Major pathways of the reno–cardiovascular link: the sympathetic and renin–angiotensin systems

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Chronic kidney disease is often characterized by enhanced activity of the renin–angiotensin system (RAS) and the sympathetic nervous system. Independent of their effect on blood pressure, these systems also contribute to the pathogenesis of both structural and functional cardiovascular abnormalities and contribute importantly to clinical outcome. There is much evidence that the diseased kidneys are of central importance in the pathogenesis of both abnormalities. Inhibitors of the RAS also reduce sympathetic overactivity. Future research should be aimed at addressing the pathophysiological mechanisms causing the enhanced activities. Given the fact that even a small kidney lesion can cause enhanced activity of the RAS and the sympathetic nervous system, it is likely that these pathophysiological mechanisms are operational in more disease conditions, including essential hypertension, heart failure, and obesity/metabolic syndrome.

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Both the renin–angiotensin system (RAS) and the sympathetic nervous system are often activated in chronic kidney disease (CKD). Independent of their effect on blood pressure, these systems also contribute to the pathophysiology of both structural and functional cardiovascular (CV) abnormalities and contribute significantly to clinical outcome. There is conclusive evidence that these systems do not operate independently, but interact throughout the CV system.

In multiple species, including humans, kidney ischemia leads to renin secretion. Inappropriate renin secretion in relation to the state of sodium-volume balance has long been recognized. Kidney ischemia is the central mechanism of stimulation of the RAS and leads to high sympathetic nerve activity (review by Siddiqi *et al.*[1]). In humans, intravenous infusion of angiotensin II (AngII) stimulates muscle sympathetic nerve activity (MSNA), which is the centrally originated sympathetic outflow toward resistance vasculature. Even a small locus of injury in one kidney, caused by intrarenal injection of phenol, which does not affect glomerular filtration rate, leads to hypertension in association with increased central sympathetic activity.[2] Renal denervation or unilateral nephrectomy results in a reduction or total prevention of hypertension.[2] Long-term low-dose AngII infusion in rats produces a gradual increase in blood pressure, which was partially prevented by kidney denervation. Using the kidney transplantation model, very convincing evidence is presented that kidney AngII receptors are of crucial importance in the pathogenesis of AngII-mediated hypertension and organ

damage. Experimental studies suggest that AngII can act on different sites, that is, in the kidney, in the central nervous system, and on peripheral sites, enhancing noradrenaline release from sympathetic nerve terminals. Whether the effects of kidney injury on sympathetic nerve activity at the kidney level are direct or mediated by AngII is unclear. Further, increased sympathetic activity enhances the renin system. Therefore, there may be a reciprocal potentiation. Thus, kidney injury, which is generally characterized by an increased activity of the RAS, can lead to high sympathetic nerve activity, hypertension, and organ damage. Renal innervation has a crucial role, because all these abnormalities are largely prevented by destruction of the renal nerves, at least in experimental settings (review by Siddiqi *et al.*[1]).

CLINICAL EVIDENCE OF SYMPATHETIC HYPERACTIVITY IN CKD

In CKD patients, there is the parallel activation of the renin and the sympathetic system.[1] Further, in normal subjects and in CKD patients, both systems show parallel shifts, with changes in fluid status.[3] These findings are very compatible with the idea of a cause and effect relationship or a common origin. Bilateral nephrectomy in CKD patients results in MSNA levels comparable to normal, whereas unilateral nephrectomy in healthy persons for transplantation purposes does not result in change in MSNA.[3] In CKD patients not on dialysis, with a creatinine clearance ranging from 10 to 100 ml/min, and in healthy controls, sympathetic activity increases with age, both in controls and in patients; however, for any age, sympathetic activity in patients is higher than in controls. In hemodialysis patients, MSNA is even higher.[4]

In sum, there seem to be (at least) two types of sympathetic activity: a kind of 'baseline activity', present in healthy controls, which exits also in bilaterally nephrectomized patients when variables of the RAS are undetectable, and an additional type, which is generated in diseased kidneys. This last type closely correlates with the activation of the RAS. The pathophysiological mechanisms are discussed in more detail elsewhere.[5,6]

CLINICAL RELEVANCE

There is vast experimental evidence linking sympathetic activity to CV organ damage. In humans as well, there is direct evidence to suggest that this is the case. For instance, sympathetic activity correlated with blood pressure.[1] Much more importantly, it has been shown that sympathetic activity is associated with CV organ damage and outcome. There are a number of studies showing the relationship between sympathetic activity and left ventricular mass (review by Siddiqi *et al.*[1] and Mancia *et al.*[7]). Such a relationship is also established in CKD patients.[8] More recently, it was reported in CKD patients not on dialysis that left ventricular mass (quantified by magnetic resonance imaging) is greater than in controls.[9] Importantly, sympathetic activity quantified by MSNA correlated closely with left ventricular mass, despite the fact that blood pressure was reasonably well controlled and all patients were on a RAS inhibitor. In fact, MSNA appears to be a predictor for left ventricular mass independently of blood pressure and other relevant factors. In hemodialysis patients, the relationship between plasma noradrenaline and all-cause mortality and CV morbidity and mortality was established a few years ago.[10] Recently, this relationship was also reported in predialysis patients.[11] Several data sets suggest that sympathetic activity is also involved in kidney failure progression (review by Joles and Koomans[6]). Thus, to summarize, there is substantial evidence that sympathetic activity contributes at several levels to the development of CV organ damage.

TREATMENT

With these pathophysiological mechanisms in mind, it seems logical to hypothesize that angiotensin-converting enzyme inhibition reduces this sympathetic hyperactivity. Indeed, more than a decade ago it was shown that enalapril reduced MSNA in CKD patients.[12] Importantly, use of amlodipine, although an effective antihypertensive, resulted in an increase in MSNA.[12] The study showed that, by inhibiting RAS, sympathetic activity was reduced. Over the past few years, in a set of studies in CKD patients, the effect of different agents was evaluated, including enalapril, losartan, eprosartan, and aliskiren. The effects of the tested agents in the dosage used in these studies did not differ much. During these treatments, MSNA is reduced but not fully normalized.[4,9,12–14] These results indicate that additional treatment might be beneficial. Moxonidine, which is a centrally acting sympatholytic agent, added to the chronic treatment with eprosartan, resulted in a further decrease in blood pressure and MNSA.[13] This was confirmed in dialysis patients in a recent study.[15]

The fact that additional sympathetic blockade indeed improves prognosis was shown a few years ago. In dialysis patients with impaired cardiac function treated with usual medication including RAS inhibitor, addition of carvedilol improved clinical outcome.[16] Therefore, these data suggest that we have a strong rationale to block sympathetic activity and that addition of a sympatholytic agent to RAS inhibitor treatment might be beneficial in selected patient groups.

More frequent dialysis is associated with better blood pressure control. A switch from 3 times weekly hemodialysis to 6 times weekly hemodialysis is associated with a decrease in sympathetic activity, no change in cardiac output, and therefore a decrease in peripheral vascular resistance.[17] It is tempting to speculate about the mechanisms of these effects; apparently, the balance between sympatho-inhibiting and stimulating factors changed substantially.

FUTURE PERSPECTIVES

An almost unexplored idea is that there is not only an enhanced sympathetic activity but also an insufficient activity of the 'counter balance' system, that is, the parasympathetic system. Unfortunately, this concept is difficult to study in humans.

If we accept the basic idea on the pathogenesis, that is, that the diseased kidneys are the primary source of stimulation of