Primary essential hypertension is second only to diabetic nephropathy as an etiology for end-stage renal disease. In addition, coexistent/superimposed hypertension plays a major role in the progression of most forms of chronic kidney disease (CKD), including diabetic nephropathy. Nevertheless, the individual risk is very low, with <1% of the hypertensive population developing end-stage renal disease. Such data indicate that there must be mechanisms that normally protect the kidneys from hypertensive injury of a severity sufficient to result in end-stage renal disease. The following Brief Review summarizes the evidence that indicates that the renal autoregulatory response, primarily mediated by the myogenic mechanism, is largely responsible for such protection. Moreover, the differing patterns of renal damage that are observed in clinical and experimental hypertension are best explained when considered in the context of alterations in the renal autoregulatory capacity. Recent data also indicate that hypertensive renal damage correlates most strongly with systolic blood pressure (BP). Accordingly, the review further emphasizes the kinetic characteristics of the renal myogenic response to oscillating BP signals that render it particularly capable of providing protection against systolic pressures.

Patterns of Hypertensive Renal Damage

Most individuals with primary hypertension develop the modest vascular pathology of benign nephrosclerosis. The glomeruli are largely spared, and, therefore, proteinuria is not a prominent feature. Because it progresses fairly slowly with limited ischemic nephron loss, renal function is not seriously compromised, except in some genetically susceptible individuals or groups, such as blacks, in whom a more accelerated course may be seen. Thus, the slope of the relationship between renal damage and BP through most of the hypertensive range is fairly flat in individuals with benign nephrosclerosis. However, if the hypertension becomes very severe and exceeds a critical threshold, severe acute disruptive injury of malignant nephrosclerosis to the renal arteries and arterioles develops that often extends into the glomeruli. Many glomeruli show evidence of ischemia from more upstream vascular injury, but lesions of focal and segmental glomerulosclerosis (GS) are uncommon. Proteinuria, hematuria and renal failure develop rapidly. By contrast, patients with pre-existent diabetic and nondiabetic proteinuric CKD exhibit a markedly enhanced susceptibility to renal damage with even moderate BP elevations. Moreover, in contrast to the predominantly vascular pathology in patients with benign or malignant nephrosclerosis, the dominant lesion associated with the progressive proteinuric CKD is that of GS, suggesting a somewhat different pathogenesis of hypertensive injury in such patients.

Renal Autoregulatory Capacity and Hypertensive Renal Damage

The concept supporting the protective importance of renal autoregulatory capacity is based on the proposition that, for a given vascular segment to be injured by hypertension, it has to be exposed to it. Normally, increases in BP, episodic or sustained, result in proportionate increases in renal vascular resistance such that renal blood flow (RBF) is unchanged. Because these resistance changes are confined to the preglomerular resistance vessels, primarily the afferent arteriole, glomerular capillary pressures are also maintained relatively constant. Thus, the glomerular capillaries are protected from barotrauma as long as the autoregulatory mechanisms are intact and the BP remains within the autoregulatory range, as is the case in the vast majority of patients with primary essential hypertension. As would be expected, remodeling changes are seen in the resistance vessels exposed to the increased pressures, and over time benign nephrosclerosis develops. However, when the BP exceeds the threshold for vascular injury, acute malignant nephrosclerosis ensues, and the autoregulatory ability of the preglomerular vasculature to protect the glomerular capillaries is breached.
remnant kidney model, in which severe (susceptibility to hypertensive renal injury is seen in the mission from Reference 4).

uninephrectomy; and in the 5/6 renal ablation model of CKD mass; with vasodilation but preserved autoregulation, eg, after RBF after step changes in BP) in normal rats with intact renal autoregulatory impairment.2–4,10 Thus, a marked increase in GS, the steepness of which is proportionate to the severity of pressure manifests as a reduced BP threshold for even modest increases in systemic BP are expected to be transmitted to the glomerular capillaries. The increased transmission of pressure manifests as a reduced BP threshold for glomerular injury and a linear relationship between BP and GS, the steepness of which is proportionate to the severity of autoregulatory impairment.2–4,10 Thus, a marked increase in susceptibility to hypertensive renal injury is seen in the remnant kidney model, in which severe (>75%) renal mass reduction results in impaired autoregulation but only a modest increase in susceptibility is seen upon uninephrectomy; as in the latter case, autoregulation is preserved, despite the associated vasodilation (Figure 2).2–4,10,13,14,17,18

By contrast, if renal autoregulatory ability is impaired, even modest increases in systemic BP are expected to be transmitted to the glomerular capillaries. The increased transmission of pressure manifests as a reduced BP threshold for glomerular injury and a linear relationship between BP and GS, the steepness of which is proportionate to the severity of autoregulatory impairment.2–4,10 Thus, a marked increase in susceptibility to hypertensive renal injury is seen in the remnant kidney model, in which severe (>75%) renal mass reduction results in impaired autoregulation but only a modest increase in susceptibility is seen upon uninephrectomy; as in the latter case, autoregulation is preserved, despite the associated vasodilation (Figure 2).2–4,10,13,14,17,18

Figure 1. Relationship between renal injury and systolic BP in rat models with intact autoregulation (normotensive Sprague-Dawley [SAD; circles]; spontaneously hypertensive rat [SHR; triangles]; SHRsp [diamonds]; SHR [gray triangles]; and SHRsp [gray diamonds] placed on increased dietary salt intake) and in the 5/6 remnant kidney model (squares), with impaired autoregulation. The renal damage score represents a composite of vascular and glomerular damage scores in the SHRsp and percentage of GS in the 5/6 ablation model. Patterns of injury parallel that of renal autoregulation. The remnant kidney exhibits impaired autoregulation and exhibits a much lower BP threshold for hypertensive injury than SHR and SHRsp kidneys. (Reprinted with permission from Reference 13 with data reproduced with permission from References 10 and 11).

Figure 2. Renal autoregulatory response patterns (steady-state RBF after step changes in BP) in normal rats with intact renal mass; with vasodilation but preserved autoregulation, eg, after uninephrectomy; and in the 5/6 renal ablation model of CKD (vasodilation and impaired autoregulation). (Reprinted with permission from Reference 4).

Figure 3. Quantitative relationships between BP and GS in rats with 5/6 renal ablation that had been left untreated or had received dihydropyridine (DHP) CCBs for 7 weeks (data from References 23 to 25). For comparison, data are also shown for rats with 5/6 ablation who had been similarly treated with renin-angiotensin systems (RAS) blockade with either the angiotensin-converting enzyme inhibitor benazepril or the angiotensin II type 1 receptor blocker losartan. The doses of benazepril used were 25, 50, or 100 mg/L and of losartan were 50, 120, or 180 mg/L of drinking water (data from Reference 27). Note the significant adverse effects of the DHP CCBs as compared with untreated and RAS blockade–treated rats on the slope of the relationship between average systolic BP and percentage of GS (increase in percentage of GS per millimeter of mercury increase in systolic BP; reprinted with permission from Reference 4).

susceptibility to hypertensive renal injury is also observed in genetic and other models exhibiting impaired renal autoregulation.13,16,19–22 In the absence of hypertension severe enough to cause necrotizing vascular glomerular injury, the predominant lesion seen in these models is that of GS, suggesting that it may be the consequence of more chronic and moderate glomerular capillary hypertension. Further support for the concept of autoregulatory capacity as a major determinant of the glomerular susceptibility to hypertensive injury is provided by the effects of dihydropyridine calcium channel blockers (CCBs) in the 5/6 ablation model of CKD.23–25 Given the critical dependence of myogenic responses on calcium entry through voltage-gated calcium channels, these agents, not unexpectedly, further impair the already impaired renal autoregulation in the 5/6 ablation model.13,23–26 Predictably, CCBs also further reduce the BP threshold and increase the slope of the relationship between GS and BP (percentage of increase in GS per millimeter of mercury in BP) such that greater GS is observed at any given BP elevation as compared with untreated rats, and protection is not achieved without achieving normotension (Figure 3).2–4,23–25,27 Conversely, if preglomerular vasodilation and autoregulatory impairment are prevented in this model through the substitution of a low-protein diet GS is also ameliorated despite continued hypertension.17,28 However, if CCBs are given to the low-protein, diet-fed rats, renal
autoregulation is impaired, and the protection against GS is also abolished.28 Similar adverse effects of dihydropyridine CCBs and/or protective effects of a low-protein diet on GS have also been noted in other proteinuric models, including the streptozotocin-induced diabetes model.29,30 That these adverse effects of CCBs on glomerular capillary injury are attributable to their effects on renal autoregulation and are not nonspecific is indicated by the fact that CCBs are very effective in situations where the target site for hypertensive injury is the larger vessels, eg, in malignant nephrosclerosis or in clinical cardiovascular end point trials.6,31

It should be noted that autoregulation is not instantaneous, and autoregulatory capacity in the studies discussed above was assessed by the steady-state RBF responses to “step” changes in BP (Figure 2). Although these data clearly show that an impairment of the steady-state magnitude of these responses to somewhat artificial step changes in BP is associated with an enhanced susceptibility to hypertensive renal damage, BP in vivo fluctuates continuously at multiple frequencies.13–16,26,32–35 The mechanics by which the renal autoregulatory mechanisms are able to provide protection against the more rapid fluctuations, eg, those attributed to the heart rate, are considered in the discussion that follows.

Mechanisms Underlying Renal Autoregulation

The phenomenon of renal autoregulation is believed to be mediated by the combined and interacting contributions of 2 mechanisms, a faster myogenic and a slower tubuloglomerular feedback (TGF) system.13–16,35 Recently, additional and even slower mechanisms have been postulated.13 Although the myogenic and TGF mechanisms are thought to act in concert to both insulate the renal excretory functions from BP fluctuations below the heartbeat frequency, there is very little evidence that they are the primary mechanism responsible for mediating the protective function. This evidence, which has been reviewed in detail elsewhere,13,32–34 is briefly summarized here.

BP Lability and the Requirements of Protection Against Hypertensive Injury

If hypertensive injury is considered to be a consequence of an excess energy delivered to the target organ vasculature from continuously oscillating pressures, an examination of the BP fluctuations and to concurrently provide protection against the more rapid fluctuations, eg, those attributed to the heart rate, are considered in the discussion that follows.

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BP Lability and the Requirements of Protection Against Hypertensive Injury

If hypertensive injury is considered to be a consequence of an excess energy delivered to the target organ vasculature from continuously oscillating pressures, an examination of the BP power (energy per unit of time) and its frequency distribution provides clues to the requirements for effective protection against hypertensive injury (Figure 4).13,14,32–34 Although a 1/frequency relationship is observed for the slower BP fluctuations below the heartbeat frequency, there is very substantial BP power at the heartbeat frequency itself (6 Hz in the rat). This is consistent with the recent findings that suggest that the systolic (peak) BP is the most damaging component of the BP load, because elevations in the systolic BP have been found to exhibit the closest correlation with hypertensive target organ injury, including renal damage.6–8,13,32–34 Figure 4 also shows the frequency range over which the myogenic and TGF mechanisms can attenuate pressure-induced changes in RBF.13–16,26,32–35 TGF is relatively slow and can contribute to stabilization of RBF over frequencies that are not above the myogenic operating range, which is beyond the myogenic operating range (Figure 5). (Reprinted with permission from Reference 13).

Recent observations obtained using the in vitro perfused hydronephrotic rat kidney preparation have provided an explanation by showing that, when exposed to pressure oscillations presented at the heart rate (6 Hz), the afferent arteriole does not behave passively but rather responds with a sustained vasoconstriction13,32–34 (Figure 5A). Moreover, as also shown in Figure 5, when the peak and nadir pressures are varied independently, only the peak signal corresponding to the systolic pressure determined the response tone. Thus, the afferent arteriole constricts when the systolic signal is increased even if mean pressure is unaltered (Figure 5B). Moreover, when a submaximal level of myogenic tone is
established by an elevated peak pressure, reductions in the diastolic and mean pressures have no effect on the level of myogenic tone (Figure 5C). Essentially, an identical response is seen when an oscillating BP signal rather than step changes is used for the input (Figure 5D). Such vasoconstrictive increases in prevalent tone in response to increases in systolic (peak) pressure in vivo would be expected to limit the downstream transmission of not only systolic pressure but also of pressure fluctuations at all of the other slower frequencies.13,14,32–34

Unfortunately, technical limitations have precluded a direct demonstration of similar characteristics of the autoregulatory responses in vivo thus far. However, mathematical modeling combined with the observations in the hydronephrotic kidney preparation have provided insights into the characteristics of the afferent arteriolar myogenic response, which allow it to respond exclusively to the peak pressure.36 These features are dependent on the differences in the kinetics of the pressure-induced vasoconstriction and vasodilatation response and are illustrated in Figure 6A. Critical to this response are the unusually short delay in the onset of the vasoconstriction of 200 to 300 milliseconds and the much longer delay in the onset of relaxation (≈1 second) after a pressure change. Moreover, once initiated, both vasoconstriction and/or vasorelaxation events proceed during these delay periods (Figure 6B). Although recent data obtained by Just and Arendhorst37 indicate that the difference in delays between constriction and relaxation in vivo are much smaller than in the hydronephrotic kidney preparation (≈140 rather than ≈700 milliseconds), primarily because of a shorter delay in relaxation, they are nevertheless still consistent with the systolic BP acting as the primary determinant of the myogenic response in vivo.36 Such modeling considerations, however, also indicate that pathophysiologic processes that

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**Figure 5.** Data illustrating the afferent arteriolar responses in the rat hydronephrotic rat kidney preparation to pressure inputs using high-speed video analysis. Note, all of the pressures are measured within the renal artery. A, A tracing illustrating the sustained afferent arteriolar vasoconstriction elicited by pressure oscillations presented at the rat heart rate (6 Hz). B, Afferent arteriole responds to increase in peak pressure signal (systolic) even when mean perfusion pressure is maintained at a constant (n=10). C, Myogenic tone established by submaximal increase in systolic (peak) pressure signal is not altered when mean pressure is reduced by marked reductions in the nadir (diastolic) pressure (n=7). D, Tracing illustrating the afferent arteriolar response to changes in the oscillating pressure signal. Note that the modest increase in systolic BP evokes vasoconstriction although mean pressure is reduced. (Reprinted with permission from References 13 and 32).
may alter the kinetics of the myogenic response, even in the absence of a clear impairment of steady-state autoregulatory responses, could result in an increased transmission of the systolic pressure transients to glomerular capillaries and contribute to an enhanced susceptibility to hypertension-induced renal damage. However, such has also not yet been experimentally validated.

Figure 7 summarizes these concepts in a working model of the interactions between the various mechanisms that serve to integrate the protective and regulatory functions of the renal vasculature. The model proposes that effective protection is achieved because the afferent arteriolar myogenic response is able to sense and respond to changes in systolic BP by setting the ambient preglomerular tone. This limits the downstream transmission of the oscillating pressures at all frequencies, including the systolic BP, and provides an explanation as to how a myogenic mechanism operating at 0.3 Hz can nevertheless protect the renal microcirculation from more rapidly oscillating systolic BP. Because under most circumstances changes in systolic BP are paralleled by changes in mean BP, concurrent autoregulation of RBF and GFR also occurs. In addition, the absolute ambient preglomerular tone may need further modulation to achieve a regulation of RBF, GFR, and volume status that is appropriate to the needs of the animal. This likely occurs through an alteration of TGF, sympathetic activity, and vasoactive mediators, as indicated. Given that renal autoregulatory impairment, both clinically and experimentally, primarily manifests itself as an enhanced susceptibility to hypertensive renal injury and not in volume dysregulation, there are probably additional redundant and as yet

Figure 6. A. Illustration of the kinetic features of the afferent arteriolar myogenic response in the hydronephrotic kidney preparation to a step change in pressure. Note the very short “delay” in onset of vasoconstriction (200 to 300 milliseconds) and a much longer delay in onset of relaxation (~1 second). B, The afferent arteriolar vasoconstriction response to a 50-millisecond pressure pulse. Note that, once initiated, events proceed during these delay periods.
incidentally defined compensatory mechanisms for regulating renal function and volume status in states of impaired autoregulation.

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None.

References

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