Sympathoinhibition by Atorvastatin in Hypertensive Patients

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Background: Experimental animal data suggest that 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase inhibitors (statins) might reduce enhanced sympathetic activity, a hallmark of hypertensive patients. This hypothesis was tested for the first time in patients with primary hypertension.

Methods and Results: Using a prospective, randomized, placebo-controlled, double-blind, cross-over design, a proof-of-principle trial was performed in 13 patients with mild to moderate primary hypertension, who were randomly assigned to a regimen of atorvastatin (80 mg/day) for 3 weeks, followed by placebo for 3 weeks or to a regimen of placebo for 3 weeks, followed by atorvastatin (80 mg/day) for 3 weeks. Microneurography was used at the end of each treatment period to measure sympathetic nervous system activity (muscle sympathetic nerve activity: MSNA). Heart rate variability (HRV) and plasma norepinephrine concentrations were also measured. Additionally, effects on blood pressure (BP) and heart rate (HR) were assessed by 24-h ambulatory BP measurement. Atorvastatin reduced postganglionic MSNA (atorvastatin 35.0 ± 2.0 vs placebo: 39.2 ± 1.5 bursts/min, P=0.008) and heart frequency corrected MSNA (atorvastatin: 58.5 ± 2.0 vs placebo: 64.7 ± 3.0 bursts/100 beats, P=0.02). Atorvastatin had no significant effect on plasma norepinephrine levels, HRV, BP or HR.

Conclusions: In patients with mild to moderate hypertension, atorvastatin reduces postganglionic MSNA, which supports the hypothesis that HMG-CoA reductase plays a role in sympathetic nervous system activity. (*Circ J* 2010; **74:** 2622–2626)

Key Words: Hypertension; Statins; Sympathetic nervous system

Hypertension is a major public health concern because it increases the risk of stroke, myocardial infarction, and congestive heart failure.[1,2] Despite improved treatment modalities, a substantial number of patients with hypertension are refractory to medical intervention.[2] Apart from well-known mechanisms that explain refractory hypertension, another potential contributing mechanism may be augmented sympathetic activity.[3–5] Several studies have shown that, despite adequate blood-pressure (BP)-lowering therapy, the increased central sympathetic tone persists.[6] Maybe more importantly, it has been suggested that increased sympathetic activity itself may play an additional pathophysiological role in the development of cardiovascular complications.[7,8]

Editorial p 2552

In animal studies 3-hydroxy-3-methylglutaryl coenzyme A

(HMG-CoA) reductase inhibitors (statins) have been shown to reduce renal sympathetic nerve traffic.[9] In stroke-prone spontaneously hypertensive rats, atorvastatin reduced systolic BP (SBP) and urinary norepinephrine excretion.[10] Szramka et al showed a sympathoinhibitory effect of atorvastatin in coronary artery disease (CAD) patients.[11] To date, the underlying mechanism by which statins reduce sympathetic outflow has not been elucidated. An effect on central nitric oxide (NO) and reactive oxygen species (ROS) formation, as well as regulation of the AT_1-receptor expression, have been proposed as possible explanations.[12–14]

We hypothesized that, as sympathoexcitation is a clear feature of primary hypertension, administration of a statin to hypertensive patients will reduce sympathetic nervous system activity.

Methods

Participants

We included 13 patients with primary hypertension were a proof-of-principle trial. Inclusion criteria were: age 18–70 years, a body mass index (BMI) 18–35 kg/m², and a history of mild to moderate hypertension (defined as average awake SBP between 140 and 179 mmHg, or diastolic BP between 90 and 109 mmHg). Secondary hypertension was excluded according to standard clinical criteria. If treated with antihypertensive drugs, the drug regimen had to be stable for 2 months. Subjects were excluded from the study if they had suffered a cardiovascular event within the past 6 months, had renal disease (plasma creatinine concentrations >120 μmol/L for females or >133 μmol/L for males, albuminuria >300 mg/day), diabetes, or any other severe medical condition. The institutional review committee approved the study and written informed consent was given by all patients before participation in the study.

Study Protocol

Using a prospective, double-blind, cross-over design, patients were randomly assigned to a regimen of atorvastatin (80 mg/day) for 3 weeks, followed by placebo for 3 weeks or to a regimen of placebo for 3 weeks, followed by atorvastatin (80 mg/day) for 3 weeks. If patients were already using statins, they were included in the study after a washout period of 2 weeks (n=4). At the end of each treatment period (atorvastatin or placebo) measurements were performed. Muscle sympathetic nervous system activity (MSNA) was assessed by microneurography of the peroneal nerve. In addition, heart rate variability (HRV) and venous plasma catecholamine concentrations were determined. Prior to each visit, ambulatory 24-h BP monitoring was performed. Experiments were conducted at 8.00 AM after an overnight (10-h) fast and with the patient lying supine in a quiet temperature-controlled room (23–24°C). Subjects had to abstain from caffeine, tea, alcohol, chocolates and smoking for at least 12 h prior to the test procedure. All experiments were carried out after voiding to prevent reflex sympathoexcitation. After complete instrumentation, 30 min of rest were included, then HRV measurement was performed for 10 min. Finally, blood samples were drawn and microneurography was performed.

Measurement of Sympathetic Activity

Multiunit postganglionic sympathetic nerve traffic was recorded using microneurography of the peroneal nerve at the fibular head.[15,16] All measurements were performed by the same investigator (M.E.G.). The peroneal nerve was located using an electrical probe delivering transdermal electrical impulses (40–60 mV, 0.2 ms, 1 Hz). Next, a sterile Tungsten microelectrode was inserted percutaneously in the underlying peroneal nerve posterior to the fibular head. Multiunit MSNA bursts were obtained as the average voltage after filtering (bandwidth 700–2,000 Hz) and integrating (time constant 0.1 s). MSNA registration is defined as optimal when: (a) electrical stimulus induces muscle twitches, without concomitant paresthesia, (b) stretching of the appropriate muscle elicits afferent, mechanoreceptive activity, without the occurrence of mechanoreceptive afferent signals after gentle touch or pressure within the cutaneous receptive field of the nerve (if paresthesia is provoked, without concomitant muscle twitch or mechanoreceptive afferent signals are recorded after touch or pressure, sympathetic skin nerve activity is measured, but this lies outside the scope of our study), and (c) MSNA occurs in bursts strictly bound to the cardiac rhythm,

and increases in frequency and amplitude during Vasalva maneuver. To quantify the frequency of MSNA bursts, only bursts with a signal to noise ratio ≥3 were included.[17,18] Bursts were identified using an automated computer program with preset parameters to exclude observer bias. A preset triangle with a base of 0.8 s, correlated to the known delay between the R-peak on electrocardiogram (ECG) and the postganglionic burst, was used to scan the MSNA signal and identify sympathetic bursts. Maximal and average amplitudes were calculated and potential bursts were correlated to a percentage of the maximal amplitude. The computer-derived measures were visually confirmed by the investigator to identify and exclude noise artefacts. Microneurography recordings were quantified as bursts per 100 beats, which has a high intra-individual reproducibility, and bursts per minute.[19]

Laboratory Determinations

Fasting total cholesterol (TC), high-density lipoprotein (HDL) and triglyceride (TG) levels were measured at the end of each treatment period by automated enzymatic methods. Low-density lipoprotein cholesterol (LDL-C) was calculated using the Friedewald equation. For detecting potential statin side-effects, plasma liver enzymes and creatine kinase levels were measured at each visit (baseline, 3 and 6 weeks).

Plasma catecholamine concentrations were measured using high-performance liquid pressure analysis and fluorometric detection.[20] Within- and between-run coefficients of variation for plasma epinephrine were 4.1% and 8.1% at a level of 0.166 nmol/L and for norepinephrine, 4.1% and 6.1% at a level of 1.76 nmol/L, respectively. Analytical detection limits were 0.003 and 0.002 nmol/L for epinephrine and norepinephrine, respectively. Catecholamines were collected in ice-chilled 10-ml Vacutainer tubes (Becton-Dickenson Co, Franklin Lakes, NJ, USA) containing 0.2 ml of a solution of EGTA (0.25 mol/L) and gluthatione (0.20 mol/L).

HRV

Using a 2-channel Holter (Medilog 4500-3, Oxford Instruments Ltd, UK) a 10-min ECG was recorded for each patient at each visit. Ectopic beats and arrhythmias were excluded using the Oxford scanning software (version 6.0). R–R interval selection was performed using a beat-to-beat filter set at N-N-N, whereby the interval being considered should start and end in a "normal" beat and so should the preceding R–R interval. Rejected intervals were interpolated over the invalid area. Before converting the interval tachogram to frequency domain analyses, the mean R–R interval was calculated from the tachogram and subtracted from each R–R interval to reduce spectral leakage. A fast Fourier transformation was performed from the interpolated tachogram resampled at 292 ms, using the Oxford spectral analysis software package. Results from the 10-min interval were averaged to form a composite spectrum. Total power between 0.003 and 0.40 Hz was calculated to represent the total variance for a 10-min interval. Power was quantified as total power, high frequency (HF: 0.15–0.40 Hz) and low frequency (LF: 0.04–0.15 Hz). HF represents the parasympathetic contribution to the spectrum, whereas LF represents a combination of parasympathetic and sympathetic influences.[21] The LF/HF ratio is a measure of autonomic balance, with an increasing ratio representing sympathetic predominance.

24-h Ambulatory BP Measurement

Prior to each experiment, a validated 24-h indirect BP monitor (Mobil-O-Graph CE0434, Firmware version 12, I.E.M.

Table 1. Baseline Characteristics of the Patients With Primary Hypertension

Age (years)	54±16
Sex (M/F)	9/4
BMI (kg/m²)	26.7±1.0
SBP (mmHg)	152±12
DBP (mmHg)	92±3
HR (beats/min)	71±3
Concomitant medication (n)	
β-blockers	7
Aspirin	3
Diuretics	7
Calcium antagonist	8
ACEI/ARB	8
Statin	4

Data are mean±SD.
BMI, body mass index; SBP, systolic blood pressure (BP); DBP, diastolic BP; HR, heart rate; ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin-receptor blocker.

Industrielle Entwicklung Medizintechnik GmbH, Stolberg, Germany) was connected to each patient.

Statistical Analysis

Data are expressed as mean±SEM unless indicated otherwise. Differences between measurements performed during atorvastatin administration or placebo were assessed using parametric (Student's t-test for paired observations) or non-parametric (paired Wilcoxon) tests as appropriate. A power calculation assuming a basal sympathetic activity of 60± 15 bursts/100 beats, revealed that in order to detect a difference of 25% in burst frequency with a power of 80% at a significance level of 0.05 (α), 11 subjects needed to be included. Allowing for a dropout and failure rate of microneurography of 20%, 13 patients needed to be included. A 2-tailed P-value <0.05 was considered to be statistically significant. Correlations between parameters were calculated using Pearson correlation coefficients.

Results

Table 1 presents the baseline characteristics of the study population. At entry, 10 of the 13 patients had BP >130 mmHg systolic or 80 mmHg diastolic. Only 1 patient was not on anti-hypertensive medication. The baseline medications remained unchanged throughout the course of the study. All patients completed the study but in 1 patient a MSNA measurement failed because of technical problems, so paired MSNA recordings were available in 12 of the 13 patients. There were no significant differences in the baseline characteristics of the groups of patients with regard to the sequence of atorvastatin or placebo.

Atorvastatin reduced the plasma TC and LDL-C levels in all patients (TC: from 5.4±0.3 to 3.5±0.2 mmol/L, P<0.001; LDL cholesterol: from 3.3±0.3 to 1.7±0.2 mmol/L, P<0.001). The HDL-cholesterol and TG levels were not significantly altered.

MSNA was significantly lower during atorvastatin 80 mg compared with placebo (**Figure 1**) (total MSNA, atorvastatin: 35.0±2.0 vs placebo: 39.2±1.5 bursts/min, P=0.008; frequency-corrected MSNA: atorvastatin: 58.5±2.0 vs placebo: 64.7±3.0 bursts/100 beats, P=0.02). Although the MSNA values positively correlated with plasma cholesterol levels
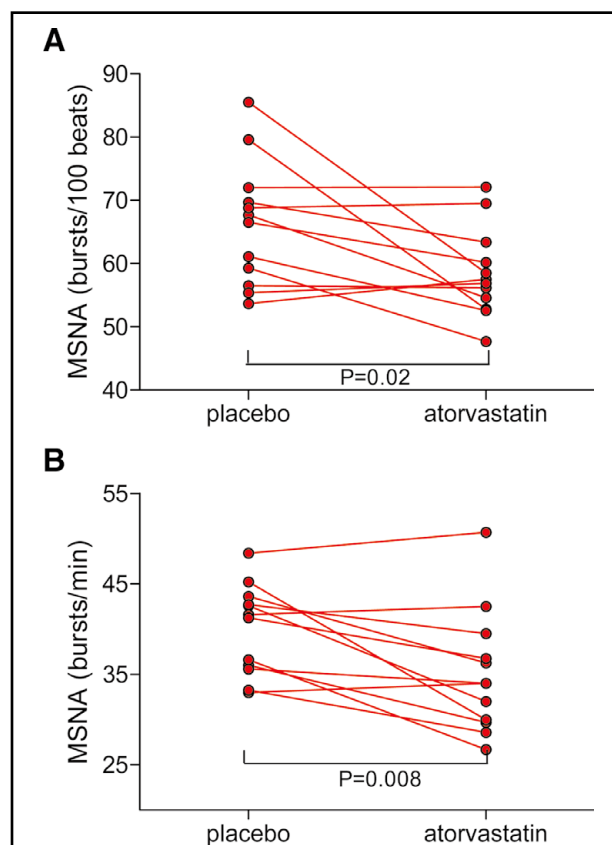
Figure 1. Individual levels of muscle sympathetic nerve activity (MSNA) inthe hypertensive patients (bursts/100 heart beats and bursts/min for total MSNA) during placebo (**A**) and atorvastatin (**B**) administration.
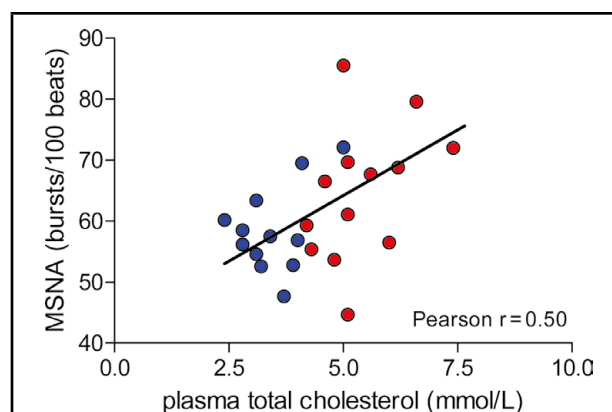
Figure 2. Relationship between muscle sympathetic nerve activity (MSNA) and plasma total cholesterol levels. The Pearson correlation coefficient is 0.50 (P=0.01). (Blue) Atorvastatin, (red) placebo.

(all measurements combined, r=0.50, P=0.01, **Figure 2**), the reduction in MSNA was independent of the degree of change in plasma cholesterol levels (r=0.24, P=0.45) and did not correlate with the change in LDL-C levels (r=−0.22, P=0.51). This finding suggests that the effect was caused by atorvastatin itself, instead of the change in cholesterol level. The atorvastatin effect on MSNA was independent of baseline BP,

Table 2. 24-h Ambulatory BP During Atorvastatin and Placebo Administration to Patients With Primary Hypertension

	Atorvastatin		Placebo	
	Day	Night	Day	Night
SBP (mmHg)	139±3	130±4	143±5	133±5
DBP (mmHg)	89±3	83±4	90±3	83±3
MAP (mmHg)	105±3	98±4	107±3	98±4
HR (beats/min)	81±5	68±5	78±4	62±4

Data are mean±SEM.
MAP, mean arterial BP. Other abbreviations see in Table 1.

Table 3. HR Variability During Atorvastatin and Placebo Administration to Patients With Primary Hypertension

	Atorvastatin	Placebo
LF (ms²)	1,480±736	1,513±729
HF (ms²)	711±248	532±136
LF/HF	1.84±0.37	2.97±0.97
Total PSD (ms²)	5,090±1,473	4,579±1,830

LF, low-frequency power; HF, high-frequency power; LF/HF, low-frequency/high-frequency ratio; PSD, power spectral density. Other abbreviation see in Table 1.

heart rate (HR), age and BMI. Plasma concentrations of nor-epinephrine (atorvastatin: 2.7±0.4 vs placebo: 2.4±0.2 nmol/L) and epinephrine (atorvastatin: 0.16±0.03 vs placebo: 0.15± 0.03 nmol/L) were similar during atorvastatin and during placebo. Day-time and night-time systolic and diastolic BPs, as assessed by 24-h ambulatory BP measurement, were not significantly different between atorvastatin and placebo (**Table 2**). There was no difference in HRV between atorvastatin and placebo (**Table 3**).

Discussion

The results of this study provide evidence that a high dose of atorvastatin produces a significant reduction in post-ganglionic sympathetic nerve activity in patients with primary hypertension. Our conclusion is based on the finding of a nearly 9% lower MSNA with atorvastatin treatment compared with placebo. The lower MSNA levels did not translate into lower venous plasma norepinephrine levels or lower BP, or in a change in HRV.

The reduction in MSNA seemed to be related to the use of atorvastatin and not to the reduction in plasma cholesterol, but our study is too small to draw conclusions on this point.

The results of the present study are in line with earlier findings in animal experimental models. Kishi et al observed a significant reduction in 24-h urinary norepinephrine concentrations after treating stroke-prone spontaneous hypertensive rats for 30 days with atorvastatin.[10] Pliquette et al demonstrated a significant reduction in renal sympathetic activity and plasma norepinephrine levels when treating rabbits with heart failure with simvastatin.[9] The hypothetical concept that underlies those findings is that statins downregulate mRNA and protein expression of the angiotensin II type 1 receptor and NAD(P)H oxidase subunits, and inhibit NAD(P)H oxidase activity in the rostral ventrolateral medulla.[12] The subsequent decline in formation of ROS, a well-known stimulator of sympathetic activity, results in reduced sympathetic outflow. In addition, statins enhance NO synthesis in areas related to integration of sympathetic activity and because NO suppresses central sympathetic outflow, the resulting effect of statins is sympathoinhibition.

Up till now, only a few studies have assessed the effects of statins on sympathetic activity in humans and most have focused on catecholamine levels and HRV, which are surrogate indices of sympathetic activity and subject to large intraindividual variation. To our knowledge, only one study has used microneurography to directly measure changes in post-ganglionic sympathetic nerve activity after treatment with atorvastatin.[22] Those authors also found a significant reduction in MSNA after 8 weeks of treatment with atorvastatin. However, in that study a parallel group design was used,

comparing 10 hypertensive patients with 8 healthy controls and only the hypertensive patients received atorvastatin. In our study, we used a randomized, placebo-controlled, double-blind, cross-over design, which has stronger statistical power.

The finding that the reduction in MSNA after administering atorvastatin 80 mg was not translated into a change in plasma norepinephrine levels is not completely unexpected. First, the plasma norepinephrine level is a global marker of noradrenergic sympathetic tone. The plasma norepinephrine level is the net result of neuronal release and clearance of norepinephrine, so it is possible that a reduced neuronal release of norepinephrine is masked if there is also a reduced clearance. An alternative explanation is that the MSNA results refer only to sympathetic activity in the skeletal muscle compartment whereas the plasma norepinephrine level is the result of all vascular beds. Indeed, it is well established that there are significant regional differences in sympathetic activity.[23] Finally, there might be a dose–effect relationship for the effect of statins on plasma norepinephrine levels and this explanation is supported by a previous study in animals.[24] In rabbits with pacing-induced chronic heart failure (CHF), plasma norepinephrine levels were only reduced when administering a simvastatin dose up to 3 mg·kg⁻¹·day⁻¹, whereas the effects on MSNA were already found at much lower doses.[9] The 3 mg·kg⁻¹·day⁻¹ dose in rabbits exceeds by far the usual dose (eg, simvastatin 40 mg once daily) in human subjects.

Several studies have shown that statins are able to significantly reduce BP in hypertensive patients.[25,26] There are several possible reasons why this effect did not occur in the current study. First, the sympathoinhibitory effect of the dose of atorvastatin might not have been large enough to be translated into a significant decrease in BP or HR. Even a simvastatin dose as high as 3 mg·kg⁻¹·day⁻¹ did not affect the hemodynamics in the CHF rabbits, although RSNA was reduced.[9] In accordance with the findings from that animal study and our current study, atorvastatin 80 mg administered to CAD patients had no effect on BP, despite a significant reduction in plasma norepinephrine levels.[11] Second, it is possible that our study population was not large enough to uncover a decrease in BP. In addition, our patients were only treated and observed for a short period of time. Therefore, our study can not exclude that statins do reduce BP in the long term. Finally, noncompliance with statin administration might be an explanation but the decrease in plasma TC and LDL-C levels in all patients argues against this possibility.

Study Limitations

Several potential limitations should be discussed. All but 1 patient were on antihypertensive treatments. Although this might interfere with the statin, it is unlikely to have con-

founded the results because all patients remained on the same medications, during both atorvastatin and placebo administration. Our study encompasses a relatively small group of subjects, but because of the cross-over design it was adequately powered for the assessment of MSNA.

Although it is difficult to dissect the contribution of atorvastatin itself from the reduction in LDL-C to sympathoinhibition, there was no indication that the degree of reduction in LDL-C correlated with the MSNA effect, thus favouring but not proving a pleiotropic effect of atorvastatin.

It is too premature to state that the findings of the present study have clinical implications. Although the decrease in sympathetic activity did not result in a change in BP or norepinephrine concentration, this does not mean that this finding has no clinical relevance. High sympathetic tone has been associated with insulin resistance, metabolic effects and reduced skeletal muscle perfusion.[27–29] All of these effects are mainly α-adrenergic mediated and were not assessed in this study. Patients with hypertension frequently have increased plasma lipids and are treated with statins. If statins indeed lower sympathetic activity, this might, apart from their effects on plasma lipids, contribute to their beneficial cardiovascular effects in the long term.[30]

In conclusion, the present study shows a small but significant reduction in sympathetic nerve traffic after short-term atorvastatin administration in patients with primary hypertension. Although these findings need confirmation in larger groups of patients, they do suggest an additional beneficial mechanism by which statins reduce cardiovascular complications.

Disclosure

None for all authors.

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