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Lovastatin Induces Relaxation and Inhibits L-Type Ca\(^{2+}\) Current in the Rat Basilar Artery

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Abstract: Statins inhibit cholesterol biosynthesis and protect against ischaemic stroke. It has become increasingly apparent that the beneficial effects of statin therapy may extend beyond lowering of serum cholesterol. The present study was done to explore possible pleiotropic statin effects at the level of the cerebral vascular smooth muscle. Lovastatin, lovastatin acid, simvastatin and pravastatin, were added to segments of the rat basilar artery and effects on contraction and Ca\(^{2+}\) handling were examined. Pravastatin had no effect on contraction. Simvastatin, lovastatin, and, to a lesser degree, lovastatin acid, caused relaxation (IC\(_{50}=0.8, 1.9\) and 22 \(\mu\)mol/l) of both intact and denuded arteries precontracted with 5-HT or high-K\(^+-\). This effect was not reversed by mevalonate, suggesting that it was not related to cholesterol or isoprenoid metabolism. Relaxation was associated with a reduction of the intracellular Ca\(^{2+}\) concentration measured with Fura 2 and with a reduced Mn\(^{2+}\) quench rate, suggesting a direct effect on ion channels in the smooth muscle cell membrane.

Current measurements in isolated and voltage clamped basilar artery muscle cells demonstrated that both lovastatin and lovastatin acid inhibit L-type Ca\(^{2+}\) current. We propose that lipophilicity is an important factor behind the effects of statins on vascular tone and that Ca\(^{2+}\) current inhibition is the likely mechanism of action.

Statins, used for treatment of hypercholesterolaemia, reduce the relative risk of major coronary events and ischaemic stroke by \(\approx 30\%\) (Crouse et al. 1998; Maron et al. 2000). Inhibition of the cholesterol biosynthetic enzyme 3-hydroxy-3-methylglutaryl (HMG)-CoA reductase in the liver is believed to be the primary mechanism of action, which leads to upregulation of liver low-density lipoprotein receptors and clearance of plasma low-density lipoprotein. Both hydrophobic and hydrophilic statins are available and this physicochemical property influences the tissue specificity. The hydrophilic statins do not pass extrahepatic cell membranes with ease but are actively transported into hepatic cells by organic anion transporters. Hydrophobic statins, on the other hand, cross lipid bilayers and may thus influence HMG-CoA reductase in extrahepatic tissues (Hamelin & Turgeon 1998; Ichihara & Satoh 2002; Liao 2002).

Despite significant risk reduction by statins in ischaemic stroke (Crouse et al. 1998), two large clinical trials failed to demonstrate a significant correlation between ischaemic stroke and serum cholesterol levels (Kannel et al. 1971; Multiple risk factor intervention trial 1982). HMG-CoA reductase not only provides the necessary building blocks for cholesterol, but also the isoprenoids farnesyl- and geranylgeranylpyrophosphate, which are used for post-translational modification of Ras and Rho GTPases, respectively. Reduced isoprenylation impairs Ras and Rho activation and this has effects on smooth muscle cell proliferation and migration (Liao 2002). It has been demonstrated that the expression of endothelial nitric oxide synthase is under the negative control of RhoA and that statins upregulate endothelial nitric oxide synthase in the cerebral vascular endothelium (Endres et al. 1998). This statin effect confers protection against ischaemic stroke (Endres et al. 1998; Liao 2002) and may thus resolve the apparent conundrum that ischaemic stroke, which does not correlate with serum cholesterol, is prevented by statins.

A further possible effect of diminished isoprenylation and impaired RhoA activation in cerebral vascular smooth muscle cells is reduced force generation as RhoA and its downstream effector Rho-associated kinase, play important roles in smooth muscle contraction (Uehata et al. 1997; Swärd et al. 2000; Fukata et al. 2001). Thus we conducted pilot experiments using lovastatin in a tissue culture model expecting to see effects after prolonged incubation, in parallel with the slow turnover of isoprenylation, requiring hours or days. Surprisingly, a rather rapid effect of lovastatin on arterial responsiveness was seen, and the experiments reported here were designed to confirm this effect and to establish a mechanism of action.

Materials and Methods

Animals and dissection. Female Sprague-Dawley rats weighing 250–300 g were sacrificed by cervical dislocation as approved by the regional ethics committee. After decapitation, the skull was cut open and the brain transferred to Ca\(^{2+}\)-free HEPES (N-2-hydroxyethylpiperazine-N-2-ethanesulphonic acid) buffered Krebs solution of the following composition (in mmol/l): NaCl, 135.5, KCl, 5.9, MgCl\(_2\), 1.2, glucose, 11.6, HEPES, 11.6, pH 7.35. The basilar artery,
including 2 mm of each vertebral artery and the entire segment up to the posterior cerebral branches, was detached under a dissection microscope. The artery was subsequently cut into four segments of identical lengths (≈2 mm). In some experiments the endothelium was removed with a hair that was pulled through the lumen repeatedly. After denudation, 1 μmol/l acetylcholin failed to induce relaxation, verifying successful functional removal of the endothelium.

**Force measurements.** Basilar artery segments were mounted in a myograph (610M, Danish Myo Technology A/S, Aarhus, Denmark) using 40 μm stainless steel wire and stretched to a basal tension of 2 mN at 37°C. After equilibration for 30 min. in HEPES buffered Krebs, containing 2.5 mmol/l Ca²⁺, preparations were repeatedly contracted (7 min. contractions followed by 25 min. relaxation periods) with 1 μmol/l 5-HT or high-K⁺ solution (obtained by isomolar substitution of NaCl for KCl) until stable contractions were attained. The effects of the drugs were then tested in pre- and post-treatment protocols and compared to the effect of vehicle (0.1–0.3% dimethyl sulfoxide or water). The dependence of the statin effect on cholesterol and isoprenoid metabolism was tested by pretreatment of tissue for 5 min. (1 mmol/l) or 1 hr (10 mmol/l) with hydrolysed mevalonate prior to drug addition.

**Measurements of the intracellular Ca²⁺ concentration with Fura 2.**
Four-mm long denuded segments of the basilar artery were mounted on glass capillaries and incubated for 3 hr at room temperature in the dark with 10 μmol/l Fura 2 AM, 0.05% pluronic F-127, and 2% dimethyl sulfoxide (DMSO). Measurements of the free intracellular Ca²⁺ concentration ([Ca²⁺]i) was then performed at room temperature as described (Gomez & Swärd 1997; Dreja et al. 2001). [Ca²⁺]i is reported as the ratio of fluorescence for excitation at 340 and 380 nm, respectively. The Mn²⁺–Fura 2 quench rate, a measure of Ca²⁺ influx, was determined as the slope of fluorescence decline during excitation at 360 nm after addition of 200 μmol/l of MnCl₂.

**Cell isolation and patch-clamp.** Muscle cells were isolated from the basilar artery and its primary branches as described (Gomez & Hellstrand 1995; Dreja et al. 2001). L-Type Ca²⁺ channel currents were measured, using 10 mmol/l Ba²⁺ as the charge carrier, by 200 msec. depolarising steps to +20 mV from a holding potential of −80 mV. The extracellular solution contained (in mmol/l): NaCl, 105, BaCl₂, 10, KCl, 5.4, MgCl₂, 1, TEA (tetraethyl ammonium chloride), 30, HEPES, 10, glucose, 5. pH was adjusted to 7.35 with NaOH. During experimentation solution was changed with a rapid superfusion system. The pipette solution contained (in mmol/l): CsCl, 140, MgCl₂, 1, TEA, 20, HEPES, 10, phosphocreatine, 10, ATP, 5, EGTA (ethylene glycol bis-(β-aminoethyl ether) N,N,N′,N′-tetraacetic acid), 1. CsOH was used to adjust pH to 7.2. Independent tests of the effects of lovastatin and lovastatin acid in the same cell were only obtained in 2 out of 17 patched cells. Accordingly, the statistical comparison of current density in fig. 5B is unpaired.

**Chemicals.** Pravastatin was a gift from Bristol-Myers Squibb-Skan- dinavia (Bromma, Sweden). Simvastatin was a gift from Merck Sharp and Dohme (Sollentuna, Sweden). Fura 2 AM and pluronic F-127 were from Molecular Probes (Eugene, OR, USA). All other chemicals were from Sigma Chemical Co. (St. Louis, MO, USA). Stocks of lovastatin (also known as mevinolin) and mevalonate were prepared in DMSO and stored in the freezer. Lovastatin acid was obtained by hydrolysis in 250 mmol/l NaOH at 37°C for 1 hr.

**Statistics.** Summarized data are expressed as means±S.E.M. Paired and unpaired statistical comparisons, as appropriate, were made with Student’s t-test. The Bonferroni correction was used for multiple comparisons. P<0.05 was considered statistically significant.

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**Fig. 1.** Lovastatin inhibits contraction elicited by 5-HT and high-K⁺ solution in intact and denuded rat basilar artery. Panels A and B show original traces of force in denuded segments contracted with 5-HT (1 μmol/l) and high-K⁺ (140 mmol/l), respectively. Following the control contraction either vehicle (1‰ DMSO, A) or lovastatin (10 μmol/l, A and B) was added. Summarised data on basilar artery contraction in intact and denuded vessels are shown in panel C. * denotes P<0.05 versus control, n=3–4 for all.
Results

Denuded basilar artery segments, mounted in a myograph, were contracted with either 5-HT (1 µmol/l) or high-K\(^+\) solution (140 mmol/l) until stable contractions were obtained. Effects of lovastatin, lovastatin acid, pravastatin or vehicle were then tested. Drugs and vehicle were present 5 min. prior to, and during, contraction elicited by the same agent (fig. 1A and B). Neither lovastatin acid, pravastatin, nor vehicle had any significant effect on contraction when compared to the prior control contraction (10 µmol/l for all, n=3–4, data not shown). Lovastatin on the other hand, inhibited contraction elicited by both 5-HT and high-K\(^+\) significantly (fig. 1A–C, 10 µmol/l, n=3–4). Lovastatin suppressed contraction to a similar extent in basilar artery segments with intact endothelium (compare bars in fig. 1C).

To test if there was a delay between drug addition and relaxation, denuded vessels were contracted and lovastatin was added during the stable plateau phase. As shown in fig. 2A and B, lovastatin caused essentially immediate relaxation. In controls, force was well maintained over the time-course of the experiment as shown in fig. 2C, and total relaxation (fig. 2D, n=4) corresponded reasonably well with that seen in the pretreatment protocol above. In experiments of similar design cumulatively increasing concentrations of simvastatin, lovastatin, lovastatin acid, pravastatin, and vehicle were added, resulting in dose-dependent

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**Fig. 2.** The onset of lovastatin-induced relaxation in the denuded rat basilar artery is essentially immediate. Original records of contraction in response to 5-HT (1 µmol/l) and high-K\(^+\) are shown in panels A–C. Lovastatin (10 µmol/l) was added during the stable (panel C) contractile plateau. Summarised data from experiments with this design are shown in panel D. * denotes P<0.05, n=4 for all.

**Fig. 3.** Concentration-response relationships for statin-induced relaxation of the rat basilar artery. Denuded basilar arteries were contracted with high-K\(^+\) solution, and lovastatin (lov.), simvastatin (sim.), lovastatin acid (lov. acid), pravastatin (prav.) or vehicle (dimethyl sulfoxide, DMSO) were added on top of the contractile plateau in a cumulative manner. Lines represent fits to the data of a logistic equation, yielding IC\(_{50}\) values of 0.8, 1.9 and 22 µmol/l. Means±S.E.M. are indicated. n=4.
Lovastatin reduces intracellular free $\left[\text{Ca}^{2+}\right]_{i}$ and Ca$^{2+}$ influx in the denuded basilar artery. Panel A shows an original record of the ratio of Fura 2 fluorescence for excitation at 340 and 380 nm respectively, which is a measure of $\left[\text{Ca}^{2+}\right]_{i}$. Stimulation with 5-HT (1 $\mu$mol/l) elicits a sustained increase in the ratio and subsequent infusion of lovastatin (10 $\mu$mol/l) leads to a prompt reduction. Summarised data from four experiments with this design are shown in panel B. Panel C shows an original record of fluorescence given as arbitrary units (a.u.) for excitation at 360 nm. Upon infusion of Mn$^{2+}$ the fluorescence declines. The slope of this decline, i.e. the quench rate, is a measure of the Ca$^{2+}$-influx rate. The preparation was relaxed for 25 min. between each quench period and Mn$^{2+}$ was added after 4 min. of stimulation with 1 $\mu$mol/l 5-HT in each cycle. Panel D shows summarised data on quench rates in controls and in the presence of lovastatin (10 $\mu$mol/l) or lovastatin acid (10 $\mu$mol/l). * denotes $P<0.05$. $n=5$ for comparisons in D.

Discussion

The present study demonstrates that lovastatin inhibits L-type current and reduces intracellular free $\left[\text{Ca}^{2+}\right]_{i}$ and contraction in the cerebral circulation of the rat. Experiments...
been reported by two other groups. Renaud et al. (1986) reported that lovastatin inhibits contractility and L-type current in cultured cardiac myocytes. This effect, at 0.1–1 μmol/l, appeared after 1–3 days of culture and was associated with reduced cellular cholesterol contents. Yada et al. (1999), on the other hand, demonstrated effects of the lipophilic simvastatin on L-type current in pancreatic β-cells, which was not reversed by mevalonic acid lactone. Comparing simvastatin with lovastatin acid and pravastatin, these authors reached the conclusion that the potency of Ca\(^{2+}\)-current inhibition correlates with increasing hydrophobicity. Interestingly, protection against ischaemic brain injury in animal models is similarly related to the hydrophobicity of the statin used (Amin-Hanjani et al. 2001).

Inhibition of L-type current by statins may account for some of their reported effects in vascular smooth muscle. For instance, Tesfamariam et al. (1999) showed that atorvastatin and simvastatin inhibited aortic contraction and Ng et al. (1994) demonstrated reduced [Ca\(^{2+}\)]\_i and reduced Mn\(^{2+}\)-quench in A10 smooth muscle cells treated with simvastatin. These studies, that of Yada et al. (1999), and the present work, have the finding in common that lipophilic statins are effective whereas the water-soluble statins are not. In contrast, while our study and that of Yada et al. (1999), argue that the effect of the lipophilic statins is independent of isoprenoid and cholesterol metabolism the studies by Tesfamariam et al. (1999) and Ng et al. (1994) demonstrate reversal by mevalonate, implicating either isoprenoids or cholesterol as important intermediaries.

Several published observations seem to refute the possibility that the rapid effects on tone and L-type current are due to reduced cholesterol content. Treatment of the rat tail artery with methyl-β-cyclodextrin reduced the arterial contents of cholesterol by 20% but was without any effect on contraction induced by depolarisation (Dreja et al. 2002). Similarly, Löhne et al. (2000) depleted cholesterol from basilar artery smooth muscle cells with cycloexetrin without observing any effects on L-type current amplitudes. Enrichment of cholesterol, on the other hand, leads to increased L-type current (Sen et al. 1992), but this may involve incorporation of cholesterol into membrane domains where it is not normally present. Thus, while effects on isoprenoid metabolism may not be entirely excluded, inhibition of L-type current by lovastatin appears to be independent of cholesterol biosynthesis.

Long-term pharmacological treatment targeting the cerebral vascular tone generally seems to offer protection against ischaemic brain damage. For instance, the reduced infarct volume and improved functional recovery obtained by L-arginine treatment after middle cerebral artery occlusion in the rat correlates closely with increased blood flow (Dalkara et al. 1994, Morikawa et al. 1994). Similarly, Limbourg et al. (2002) demonstrated protection against ischaemic stroke depending on enhanced cerebral blood flow with pharmacological levels (20 mg/kg intraperitoneally) of corticosteroids. In addition, attempts to increase cerebral blood flow with dihydropyridines offered signifi-
cant protection against ischaemic stroke (Gelmers et al. 1988), although this effect has subsequently been questioned (Horn et al. 2001).

A critical consideration is whether the plasma concentration of lovastatin ever reaches high enough levels to influence cerebrovascular L-type current (i.e. ≥0.3 μM). Reported (e.g. Neuvonen & Jalava 1996) peak (C_max) plasma concentrations of lovastatin on oral dosage in man range between 0.01–0.1 μmol/l and are thus at least three-times lower than the lowest effective concentration in our study. However, lovastatin is metabolised in the liver by the cytochrome P450 enzyme CYP3A4 in competition with other drugs. The combination of lovastatin with itraconazole, a CYP3A4 inhibitor, increased the plasma concentration of lovastatin 20–times (Neuvonen & Jalava 1996). Thus, certain oral drug combinations may lead to cerebrovascular Ca2+ current inhibition. Interestingly, the calcium antagonist diltiazem, often used in combination with statins, is also an effective blocker of CYP3A4. Furthermore, it cannot be excluded that human cerebral vessels, which are chronically exposed to statins, are somewhat more sensitive than rat vessels, as this situation allows longer time for cellular penetration.

In summary, we have shown that the lipophilic statins inhibit cerebrovascular tone and that lovastatin inhibits L-type current in a manner seemingly independent of both cholesterol and isoprenoid biosynthesis. Ca2+-channel blockade by lipophilic statins may confound in vitro experiments in which the mevalonate pathway is probed. Provided that high enough levels of lipophilic statins are reached in the vicinity of the brain arterioles in vivo, this effect may tentatively play a role in the reported protection against ischaemic stroke.

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References


