macrophages, and that nucleotide exchange or the conversion of GTP are not necessarily involved.24

The role of the Rho kinase p160-ROCK in the production of O2· by human polymorphonuclear leukocytes, and in the aggregation and adhesion of this cell type has been investigated under physiologic conditions, using the selective p160-ROCK inhibitor Y-27632.55 Here it was observed that production of O2· stimulated by phorbol ester was inhibited by Y-27632 in a concentration-dependent manner, indicating that p160-ROCK participated in this process and in the aggregation of human polymorphonuclear leukocytes.

Hydrogen peroxide, a reactive oxygen species, causes pulmonary edema, and increases hydrostatic pressure and vascular permeability. Increased permeability is accompanied by contraction and reorganization of the cytoskeleton in endothelial cells that leads to the formation of intercellular adhesions. The Rho family is also implicated in cell contraction. It has been demonstrated that an inhibitor of Rho kinase blocks the generation of this type of edema in rabbit lung, antagonizing the effects of H2O2. This finding indicates that Rho is involved in H2O2-induced pulmonary edema.25

PLEIOTROPIC EFFECTS OF THE STATINS THROUGH THE RHO SIGNALING PATHWAY

Statins, inhibitors of HMG-CoA reductase, are potent inhibitors of cholesterol biosynthesis. A number of clinical studies have demonstrated beneficial effects of statins in the primary and secondary prevention of heart disease. However, their action seems to extend beyond what would be expected on the basis of hypolipidemic effects alone. Recent experimental and clinical evidence reveals that the pleiotropic effects of statins are independent of their actions on cholesterol and involve an improvement or restoration of endothelial function, increasing plaque stability and reducing oxidative stress and vascular inflammation. A number of the pleiotropic effects of the statins are mediated by their capacity to block the synthesis of important isoprenoid intermediates (farnesyl or geranylgeranyl) that serve as lipid anchors for various intracellular signaling molecules. In particular, the inhibition of small GTPases (Figure 4), whose membrane localization and function depend on the process of isoprenylation (specifically farnesylation or geranylgeranylation), would play an important role in mediating the direct cellular effects of the statins on the vessel wall.57

Despite all of the recent findings that have been discussed here, a number of questions remain to be answered in the coming years. It will be important to address whether similar patterns of cardiovascular activation of the Rho signaling pathway occur in different experimental models of arterial hypertension, to identify the main stimuli, and to assess how activation of the pathway is linked to the expression of genes that encode proteins with proinflammatory, profibrotic, and prothrombotic effects on the arteries. Furthermore, it will be of interest to determine whether there is any relationship between vascular activation of Rho signaling and local or systemic changes in vasoactive peptides, cell adhesion molecules, and/or prooxidant pathways in the development of arterial hypertension. Finally, it will be important to determine whether inhibition of distinct points in the Rho signaling pathway, once activated, affects the process of vascular remodeling in arterial hypertension or only blood pressure, given the many possible therapeutic targets beyond arterial hypertension (Table 2 and Figure 4).

In conclusion, the Rho/Rho kinase signal transduction pathway represents a newly recognized mechanism of vasoconstriction in arterial hypertension, pathologic cardiovascular remodeling, and a number of other cardiovascular and noncardiovascular conditions, and may represent a novel and promising therapeutic target.

REFERENCES


TABLE 2. Diseases in Which Rho/Rho Kinase Could Represent a Therapeutic Target

<table>
<thead>
<tr>
<th>Cardiovascular diseases</th>
<th>Arterial hypertension</th>
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<tr>
<td>Cerebral and coronary vasospasm</td>
<td>Postangioplasty restenosis</td>
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<td>Pulmonary hypertension</td>
<td>Erectile dysfunction</td>
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<td>Noncardiovascular diseases</td>
<td>Bronchial asthma</td>
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<td>Premature birth</td>
<td>Cancer (angiogenesis, cell proliferation, and motility and migration of tumor cells)</td>
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Taken from Saito et al.26

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Figure 4. Inhibition of the Rho kinase pathway and potential cardiovascular therapeutic effects. The addition of a farnesyl group to the small GTPases, necessary for their association with the plasma membrane and physiologic activity, can be blocked by statins and farnesyltransferase inhibitors (FTI). Statins inhibit HMG-CoA reductase, a key enzyme in the regulation of isoprenoid synthesis from acetyl-CoA, while FTIs directly inhibit farnesyltransferase. Y27632 and fasudil inhibit Rho kinase. All of these are potential therapeutic targets for the treatment of cardiovascular diseases.


