Mechanisms of Arterial Remodeling in Hypertension
Coupled Roles of Wall Shear and Intramural Stress
Jay D. Humphrey

Data collected over the past 4 decades suggest the existence of a mechanical homeostasis across multiple length and time scales in the vasculature. For example, stress fibers within endothelial and vascular smooth muscle cells appear to disassemble and then reassemble in a mechanically preferred manner when perturbed from a normal value of mechanical stress or strain; focal adhesions in smooth muscle cells and fibroblasts tend to increase in area in response to local increases in mechanical loading so as to maintain the stress constant at a preferred value; fibroblasts tend to increase the tractions that they exert on the extracellular matrix when external loads are decreased from a preferred value, thus suggesting an attempt to enforce a “tensional homeostasis”; vascular smooth muscle cells tend to re-lengthen to their normal, preferred values when an arteriole is forced into a vasoconstricted state for an extended period; and arteries tend to decrease in caliber in response to sustained increases in pressure-induced circumferential stress, and to lengthen in response to extension-induced increases in axial stress. Although changes in the cytoskeleton and integrins occur within minutes, changes at the cell-cell and cell-matrix levels occur over hours, and those at the vessel level occur over days to weeks or months. Hence, despite marked differences in length scales (dimensions from nanometers to centimeters) and time scales (durations from minutes to months), mechanobiological control mechanisms in the vasculature tend to restore values of stress or strain toward preferred (homeostatic) values in response to diverse perturbations from normal.1-5 Biomechanics and mechanobiology thus play key roles in vascular development, tissue maintenance in maturity, normal adaptations, aging, disease progression, and responses to injury or clinical interventions.

A current challenge in hypertension research is to understand how mechanobiological mechanisms at molecular and cellular levels (eg, altered turnover of collagen) manifest at tissue and organ levels and, conversely, how mechanical loads at tissue and organ levels (eg, increased pulse pressure) are sensed by molecular structures and result in altered gene expression. To gain increased understanding, we can exploit lessons learned from all areas of vascular research, because it appears that the same fundamental cell-mediated mechanisms govern diverse cases of vascular growth (ie, change in mass) and remodeling (ie, change in structure) via the reorganization and/or turnover of cells and extracellular matrix in evolving biomechanical states.1

**Biomechanical Consequences of Perturbed Flow and Pressure**

Notwithstanding complexities of in vivo mechanics because of pulsatile blood flow and nonlinear anisotropic wall properties, the normal artery is subjected to 3 primary mechanical stresses: a blood flow-induced wall shear stress \( \tau_w \), a blood pressure-induced circumferential wall stress \( \sigma_v \), and an axial wall stress \( \sigma_a \) that appears to arise during development and to persist into maturity because of the long half-life of elastin.6 Mean values of these 3 components of stress (ie, forces acting over oriented areas) can be calculated as follows:

\[
\tau_w = \frac{4 \mu Q}{\pi a h}, \quad \sigma_v = \frac{Pa}{h}, \quad \sigma_a = \frac{f}{\pi h(2a+h)},
\]

where \( \mu \) is the blood viscosity, \( Q \) the mean volumetric flow rate, \( a \) and \( h \) the luminal radius and wall thickness in any pressurized configuration, \( P \) the transmural pressure (with low perivascular pressure), and \( f \) the axial force that maintains the axial “prestretch” (which is appreciated via the axial retraction of a transected artery). The second equation reveals the importance of the thickness:lumen ratio (\( h/l \)), noting that \( h \) is total, not intimal-medial, thickness, and the third equation shows the importance of wall cross-sectional area, which is often reported with regard to “eutrophic” versus “hypertrophic” remodeling. Although the importance of axial stress and stretch in hypertension was recognized years ago,7 it has received little attention because of the inability to infer values in vivo.

Large arteries appear to maintain these stresses near homeostatic values (eg, on the order of 1.5 Pa for \( \tau_w \) and 100 kPa for both \( \sigma_v \) and \( \sigma_a \) in specific arteries2-4 where 1 kPa=7.5 mm Hg). Hence, it is instructive to consider how clinically measurable changes in flow or pressure might lead...
to tissue level changes in geometry (in addition to changes in structure and function). Let perturbed values of flow $Q$ and pressure $P$ be related to original values via $Q = eQ_o$ and $P = \gamma P_o$, where a subscript or superscript $o$ denotes original and $e$ and $\gamma$ denote sustained percent changes from original (eg, $\gamma = 1.3$ if $P$ increases 30% from original). Equation 1 reveals that if mean wall shear stress and then mean circumferential stress are restored via growth and remodeling processes, then specific morphological changes to large arteries should be as follows:

$$\tau_w = \frac{4\mu (e Q_o)}{\pi a^2} \text{ (perturbed) and } \tau'_w = \frac{4\mu Q_o}{\pi a_o} \text{ (original)},$$

then $\tau_w = \tau'_w$ requires

$$\frac{4\mu (e Q_o)}{\pi a^2} = \frac{4\mu Q_o}{\pi a_o}, \text{ or } a = e^{1/3} a_o.$$

$$\sigma_w = \frac{(\gamma P_o) (e^{1/3} a_o)}{h} \text{ (perturbed) and } \sigma'_w = \frac{P_o a_o}{h_o} \text{ (original)},$$

then $\sigma_w = \sigma'_w$ requires

$$\frac{(\gamma P_o) (e^{1/3} a_o)}{h} = \frac{P_o a_o}{h_o}, \text{ or } h = e^{1/3} h_o.$$

For example, a 30% sustained increase in flow alone should cause a 9% increase in both caliber and wall thickness [ie, if $e = 1.3$, then $(1.3)^{1/3} = 1.09$ with $\gamma = 1.0$]; in contrast, a 30% sustained increase in pressure alone should cause a 30% increase in thickness but no change in caliber (ie, $\gamma = 1.3$ with $e = 1.0$). In other words, a mean stress-mediated growth and remodeling response would require coordinated changes in luminal radius $a$ and wall thickness $h$ based directly on the percentage of perturbations in hemodynamics from the original. Such changes are commonly observed clinically and in animal studies, and hence supporting this general hypothesis. Note, too, that if luminal radius and wall thickness are dictated by flow and pressure, then restoring $\sigma_w$ (eq 1) to its original value requires a change in axial force $f$, which typically would cause a change in length (eg, possible tortuosity). That responses to all of the stresses must be considered together is reinforced by observed, coupled effects of pressure (eg, cyclic circumferential stress or strain) and flow (wall shear stress) induced changes at cellular and tissue levels.

Before considering cellular mechanisms by which arteries can achieve gross changes in geometry, structure, and function, note 3 subtle points. First, the above (equilibrium) equations for $\sigma_w$ and $\sigma'_w$ are deceptively simple because nonlinear dependencies of pressure on radius (traditional pressure-diameter data) and axial force on length (common uniaxial data) are not denoted explicitly nor are observations that pressure-diameter relations differ at different axial stretches and axial force-length relations differ at different pressures. There is a need, therefore, to account for changes in wall composition, that is, material properties. Second, eqs 1 to 3 do not account for changes in perivascular tethering or the pulsatility of flow and pressure, which can play important roles in arterial growth and remodeling. There is a need, therefore, for more research on the associated mechanobiology. Third, changes in arterial geometry in response to altered loads depend on coupled elastic deformations (ie, nonlinear wall properties), acute and chronic changes in vascular tone (ie, smooth muscle contraction or relaxation), and reorganization or turnover of cells and matrix in potentially evolving biomechanical states (ie, growth and remodeling). Hence, even in a simple case of a single sustained change of flow or pressure, the means by which and the durations over which radius tends toward $e^{1/3} a_o$ and thickness tends toward $e^{1/3} h_o$ can be complex and depend on both short-term and long-term cellular responses, including altered proliferation, migration, differentiation, apoptosis, synthesis and degradation of matrix, cross-linking of matrix, integrin binding that governs cell-matrix interactions, and cadherin activity that governs cell-cell interactions.

### Vascular Mechanobiology

The first reports of mechanobiological responses by vascular cells appeared in the mid-1970s. Since then, it has been shown that many different nonstructurally significant molecules (eg, vasoactive, growth factors, cytokines, proteinases, coagulation factors, etc) and structurally significant constituents (eg, fibronectin, elastin, collagens, and proteoglycans) are produced by fibroblasts, smooth muscle, and endothelial cells in response to altered mechanical loads. Although associated mechanisms of mechanotransduction are not understood fully, G proteins, ion channels, receptors for growth factors and vasoactive molecules, and the cytoskeletal-integrin-extracellular matrix axis play fundamental roles. For example, changes in tissue-level loads can cause rapid reorganization or remodeling of integrins and associated intracellular proteins so as to promote mechanical homeostasis. Integrins play diverse roles, from influencing cell migration, proliferation, and apoptosis to enabling cells to survey their local mechanical environment or to alter myogenic responses. Recall, however, that $\sigma_w$ is often on the order of 100 kPa in arteries. Although some investigators suggest that intramural cells necessarily “feel” this level of stress, the aforementioned findings that some cells attempt to maintain stress on the order of 3 to 10 kPa at focal adhesions suggest that the full load supported by the extracellular matrix need not be felt by resident cells, with the possible exception of contractile smooth muscle cells. Rather, cells can be “stress shielded” by matrix and may merely survey their local environment to determine appropriate mechanobiological responses.

There is a need for more research on this important aspect of mechanotransduction, which will be essential for linking molecular level responses and tissue-level stimuli.

Even after molecular mechanisms of mechanotransduction are understood fully, tissue level responses (eg, increasing wall thickness in response to increased pressure because of increases in collagen) should continue to be correlated with changes in the continuum metrics of stress or strain, for this level of understanding is fundamental to clinical care (eg, prognosis, surgical planning, and medical device design).
That said, such correlations must capture underlying complexity; altered gene expression often relates nonlinearly to mechanical stimuli. Thus, cellular responses must be measured at multiple levels of stress or strain. For example, consistent with observed tissue-level changes in caliber, data reveal an increasing sigmoidal relationship between increased τw and endothelial NO synthase mRNA21 and a decreasing sigmoidal relationship between increased τw and endothelin-1 (ET-1) mRNA.22 Ultimately, however, we must know the amounts of NO and ET-1 produced, not just changes in mRNA expression. Li et al23 reported data sufficient to quantify collagen synthesis in terms of smooth muscle cell stretch, again suggesting an increasing sigmoidal relationship. Unfortunately, data from most reports are not sufficient to construct appropriate nonlinear relationships, because the objective is often to show statistical differences between an unloaded and 1 or 2 loaded cases. There is a need, therefore, for data sufficient to quantify “mechanical dose response curves,” which is to say that we must quantify better the responses at multiple levels of loading.

There are 2 issues related to such quantification. First, cellular production of a particular molecule often depends on changes in multiple types of loads. For example, whereas endothelial production of ET-1 decreases with increasing wall shear stress22 (eg, 3.5-fold because of an increase in shear from 0 to 2.0 Pa), it increases with increasing cyclic stretch24 (eg, 1.7-fold because of a 10% stretch relative to no stretch). Similarly, whereas endothelial production of endothelial NO synthase increases with increasing wall shear stress21 (eg, 2.5-fold because of an increase in shear from 0 to 1.5 Pa), it also increases with increases in cyclic strain25 (=1.9-fold at 6% and 3.1-fold at 10% stretch relative to no stretch). Wall shear stress and cyclic circumferential stretch can change simultaneously in vivo; hence, mechanical dose response curves (actually surfaces) must account for complex responses to multiple stimuli. Second, there is a need to quantify changes in terms of all of the known pathways even for phenomenological modeling. For example, cyclic stretch (or stress)—mediated production of collagen by smooth muscle cells likely occurs via multiple processes23: mechanical stress appears to increase both angiotensin-II (Ang II) production and Ang II type 1 receptor sensitivity, which, in turn, can stimulate the production of latent transforming growth factor-β (TGF-β), which can be activated by mechanical stress and thereby cause an increased production of collagen. Hence, although collagen production can be correlated directly to changes in cyclic stretch (or stress), it can also be correlated with mechanoregulated Ang II activity and subsequent production and activation of TGF-β.26,27 Knowing that blood flow also alters TGF-β activity,28 we again see the need for quantification in terms of multiple stimuli to appreciate potential overlaps in cases of altered wall shear stress and intramural stress (or stretch). Indeed, cyclic stretch correlates with smooth muscle cell proliferation in culture, with stretch upregulating platelet-derived growth factor. The importance of stress-mediated changes in TGF-β and platelet-derived growth factor, as well as other growth factors and cytokines, has been confirmed in numerous in vivo studies of hypertension.8,29,30 There is a need, however, to quantify time-dependent intramural changes in molar concentrations of growth factors produced as a function of multiple simultaneously applied stresses or stretches and to determine, probably in cell culture, whether such effects are competitive or synergistic. Finally, although most attention in arterial biology and mechanics has been focused on endothelial and smooth muscle cells, there is increasing evidence that adventitial fibroblasts play important roles in vascular homeostasis, as well as in disease progression and injury responses.31–32 Thus, there is a need for similar data on mechanocontrol of fibroblast activity.

**Complementary Roles of Vasoactivity and Matrix Remodeling**

Briefly, there are 2 primary roles of altered vasoactivity relative to growth and remodeling. First, altered smooth muscle tone changes the biochemomechanical state in which cell and matrix reorganization and turnover occurs, and, second, vasoactive molecules play important roles in modulating the rates of cell and matrix turnover within the vasoaltered states.

**Vasoaltered States**

In response to a local increase in blood flow above normal, which increases τw, the endothelium upregulates endothelial NO synthase and increases its production of NO, which causes the wall the dilate and return shear stress toward the original. If the flow returns to normal soon thereafter, NO production likewise returns toward normal, and the vessel regains its original caliber. This is the normal vasoactive response. If the local increase in flow is sustained, however, as, eg, in an arteriovenous fistula or vigorous exercise, the increased production of NO enables cell and matrix reorganization or turnover to occur in the dilated state (noting that an increased radius a and isochorically decreased thickness h increase σz but not necessarily σt). Hence, combined wall shear and intramural stress-mediated growth and remodeling in a vasodilated state allows the wall to become entrenched at a larger radius and wall thickness. NO production may then return to normal if τw is normalized, which may “reset” control with regard to increased flow.

Similarly, consider the case of a sustained increase in pressure. Because large arteries are nearly elastic and, thus, distensible, an initial local increase in pressure tends to increase the luminal radius and isochorically decrease thickness. Again, these changes serve to increase σz, which sets into motion smooth muscle and possibly endothelial- and fibroblast-mediated growth and remodeling. Yet, the initial pressure-induced increase in caliber would also decrease τw, which, in turn, would tend to decrease endothelial production of NO and increase production of ET-1 to restore shear toward normal. Thickening thus occurs in an initially constricted state at the original caliber via increases in smooth muscle (hypertplasia and/or hypertrophy driven by stress-mediated increases in platelet-derived growth factor, TGF-β, etc) and extracellular matrix (particularly fibrillar collagens driven by increases in TGF-β, connective tissue growth factor, etc) mass.3,5,14,15,23 Hence, the wall again becomes entrenched within a vasoaltered state, with multiple stresses
simultaneously playing important roles. Once the wall has thickened sufficiently to restore $\sigma_w$ toward original (ie, increased the ability of the wall to withstand the increased pressure), at a preserved caliber and, thus, $\tau_c$, it would seem that the endothelium could return to its normal production of NO. It appears, however, that NO production may not normalize in hypertension, a situation often referred to as “endothelial dysfunction.” Whether the endothelium is actually impaired in its ability to produce NO or whether there is a resetting of its mechanoregulatory target, an increased competition for L-arginine (eg, by arginase) or a competitive upregulation of other vasoactive molecules (eg, Ang II) is not clear, however. Finally, although usually not discussed, the overall increase in thickness at the same radius necessarily increases cross-sectional area and thereby decreases $\sigma_w$ unless the axial force decreases proportionately. The latter may occur because of a net increase in the collagen:elastin ratio that unloads the prestretched elastin, which may be related to the aforementioned observation that axial prestretch decreases collagen production in hypertension. Potential implications of this to overall (biaxial) mechanical homeostasis remain unknown, however.

**Altered Rates of Turnover**

Another important aspect of wall shear stress-regulated changes in vasodiator/vasoconstrictor production is that NO is an inhibitor of smooth muscle cell proliferation and synthesis of collagen, whereas ET-1 is a promoter of smooth muscle proliferation and synthesis of collagen. For example, NO has been shown to decrease collagen production by cultured vascular smooth muscle cells by 30% to 40% in a dose-dependent (perhaps sigmoidal) manner depending on NO donor concentration. Conversely, collagen I production has been shown to depend nonmonotonically on ET-1 concentration, peaking at an ~5-fold increase at $10^{-8}$ M. Effects because of ET-1, which are fundamental in hypertension, can be augmented by those of other vasoconstrictors, particularly Ang II. Recall, therefore, that cyclic mechanical stretch increases collagen production via an Ang II/TGF-β pathway, apparently involving an increase in Ang II type 1 receptor synthesis or sensitivity.

Although Ang II tends to have a stronger effect than ET-1 on smooth muscle cell proliferation (125% increase versus 25% increase, both at $10^{-8}$ mol/L), both can affect collagen production by inducing growth factors. For example, ET-1 induces an increased production of connective tissue growth factor; Ang II induces an increased production of connective tissue growth factor further. Note that TGF-β acts through a Smad signaling pathway, Ang II/TGF-β control of collagen synthesis is complicated further by the ability of Ang II to directly activate Smad signaling. Because of the key role played by Ang II, it is not surprising that angiotensin-converting enzyme inhibitors and Ang II type 1 receptor antagonists (eg, losartan) have been effective in reducing Ang II-stimulated collagen production. Nevertheless, quantitative relationships between mechanically induced changes in intramural concentrations of NO, ET-1, and Ang II and their combined effects on the growth factor production or activation that modulate collagen synthesis would increase our overall understanding.

In addition to altered collagen production (eg, mass fraction), its undulation, orientation, cross-linking, and interactions with other matrix proteins or proteoglycans are fundamental to defining the stiffness of the arterial wall. There is a need, eg, for information on the “prestretch” at which new fibers are incorporated within extant matrix and similarly what mechanical cues dictate the orientation of collagen fibers that are deposited by smooth muscle cells or fibroblasts. With regard to cross-linking, both lysyl oxidase and tissue transglutaminase activity (tTG) play important roles in cross-linking matrix proteins within vasoconstricted states and thereby entrenching a vessel at a different caliber. For example, reduced $\tau_c$ decreases endothelial production of NO, which is an inhibitor of tTG activity. Conversely, tTG activity appears to be increased by increased intracellular calcium associated with increased smooth muscle contractility, as occurs in cases of reduced $\tau_c$. There is a need to identify possible mechanoregulation of tTG availability and activity, particularly because tTG associates with β-integrins, and integrin clustering is sensitive to changes in mechanical loading.

**Matrix Metalloproteinase Activity**

The structural integrity of the extracellular matrix depends on a delicate balance between synthesis and degradation, and its contribution to arterial stiffness is increasingly recognized as an important determinant of vascular health or disease. Matrix metalloproteinases (MMPs) represent an important class of enzymes capable of degrading matrix constituents; they are produced by endothelial cells, smooth muscle cells, fibroblasts, and infiltrating inflammatory cells. MMP expression is controlled transcriptionally by inflammatory mediators, growth factors, cell-cell and cell-matrix interactions, and mechanical stress or strain. By degrading the matrix, MMPs not only affect wall stiffness, they also impact cell migration, proliferation, apoptosis, and differentiation and thereby play an important role in vascular remodeling in hypertension, as well as other vascular diseases, particularly atherosclerosis and aneurysms. There are 22 members of the MMP family, but MMP-2 and MMP-9 (gelatinases), MMP-1 (interstitial collagenase), MT1-MMP (membrane type MMP), and MMP-12 (macrophage metalloelastase) have tended to attract considerable attention in vascular research. For example, it has been shown that 5% static and 10% cyclic uniaxial stretch upregulate the production of MMP-2 and MMP-9 (2-5 fold) by vascular smooth muscle cells in culture, and 2.5%, 5.0%, and 10.0% cyclic uniaxial stretches similarly increase MMP-2 production (2-10 fold) by endothelial cells in a dose-dependent manner.

Although MMPs are secreted primarily as inactive proforms, they are activated by serine proteases, reactive oxygen species, other MMPs, and even multiple types of mechanical stress. Indeed, stress can affect the kinetics of MMP-matrix interactions and, thus, rates of collagen degradation. The activity of MMPs is regulated further by tissue inhibitors of MMPs, but there has been little attention paid to the possible mechanoregulation of tissue inhibitors of MMPs. Despite
significant information on the role of MMPs and associated intracellular signaling pathways, in vascular development, adaptation, disease progression, and response to injury, there has been little attempt to quantify MMP/tissue inhibitor of MMP (TIMP) production or activation as a function of multiple levels of mechanical stimuli, including the biaxial loading as exists in vivo, which, as noted above, is essential for determining mechanical dose-response curves and achieving predictive capability. There is also a need to understand better the time course of MMP activity, which appears to increase soon after any mechanical perturbation or injury and then return slowly toward baseline values.47

**Mechanical Damage**

Although considerable attention has appropriately been directed toward the turnover of vascular collagen,29 the important roles of elastin cannot be ignored.48,49 Vascular elastin, with its associated fibrillins and fibulins, appears to be produced primarily during development and early postnatal periods. Hence, in contrast to vascular collagen, which is produced continuously and has a normal half-life of ~70 days, structurally significant vascular elastin appears to be produced early in life and to have a half-life on the order of decades.4 Thus, degradation or mechanical damage of elastin, not frank turnover, is of the most importance in vascular disease and injury, particularly in aneurysms, atherosclerosis, hypertension, restenosis after angioplasty/stenting, and aging.

Elastin is likely susceptible to mechanical fatigue damage (ie, gradual weakening because of repetitive cycling, noting that arteries can experience 30-million loading cycles per year), which could be more problematic in cases of increased pulse pressure.48 There is, of course, increasing evidence that increased pulse pressure in hypertension may be a more important mechanical stimulus for growth and remodeling in large arteries than increased mean pressure.50 Much can be learned about load-induced fragmentation of elastin in hypertension from the literature on arterial aging.48,49 Similarly, Marfan syndrome, because of a mutation in the fibrillin-1 gene, appears to represent a type of “accelerated aging,” particularly in the aorta, and, thus, may provide insight into general aspects of mechanically induced damage to elastin. In addition to its important structural role, elastin plays important biological roles, as, eg, by influencing smooth muscle cell migration, proliferation, and differentiation status. There is a need, therefore, to understand better the mechanical basis of rates of degradation or damage of elastin in hypertension and associated effects on wall remodeling.

**Need for Integrative Mathematical Models**

The 1998 Bioengineering Consortium Report of the National Institutes of Health stated, “The success of reductionist and molecular approaches in modern medical science has led to an explosion of information, but progress in integrating information has lagged... Mathematical models provide a rational approach for integrating this ocean of data, as well as providing deep insight into biological processes.”

Although the need remains to develop more robust mathematical models at all scales (eg, macro, micro, and nano), there is also a need to develop approaches that integrate models across diverse scales. That is, “multiscale modeling” promises to be an important contributor to integrating information on molecular and cellular mechanisms with understanding at the tissue level. Note, eg, that significant progress is being realized in modeling the kinetics of basal NO release by the endothelium,51 diffusion of NO within the arterial wall,52 and kinetics of NO activation of soluble guanylate cyclase within smooth muscle cells.53 Similar effort must be directed toward modeling the kinetics, diffusion, and activity of ET-1 and Ang II, as well as key cytokines, growth factors, and MMPs. Moreover, progress is being made in developing tissue-level mathematical models that account for mechanoregulated deposition and degradation of individual structurally important constituents within the arterial wall, their contributions to overall structural integrity, and associated reaction-diffusion models for the nonstructurally significant substances that influence cell and matrix turnover,1,20 which can exploit the increased understanding at the molecular level. Much remains to be accomplished, however, before such models can provide reliable descriptive and predictive capability; thus, there is a need for increased effort in this direction.

**Perspectives**

Since the mid-1970s, myriad experiments have demonstrated a mechanical homeostasis across multiple length and time scales in the vasculature and, similarly, the ubiquitous role of cell-mediated mechanoregulation of structure and function in nearly all aspects of vascular health and disease. Nevertheless, there is a need for additional experiments that provide data sufficient to quantify mechanical dose-response curves and that explore potentially competitive or synergistic effects by multiple cell types exposed simultaneously to changes in multiple components of stress or strain; there is also a need for mathematical models that can help integrate information from molecular, cellular, and tissue level studies. For example, understanding better the molecular mechanisms of stress-mediated regulation of collagen synthesis and degradation in vasoaltered states promises to suggest new pharmacological interventions to control the altered wall stiffness that causes and is caused by hypertension.

**Acknowledgment**

Professor James E. Moore, Jr, provided important suggestions on portions of this work.

**Sources of Funding**

This work was supported, in part, by National Institutes of Health grants HL-64372 and HL-80415.

**Disclosures**

None.

**References**

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Hypertension. 2008;52:195-200; originally published online June 9, 2008;
doi: 10.1161/HYPERTENSIONAHA.107.103440
Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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