Hypertension is the most common reversible risk factor for stroke, myocardial infarction, and heart failure, affecting >60 million individuals in the United States alone and 1 billion globally.1 According to the World Health Organization, hypertension is now the leading cause of preventable death worldwide.2 Importantly, the prevalence and complications of hypertension increase significantly with age. However, despite the availability of many antihypertensive agents of distinct pharmacologic classes and evidence-based guideline recommendations for stepwise, multidrug regimens, control of hypertension remains suboptimal, with target blood pressure achieved in <50% of patients.3 Although patient noncompliance and submaximal dosing of antihypertensive agents contribute to lack of blood pressure control, there is an unmet need for new approaches for treatment of hypertension. In this issue of Circulation, Boe et al4 report that pharmacological inhibition of plasminogen activator inhibitor-1 (PAI-1) is protective against the development of hypertension, cardiac hypertrophy, and periaortic fibrosis (ie, arteriosclerosis) in mice treated with l-NAME, an inhibitor of endothelial nitric oxide synthase.

Because the molecular basis for primary or essential hypertension is unknown, the treatment of hypertension, excluding secondary or identifiable hypertension with known causes (eg, chronic renal disease, renovascular, hyperaldosteronism, Cushing syndrome, pheochromocytoma), has been based primarily on targeting the underlying physiologic determinants of blood pressure—namely, intravascular volume (eg, diuretics), neurohormonal drive (eg, centrally acting agents, renin angiotensin system blockade), systemic vascular resistance (eg, vasodilators), and cardiac inotropy and chronotropy (eg, beta blockers; Figure). Another hallmark of hypertension is vascular remodeling of both small (inward eutrophic remodeling) and large (hypertrophic remodeling that increases lumen area and increases systemic vascular resistance) arteries.4 Antihypertensive agents variably affect vascular remodeling, possibly accounting for differential effectiveness of specific agents in preventing cardiovascular events.5 Arterial collagen accumulation results in age-related arterial stiffening characterized by increased pulse pressure, which is an independent predictor of heart attack and stroke.5 Therapeutic approaches specifically targeting structural remodeling represent an important new area in cardiovascular disease.

Boe et al6 investigated whether a novel, orally active PAI-1 antagonist (TM5441) has a protective effect against l-NAME-induced systemic hypertension, arteriosclerosis, and vascular senescence. Wild-type mice received either l-NAME alone or l-NAME and TM5441 for 8 weeks. TM5441 attenuated the development of hypertension and cardiac hypertrophy compared with animals that had received l-NAME alone. Additionally, TM5441-treated mice had a 34% reduction in periaortic fibrosis. Finally, the development of vascular senescence was investigated by measuring p16INK4a expression and telomere length in aortic tissue. l-NAME increased p16INK4a expression levels and decreased telomere length, both of which were prevented with TM5441 cotreatment. Importantly, the favorable blood pressure and remodeling effects of PAI-1 inhibition appear to extend to other models of hypertension. PAI-1 deficiency prevented angiotensin II-induced arteriosclerosis7 and, in supplemental data in the present study, reduced blood pressure.

The precise mechanism(s) responsible for the blood pressure-lowering effect of PAI-1 inhibition is uncertain. The fact that wild-type mice treated with TM5441 alone exhibited no change in blood pressure suggests that inhibition of PAI-1 likely does not affect vascular tone or volume but rather has structural effects. A closer look at the plasminogen activator system provides potential insights into TM5441 action. Plasmin is the major protease of the fibrinolytic system8 and plays an important role in cell migration and tissue remodeling9 by virtue of the fact that it is capable of degrading extracellular matrix proteins directly (fibrin, fibronectin, thrombospondins, laminins) or indirectly (collagen, elastin) via the activation of metalloproteases.9 Plasmin is derived from plasminogen by the endogenous plasminogen activators tissue-type plasminogen activator10 and urokinase-type plasminogen activator11 (Figure). The generation of plasmin is regulated by a balance between the plasminogen activators tissue-type plasminogen activator and urokinase-type plasminogen activator and their SERPIN (for serine proteinase inhibitor) family inhibitors PAI-112 and PAI-2.13 Two functionally distinct forms of PAI-1, termed active and latent, have been identified.14 In plasma, most of the PAI-1 circulates in the active form,15 which deactivates spontaneously with a
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PAI-1, with a half-life of 1 to 2 h,16 is stabilized by vitronectin.17 PAI-1 is the primary physiological inhibitor of plasminogen activation. Active PAI-1 acts as a suicide substrate for tissue-type plasminogen activator and urokinase-type plasminogen activator and rapidly neutralizes these plasminogen activators by forming a covalent complex.18 In plasma, PAI-1 has a critical role in regulating endogenous fibrinolytic activity and resistance to thrombolysis. In vascular tissues, PAI-1 mediates the response to injury by inhibiting cellular migration19 and matrix degradation.20 Excess PAI-1 is known to exacerbate the development of fibrosis in a variety of animal models.21,22 The plasminogen activator system also regulates vascular cell growth and remodeling as a consequence of plasmin-dependent processing of various cytokines and chemokines, including transforming growth factor-β, interleukin-1, basic fibroblast growth factor, tumor necrosis factor-α, and monocyte chemotactic protein-1.23 TM5441 treatment did not fully attenuate the increase in systolic blood pressure attributable to chronic endothelial nitric oxide synthase inhibition but almost completely prevented collagen deposition and periaortic fibrosis. Thus, PAI-1 likely blocks proteolytic pathways that are critical to the maintenance of high blood pressure state as well as hypertension-associated arteriosclerosis.

This study challenges the present paradigm of antihypertensive treatments that focus on intravascular volume, neurohumoral drive, systemic vascular resistance, and cardiac inotropy and chronotropy. Understanding the broader functions of PAI-1 in distinct cellular compartments and environments in vascular homeostasis and disease will be required to determine the clinical significance of these findings. First, is there any evidence that PAI-1 is involved in human hypertension? Indeed, this appears to be the case based on an analysis of arterial stiffness in the Framingham population. PAI-1 was positively related to measures of conduit artery stiffness (ie, mean arterial pressure, central pulse pressure, and forward pressure wave amplitude).
even after multivariable adjustment. Second, is selective inhibition of PAI-1 achievable in vivo in humans? If so, what is the most appropriate timing of PAI-1 inhibition—namely, to prevent hypertension in prehypertensive individuals or in patients with established hypertension? Third, is it possible for inhibition of PAI-1 to reverse arteriosclerosis and periarterial fibrosis, thereby, for example, lowering pulse pressure? Fourth, will blockade of PAI-1 and unchecked proteolysis be associated with adverse effects, including increased risk of bleeding, intracerebral hemorrhage, or unfavorable vascular remodeling that could promote aneurysm formation? Fifth, in genome-wide association studies of hypertension, is there linkage with genes related to the plasminogen activator system or proteolysis? Finally, could targeting PAI-1 be useful in pulmonary hypertension, which is also associated with significant vascular remodeling?

The contribution by Boe et al in this issue of Circulation highlights the emergence and potential importance of vascular remodeling in animal models of hypertension (chronic inhibition of endothelial nitric oxide synthase or angiotensin II infusion) that may guide the study of human disease. The involvement of the plasminogen activator system in vascular homeostasis/remodeling and blood pressure, especially in the elderly, has profound implications for our patients. Novel therapeutic approaches available to reduce the increase in pulse pressure and arterial stiffness with age have been proposed previously. These approaches involve converting enzyme inhibitors, nitrate derivatives, agents acting on collagen crosslinking, spironolactone, and vaso- peptide inhibitors. This study suggests a new approach involving structural remodeling of large and small arteries to prevent arteriosclerosis in hypertension. Understanding how to safely and efficiently translate these experimental observations might lead to new clinical applications, perhaps targeting PAI-1.

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References
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