Abstract

We performed experiments to test the hypothesis that endogenous adenosine acts as an essential cofactor required for eliciting angiotensin II (Ang II)–induced afferent and/or efferent arteriolar vasoconstriction. Enalaprilat (2 mg IV) was administered to anesthetized rats to reduce endogenous Ang II levels. Kidneys and blood were harvested from these animals and used for study of renal microvascular function using the in vitro blood-perfused juxtamedullary nephron technique. Arteriolar inside diameter was monitored videomicroscopically in (1) normal kidneys, (2) kidneys subjected to adenosine receptor blockade (100 μmol/L 1,3-dipropyl-8-p-sulfophenylxanthine), and (3) kidneys continuously exposed to 1 μmol/L adenosine. Under resting conditions, arteriolar diameters were similar in all three groups of kidneys, averaging 24.8±1.0 μm (n=23) in afferent arterioles and 24.0±0.9 μm (n=16) in efferent arterioles. In normal kidneys, adenosine (10 μmol/L) decreased both afferent (10.2±2.0%) and efferent (6.5±0.8%) diameters, an effect that was absent in kidneys subjected to adenosine receptor blockade. Ang II (10 pmol/L to 100 nmol/L) elicited dose-dependent vasoconstriction of both vascular segments in normal kidneys. At a concentration of 100 nmol/L, Ang II decreased afferent diameter by 36.8±8.5% and efferent diameter by 30.8±9.6%. Neither afferent nor efferent arteriolar Ang II dose-response relations were significantly different in kidneys treated with low-dose adenosine or the adenosine receptor blocker. These observations refute the hypothesis that a receptor-mediated action of adenosine is required for Ang II–induced constriction of juxtamedullary afferent or efferent arterioles. Furthermore, subconstrictor adenosine levels do not potentiate renal arteriolar vasoconstrictor responses to Ang II.

Methods

All experiments used the in vitro blood-perfused juxtamedullary nephron technique to provide direct access to afferent and efferent arterioles of the rat kidney and were performed in accordance with the guidelines of the Advisory Committee.
for Animal Resources of Tulane University School of Medicine. Male Sprague-Dawley rats weighing 350 to 410 g were anesthetized with pentobarbital sodium (40 mg/kg IP). Thirty minutes after enalaprilat (2 mg IV) administration, tissue was harvested for use in in vitro experiments. Kidney Ang II levels measured by radioimmunoassay are reduced by 60% and Ang II levels in the perfusate are undetectable in tissue pretreated with enalaprilat (unpublished observations).

Kidney donor rats were subjected to the following procedure: After enalaprilat administration, a cannula was introduced into the aortic mesenteric artery and advanced into the right renal artery, thus initiating perfusion of the right kidney with Tyrode's solution (pH 7.40) containing 773 μmol/L (51 g/L) bovine serum albumin. The Tyrode's perfusate was replaced with a perfusate containing 152 μmol/L (10 g/L) bovine serum albumin. Perfusate and bathing solutions were prepared fresh daily. Stock solutions of Ang II (100 μmol/L) and adenosine (1 mmol/L) were stored in aliquots at -70°C and diluted, as necessary, with standard Tyrode's superfusate solution on the day of the experiment. PSPX was purchased from Research Biochemicals, Natick, Mass. Enalaprilat was provided by Merck Sharp & Dohme Research Laboratories, Rahway, N.J. All other chemicals were purchased from Sigma Chemical Co, St Louis, Mo.

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The Tyrode's perfusate was replaced with a perfusate derived from homologous blood obtained by exsanguination of enalaprilat-treated, acutely nephrectomized rats. The blood was collected into a syringe containing 3000 U heparin, centrifuged at 4°C, and plasma and erythrocytes were collected separately. Plasma [Ca2+] was measured and adjusted to 1.0 to 1.2 mmol/L. The plasma was passed sequentially through a 5-μm nylon mesh before entering the double-barreled perfusion cannula and the renal vasculature. Pressure in the reservoir was adjusted to maintain a renal arterial pressure (measured at the tip of the perfusion cannula) of 110 mm Hg. The inner cortical surface of the kidney was continuously superfused with warmed (37°C) Tyrode's solution containing 152 μmol/L (10 g/L) bovine serum albumin. The organ chamber was positioned on the stage of a Nikon Optiphot microscope equipped with a water-immersion objective (Zeiss, x40, 0.75 NA). The renal tissue was transilluminated with light from a halogen lamp. Images were transmitted via a Newivcon camera (Dage-MTI, Michigan City, Ind) through a time-date generator (Panasonic, Secaucus, NJ) and an image-enhancing processor (MFJ Enterprises, Starkville, Miss) and displayed at x1340 on a high-resolution video monitor (Conrac Display Systems, Covina, Calif). The video signal was simultaneously recorded on videotape using a SuperVHS format VCR (Panasonic). A single vessel was chosen for study in each kidney, based on rapid flow of erythrocytes and clear visualization of the inside edges of the arteriolar wall. Afferent arteriolar diameter was measured at sites greater than 50 μm upstream from the glomerulus, and efferent arteriolar measurement sites were less than 100 μm downstream from the point where the vessel emerges from the glomerular tuft. Three randomly designated groups of kidneys were studied: normal, adenosine receptor blockade, and elevated adenosine concentration. The experimental protocol consisted of consecutive 5-minute treatment periods, during which images of a single afferent or efferent arteriole were continuously recorded on videotape. In the normal kidneys, each arteriole was subjected to an initial adenosine challenge (10 μmol/L), followed by recovery from the adenosine exposure. Thereafter, vessels were exposed to increasing concentrations of Ang II (10 and 100 pmol/L and 1, 10, and 100 nmol/L) via the superfusate bathing solution. Kidneys in the adenosine receptor blockade group were subjected to an identical treatment regimen, except all superfusate bathing solutions contained 1,3-dipropyl-8-p-sulfophenylxanthine (PSPX, 100 μmol/L), an adenosine A1,A2 receptor blocker.16 All superfusate solutions in the elevated adenosine concentration group contained 1 μmol/L adenosine. Afferent and efferent arteriolar diameters were not subjected to the 10-μmol/L adenosine challenge, but the Ang II treatment regimen was identical to that imposed on normal and adenosine receptor blockade kidneys.

Perfusate and bathing solutions were prepared fresh daily. Stock solutions of Ang II (100 μmol/L) and adenosine (1 mmol/L) were stored in aliquots at -70°C and diluted, as necessary, with standard Tyrode's superfusate solution on the day of the experiment. The average diameter during the final 2 minutes of each 5-minute treatment period was used for statistical analysis. Statistical differences were determined by analysis of variance for repeated measures and least significant difference comparison using the PC ANOVA statistical package (Human Systems Dynamics, Northridge, Calif). Comparisons between groups used the unpaired t test. A value of P<.05 was considered significant. Data are presented as mean±SEM.

Results

In normal kidneys, inside diameters of juxtamedullary afferent and efferent arterioles averaged 27.6±2.0 (n=6) and 24.8±1.2 (n=5) μm, respectively. Adenosine (10 μmol/L) reduced afferent arteriolar diameter to 24.8±2.0 μm, and efferent diameter decreased to 23.2±1.2 μm (Fig 1). The vasoconstrictor effect of adenosine was statistically significant in each arteriolar type and did not differ significantly between afferent and efferent arterioles. Removal of adenosine from the superfusate bathing solution allowed complete recovery of afferent diameter to 27.5±2.0 μm, whereas efferent diameter was restored to 24.7±1.2 μm. Thus, 10 μmol/L adenosine evoked a reversible vasoconstriction of both afferent and efferent arterioles of juxtamedullary nephrons in normal kidneys.

In PSPX-treated kidneys, afferent arteriolar diameter averaged 23.3±1.5 μm (n=8) and efferent diameter was 25.4±1.8 μm (n=5). These values did not differ significantly from arteriolar diameters in normal kidneys (ie, in the absence of PSPX). In contrast with the behavior of normal kidneys, adenosine failed to alter arteriolar diameters significantly in PSPX-treated kidneys (Fig 1). Afferent arteriolar diameter in PSPX-treated kidneys was 23.3±1.5 μm during exposure to 10 μmol/L adenosine, whereas efferent diameter averaged 25.3±1.8 μm. Thus, treatment of the in vitro blood-perfused juxtamedullary nephron microvasculature with 100
μmol/L PSPX provided complete abolition of both the afferent and efferent arteriolar vasoconstriction evoked by exogenous adenosine.

In kidneys subjected to continuous adenosine exposure, afferent and efferent arteriolar diameters averaged 25.0±1.5 (n=9) and 21.5±1.5 (n=6) μm, respectively, before adenosine exposure. After addition of 1 μmol/L adenosine to the bathing solution, afferent diameter was 24.3±1.5 μm and efferent diameter was 22.2±1.5 μm. These values did not differ significantly from arteriolar diameters before exposure to adenosine, in accord with our previous observation that 10 μmol/L adenosine is required to evoke a significant change in afferent arteriolar diameter.17 Furthermore, arteriolar diameters in tissue exposed to 1 μmol/L adenosine did not differ from PSPX-treated vessels. Thus, baseline arteriolar diameters were similar in all three treatment groups.

Responses of afferent arterioles to Ang II are depicted in Fig 2 (top). In normal kidneys, Ang II evoked dose-related decreases in afferent arteriolar inside diameter from 27.5±2.0 μm to values averaging 27.4±2.0 (10 pmol/L), 26.5±2.0 (100 pmol/L), 25.2±2.0 (1 nmol/L), 22.3±2.4 (10 nmol/L), and 17.1±2.5 (100 nmol/L) μm. In the adenosine receptor blockade group, Ang II decreased afferent diameter from 23.3±1.5 μm to 22.7±1.4 (10 pmol/L), 22.1±1.3 (100 pmol/L), 21.5±1.3 (1 nmol/L), 18.5±1.5 (10 nmol/L), and 14.3±2.1 (100 nmol/L) μm. Thus, adenosine receptor blockade with 100 μmol/L PSPX failed to elicit any discernible shift in the concentration-related afferent arteriolar vasoconstrictor response to Ang II. In kidneys exposed continuously to 1 μmol/L adenosine, Ang II caused similar concentration-related decreases in afferent arteriolar diameter, from 24.3±1.5 μm to values averaging 23.5±1.4 (10 pmol/L), 22.7±1.6 (100 pmol/L), 21.6±1.8 (1 nmol/L), 19.6±1.8 (10 nmol/L), and 18.4±1.7 (100 nmol/L) μm. None of these values differed significantly from those observed in normal or PSPX-treated afferent arterioles at a given Ang II concentration.

Fig 2 (bottom) illustrates the effects of Ang II on efferent arterioles. In normal kidneys, Ang II induced concentration-related efferent arteriolar vasoconstriction that was quantitatively similar to that observed in afferent arterioles. Ang II reduced efferent arteriolar inside diameter from 24.7±1.2 μm to 24.1±1.2 (10 pmol/L), 23.3±1.2 (100 pmol/L), 22.8±1.3 (1 nmol/L), 20.8±2.1 (10 nmol/L), and 17.3±2.8 (100 nmol/L) μm. In PSPX-treated kidneys, angiotensin evoked similar concentration-related efferent vasoconstriction. Efferent diameter was decreased from 25.3±1.7 μm to 24.9±1.7 (10 pmol/L), 24.7±1.7 (100 pmol/L), 23.9±1.8 (1 nmol/L), 20.8±1.8 (10 nmol/L), and 19.9±2.0 (100 nmol/L) μm in PSPX-treated kidneys. Thus, there was no statistically significant effect of PSPX treatment on Ang II-induced efferent arteriolar vasoconstriction. In kidneys exposed to 1 μmol/L adenosine, Ang II reduced efferent diameter from 22.2±1.5 μm to 22.0±1.4 (10 pmol/L), 21.6±1.4 (100 pmol/L), 21.1±1.3 (1 nmol/L), 19.4±1.5 (10 nmol/L), and 18.1±1.3 (100 nmol/L) μm. These efferent arteriolar Ang II responses in adenosine-supplemented tissue did not differ significantly from those observed in normal or PSPX-treated kidneys at any given Ang II concentration.

Discussion

The results of the present study reveal a vasoconstrictor influence of adenosine on both afferent and efferent arterioles of juxtamedullary nephrons. This vasoconstriction was abolished in the presence of the adenosine receptor antagonist PSPX; however, Ang II concentra-
Adenosine and Renal Responses to Angiotensin II


tion-response profiles were not influenced by adenosine receptor blockade or adenosine supplementation. These observations have numerous implications regarding the renal microvascular responses to adenosine and Ang II.

Adenosine interacts with A$_1$ receptors to elicit vasodilation of most vascular beds; however, the kidney$^{18}$ and skin$^{19}$ are distinct in that the vasculature is also endowed with A$_2$ receptors known to evoke vasoconstriction. In the renal vasculature, afferent arterioles are known to be endowed with A$_1$ receptors,$^{12,20-22}$ whereas A$_2$ receptors are thought to mediate vasodilation in efferent arterioles alone$^{23}$ or both afferent and efferent arterioles.$^{12,18,20}$ Reports are available detailing the effects of adenosine and adenosine agonists on the renal microvascular structure of split hydronephrotic kidneys,$^{9,12}$ renal implants into hamster cheek pouch,$^{13}$ and isolated afferent arterioles$^{22;}$ however, all three of these experimental models provide access to renal microvascular structures in settings that preclude the glomerular filtration and tubular transport processes of the nephron.

The present study used the in vitro blood-perfused juxtamedullary nephron technique to allow videometric study of afferent and efferent arteriolar function under conditions that have been documented to allow continued glomerular filtration, proximal tubular reabsorption, and tubuloglomerular feedback.$^{15,23,24}$ In this experimental setting, paired observations have failed to reveal any significant alteration in resting juxtaglomerular afferent arteriolar diameter when exposed to maximally effective concentrations of the A$_1$/A$_2$ receptor antagonist PSPX.$^{25}$ Similarly, group comparisons between resting diameters in normal and PSPX-treated kidneys in the present study failed to provide evidence of any substantial vasoactive influence of endogenous adenosine on arteriolar diameters under our experimental conditions. We previously reported that 2-chloroadenosine evokes concentration-dependent effects on afferent arteriolar diameter,$^{17,25}$ with lower concentrations yielding vasoconstriction (maximum effect at 1 $\mu$mol/L) and higher concentrations (100 $\mu$mol/L) stimulating vasodilation. These observations indicate the presence of both A$_1$ and A$_2$ receptors on juxtaglomerular afferent arterioles. The present data confirm and extend these observations to include evidence that adenosine can evoke efferent arteriolar vasos constriction in the juxtaglomerular nephron microvasculature.

The ability of PSPX to block the response to exogenous adenosine indicates that the vasoconstriction is receptor mediated, presumably reflecting the presence of A$_1$ receptors on both afferent and efferent arterioles. Furthermore, an adenosine concentration that maximally constricts juxtaglomerular afferent arterioles$^{17}$ caused an effenter arteriolar response of similar magnitude, indicating comparable responsiveness of these vessel segments to the vasoconstrictive effects of adenosine. Because substances can potently dilate$^{26}$ or constrict$^{17}$ juxtaglomerular afferent arterioles without accompanying alterations in efferent arteriolar diameter, it is unlikely that the decrease in efferent diameter evoked by adenosine reflects a passive response that occurs secondary to the afferent vasosconstriction. Taken together, these observations are not consistent with previous assertions that A$_1$ receptors, and thus vasconstrictor responses to adenosine, are restricted to the preglomerular vasculature.$^{12}$ Both afferent and efferent arterioles of juxtaglomerular nephrons appear to be endowed with A$_1$ receptors that evoke vasoconstriction in response to adenosine; however, the juxtaglomerular nephron population may differ from superficial nephrons in this regard. Indeed, an internephron heterogeneity in the renal hemodynamic response to adenosine has been suggested by other investigators.$^{22,27}$

At the whole-kidney level, the hemodynamic response to intrarenal arterial adenosine infusion is characterized by a rapid decrease in blood flow, followed by a gradual recovery to control levels. This response is thought to reflect a rapid and sustained preglomerular vasoconstriction and a more slowly developing and superimposed postglomerular vasodilation. In a recent report, the vasodilator component lagged 70 seconds behind the vasoconstriction.$^{28}$ In the present study, the time courses of afferent and efferent vasconstrictor responses to adenosine were similar (data not shown). Responses of both vessel segments displayed a sustained decrease in diameter, with no tendency for recovery to control values during the 5-minute treatment period. Differences in these observations likely arise from the mode of adenosine pretreatment (intravenous versus intrarenal). A transendothelial diffusion barrier to adenosine$^{29}$ and/or an endothelium-dependent component of the response$^{30}$ could underlie a more prominent vasodilator influence of exogenous adenosine when administered intravenously.

The results of the present study, which used topically applied adenosine, may better indicate the influence of adenosine produced endogenously by the transporting epithelium$^{14}$ and its subsequent approach to the vasculature via the interstitial compartment.

In addition to the direct vasoactive influence of adenosine, this substance may interact with Ang II to determine vascular tone. Numerous reports indicate that Ang II levels are important modulators of the renal hemodynamic response to adenosine.$^{3,9,11,14}$ Although some data fail to support this contention,$^{31}$ the ability of adenosine to modulate Ang II–induced vasoconstriction is less well defined. In the mesenteric vasculature, for example, the action of exogenous adenosine can attenuate Ang II–induced vasoconstriction.$^{32}$ In contrast, studies in the kidney have suggested that adenosine may act through A$_1$ receptors to enhance Ang II–induced vasconstriction. This postulate was first raised with regard to the mechanism of postocclusive renal vasosconstriction.$^{11}$ Hall and Granger$^2$ more fully addressed the hypothesis through comparison of the effects of Ang II on glomerular filtration rate in the presence and absence of an intrarenal adenosine infusion. During adenosine infusion, Ang II evoked a reduction in glomerular filtration rate that was not observed in dogs not receiving adenosine. Estimates of preglomerular and postglomerular resistance responses suggested that adenosine altered the glomerular filtration rate response to Ang II by allowing a marked preglomerular vasconstrictor response to the peptide. The effects of Ang II on postglomerular resistance were not influenced by adenosine infusion. Thus, tissue adenosine levels were proposed to exert important functional consequences by determining whether Ang II evokes both preglomerular and postglomerular vasoconstriction or a more prominent efferent arteriolar action. Based on their observations, Hall and Granger$^2$ suggested that high adenosine levels that might accompany malignant hypertension, acute renal failure, or ischemia...
could severely reduce glomerular filtration rate by causing Ang II to constrict preglomerular vessels. More recently, Schnermann and coworkers\(^{10}\) reported data which indicated that endogenously formed adenosine and Ang II acted in a synergistic manner to elicit preglomerular vasoconstriction in the anesthetized rat. This observation led to the hypothesis that coactivation of Ang II and adenosine receptors is required for either agonist to act as a potent afferent arteriolar vasoconstrictor. However, Dietrich and colleagues\(^{5}\) were unable to document an adenosine-dependent component of Ang II–induced vasoconstriction in the hydronephrotic rat kidney, a fact that might reflect the uncertain state of endogenous adenosine production in that experimental setting.

The present studies were performed to address this issue in a setting that provides access to the renal microvasculature while maintaining glomerular and tubular function, thus more closely reflecting the ability of endogenous adenosine to modulate Ang II responsiveness. The in vitro blood-perfused juxtamedullary nephron technique is particularly useful for these studies because both the afferent and efferent arterioles are responsive to exogenous Ang II. Thus, the strategy in determining the role of endogenous adenosine in modulating Ang II responsiveness was to compare Ang II concentration-response profiles in normal tissue and in tissue subjected to pharmacologic blockade of adenosine receptors or supplementation of adenosine levels. If endogenous adenosine acts as a cofactor that is required to elicit Ang II–induced afferent and/or efferent arteriolar vasoconstriction, Ang II–dependent vasoconstriction should be attenuated or abolished during adenosine receptor blockade. In agreement with the data of Dietrich et al\(^{5}\) from the hydronephrotic kidney, the results of the present study indicate that the concentration-dependent Ang II–induced vasoconstriction of both afferent and efferent arterioles is sustained during documented PSPX-induced blockade of adenosine receptors. Because Ang II responses were not influenced by adenosine receptor blockade, these data refute the hypothesis that a receptor-mediated action of endogenous adenosine is required for expression of Ang II–induced constriction of juxtamedullary arterioles. Furthermore, supplementation of endogenous adenosine with a constrictor concentration of exogenous adenosine failed to enhance Ang II responsiveness of either afferent or efferent arterioles. Thus, local adenosine concentrations do not appear to be a potent determinant of vascular responsiveness to Ang II in the juxtamedullary nephron population, although we cannot rule out the possibility that adenosine levels high enough to exert a direct vasoconstrictor influence might interact with Ang II in a more than additive manner. Discrepancies between these observations and previous reports may reflect functional differences between superficial and juxtamedullary nephrons or a heightened influence of endothelium-dependent factors in previous studies that used intravascular administration of adenosine or adenosine analogues.\(^{5,10}\)

In summary, the vasoconstrictor influence of exogenous adenosine on afferent and efferent arterioles and the blockade of these responses by PSPX suggest that adenosine \(A\(_2\)\) receptors are present at both preglomerular and postglomerular sites in rat juxtamedullary nephrons. In accord with our previous observations, resting arteriolar diameters did not differ between normal and PSPX-treated kidneys, indicating that endogenous adenosine levels do not exert a substantial tonic vasoconstrictor influence on the renal microvasculature when studied using the in vitro blood-perfused juxtamedullary nephron technique. Both afferent and efferent arteriolar responses to Ang II were sustained during PSPX blockade of adenosine receptors, thus refuting the hypothesis that a receptor-mediated action of adenosine is required for expression of Ang II–induced constriction of juxtamedullary afferent arterioles. Furthermore, neither arteriolar segment exhibited enhanced Ang II responsiveness in the presence of subconstrictor concentrations of exogenous adenosine. We conclude that the Ang II responsiveness of juxtamedullary afferent and efferent arterioles does not require a receptor-mediated action of adenosine and is not potently modulated by tissue adenosine concentration.

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**References**

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