Effects of Some Guanidino Compounds on Human Cerebral Arteries

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Background and Purpose—Accumulation of endogenous guanidino-substituted analogues of L-arginine in chronic renal failure might contribute to some of the vascular and neurological disorders of this pathology. We tested the hypothesis that in human cerebral arteries, some guanidino compounds may increase vascular tone, through nitric oxide (NO) synthase inhibition, and impair endothelium-dependent relaxation.

Methods—Rings of human middle cerebral artery were obtained during autopsy of 26 patients who had died 3 to 12 hours before. The rings were suspended in organ baths for isometric recording of tension. We then studied the responses to \( \text{N}^2 \)-monomethyl-L-arginine (L-NMMA), \( \text{N}^2,\text{N}^6 \)-dimethyl-L-arginine (asymmetrical dimethylarginine; ADMA), amino- guanidine (AG), and methylguanidine (MG).

Results—L-NMMA (10\(^{-6}\) to 3\(\times\) 10\(^{-4}\) mol/L) and ADMA (10\(^{-6}\) to 3\(\times\) 10\(^{-4}\) mol/L) caused concentration- and endothelium-dependent contractions (median effective concentrations \( [\text{EC}_{50}] = 1.1 \times 10^{-5} \) and 1.6\(\times\) 10\(^{-5}\) mol/L, respectively; \( \text{E}_{\text{max}} = 35.5 \pm 7.9\% \) and 43.9\(\pm\) 5.9\% of the response to 100 mmol/L KCl). AG (10\(^{-5}\) to 3\(\times\) 10\(^{-3}\) mol/L) and MG (10\(^{-5}\) to 3\(\times\) 10\(^{-3}\) mol/L) produced endothelium-independent contractions (\( \text{E}_{\text{max}} = 44.3 \pm 8.8\% \) and 45.7\(\pm\) 5.8\% of the response to 100 mmol/L KCl, respectively). L-Arginine (10\(^{-3}\) mol/L) prevented the contractions by L-NMMA and ADMA but did not change contractions induced by AG and MG. L-NMMA and ADMA inhibited endothelium-dependent relaxation induced by acetylcholine in a concentration-dependent manner; AG and MG were without effect.

Conclusions—The results suggest that the contractions induced by L-NMMA and ADMA are due to inhibition of endothelial NO synthase activity, whereas AG and MG do not affect the synthesis of NO. An increase in the plasma concentration of L-NMMA and ADMA associated with uremia is likely to represent a diminished release or effect of NO, and consequently, an increased cerebrovascular tone in uremic patients is highly conceivable. (Stroke. 1999;30:2206-2211.)

Key Words: cerebral arteries ■ endothelium ■ nitric oxide

Nitric oxide (NO) synthesized from L-arginine accounts for the powerful vasodilator effects of endothelium-derived relaxing factor\(^1\)\(^-\)\(^2\) and consequently plays a decisive role in determining vasomotor tone in several vascular beds, including the cerebral circulation.\(^3\)\(^-\)\(^7\) The synthesis of NO can be specifically and competitively antagonized by arginine analogues such as \( \text{N}^2 \)-monomethyl-L-arginine (L-NMMA).\(^4\)\(^,\)\(^8\) Histochemical studies have demonstrated the presence of NO synthase immunoreactivity in the adventitia of rat and human cerebral arteries.\(^9\)\(^,\)\(^10\) Consistent with these observations, several reports have shown that NO from perivascular nerve endings mediates dilatation in the cerebral arteries through a nonadrenergic, noncholinergic mechanism,\(^11\)\(^-\)\(^13\) whereas NO of endothelial origin can modulate contractile responses of isolated human cerebral arteries to sympathetic stimulation.\(^6\)

Uremia is an established risk factor for cardiovascular disease and cerebrovascular accidents.\(^14\)\(^-\)\(^16\) Patients with end-stage chronic renal failure show an increase in plasma levels of \( \text{N}^2,\text{N}^6 \)-asymmetrical dimethylarginine (ADMA), an endogenous inhibitor of NO synthesis, which might contribute to some of the vascular and neurological disorders of this pathology.\(^17\)\(^,\)\(^18\) Other guanidino-substituted analogues of arginine such as methylguanidine (MG) and L-NMMA also increase in renal failure and have been implicated as uremic toxins.\(^17\)\(^,\)\(^19\)\(^,\)\(^20\) Plasma levels of ADMA are also significantly elevated in a rat model of congestive heart failure,\(^21\) in patients with congestive heart failure,\(^22\) and in graded hemorrhagic shock in the pig.\(^23\) Recent experiments in the rat indicate that increased plasma levels of ADMA may play an important role in the appearance of hypertension in renal failure\(^24\) and in the pathogenesis of salt-sensitive hyperten- sion.\(^25\) Furthermore, these compounds produced dose-dependent inhibition of nitrite production by macrophages...
(J774 cells) and reversed endothelium-dependent relaxation in human saphenous veins. Whether these compounds affect the responsiveness of human cerebral vessels remains to be determined. The purpose of the present study was to evaluate the potency and selectivity of ADMA, L-NMMA, MG, and aminoguanidine (AG) on endothelium-dependent and -independent relaxation of human cerebral arteries. Because continuous release of NO from endothelial cells is an important determinant of the underlying smooth muscle tone in animals and humans, in artery rings under resting tension. In another series of experiments, the contractile effects of guanidino compounds were studied in the presence of L-arginine (10−5 mol/L). To establish the resting tension for maximal force development, a series of preliminary experiments were performed on arteries of similar length and outer diameter that were exposed to L-NMMA or ADMA, AG, and MG (10−5 mol/L). To study the effects of guanidino compounds on relaxation, vessels were precontracted with norepinephrine (10−5 mol/L; n=1 g), and cumulative relaxation curves to either acetylcholine (10−8 to 10−3 mol/L) or sodium nitroprusside (3×10−10 to 10−7 mol/L) were constructed in the absence and presence of L-NMMA, ADMA, AG, or MG (all at 10−3 to 10−5 mol/L). In a separate series of experiments, the effects of guanidino compounds on acetylcholine-induced relaxation were studied in the presence of L-arginine (10−3 mol/L).

**Methods**

Human cerebral arteries were obtained during autopsy of 26 patients (14 men and 12 women, aged 32 to 82 years) who had died 3 to 12 hours before. The cause of death varied: 12 patients had died of myocardial infarction, 10 were victims of thoracic trauma, and 4 had died of respiratory insufficiency. There was no relationship between age or cause of death and the ability of the vessels to develop tension in response to norepinephrine or KCl or to relax in response to acetylcholine and sodium nitroprusside. The arteries were immediately placed in Krebs-Henseleit solution of the following composition (in mmol/L): NaCl 115, KCl 4.6, MgCl2·6H2O 1.2, CaCl2 2.5, NaHCO3 25, glucose 11.1, and disodium EDTA 0.01. Rings (4 mm long, 1 to 2 mm in outside diameter) were cut from branches of the middle cerebral artery. In ~50% of the artery rings, the endothelium was removed mechanically by inserting a roughened stainless steel wire into the lumen and gently rolling the vessel ring on wet filter paper.

Two stainless steel pins, 100 μm in diameter, were introduced through the arterial lumen. One pin was fixed to the organ bath wall while the other was connected to a force-displacement transducer (Grass FT03). Changes in isometric force were recorded on a Macintosh computer by use of CHART version 3.4/S software and a MacLab/8e data acquisition system (AD Instruments). Each artery ring was placed in a 4-mL bath filled with oxygenated (95% O2, 5% CO2) warmed (37°C) Krebs solution in the presence of indomethacin (2×10−6 mol/L). While the other was connected to a force-displacement transducer (Grass FT03), changes in isometric force were recorded on a Macintosh computer by use of CHART version 3.4/S software and a MacLab/8e data acquisition system (AD Instruments). Each artery ring was placed in a 4-mL bath filled with oxygenated (95% O2, 5% CO2) warmed (37°C) Krebs solution in the presence of indomethacin (2×10−6 mol/L). An applied resting tension of 1 g was found to be optimal. The vessels were allowed to attain a steady level of tension during a 2-hour accommodation period before testing. Functional integrity of the endothelium was confirmed by the presence of relaxation induced by acetylcholine (10−6 to 10−4 mol/L) during contraction obtained with norepinephrine (10−7 to 3×10−5 mol/L). To study contraction, concentration-response curves to L-NMMA (10−6 to 3×10−4 mol/L), ADMA (10−5 to 3×10−3 mol/L), or MG (10−5 to 3×10−3 mol/L) were determined in artery rings under resting tension. In another series of experiments, concentration-response curves were determined after evoking tone (~500 mg) with 3×10−5 mol/L norepinephrine. In a separate group of experiments, the contractile effects of guanidino compounds were studied in the presence of L-arginine (10−3 mol/L).

To study the effects of guanidino compounds on relaxation, vessels were precontracted with norepinephrine (10−6 mol/L; n=1 g), and cumulative relaxation curves to either acetylcholine (10−8 to 10−3 mol/L) or sodium nitroprusside (3×10−10 to 10−7 mol/L) were constructed in the absence and presence of L-NMMA, ADMA, AG, or MG (all at 10−3 to 10−5 mol/L). In a separate series of experiments, the effects of guanidino compounds on acetylcholine-induced relaxation were studied in the presence of L-arginine (10−3 mol/L).
L-arginine (n=4). Relaxation is expressed as a percentage of the

were not determined for MG and AG, as their curves did not reach

relaxant response was 87.6% (n=4) (Figure 1) but did not change contractions induced by AG (n=4) and MG (n=4) (Figure 2).

Acetylcholine (10⁻⁸ to 10⁻⁵ mol/L) caused endothelium-dependent relaxations (EC₅₀=1.0×10⁻⁷ mol/L) in arterial rings contracted with norepinephrine (Figure 3). The maximal relaxant response was 87.6±2.5% in arteries with endothelium (n=10) and 10.5±1.5% in arteries without endothelium (n=8). The relaxation induced by acetylcholine was inhibited in a concentration-dependent manner by L-NMMA (10⁻⁵ to 10⁻³ mol/L) and ADMA (10⁻⁵ to 10⁻³ mol/L), with IC₅₀ values of 9.5×10⁻⁶ and 5.4×10⁻⁷ mol/L, respectively (Figure 3). Maximal relaxations evoked by acetylcholine in the presence of L-NMMA (10⁻³ mol/L, n=5) and ADMA (10⁻³ mol/L, n=5) were 41.1±11.1% and 43.8±8.4%, respectively. The inhibitory effects of L-NMMA and ADMA on acetylcholine-induced relaxation were completely prevented in the presence of L-arginine (10⁻³ mol/L). Neither MG (10⁻⁵ to 10⁻³ mol/L, n=4) nor AG (10⁻⁷ to 10⁻⁵ mol/L, n=4) had any effect on the relaxation induced by acetylcholine (Figure 4).

In endothelium-intact and endothelium-denuded rings, sodium nitroprusside (3×10⁻⁶ to 10⁻⁷ mol/L, n=8) induced complete (100%) relaxation of precontracted artery rings, with an EC₅₀ of 5.1×10⁻⁸ mol/L. None of the guanidino compounds (10⁻⁴ mol/L) modified the relaxation curves to sodium nitroprusside (n=4 for each compound; results not shown).

Discussion

The study reported herein was designed to determine whether various guanidino compounds affect the tone of human cerebral arteries and inhibit endothelium-dependent relaxation. Our results demonstrate that L-NMMA and ADMA caused concentration-dependent contractions of cerebral arteries. The contractile effects were endothelium dependent and were reversed by L-arginine, the substrate for the enzyme for NO synthesis. These findings indicate that L-NMMA and ADMA increase the tone of cerebral arteries by inhibiting the basal release of NO from the endothelium. The magnitude of the contractile effects suggests that NO production is particularly important in maintaining basal tone in the relatively large (1 to 2 mm) cerebral vessels used in this study. However, AG and MG produced endothelium-independent contractions and only at high concentrations. L-Arginine (10⁻³ mol/L) did not inhibit the contractions induced by AG and MG, thus indicating that the contractions were not a consequence of inhibition of NO synthesis but rather due to nonspecific interaction with the vascular smooth muscle. This finding is not unexpected, since MG is structurally similar to AG, a compound reported to have a weak inhibitory effect on NO production by the vascular constitutive isof orm of NO synthase.²⁶,³⁰,³¹ Non specific contractions induced by high concentrations of AG and MG have previously been shown in human saphenous vein.²⁶
We also examined the effects of guanidino compounds on the relaxation induced by acetylcholine, which releases endothelium-derived relaxing factor, and by sodium nitroprusside, which releases NO within the smooth muscle cells. We observed that the relaxation induced by acetylcholine was significantly decreased by L-NMMA and ADMA. Because the relaxation to sodium nitroprusside, an endothelium-independent vasodilator, was not impaired, the absence of relaxation to acetylcholine appears to be a consequence of a decreased synthesis or release of endothelial NO. In contrast, AG and MG had no effect on the relaxation induced by acetylcholine and sodium nitroprusside, thus suggesting that these compounds do not affect the synthesis of endothelial NO. These results are in contrast with those observed in isolated human saphenous veins in which high concentrations of MG (>10^{-5} mol/L) have been shown to reverse the endothelium-dependent relaxation induced by bradykinin or the endothelium-independent relaxation induced by sodium nitroprusside. Besides regional differences, the reversal of bradykinin-induced relaxation is most likely a consequence of functional antagonism resulting from the increased resting tension in precontracted rings with phenylephrine rather than inhibition of NO synthesis. Nevertheless, the concentrations of MG producing contractile effects in saphenous vein are much higher than those reported to occur in the plasma of patients with chronic renal failure (1 to 5×10^{-6} mol/L).

Humans possess endogenous analogues of L-arginine, especially ADMA and L-NMMA, and the enzyme responsible for their synthesis is present in several tissues. However, there is controversy concerning absolute plasma values of ADMA and L-NMMA, largely due to the different analytical methods used. Plasma concentrations of ADMA in healthy volunteers are <10^{-6} mol/L and in uremic patients range from 1.0 to 8.7×10^{-6} mol/L. Concentrations of L-NMMA in healthy controls appear to be 10 times lower than that of ADMA, but are increased significantly (1.4×10^{-5} mol/L) in uremic patients. These values in uremic patients are within the range of concentrations tested in the present study. Plasma ADMA levels in normotensive and hypertensive rats (0.7×10^{-6} mol/L) are similar to those observed in healthy volunteers.

The vasodilator response to acetylcholine was substantially decreased but not abolished by L-NMMA and ADMA. This remaining dilatation may result from the action of acetylcholine on endothelium-derived hyperpolarizing factor. Although the identity of this non-NO, nonprostanoid, endothelium-derived hyperpolarizing factor remains unknown, in vitro studies have shown that this factor causes hyperpolarization that has been attributed to an increase in potassium conductance of the smooth muscle cell membrane. In the rabbit middle cerebral artery, the 2 key endothelium-derived relaxing factors released by acetylcholine are NO and a prostanoid (presumably prostaglandin I_2). However, no evidence of prostanoid intervention was observed in postmortem human middle cerebral artery and in rat basilar artery, since acetylcholine-induced relaxation was unaffected by indomethacin, the inhibitor of cyclo-oxygenase.

A critical factor in the analysis of NO activity in postmortem human cerebral arteries is the possible time-dependent reduction of endothelial cell function. With regard to this, previous reports have shown that cerebral arteries obtained within 12 hours postmortem should be adequate for studies concerning smooth muscle contraction and endothelium-dependent and NO-induced relaxation.

The question of whether high levels of guanidino compounds in biological fluids or brain tissue can influence the arterial lumen or blood flow of the brain under pathological conditions remains unknown. In the concentrations found in the plasma or urine of patients with chronic renal failure, it is possible that L-NMMA and ADMA would inhibit NO synthesis. On the other hand, AG and MG have no effect on the endothelium-dependent relaxation of human cerebral vessels. Inhibition of NO could play a role in the vasospasm that follows subarachnoid hemorrhage. Impairment of NO formation in the vessel wall will predispose to vasoconstriction and favor platelet adhesion and aggregation, with the consequent release of vasoconstrictor substances that may exacerbate vasospasm. Indeed, there are experimental observations showing that the levels of several guanidino compounds are markedly increased in human serum, cerebrospinal fluid, and various brain regions in uremic patients. Thus, the results of the present experiments further support the hypothesis that guanidino compounds should be considered as possible uremic toxins that may play a primary role in the cerebrovascular and neurological disorders observed in uremia.

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References

There are a number of guanidino compounds, some of which are L-arginine analogues, that are synthesized endogenously and can act as inhibitors of nitric oxide synthase (NOS). Of particular interest are N\(^2\),N\(^6\)-dimethyl-L-arginine (asymmetric dimethylarginine; ADMA) and N\(^6\)-monomethyl-L-arginine (L-NMMA). The circulating levels of both of these L-arginine analogues have been reported to be elevated in a variety of pathological conditions, including end-stage renal disease,\(^1\) preeclampsia,\(^2\) congestive heart failure,\(^3\) and hypercholesterolemia.\(^4\) One possible manifestation of an increase in novel inhibitor of nitric oxide formation, prevents diabetic vascular dysfunction. \textit{Diabetes}. 1992;41:552–556.


in endogenous inhibitors of NOS is hypertension, a condition often associated with the pathologies listed above. Methyl-arginines may be produced in a variety of tissues and appear to be concentrated in the brain.\textsuperscript{5,6} The question therefore arises as to whether pathology-associated increases in circulating and cerebral levels of ADMA and L-NMMA are sufficient to impair NO-dependent cerebral vasodilating function. The only published work to date addressing this issue was performed in rats,\textsuperscript{7} and showed that ADMA, at concentrations that may be found in sera of uremic patients (10 \textmu mol/L), was capable of constricting cerebral vessels in vivo and attenuating acetylcholine-induced vasodilation. The present study is the first to test the influence of endogenously generated guanidino compounds on vascular tone and NO-dependent vasodilating function in human cerebral arteries (middle cerebral artery rings obtained from cadavers). The authors found that both ADMA and L-NMMA, at 10 \textmu mol/L and higher doses and with a similar potency, increased arterial tone and attenuated endothelium (acetylcholine)-dependent relaxation. The L-NMMA effect may not necessarily be of clinical relevance, insofar as endogenous levels of L-NMMA may only be one tenth of those measured for ADMA.\textsuperscript{1} Nevertheless, the ADMA findings do indicate that the levels achieved under a variety of pathological states, renal disease in particular, can have a marked influence on cerebrovascular tone. Moreover, when one combines these results with the reported reductions in circulating L-arginine levels in uremic patients,\textsuperscript{8} an even greater exacerbation of NO-dependent cerebral vasodilating function may result.

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