Studies on the biological effects of ozone: 11. Release of factors from human endothelial cells

Giuseppe Valacchi and Velio Bocci

Institute of General Physiology, University of Siena, Vía A. Moro, 53100 Siena, Italy

Background: Empirical observations have shown that ozonated autohemotherapy markedly improves the symptoms of chronic limb ischemia (muscular pain at rest, intermittent claudication, etc) in atherosclerotic patients, but mechanisms of action remain unclear. Aims: Human endothelial cells (HUVECs) are known to release nitrogen monoxide (NO) and we investigated the biological effects of human ozonated serum on HUVECs in culture.

Methods: We assessed the relevance of peroxidation, the release of NO as nitrite and of three classical cytokines.

Results: The treatment of HUVECs with ozonated serum yields a dose dependent increase of thiobarbituric acid reactive substances (TBARS) and of hydrogen peroxide (H$_2$O$_2$) and a decrease of protein thiol groups (PTG). Concomitantly, in comparison to either the control or the oxygenated sample, there is a significant and steady increase of nitric oxide (NO) production; this is markedly enhanced by the addition of L-arginine (20 µM) and inhibited in the presence of the NO inhibitor, L-NAME (20 mM). The main mediator of ozone action is H$_2$O$_2$ as it has been shown either after its direct measurement or by the addition of 20, 40 and 100 µM. Moreover, during 24 hours incubation we have investigated the production of endothelin 1 (ET-1), E-selectin and Interleukin 8 (IL-8) and it appears that ozonation enhances IL-8, inhibits E-selectin and hardly modifies ET-1 production.

Conclusions: It appears that reinfusion of ozonated blood, by enhancing release of NO, may induce vasodilation in ischemic areas and reduce hypoxia.

Key words: Ozone, Reactive oxygen species, Hydrogen peroxide, Nitric oxide, Endothelial cells, Endothelin-1, E-selectin, Interleukin-8

Introduction

Blood vessel tone undergoes a complex regulation by vasodilators (NO, CO, acetylcoline, adenosine, prostacyclin) and vasoconstrictor factors such as superoxide anion, endothelins, tromboxane, angiotensin II and noradrenaline. In vascular disorders, particularly atherosclerosis, the regulation becomes chaotic owing to the interference of oxidants, adhesion molecules, cytokines and growth factors leading to partial vessel occlusion and hypoxia. Chronic limb ischemia is a progressive disease often observed in atherosclerosis and diabetes leading to necrosis of extremities. Conventional therapy is carried out with infusion of prostanoids, vasodilators and antiaggregants but there is vast empirical evidence that reinfusion of autologous blood briefly exposed to a gas mixture composed of oxygen-ozone (O$_2$O$_3$) is similarly, if not more beneficial.

However, so far double-blind randomized clinical trials have not been performed and, for the time being, we considered it worthwhile to investigate whether human ozonated plasma elicits any effects on human umbilical vein endothelial cells (HUVECs) in culture that may help to understand the supposed therapeutic effect. The present data show that reactive oxygen species (ROS) and/or lipid oxidation products (LOP) derived from the interaction of ozone with plasma enhance the production of nitric oxide (NO), interleukin-8 (IL-8) while the release of either E-selectin or endothelin-1 (ET-1) is either inhibited or hardly modified, respectively.

Materials and methods

Materials

Analytical grade H$_2$O$_2$ 30% was purchased from Fluka GmbH, Switzerland. L-Arginine, the NO synthase inhibitor NG-nitro-L-arginine methyl ester (L-NAME) and all the materials not specified below were purchased from Sigma Aldrich srl, Milano, Italy.
Ozone generation and measurements
O₃ was produced from medical grade O₂ using electrical corona arc discharge with a modern O₃ generator (Model Ozonosan PM 100K, Hansler GmbH, Iffezheim, Germany) which allows the gas flow rate and O₃ concentration to be controlled in real time by photometric determination at 253.7 nm as recommended by the Standardization Committee of the International Ozone Association. Tygon polymer tubing and glass syringes were used throughout the reaction procedure to ensure containment of O₃ and consistency in concentration.

Ozone delivery to biological samples
A predetermined volume of O₂/O₃ gas mixture at various O₃ concentrations within the therapeutic range (20–80 μg/ml of gas per ml of serum) was collected with a glass syringe and immediately introduced into a second glass syringe, via a ‘Y’ connector, containing an identical volume of a pool of human serum (obtained from the Siena Clinical Blood Center). The final gas pressure remained at normal atmospheric pressure. In order to obtain reproducible results it needs to be emphasized that O₃ is a very reactive gas so rapid and precise handling is required. Samples were gently but continuously mixed with the gas for 20 min and afterwards dispensed either into test tubes for analyses or added to cell cultures. Control samples were mixed with an equal volume of O₂. It is worth mentioning that O₂ represents at least 96% of the O₂/O₃ mixture.

Culture of Human Umbilical Vein Endothelial Cells (HUVECs)
Primary endothelial cells were obtained from the neonatal umbilical cord vein according to Jaffe et al. The main vein of umbilical cords (kindly provided by the nursery of ‘Le Scotte’ hospital of Siena) was thoroughly washed with PBS and then incubated with 10 ml collagenase (0.2 % dissolved in Medium 199) from Clostridium histolyticum (type XI, Sigma) for 20–25 min at 37°C. The endothelial cells layer was removed from the vein using 50 ml of Hanks buffer (Sigma). The cells were sedimented at 250 g for 10 min and washed once with 20 ml of Medium 199 with 20% FCS (Seromed), and resuspended in 5 ml of fresh medium. Cells were grown in Medium 199, pH 7.4 (Gibco BRL, Rockville, MD) supplemented with 20% FCS, 2 mM glutamine, 10 mM Hepes, 100 μg/ml heparin, streptomycin-penicillin and 100 μg/ml of endothelial cell growth factor (ECGF). For subculture, the cells were harvested with 0.01% EDTA-0.1% trypsin.

HUVECs were utilized for experiments at 90–95% (3–3.5×10⁶ cell/well) apparent confluence within passage 3 and through 6. Passage were performed according to standardized protocols and by diluting the cell population 1:3.

Cell treatment
The cells were pelleted by centrifugation and seeded in 6 well plates pre-treated with 1.5% gelatin (type B from bovine skin). To each well 2 ml of M199 supplemented with 1% FCS, without heparin and ECGF was added for 24 h. The day after cells confluence was around 90–95% (3–3.5×10⁶ cell/well). The cells were washed once in Hank’s balanced salt solution. Ozonated serum (2 ml) was added to the cells but after 20 min incubation the serum was collected for biological determination and the cells were grown as described above, but without phenol red in the medium.

Determinations
Hydrogen peroxide (H₂O₂) was measured in serum before and after addition of oxygen and ozone by the enzymatic method described by Green and Hill. Protein thiol groups (PTG) were measured in serum according to Hu using procedure 1 with 5,5’-dithiobis(2-nitrobenzoic acid) (DTNB) dissolved in absolute methanol. The thiobarbituric acid (TBA) assay was carried out in serum as described by Buege and Aust. Values are expressed as μM of TBA reactive substances (TBARS) relative to a malondialdehyde standard. By collecting samples at different incubation times (from 2 to 48 h), NO production was assayed by determining the increase in nitrite concentration using the classical Griess reaction. Cytokines such as IL-8, ET-1 and E-selectin present in centrifuged tissue cultured fluids, were kept at –80°C until determinations were carried out by immunoassay using standard kits purchased from R&D Systems (GmbH, Wiesbaden, Germany). Duplicate samples were diluted 1:1 with the appropriate diluent and a 3-cycle automatic washing process was routinely performed.

Statistical analyses
All statistical analyses were performed using one-way analysis of variance (ANOVA) with the Scheffé multi-range test. All values are expressed as Means and Standard Deviation (±SD). P values less than either 0.05 or 0.01 were considered significant and are marked with 1 or 2 asterisks, respectively.

Results
Initially we investigated whether ozonated human serum added to HUVECs modifies NO production. Figure 1 shows that the exposure of serum for 1 min to two different concentrations (40 and 80 μg/ml of
gas per ml of serum) induces a significant ($P<0.01$) reduction of PTG levels while TBARS and $H_2O_2$ levels increase. Both control serum (untreated) or $O_2$ exposed samples show neither modification of TBARS and PTG values, nor any production of $H_2O_2$. HUVECs incubated with $O_2$-treated serum samples show an increase of NO production measured as nitrite, that becomes significant ($P<0.05$) after 24 and 48 h and is $O_3$ dose dependent. Nitrite levels were not modified during the first 6 h of incubation.

Following this we checked if NO release could be influenced by the addition of the substrate L-arginine, or by the inhibitor L-NAME (Fig. 2). L-arginine on its own markedly ($P<0.05$) increases NO release in both control and $O_2$-serum treated HUVECs but NO production is significantly higher when cultures are added with ozonated serum samples, particularly at ozone concentration of 80 µg/ml. The presence of L-NAME inhibits NO release in all cases.

Figure 1 shows that ozonation of serum is accompanied by $H_2O_2$ production confirming Pryor's reaction$^{11}$ and our previous data.$^{12}$ Thus it would be interesting to evaluate if $H_2O_2$ is able to influence NO release. Figure 3 shows that there is an almost linear increase between NO release and progressively higher amounts (20, 40 and 100 µM) of $H_2O_2$ added to HUVECs. Moreover addition of L-arginine strongly reinforced NO production while L-NAME inhibited to a great extent, but not entirely, its production.

$H_2O_2$ is now considered a crucial trigger of NF-kB$^{13,14}$ and it appeared obvious to examine whether $O_3H_2O_2$ induces release of a few typical cytokines such as ET-1 (Fig. 4), E-selectin (Fig. 5) and IL-8 (Fig. 6). Ozone at both concentrations (40 and 80 µg/ml) significantly enhances the release of IL-8 after 4, 6 and 24 hours incubation with and without addition of L-arginine confirming the ability of ozone to induce IL-8 production in blood$^{15,16}$ and respiratory epithelial cells.$^{17}$ Release of E-selectin or ET-1 appears either depressed or practically unmodified.

### FIG. 1. Effect of different concentrations of ozone on the production of nitrite by HUVECs, 24 and 48 h after addition of ozonated human serum (top panel). Effect of either oxygen or ozone on PTG, TBARS and $H_2O_2$ levels in the serum before addition to HUVECs. The data are presented as the arithmetic mean ±SD of 6 different experiments.

### FIG. 2. Production of nitrite by HUVECs, measured after 24 h incubation, after addition of normal human serum either oxygenated or ozonated (at 40 and 80 µg/ml). Effects of addition of L-arginine and L-NAME. The data are presented as the arithmetic mean ±SD of 6 different experiments.

### FIG. 3. Production of NO by HUVECs, measured after 24 h incubation, after addition of three concentration of $H_2O_2$. Effects of the addition of L-arginine and L-NAME. The data are presented as the arithmetic mean ±SD of 6 different experiments.
Vascular disorders caused by atherosclerosis, diabetes and smoking at the level of the brain, heart and limbs represent a formidable social-economical problem affecting several millions of people worldwide. Orthodox medicine uses a variety of approaches such as surgery, anticoagulants, thrombolytic compounds, vasodilators, antioxidants and now even gene therapy\cite{18} for normalizing damaged vessels, reducing restenosis and minimising damage following severe ischemia. During the last decade our laboratory has been involved in clarifying mechanisms of action triggered by ozone when this gas is briefly mixed with human blood.\cite{4,21} Like oxygen, ozone dissolves in the plasma and reacts quickly with a number of substrates such as polyunsaturated fatty acids (PUFA), -SH groups present in several compounds and antioxidants.\cite{11} An array of generated products namely \( \text{H_2O_2}, \) malondialdehyde, 4-hydroxynonenoal, hydroperoxides and lipoperoxides\cite{19} may act as cellular signals and trigger biological effects. It must be said that these compounds, depending on their concentrations, seem to behave as a double-edged sword.\cite{20} For this reason we have been very careful in defining the biological active dose that, in terms of ozone concentration, ranges between 20 and 80 \( \mu g/ml \) gas per ml of blood without displaying toxic effects neither \textit{in vitro} nor \textit{in vivo}.\cite{4,21} Empirical observations have shown that ozone enhances delivery of oxygen to hypoxic tissue and we have hypothesized that ozonated plasma during reinfusion may elicit some effects on the vessel wall possibly enhancing vasodilatation. Indeed the present results give credence to this idea by showing an enhanced production of NO, which is an important component of the negative feed-back loop that prevents thrombogenesis. The adherence of platelets to the vessel wall, and their aggregation, is suppressed by nitrovasodilators capable of increasing the intracellular cGMP, with consequent phosphorylation of cGMP-dependent phosphoproteins and suppression of platelet reactivity.\cite{22} The possible formation \textit{in vivo} of nitrosocompounds, with longer lifetime than NO, may slowly decrease the vasospasm.

Our data showing inhibition of release of E-selectin, especially after 2 and 6 hours, and no increase of ET-1. This is consistent with previous reports\cite{23-26} showing a reciprocal regulation of the expression of ET-1 and endothelial cell adhesion molecules in comparison to

**Discussion**

**Fig. 4.** Kinetic of release of endothelin-1 from HUVECs after addition of human serum either after oxygenation or after ozonation. Effect of the addition of L-arginine and L-NAME. The data are presented as the arithmetic mean ± SD of 6 different experiments.

**Fig. 5.** Kinetics of release of E-selectin from HUVECs after addition of human serum either after oxygenation or after ozonation. Effect of the addition of L-arginine and L-NAME. The data are presented as the arithmetic mean ± SD of 6 different experiments.
production of NO. At present, we cannot say whether ozonated serum is able to increase gene expression of VEGF, 

FIG. 6. Kinetics of release of IL-8 from HUVECs after addition of human serum either after oxygenation or after ozonation. Effect of the addition of L-arginine and L-NAME. The data are presented as the arithmetic mean ± SD of 6 different experiments.

production is due to constitutively present NO- synthase (Ca²⁺ dependent), typical of the endothelium, or the newly induced enzyme (iNOS, Ca²⁺ independent) which seems most likely as at 2, 4 and 6 hours after treatment we could not measure any nitrite increase. However work in progress will clarify this question and elucidate whether ozonated blood added to HUVECs, simulating the reinfection of ozonated blood in patients, is able to induce neoangiogenesis.

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References

1. Levin ER. Endothelins. N Engl J Med 1995; 335: 356–363.
2. Katucic ZS. Superoxide anion and endothelial regulation of arterial tone. Free Radical Biol Med 1996; 20: 443–448.
3. Cines DB, Polak ES, Buck CA, Loscalzo J, Zimmerman GA, McEver RP, Pober JS, Wick TM, Konkle BA, Schwartz BS, Barnathan ES, Mcgrae KR, Hug BA, Schmidt AM, Stern DM. Endothelial cells in physiology and in the pathophysiology of vascular disorders. Blood 1998; 91: 1537–1546.
4. Bocci V. Biological and clinical effects of ozone. Has ozonotherapy any future in medicine? Brit J Biomed Sci 1999; 56: 270–279.
5. Pryor WA, Squadrini GL, Friedman M. The cascade mechanism to explain ozone toxicity: the role of lipid ozonation products. Free Radical Biol Med 1995; 19: 935–941.
6. Jaffe EA, Nachman RL, Becker CG, Minick CR. Culture of human endothelial cells derived from umbilical veins: identification by morphologic and immunologic criteria. J Clin Invest 1992; 89: 2123–2129.
7. Pryor WA. Mechanisms of radical formation from reactions of ozone with target molecules in the lung. Free Radical Biol Med 1994; 17: 451–465.
8. Bocci V, Valacchi G, Corradeschi F, Aldinucci C, Silvestri S, Paccagnini E, Gerli R. Studies on the biological effects of ozone: 7. Generation of reactive oxygen species (ROS) after exposure of human blood to ozone. J Biol Regul Homeost Agents 1995; 9: 67–75.
9. Savaert P, Westeel T. Function and activation of NF-kB in the immune system. Annu Rev Immunol. 1994; 12: 141–179.
10. Bocci V, Coradeschi F, Aldinucci C, Silvestri S, Paccagnini E, Gerli R. Studies on the biological effects of ozone: 9. Effects of ozone on human blood. Free Radical Biol Med 1997; 25: 352–361.
11. DeForge LE, Fontaine JC, Kenney JS, Remick DG. Oxygen radical scavengers selectively inhibit interleukin 8 production in human whole blood. J Clin Invest 1992; 90: 2123–2129.
12. Bocci V, Valacchi G, Corradeschi F, Aldinucci C, Silvestri S, Paccagnini E, Gerli R. Studies on the biological effects of ozone: 8. Effects on the total antioxidant status and on interleukin-8 production. Mediat Inflamm 1998; 7: 313–317.
13. Jaspers I, Fleischer E, Chen LC. Ozone-induced IL-8 expression and transcription factor binding in respiratory epithelial cells. Am J Physiol 1997; 272: L1504-L1511.
14. Laitinen M, Mäkinen K, Manninen H, Matsi P, Kossila M, Agrawal RS, Pakkanen T, Luoma JS, Viita H, Ylä-Herttuala S. Adenovirus-mediated gene transfer to lower limb artery of patients with chronic critical leg ischemia. Hum Gene Ther 1998; 9: 1481–1486.
15. Pryor WA. Ozone as an in vitro reactive-solvent. J Lab Clin Med 1993; 122: 485–486.
16. Dianzani MU, 4-Hydroxynonenal and cell signalling. Free Rad Res 1998; 28: 551–560.
17. Di Paolo N, Bocci V, Garosi G, Borelli E, Bravi A, Bruci A, Aldinucci C, Capotondi L, Extracorporeal blood ozonation and oxygenation (EBOO) in man. Preliminary report. Int J Artif Organs 2000; 23: 131–141.
24. Takahashi M, Ikeda U, Masuyama J, Funayama H, Kano S, Shimada K. Nitric oxide attenuates adhesion molecule expression in human endothelial cells. *Cytokine* 1996; 8: 817–821.

25. Armstead VE, Minchenko AG, Schuhl RA, Hayward R, Nossuli TO, Lefer AM. Regulation of P-selectin expression in human endothelial cells by nitric oxide. *Am J Physiol* 1997; 273: H740-H746.

26. Cartwright JE, Whitley GS, Johnstone AP. Endothelial cell adhesion molecule expression and lymphocytic adhesion to endothelial cells: effect of nitric oxide. *Exp Cell Res* 1997; 235: 431–434.

27. Ferrara N, Davis-Smyth T. The biology of vascular endothelial growth factor. *Endocr Rev* 1997; 18: 4–25.

28. Chua CC, Hamdy RC, Chua BHL. Upregulation of vascular endothelial growth factor by H$_2$O$_2$ in rat heart endothelial cells. *Free Rad Biol Med* 1998; 25: 891–897.

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