Both lipid and protein intakes stimulate increased generation of reactive oxygen species by polymorphonuclear leukocytes and mononuclear cells1–3

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ABSTRACT

Background: It was recently shown that glucose challenge leads to increased generation of reactive oxygen species (ROS) by polymorphonuclear leukocytes (PMNs) and mononuclear cells (MNCs).

Objective: To further elucidate the relation between nutrition and ROS generation, we investigated the effect of lipid and protein challenges on ROS generation by leukocytes.

Design: After having fasted overnight, one group of healthy subjects consumed a carbohydrate- and protein-free cream preparation (1257 kJ) and another group of healthy subjects consumed an equienergetic pure preparation of casein. Sequential blood samples were obtained after the intake of cream and casein. ROS were measured by chemiluminescence after stimulation by N-formylmethionyl-leucinyl-phenylalanine. Lipid peroxidation was measured as thiobarbituric acid–reactive substances (TBARS) and α-tocopherol was measured by HPLC.

Results: ROS generation by MNCs and PMNs increased significantly 1, 2, and 3 h after cream intake and 1 h after protein intake. Cholesterol concentrations did not change significantly, whereas triacylglycerol concentrations increased significantly 2 h after cream intake. Total TBARS concentrations increased 1 h after cream intake and remained elevated 3 h after intake, but the increase was not significant when corrected for changes in triacylglycerol. After casein intake, total cholesterol, triacylglycerol, and TBARS concentrations did not change significantly.

Conclusions: Both fat and protein intakes stimulate ROS generation. The increase in ROS generation lasted 3 h after cream intake and 1 h after protein intake. Cream intake also caused a significant and prolonged increase in lipid peroxidation. These data are important because increased ROS generation and lipid peroxidation are key events in atherogenesis.

KEY WORDS Lipids, proteins, reactive oxygen species, leukocytes, lipid peroxidation, aging, thiobarbituric acid–reactive substances, TBARS, polymorphonuclear leukocytes, mononuclear cells, α-tocopherol

INTRODUCTION

Oxidative damage to lipids is considered to be important in the pathogenesis of atherosclerosis and microvascular complications of diabetes (1, 2). It has been suggested that hyperglycemia may modulate oxidative damage in diabetes mellitus (3, 4). It was also shown that antioxidant administration may improve atherosclerosis- or diabetes-related endothelial, leukocytic, and platelet damage and vascular reactivity (5–8). The factors that determine reactive oxygen species (ROS) generation require further investigation because ROS determine oxidative damage to proteins (9), lipids (4), and DNA (10).

We recently showed that a glucose challenge is followed by an increase in ROS generation by polymorphonuclear leukocytes (PMNs) and mononuclear cells (MNCs) and a decrease in plasma α-tocopherol concentrations (11). Glucose and meal challenges also increase lipid peroxidation and decrease antioxidant reserves (12, 13). These findings raise the question of whether macronutrients other than carbohydrates may also increase ROS generation and oxidative load.

In the present study we examined whether lipid or protein challenge also increases ROS generation by leukocytes and whether there are differences in response to these 2 nutrients when given in equienergetic amounts. We also examined the effect of lipid or protein challenge on a commonly used index of lipid peroxidation, ie, the plasma concentration of thiobarbituric acid–reactive substances (TBARS). This index of lipid peroxidation is relatively crude but provides a readily measurable way of assessing this process that is cardinal to the formation of a fatty streak and atherosclerosis. In our recent study on the effect of glucose on ROS generation, we observed a trend toward an increase in TBARS and a significant decrease in plasma α-tocopherol concentrations. Therefore, we included α-tocopherol concentration as one of the indexes measured.
SUBJECTS AND METHODS

Subjects

Fifteen healthy subjects (10 men and 5 women) aged 28–65 y (mean age: 36 ± 10.7 y) were included in the study. All subjects had normal body weights [body mass index (BMI; in kg/m²): 25.3 ± 2.0], normal blood pressure measurements (<140 mm Hg systolic and <85 mm Hg diastolic), and normal serum cholesterol concentrations (<5.2 mmol/L) and none smoked cigarettes.

All subjects arrived at the Clinical Research Center of the Diabetes-Endocrinology Center between 0800 and 0900 after having fasted overnight. All subjects had a blood sample obtained from the antecubital vein. Eight subjects were then given 100 mL dairy cream (gourmet heavy whipping cream; Land O Lakes Inc, Arden Hills, MN) to drink. This preparation of dairy cream has 33 g fat and 1257 kJ (300 kcal) per 100 mL cream. The saturated fat content of the cream preparation was 70% (28% unsaturated fat), the protein content was <2%, and the glucose content was 0%. Seven subjects were given 75 g (1257 kJ) protein as casein (Spectrum Quality Products, Gardena, CA). Casein is a pure protein that contains no energy from fat or carbohydrate. Blood samples were then obtained 1, 2, and 3 h after intake of the cream or casein. All blood samples were collected in EDTA-containing evacuated tubes. Four of the subjects were also given 300 mL water to drink. Blood samples were collected before and 1, 2, and 3 h after water intake. All subjects gave their written, informed consent to participate in the protocol, which was approved by the internal review board of the State University of New York at Buffalo, based at Millard Fillmore Hospital.

PMN and MNC preparation

A portion (3.5 mL) of the anticoagulated blood sample was carefully layered over 3.5 mL PMN medium (Robbins Scientific Corp, Sunnyvale, CA). The sample was centrifuged at 450 × g for 30 min at 22°C to separate out 2 bands at the top of the red blood cell pellet. The top band consists of MNCs and the bottom consists of PMNs. The bands were harvested, repeatedly washed with Hank’s Balanced Salt Solution (HBSS; Life Technologies Inc, Rockville, MD), and reconstituted to a concentration of 4 × 10⁸ cells/L in HBSS. This method yields >95% pure PMN and MNC suspensions. The purity of the PMN and MNC preparations was checked randomly, once every 5–10 preparations.

Measurement of plasma, glucose, insulin, and lipids

The effects of cream and casein intakes on glucose, insulin, cholesterol, and triacylglycerol concentrations were measured at the central laboratories at Kaleida (Buffalo, NY) with the use of cholesterol, and triacylglycerol concentrations were measured at the central laboratories at Kaleida (Buffalo, NY) with the use of cholesterol, and triacylglycerol concentrations were measured at the central laboratories at Kaleida (Buffalo, NY). Normal blood pressure measurements (<140 mm Hg systolic and <85 mm Hg diastolic), and normal serum cholesterol concentrations (<5.2 mmol/L) and none smoked cigarettes.

The specific inhibitory effect of diphenyleneiodonium on NADPH oxidase was established by Hancock and Jones (17). Because baseline ROS generation varied markedly between the subjects, we previously showed interindividual variability in ROS production, the data were normalized to a baseline of 100% because baseline ROS generation varied markedly between the subjects. We previously showed interindividual variability in ROS production, the data were normalized to a baseline of 100% because baseline ROS generation varied markedly between the subjects. We previously showed interindividual variability in ROS production, the data were normalized to a baseline of 100% because baseline ROS generation varied markedly between the subjects. We previously showed interindividual variability in ROS production, the data were normalized to a baseline of 100% because baseline ROS generation varied markedly between the subjects.
intake of cream or casein are shown in Table 1. Plasma glucose concentrations did not change significantly after intake of either cream or casein. Insulin concentrations did not change significantly after cream intake but increased significantly from 39.0 ± 15.6 pmol/L at baseline to 108.6 ± 69.6, 117.0 ± 77.4, and 90.0 ± 31.2 pmol/L, respectively, 1, 2, and 3 h after casein intake. Total cholesterol concentrations did not change significantly after intake of either cream or casein. Triacylglycerol concentrations increased, but not significantly, from 1.48 ± 0.42 mmol/L at baseline to 1.63 ± 0.42 mmol/L 1 h after cream intake but increased significantly to 2.12 ± 0.60 mmol/L 2 h after and to 2.04 ± 0.60 mmol/L 3 h after cream intake. Triacylglycerol concentrations did not change significantly after casein intake.

Plasma α-tocopherol concentrations did not change significantly after intake of cream or casein. When corrected for the increase in triacylglycerol concentrations, the ratio of α-tocopherol (mmol) to triacylglycerol (mol) tended to decrease from baseline (17.3 ± 3.3) to 16.4 ± 5.1, 13.5 ± 6.2, and 13.1 ± 4.8, respectively, 1, 2, and 3 h after cream intake, but none of the differences were significant. The ratio of α-tocopherol to triacylglycerol did not change significantly after casein intake.

Generation of reactive oxygen species

ROS generation by MNCs increased after cream intake in all subjects (Figure 1). All values were normalized to a baseline concentration of 100% because of the interindividual variation in ROS generation. ROS generation by MNCs increased significantly from baseline by 169.0 ± 24.4% (baseline reading of 118 ± 16 mV = 100% in further comparisons) at 1 h, by 195 ± 66.1% at 2 h, and by 131 ± 12.7% at 3 h. ROS generation

![Figure 1](https://academic.oup.com/ajcn/article-abstract/75/4/767/4689384/250)
by PMNs also increased after cream intake in all subjects. ROS generation by PMNs increased significantly from baseline (101 ± 15 mV = 100%) by 197 ± 60.8% at 1 h, by 189 ± 73.3% at 2 h, and by 131 ± 25.9% at 3 h.

Six of 7 subjects showed a significant increase in ROS generation by MNCs after casein intake (Figure 2). ROS generation by MNCs increased from baseline (385 ± 47 mV = 100%) by 161.0 ± 59.4% at 1 h (P < 0.05), by 116 ± 30.2% at 2 h (NS), and by 103.0 ± 19.7% at 3 h (NS). The increase in ROS generation by MNCs was not significant when expressed in absolute values (mV) and when not normalized to the baseline value because of the wide scatter of baseline values and because of the decrease in ROS generation by MNCs in one subject. ROS generation by PMNs in all subjects after casein intake. ROS generation by PMNs increased from baseline (143 ± 45 mV = 100%) by 193 ± 55.5% at 1 h (P < 0.05), by 144 ± 37.5% at 2 h (NS), and by 101 ± 14.9% at 3 h (NS). The increase in ROS generation at 1 h was significant whether expressed as mV/10^6 cells or as the increase over baseline corrected to 100%. There was no significant change in ROS generation by leukocytes after a drink of water (300 mL).

**Plasma thiobarbituric acid–reactive substances**

The increase in plasma TBARS concentrations was significantly greater than the increase in triacylglycerol concentrations after cream intake. Plasma TBARS concentrations increased significantly from baseline (1.09 ± 0.13 μmol/L) to 1.62 ± 0.38 μmol/L at 1 h, to 1.47 ± 0.12 μmol/L at 2 h, and to 1.41 ± 0.25 μmol/L at 3 h. The increase in TBARS was greatest at 1 h, whereas the increase in triacylglycerol was greatest at 2 h. When TBARS concentrations were corrected for the change in triacylglycerol concentrations, this increase was not significant. TBARS concentrations (μmol/mmol triacylglycerol) were 0.773 ± 0.206 at baseline, 1.041 ± 0.348 at 1 h, 0.771 ± 0.329 at 2 h, and 0.767 ± 0.206 at 3 h. Plasma TBARS concentrations did not change significantly after casein intake. The difference in the peak of TBARS and triacylglycerols and the statistical trend toward an increase in the ratio of the 2 substances suggest that the increase in TBARS was not totally dependent on the increase in triacylglycerols.

**DISCUSSION**

Our data show for the first time that both the cream and casein challenges consistently result in a significant increase in ROS generation by both PMNs and MNCs. The peak effect occurred between 1 and 2 h after cream intake and 1 h after casein intake. Thereafter, ROS generation decreased, but was still higher than that at baseline 3 h after cream intake, whereas it reverted to baseline 3 h after casein intake. We previously showed an increase in ROS generation by PMNs and MNCs after a glucose challenge (11). Thus, we have produced evidence that all 3 major macronutrients (carbohydrate as glucose, fat as cream, and protein as casein) induce an increase in ROS generation. Our data also show that different nutrients produce distinct patterns of stimulation of ROS generation after their intake. Of the 3 nutrients, glucose induced the greatest ROS generation (the peak increase being 2 h after intake), followed in decreasing order by cream and by casein (the peak increase being 1 h after intake). Whether these differences in ROS generation are due to differences in metabolic stimulation after the energetic challenge or whether it reflects different mediators being released after the intake of different nutrients is not clear. We were unable to specify the mediators that may underlie the increase in ROS generation on the basis of our current experiments. Plasma insulin concentrations increased significantly after casein intake, but not after cream intake. Thus, it appears that insulin is not the mediator of increased ROS generation. Furthermore, we recently showed that insulin inhibits ROS generation by MNCs and PMNs in vivo (19).

The fact that both lipid and protein intakes cause an acute increase in ROS generation similar to that induced by glucose indicates that nutrient intake is probably a major modulator of ROS generation. This indication is consistent with our previous observation that ROS generation by MNCs from obese persons is relatively nonsuppressible (20). It is possible that the nonsuppressible ROS generation in obese persons may partly be a reflection of excessive nutrient intakes rather than of obesity itself. In addition, we recently showed that the indexes of lipid peroxidation—protein carbonylation and oxidative damage to amino acids—are elevated in obese persons and that dietary restriction and weight loss will result in the normalization of

**Figure 2.** Mean (±SD) generation of reactive oxygen species (ROS) by mononuclear cells (MNCs) and polymorphonuclear leukocytes (PMNs) before (0 h, baseline) and 1, 2, and 3 h after casein intake (75 g). *Significantly different from baseline, P < 0.05 (Tukey’s test).
these indexes without the use of antioxidants (21). Furthermore, we also showed that ROS generation and oxidative damage to amino acids decreased significantly in healthy subjects after a 48-h fast (22). Thus, nutritional intake is an important determinant of ROS generation and ROS load. This finding raises the issue of the relative effect of different diets on ROS generation, ROS load, and potential oxidative damage. We are currently investigating the effect of comprehensive diets (e.g., the American Heart Association diet, in which the fat content decreases progressively, and diets recommended by the American Diabetes Association) on ROS generation. Clearly, a progressive decrease in fat content should reduce the potential for lipid peroxidation. Similarly, the 10% fat content in the diet proposed by Ornish et al (23) should reduce the oxidative load further. Indeed, this diet was shown previously to reverse atherosclerosis and to reduce the risk of myocardial ischemia.

The significant increase in plasma TBARS concentrations after the cream challenge (which was evident at 1 h and persisted until 3 h) is important because it indicates a protracted increase in oxidatively damaged lipids. The TBARS concentration in cream was 5.6 μmol/L. Because the volume of cream administered to volunteers was 100 mL, the load of TBARS provided was 0.56 μmol per 100 mL cream. This would produce a maximal increase of 0.15 μmol/L if we assume that TBARS is distributed only in plasma. Because the distribution volume of TBARS is likely to be larger, the increase in TBARS concentrations as a result of cream intake would probably be even smaller. Thus, the increase in plasma TBARS after the cream challenge was probably due to lipid peroxidation in vivo.

The mechanism underlying the increase in ROS generation by leukocytes requires further investigation. In a previous study, we showed that glucose causes an increase in NADPH oxidase in leukocytic membranes as reflected in the p47phox (i.e., a component of NADPH oxidase in which “phox” is phagocyte oxidase) subunits (11), which are essential to the formation of NADPH oxidase complex in the membrane. NADPH oxidase is the enzyme that generates the superoxide radical (24, 25). It is possible that lipid and protein intakes also increase the activity of NADPH oxidase and its content in leukocytic membranes.

The link between nutrition, oxidative load, and lipid peroxidation is an important one because the oxidative damage of lipids, particularly of the LDL particle, may result in the formation of foam cells, the fatty streak, and atherogenic plaque (26). Oxi-
dized LDL is internalized via the scavenger receptor of the subendothelial macrophage, which forms the foam cells; the foam cells form the fatty streak—the initial lesion of atherosclerosis (27). The association between nutritional intake and oxidative damage is important in terms of aging. It was previously shown that there is progressive oxidative damage in the aging process in small mammals (28). Gene transfection–induced increases in catalase and superoxide dismutase result in both a reduction in oxidative damage and in a slowing of the aging process in Drosophila melanogaster (29). Although these data cannot be extrapolated to humans, it is important that oxidative damage appears to modify aging across the species. Thus, overnutrition may be both a risk of atherosclerosis and accelerated aging.

In conclusion, both lipid and protein intakes induce a reproducible increase in ROS generation by PMNs and MCNs as previously reported for glucose. The protracted significant increase in TBARS (lipid peroxidation) over 3 h after a large lipid load may potentially accelerate foam cell formation and the process of atherosclerosis. The rapid increase in TBARS observed after the cream challenge is of interest because the peak increase (1 h after intake) preceded the peak increase in triacylglycerol (2 h after intake) and coincided with the time of peak ROS generation. Clearly, cream intake increased lipid peroxidation, whereas casein intake did not. This has important implications for atherogenesis in subjects consuming diets with a high fat content because lipid peroxidation is a key step in atherogenesis.

**REFERENCES**


