2-Hydroxyoleic Acid
A New Hypotensive Molecule

Regina Alemany, Silvia Terés, Carmela Baamonde, Mikhail Benet, Oliver Vögler, Pablo V. Escribá

Abstract—Recent studies have shown that diets rich in monounsaturated fatty acids (MUFA) from olive oil, a natural source of oleic acid, have beneficial effects on blood pressure (BP) in hypertensive patients. With this in mind, we investigated whether a synthetic derivative of the MUFA oleic acid, 2-hydroxyoleic acid (2-OHOA), was capable of regulating the BP of Sprague-Dawley rats. Intraperitoneal and oral administration of 2-OHOA to rats induced significant and sustained decreases in BP in a time-dependent manner. Without affecting heart rate, treatments for 7 days provoked reductions in systolic BP of 20 to 26 mm Hg. At the molecular level, the density of Gq, but not Goi, or Goa, increased in membranes from the hearts and aortas of 2-OHOA–treated rats, whereas in heart membranes, the density of Goq/11 and protein kinase Ca proteins was also augmented. These molecular alterations were reflected in the increase in cAMP levels after Goa protein and β-adrenergic receptor stimulation. On the contrary, inhibitory hormones reduced adenylyl cyclase activity to the same extent in 2-OHOA–treated rats as in vehicle-treated ones. Our results indicate that cardiovascular tissues from 2-OHOA–treated rats exhibited increased cAMP production in response to Goq activation, which might be attributed to enhanced expression of Goa proteins. As a result of this change, a significant reduction in systolic BP was observed. Therefore, BP can be lowered by administration of 2-OHOA, which might represent the first member of a new family of antihypertensive drugs. (Hypertension. 2004;43:249-254.)

Key Words: blood pressure • fatty acids • signal transduction • G proteins • hypotension

Many alterations in the structure and function of the cell membrane have been associated with hypertension. Changes in the plasma or membrane lipid composition have been reported in both hypertensive humans1 and in animal models of hypertension.2,3 These changes have been associated with abnormalities in cation transport systems,4 cytosolic Ca2+ regulation,5 and impaired signal transduction.6 As a result, it has been proposed that modifications of the membrane lipid composition can affect the physical and functional properties of membranes and in consequence, might account for the alterations in signaling implicated in the physiological control of blood pressure (BP). In this context, long-term fatty acid (FA) intake is known to influence both membrane lipid composition and BP. Olive oil, a natural source of the monounsaturated FA (MUFA) oleic acid, has been shown to have beneficial effects on BP (when high doses are consumed for long periods) and is associated with a low incidence of coronary heart disease.7 Olive oil consumption causes favorable changes in plasma lipid and lipoprotein profiles8,9 and also in the phospholipid content and FA composition of both erythrocyte membranes from hypertensive patients and aorta membranes from spontaneously hypertensive rats.10,11 Moreover, a slight reduction in saturated fat intake along with the use of olive oil markedly lowers the drug requirements of hypertensive patients.12 Nevertheless, the mechanisms underlying the cardiovascular benefits of this diet are not fully understood.

Guanine nucleotide regulatory proteins (G proteins) are GTP-binding proteins that play a pivotal role in the control of BP. They are heterotrimeric proteins composed of α-, β-, and γ-subunits. The α-subunit binds and hydrolyzes GTP and also confers the specificity of G proteins for receptors and effectors. G proteins are implicated in the regulation of a variety of signal transduction systems, including the adenylyl cyclase (AC)/cAMP signaling pathway. Interestingly, the AC/cAMP system has been shown to be involved in a variety of cellular functions related to the regulation of BP, including vascular permeability,13 salt and water transport,14 catecholamine release,15 and the regulation of vascular smooth muscle tone16 and heart contractility,17 cAMP being a potent vasodilator.18

The purpose of our study was to evaluate the effects of the MUFA 2-hydroxyoleic acid (2-OHOA), a synthetic derivative of oleic acid, on BP in rats. In addition, we investigated the effects of this compound on cardiovascular signaling to document the molecular mechanisms of 2-OHOA on BP.
Methods

Animal Treatments
Female Sprague-Dawley rats (12 weeks old, 230 to 250 g; Charles River Laboratories, Barcelona, Spain) received either vehicle (10% ethanol IP, n=18) or 2-OHOA (10 or 30 mg/kg IP, n=24) every 8 hours for 7 days. To determine possible toxic effects and the oral effectiveness of 2-OHOA treatments, rats were administered a high oral dose of this compound (600 mg/kg, n=4) every 12 hours for 7 days. BP was measured at least in triplicate 2 hours after drug administration in warmed, restrained, conscious rats by the tail-cuff method with a computerized oscillometric system recorder (Nyprem system 645, Cibertec). This method was chosen because of its noninvasive character, enabling daily measurements with the same rats throughout the entire treatment. After the final measurement, the rats were killed by decapitation, and their hearts and aortas were dissected out and immediately frozen in LN₂ before being stored at -80°C. All experiments were carried out according to the Institutional Committee of Animal Research (Comissió de Bioètica de la Universitat de les Illes Balears).

Preparation of Cell Membranes From Left Ventricles and Aortas
Left ventricles and aortas were ground in a mortar with LN₂. The tissue powder was then homogenized in a tissue blender (Ultra-Turrax, Janke & Kunkel) containing ice-cold 50 mmol/L Tris-HCl buffer, pH 7.5, with 1 mmol/L EDTA, 2 mmol/L MgCl₂, 1 mmol/L phenylmethylsulfonyl fluoride, and 5 mmol/L iodoacetamide. The homogenate was centrifuged for 10 minutes at 1100g and 4°C, and the supernatant was subsequently centrifuged for 20 minutes at 40 000g. The final pellet was washed in homogenization buffer, resuspended in assay buffer, and used for immunoblotting experiments and the determination of AC activity.

Immunoblot Analysis and Quantification of Specific Immunoreactivity
Quantitative immunoblotting of membrane G proteins and protein kinase (PK) Ca, as well as of total PKA subunits from left ventricles and aortas, was performed as described before. Primary polyclonal antibodies anti-Gas, anti-Goro, and anti-Gα11 were from Santa Cruz Biotechnology, and anti-Garα1 was from New England Nuclear Corp. Primary monoclonal antibodies anti-PKCa, anti-PKAcα, anti-PKAγα, and anti-PKAγβ were from BD Transduction Laboratories. Quantification was performed by image analysis by using standard curves with 5 points (ie, total protein loaded vs integrated optical density) of different protein contents loaded on the same gels, as described. This quantification procedure was repeated at least 3 times for each sample by running duplicates on different gels. Values from 2-OHOA-treated rats were normalized to the protein content values of the vehicle-treated rats, which were considered 100%.

AC Assay
For the AC assay, cell membrane preparations were diluted to a protein content of 1 mg/mL, with a solution of 10 mmol/L Tris-HCl, pH 7.4, 250 mmol/L sucrose, and 1 mmol/L EGTA. The membrane suspension (40 μL) was added to 210 μL of a solution containing 100 mmol/L Tris-HCl, pH 7.4, 1 mmol/L ATP, 10 mmol/L MgCl₂, 1 mg bovine serum albumin, and a creatine phosphokinase–ATP-generating system (consisting of 10 mmol/L sodium phosphocreatine, 8 IU phosphocreatine kinase, and 10 μmol/L GTP and S) and incubated for 10 minutes at 30°C. The enzymatic reaction was stopped by boiling, and the mixture was immediately centrifuged at 3000g for 15 minutes. The production of cAMP was measured in the supernatant with a [FH]cAMP radioimmunoassay kit (Amer sham Pharmacia). Basal AC activity and its responsiveness to activators such as GTPyS (10 μmol/L), isoprenaline (100 μmol/L), noradrenaline (100 μmol/L), and forskolin (100 μmol/L), as well as to inhibitors such as angiotensin II (Ang II, 10 μmol/L) and the atrial natriuretic factor analogue C-ANF₂₃ (0.1 μmol/L), were investigated in the membranes isolated from left ventricles and aortas. AC activity was calculated as picomoles cAMP formed per milligram protein per minute.

Data Analysis
Data are mean±SEM from the number of animals indicated (n). Statistical significance was calculated with GraphPad software. Two groups of values were compared by the 2-tailed t test, whereas ≥2 groups of values were compared by 1-way ANOVA followed by Duncan multiple-comparison test. Differences between experimental groups were considered statistically significant at a value of P<0.05.

Results

In Vivo Effects of 2-OHOA on BP
The effect of 2-OHOA on BP was investigated by measuring systolic BP (SBP) before and during administration in Sprague-Dawley rats. Treatments with 10 and 30 mg/kg 2-OHOA IP decreased the SBP with respect to vehicle-treated rats at all time points (Figure 1A). Maximal SBP reductions measured on the last day of treatment with 10 and 30 mg/kg were 26 and 20 mm Hg, respectively (Figure 1A). Hypotensive effects of 2-OHOA were also observed at times shorter than 24 hours. Administration of a single dose of 10 and 30 mg/kg IP 2-OHOA induced SBP reductions of 16±4 mm Hg (P<0.05, n=10) and 18±4 mm Hg (P<0.05, n=12), respectively, within 4 hours after compound administration (mean basal SBP was 131±2 mm Hg, n=20). To
study any possible toxicological effects of this compound and its effectiveness after oral administration, 2-OHOA dissolved in soybean oil was administered to another group of rats. Oral administration of 2-OHOA (600 mg/kg every 12 hours) decreased BP when compared with vehicle-treated rats (reductions of 13, 25, and 22 mm Hg after 2, 4, and 6 days of treatment, respectively; Figure 1B). Cardiac rate values were unchanged with respect to those of vehicle-treated rats. Moreover, despite the high 2-OHOA doses administered, no histologic or cytologic toxicity was detected on autopsy by both optical and electron microscopy (data not shown).

**Effects of 2-OHOA Treatment on Cellular Signaling Proteins**

To investigate the molecular mechanisms underlying the effects of 2-OHOA on BP, we measured the levels of signaling proteins implicated in the control of BP, such as G proteins, PKCα, and PKA. The concentrations of these proteins in membranes isolated from the left ventricles and aortas of vehicle- and 2-OHOA–treated rats (30 mg/kg IP for 7 days) were determined by quantitative immunoblotting. This analysis showed that the amounts of the AC-stimulatory G protein Gs were increased in cardiovascular tissues from 2-OHOA–treated rats. Levels of the Gq protein (52 kDa) were increased by 65±14% in heart membranes (Figure 2A) and by 52±12% in aorta membranes (Figure 2B) from 2-OHOA–treated rats when compared with vehicle-treated rats. Likewise, in 2-OHOA–treated rats, the levels of cardiac but not of aortic Gqα11 protein (42 kDa) were also upregulated by 31±9% with respect to vehicle-treated rats. In contrast, heart and aorta membranes from 2-OHOA–treated rats did not exhibit significant variations in the levels of the AC-inhibitory G proteins Giα1 (40 kDa; Giα1 is not expressed in rat heart and aorta) and Goα (40 kDa) when compared with vehicle-treated animals (Figure 2).

Finally, the levels of membrane PKCα (Figure 3A), but not the levels of the total catalytic (cat) or regulatory (I and II) PKA subunits (Figure 3B), were increased significantly in left ventricles from 2-OHOA–treated rats (48±5%).

**Effect of 2-OHOA Treatment on AC Activity**

Having observed that 2-OHOA treatment (30 mg/kg IP for 7 days) increased Gs protein levels, we set out to determine whether G protein–mediated signaling was also influenced. Thus, AC stimulation, both independent of and dependent on Gs protein–coupled receptors, was studied in cardiovascular tissues from 2-OHOA–treated rats. Exposure to GTPγS (10 μmol/L) stimulated AC activity in left ventricle (Figure 4A) and aorta (Figure 4B) membranes from vehicle- and 2-OHOA–treated rats. However, cAMP accumulation was significantly higher in 2-OHOA–treated rats, increasing by 20±3% in heart membranes and by 76±31% in aorta membranes (Figure 4). β-Adrenergic stimulation of heart and aorta membranes with isoprenaline (100 μmol/L) or noradrenaline (100 μmol/L) increased AC activity >2-fold in both vehicle- and 2-OHOA–treated rats when compared with the basal activity. Nevertheless, stimulation of AC through Gs protein–coupled β-adrenergic receptors was augmented further as a result of 2-OHOA treatment. The production of cAMP stimulated by either adrenergic agonist was significantly greater in 2-OHOA–treated rats when compared with vehicle-treated rats, increasing by 20±5% in heart membranes and by 92±38% in aorta (Figure 4). Thus, it appears that 2-OHOA treatment does indeed increase both receptor-independent and -dependent G-protein activity.

To investigate whether the increase in cAMP levels could be caused by a direct effect of 2-OHOA on the AC enzyme, forskolin-stimulated cAMP accumulation was also studied. In heart membranes, forskolin (100 μmol/L) induced similar levels of cAMP production in vehicle- and 2-OHOA–treated rats (17-fold with respect to basal activity; Figure 5A). In contrast, stimulation of aortic AC by forskolin was increased by 40±8% in 2-OHOA–treated rats when compared with vehicle-treated rats (Figure 5B).

Finally, inhibition of cAMP accumulation through the Gq/o protein–coupled receptors, angiotensin (AT) and ANF receptors, was investigated in vehicle- and 2-OHOA–treated rats. No difference was seen between vehicle- and 2-OHOA–treated rats.
treated rats in the inhibition of forskolin-stimulated cAMP accumulation by Ang II (10 μmol/L) and C-ANF 4-23 (0.1 μmol/L), either in heart (Figure 5A) or aorta (Figure 5B) membranes.

Discussion

Cells that participate in cardiovascular regulation might undergo lipid-dependent modifications of their membrane composition that are responsible for the elevation of BP. Indeed, alterations of membrane cholesterol or phospholipid content, phospholipid distribution, the molecular species of particular phospholipid classes, and the degree of FA saturation have all been reported in both hypertensive humans and in experimental animal models of hypertension. Interestingly, we recently demonstrated that in elderly hypertensive patients, alterations in cell membrane lipid levels are also associated with a reduction in the density of signaling proteins involved in the control of BP, such as G proteins and PKC. Therefore, changes in lipid composition of the plasma membrane might alter signaling pathways involved in the control of BP. If this hypothesis were correct, nutritional and pharmacologic interventions aimed at normalizing the abnormal lipid composition of the plasma membrane could prove to be a useful therapy for high BP. In this context, interest in the potential cardiovascular health benefits of dietary MUFAs has increased in recent years. There has been considerable research effort directed toward analyzing the effects of MUFA-rich diets, focusing on plasma lipids and the lipid/FA composition of cell membranes, but the molecular mechanisms underlying its effects have not been investigated yet. However, olive oil, a natural source of the MUFA oleic acid, had moderate beneficial effects on BP, but only when high doses were consumed for several months. We demonstrate for the first time that short-term administration of the synthetic MUFA 2-OHOA, a structural analogue of oleic acid, decreases BP in rats (reductions of up to 26 mm Hg) by modulating G protein–mediated cellular signaling. The decrease in BP induced by 2-OHOA occurred in parallel with an increase in cAMP levels in cardiovascular membranes. Activation of AC and the consequent increase in intracellular cAMP concentrations are well-known mechanisms mediating vasorelaxation via several vasodilators, eg, prostaglandin I2. Different molecular mechanisms could account for the observed increases in cAMP production, including alterations in the levels or activity of G proteins that link membrane receptors to the AC and/or changes in the activity of this enzyme. We have shown that membranes isolated from the aorta and heart of 2-OHOA–treated rats exhibit increased AC activity in response to β-adrenergic receptor–dependent and –independent stimulation. More-

![Graph](image1.png)

Figure 3. Effect of 2-OHOA administration on membrane PKCα and total PKA levels in rat left ventricle. Rats received an intraperitoneal injection of either vehicle (10% ethanol) or 2-OHOA (30 mg/kg) every 8 hours for 7 days. Levels of membrane PKCα (A) and total levels of catalytic (PKAcat) and regulatory (I and II) PKA subunits (PKARI and PKARII) (B) were quantified against standard curves, as described in Methods. Values are expressed as percentages of vehicle-treated rats (taken as 100%). Columns represent the mean±SEM of 7 experiments. *P<0.001 compared with vehicle-treated group.

![Graph](image2.png)

Figure 4. Effect of 2-OHOA treatment on AC stimulation in rat heart and aorta. Rats received an intraperitoneal injection of either vehicle (10% ethanol) or 2-OHOA (30 mg/kg) every 8 hours for 7 days. Basal and stimulated AC activity was determined in the absence (basal) or presence of GTPγS (10 μmol/L), alone or in combination with isoprenaline (100 μmol/L) or noradrenaline (100 μmol/L) in left ventricle (A) and aorta (B) membranes from vehicle- and 2-OHOA–treated rats, as described in Methods. Values are mean±SEM of 6 to 8 experiments. *P<0.05, **P<0.01, compared with vehicle-treated group.
over, an increase in the levels of Gs protein was found in cardiovascular tissues after 2-OHOA treatment, and 2-OHOA directly enhanced AC activity in aorta membranes. These results suggest that 2-OHOA induces an increase in cAMP levels, thereby influencing the density/activity of both G proteins and AC. Accordingly, in animal models of hypertension and in response to a number of different hormones, Gs-coupled receptors have been shown to exhibit decreased efficacy and/or potency to increase cAMP concentrations.\(^6\)

Furthermore, decreased Gs-protein function has been detected in hypertensive subjects,\(^{29,30}\) and lower levels of Gs protein have been found in salt-induced hypertensive rats.\(^{31}\) Upregulation of Gq/11 and PKC\(\alpha\) was only found in heart membranes of 2-OHOA-treated rats. Because an increase in cAMP levels as well as signal transduction through Gq in the heart can lead to higher cardiac contractility via Ca\(^{2+}\) and PKC activation, alterations in the levels of these signaling proteins could be considered a compensatory mechanism to avoid further BP reduction in rats.

Besides the fact that FAs alter membrane lipid composition, it has been demonstrated that they also modulate membrane structure, thereby regulating cell signaling.\(^{32}\) This hypothesis is supported by recent reports suggesting that those compounds that increase the membrane propensity to form hexagonal (H\(_\text{II}\)) phases also increase membrane localization and function of G proteins and PKC.\(^{33-35}\) Biophysical studies performed in our laboratory have shown that 2-OHOA, similar to oleic acid,\(^{36}\) is capable of facilitating the formation of hexagonal phases of phosphatidylethanolamine membranes in vitro (F. Barceló et al, unpublished data, 2003). Therefore, it might be possible that the changes in localization and activity of pivotal signaling proteins found in cardiovascular membranes from 2-OHOA-treated rats could be the result of an alteration in membrane lipid structure provoked by 2-OHOA. The effects promoted by 2-OHOA are exerted at low doses, most likely because of the presence of the hydroxyl moiety on the \(\alpha\)-carbon of the FA. This modification, with respect to natural FAs, possibly impairs its mitochondrial import and later degradation, making possible rapid and long-lasting (ie, pharmacological) hypotensive effects. However, the putative mechanisms that might underlie the molecular alterations implicated in the effect of 2-OHOA on BP need to be further investigated in future studies.

**Perspectives**

Cardiovascular pathologies are involved in \(\approx 50\%\) of all causes of death in industrialized countries, with hypertension being one of the major risk factors. This reason underlines the actual need for new, potent, and side effect–free treatments for hypertension. The Mediterranean diet, rich in olive oil, leads to a high consumption of its major component, the natural MUFA oleic acid. Clinical trials have actually proven its beneficial effects on BP and have given a possible explanation for the low incidence of cardiovascular diseases in the appropriate countries, although the effects were only convincing when high doses were consumed for longer times.

In this study, we evaluated for the first time the in vivo effects of a synthetic derivative of oleic acid on BP. This compound, 2-OHOA, demonstrated improved effectiveness by strongly and rapidly reducing rat BP. The hypotensive effect was accompanied by upregulation of the density of membrane Gs proteins, which in turn led to increased levels of cAMP in cardiovascular tissues and the attenuation of BP. Moreover, the low toxicity of 2-OHOA compared with its natural derivative and the fact that it can be administered orally might allow the development of a novel type of antihypertensive drug, based on an improvement of its natural analogue. Accordingly, our current goal is to evaluate the effects of this new molecule in lowering BP in genetic and experimental animal models of hypertension.

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