Chronic coffee and caffeine ingestion effects on the cognitive function and antioxidant system of rat brains

Renata Viana Abreu [a,b], Eliane Moretto Silva-Oliveira [a], Márcio Flávio Dutra Moraes [b], Grace Schenatto Pereira [b], Tasso Moraes-Santos [a,*]

[a] Laboratório de Nutrição Experimental (LNE), Faculdade de Farmácia, Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte, Minas Gerais, 31270-901, Brazil
[b] Núcleo de Neurociências, Departamento de Fisiologia e Biofísica, Instituto de Ciências Biológicas, Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte, Minas Gerais, 31270-901, Brazil, 31270-901

ABSTRACT

Coffee is a popular beverage consumed worldwide and its effect on health protection has been well studied throughout literature. This study investigates the effect of chronic coffee and caffeine ingestion on cognitive behavior and the antioxidant system of rat brains. The paradigms of open field and object recognition were used to assess locomotor and exploratory activities, as well as learning and memory. The antioxidant system was evaluated by determining the activities of glutathione reductase (GR), glutathione peroxidase (GPx) and superoxide dismutase (SOD), as well as the lipid peroxidation and reduced glutathione content. Five groups of male rats were fed for approximately 80 days with different diets: control diet (CD), fed a control diet; 3% coffee diet (3%Co) and 6% coffee diet (6%Co), both fed a diet containing brewed coffee; 0.04% caffeine diet (0.04%Ca) and 0.08% caffeine diet (0.08%Ca), both fed a control diet supplemented with caffeine. The estimated caffeine intake was approximately 20 and 40 mg/kg per day, for the 3%Co–0.04%Ca and 6%Co–0.08% Ca treatments, respectively. At 90 days of life, the animals were subjected to the behavioral tasks and then sacrificed. The results indicated that the intake of coffee, similar to caffeine, improved long-term memory when tested with object recognition; however, this was not accompanied by an increase in locomotor and exploratory activities. In addition, chronic coffee and caffeine ingestion reduced the lipid peroxidation of brain membranes and increased the concentration of reduced-glutathione. The activities of the GR and SOD were similarly increased, but no change in GPx activity could be observed. Thus, besides improving cognitive function, our data show that chronic coffee consumption modulates the endogenous antioxidant system in the brain. Therefore, chronic coffee ingestion, through the protection of the antioxidant system, may play an important role in preventing age-associated decline in the cognitive function.

© 2011 Elsevier Inc. All rights reserved.

1. Introduction

There is a general agreement on the existence of a normal cognitive decline from early to late adulthood and that disorders, such as Alzheimer's disease (AD), are associated with an overall impairment of higher functions and cognitive faculties, one of which is a symptomatic loss of memory (Bertaina-Anglade et al., 2006). Evidence suggests that a progressive accumulation of oxidative damage to the brain may well lead directly to such age-associated cognitive losses (Head, 2009; Martin and Grotewiel, 2006). Taking these arguments into consideration, the oxidative damage theory was proposed in an attempt to explain the underlying biological mechanisms of age-associated cognitive impairment. This theory postulates that the age-dependent accumulation of oxidative damage to macromolecules in the brain causes a progressive functional deterioration of cells, tissues, and organ systems, which commonly appear as functional senescence (Weinert and Timinas, 2003). Oxidative damage to lipids, proteins, and DNA occurs primarily through reactive oxygen species (ROS) actions. The brain, in particular, is highly vulnerable to ROS, as it consumes approximately 20% of the body's total oxygen and contains a high content of polyunsaturated fatty acids and lower levels of endogenous antioxidant activity as compared to other tissues (Halliwell and Gutteridge, 1985). A wide array of enzymatic and non-enzymatic antioxidant defenses exist, including superoxide dismutase (SOD), glutathione peroxidase (GPX), catalase (CAT), glutathione (GSH), beta-carotene, ascorbic acid (vitamin C), and alpha-tocopherol (vitamin E). A balance can be identified between both the activities and the intracellular

* Corresponding author at: Faculdade de Farmácia, Universidade Federal de Minas Gerais. Departamento de Alimentos—Sala 2099-B3, Av. Antônio Carlos, 6627, Pampulha, 31270-901—Belo Horizonte, MG, Brazil. Tel.: +55 31 3409 6917; fax: +55 31 3409 6989.
E-mail address: tmoraes@ufmg.br (T. Moraes-Santos).

levels of these antioxidants which are essential for the survival of organisms and their health (Matés and Sánchez-Jiménez, 1999).

In recent years, based on this possible link between oxidative damage and cognitive decline, there has been a growing interest in studying diet bioactive compounds that delay or prevent cell damage, provide symptomatic relief, and improve people's quality of life. Coffee, a very popular beverage consumed worldwide, has been extensively studied as a protective food, able to produce physiological or metabolic effects on the human organism, adapting it to withstand environment adversities. Research has shown that caffeine, a major constituent of coffee, induces a broad spectrum of cellular and pharmacological responses, such as the central nervous system and motor activity stimulation (Fredholm et al., 1999), cognitive performance improvement (Cunha and Agostinho, 2010), anxiety and sleep disturbance (Nardi et al., 2009; Paterson et al., 2009), antioxidant activity (Noschang et al., 2009; Shi et al., 1991), among others. Besides caffeine, coffee contains a number of other substances—phenolic polymers, chlorogenic acids, lipids, and terpenes—that have different biological effects, such as antioxidant (Cho et al., 2009; Natella et al., 2002), anticarcinogenic (Cavin et al., 2002), antimicrobial (Almeida et al., 2006), and neuroprotection activities (Herraiz and Chaparro, 2006; Hwang and Jeong, 2008). Despite the known effects of coffee isolated components, little is known about the effect of brewed coffee, where functional interactions among components may well increase or decrease individual action, rendering the beverage a potential protective food against events that can lead to a decline in brain functions. Evidence suggests that in humans there is a link between chronic coffee/caffeine consumption and cognitive performance (Ritchie et al., 2007; Santos et al., 2010). However, very little is known about how coffee ingestion really affects cognitive function.

Therefore, the present study was carried out to assess the effect of chronic coffee and caffeine ingestion on cognitive performance in rats by modulating the endogenous antioxidant system of the brain.

2. Material and methods

2.1. Diets

The control diet was prepared using a mixture of 80% of a powdered rat lab chow (Labina, Purina, Paulínia, SP, Brazil) and 20% of powdered dog food (Bonzo, Purina, Paulínia, SP, Brazil). For every 90 g of the mixture, 100 ml of a solution containing 4% commercial gelatin, 1% cornstarch, and 5% sugar in hot water was added. The formed dough was pelleted and dried at 60 °C in a forced air oven (Nova Ética 420-D, Vargem Grande Paulista, SP, Brazil) for a time necessary to return the diet weight to 100 g.

The present study used the *Coffea arabica* species, cultivated in the southern regions of the state of Minas Gerais (Brazil), an exportation type, grain with no defects, with an average granulation and processed by toasting at a temperature of 160 °C for nearly 13 min, at classification 45. The classification of the toasting point was determined by using the Roast Color Classification System (AGTRON/SCAA, 1995), according to the standards applied by the Brazilian Coffee Industry Association (ABIC). The content of caffeine in coffee powder was 12.5 mg caffeine/g of coffee (1.25%), determined by HPLC.

Boiled, distilled water was added to milled toasted coffee at a concentration of 3% w/v and 6% w/v. The suspension was centrifuged (27 xg) for 10 min and the supernatant was collected (Centrifuge Hitachi CR21, Hitachinaka, Japan). The diet supplemented with coffee used the control diet as a basis. However, to this diet, 100 mL of 3% or 6% brewed coffee, containing the gelatin/starch/sugar solution described above, was added to prepare the dough. Similarly, the diet supplemented with caffeine was based on the control diet. However, in this case, the solution formulated to prepare the dough contained caffeine at the concentration of 0.04% or 0.08% (values

corresponding to caffeine content in the diet with coffee at 3% and 6%, respectively). The remaining procedure for preparing the control diet was then carried out. Control and experimental coffee and caffeine diets were prepared weekly in the laboratory and stored at 4 °C.

2.2. Animals

Female Wistar rats were mated. During the gestation and lactation period, they were fed a diet composed of rat lab chow (Labina, Purina, Paulínia, SP, Brazil), enriched with 20% dog food (Bonzo, Purina, Paulínia, SP, Brazil). Shortly after birth, when the pups were cleaned and fed by the mother, eight per dam were maintained, with as many male rats as possible. At weaning (21 days of life), the dams and female pups were discarded. The male rats were randomly divided into five groups (n = 16), with one animal per cage: (1) control diet (CD)—fed the control diet; (2) 3% coffee diet (3%Co)—fed a diet containing 3% of brewed coffee; (3) 6% coffee diet (6%Co)—fed a diet containing 6% of brewed coffee; (4) 0.04% caffeine diet (0.04%Ca),—fed a control diet supplemented with 0.04% caffeine; and (5) 0.08% caffeine diet (0.08%Ca)—fed a control diet supplemented with 0.08% caffeine.

Water was offered *ad libitum*. Every other day, the dietary consumption was determined by subtracting the weight of the amount of food offered (in the two days before) from that not ingested. The animal's body weight was monitored weekly.

At 90 days of life, the animals were subjected to two behavioral tasks: open field and object recognition memory (novel object preference). At approximately 100 days of life, the rats were sacrificed by decapitation. The brain was processed for further biochemical analysis of oxidative stress markers. The experimental protocol was in accordance with the Ethical Principles for Animal Experimentation as established by the Ethics Committee on Animal Experiments from the Federal University of Minas Gerais, Brazil (protocol nº 126/2007).

2.3. Behavioral test

Apparatus—Open field and novel preference tasks occurred in an open-topped arena (50×50×40 cm) made of acrylic. The walls inside the arena were surrounded with a black paper so that no external stimuli could be seen during the experiment, and the floor of the arena was divided into sixteen quadrants of equal size, using thin indentation marks, into a 4×4 matrix of squares (12.5×12.5 cm). The stimuli presented in the object recognition test were copies of objects composed of plastic pieces (Gulliver, São Caetano do Sul, SP, Brazil) that varied in shape, color, and size and were fixed to the floor of the arena to avoid moving during tasks. After each trial, the objects were thoroughly cleaned with a 75% ethanol solution to remove odor cues.

Prior to each behavioral test, the animals were placed in the testing room 20 min before the task to allow habituation to the environment. All tasks were performed between noon and 4 p.m. The observer (unaware of the experimental group being tested) made direct visual observations for both open field test and new subject preference task.

Open field—To analyze exploratory and locomotor activities, as well as non-associative habituation memory, animals were placed in the left rear quadrant of the arena described above. The observer took note every time the animal crossed from one square to another (number of crossings). The observer also counted the number of rearings ("erect" posture sustaining weight on hind limbs, with fore limbs elevated and head usually in profile). The number of line crossings and the number of rearings were measured in 5 min periods on 2 consecutive days.

Novel preference task—The animals were habituated to the arena without stimuli for 20 min daily for 3 days before beginning the behavioral test. The task consisted of an acquisition or sample phase, followed by two preference tests, one after a delay of 90 min (short-term memory) and another 24 h after the sample phase (long-term

memory). In the sample phase, duplicate copies (A1 and A2) of an object were placed near the two corners at either end of one side of the arena (15 cm from each adjacent wall). The animal was placed in the arena facing the center of the opposite wall and allowed 5 min for exploration. After 90 min, the animal was replaced in the arena, presented with two objects in the same positions: one object (A3) was a third copy of the set of the objects used in the sample phase, while the other object was a novel object (B). Using two distinct chronometers, the observer quantified the total time spent exploring each object placed in the arena, within a 5-minute time window. The second test phase was performed after 24 h, with a copy of the object used in the sample phase (A4) and a new object (C) (Ennaceur and Delacour, 1988).

The positions of the objects in the test and the objects used as novel or familiar were counterbalanced between the animals.

Exploratory behavior of a particular object was defined as the animal directing its nose toward the object at a distance of <2 cm. Any other behavior, such as looking around while sitting on or resting against the object, was not considered as exploration.

The discrimination index was calculated as the time spent by each animal exploring the novel object divided by the total time spent exploring both objects.

2.4. Biochemical analysis

Brain homogenate—After removing the cerebellum, the brain was weighed, homogenized in 10 volumes (1:10 w/v) of sodium phosphate buffer at 50 mM plus KCl 140 mM, pH 7.4, and centrifuged at $750 \times g$ for 10 min (Centrifuge Hitachi CR21, Hitachinaka, Japan). The supernatant was collected. Aliquots of 1.0 ml of all samples were frozen in liquid nitrogen and subsequently stored in a freezer at −70 °C until further processing.

Biochemical analysis—The lipid peroxidation index was determined according to Yagi (1984), whereas the glutathione (GSH) content was determined according to Tietze (1969). The activity of glutathione peroxidase was determined according to Paglia and Valentine (1967), whereas the glutathione reductase was determined according to Carlberg and Mannervik (1975). The superoxide dismutase activity was determined according to Marklund and Marklund (1974) and was based on the inhibition of pyrogallol auto oxidation.

Measurements in all assays described were carried out in triplicate. The protein amount in all samples was determined according to Lowry et al. (1951) and modified by Hartree (1972). All chemicals used were of analytical grade and were purchased from Sigma Chemical Co. (St. Louis, MO, USA).

2.5. Statistical analysis

Open field crossing, as well as memory data of rearing values and object recognition, underwent ANOVA analysis. The significant differences in the experimental values were determined using the Duncan test and Bonferroni test, respectively.

ANOVA, followed by the Duncan test, was applied to biochemical data. Values were considered statistically different at $P < 0.05$.

3. Results

Diet supplemented with of 3% or 6% coffee extract and 0.04% or 0.08% caffeine, as compared to the control group, had no effect on the rats' food consumption and body weight gain (Table 1).

The effect of diet supplementation with coffee or caffeine on the rats' locomotor and exploratory activities was evaluated by an open field test and is shown in Table 2. The intake of coffee or caffeine in the diet, as compared to the control group, did not modify the number of crossings and rearings in the open field test, indicating that the presence of coffee or caffeine in the diet did not increase the exploratory activity of these animals. All experimental groups showed a lower number of locomotor and exploratory activities on the second

Table 2
Open field: number of line crossings and number of rearings measured on 2 consecutive days.

Groups	Crossing		Rearing	
	Day 1	Day 2	Day 1	Day 2
CD	62.3 ± 4.0	47.5 ± 4.2*	13.9 ± 1.2	8.1 ± 1.1**
3%Co	61.7 ± 4.1	38.0 ± 4.9*	9.3 ± 1.3	6.3 ± 0.6**
6%Co	65.4 ± 4.5	42.8 ± 2.4*	12.9 ± 1.4	5.4 ± 0.8**
0.04%Ca	66.6 ± 5.0	37.6 ± 4.8*	14.5 ± 2.5	5.6 ± 0.9**
0.08%Ca	62.1 ± 3.7	38.1 ± 4.3*	12.2 ± 1.5	6.3 ± 1.1**

All values are mean ± SEM (n = 16). No statistical difference could be observed among the groups on the same day (column) according to ANOVA and Duncan test (p<0.05). * and ** indicate statistical difference (p<0.05—Duncan test) in the same group from day 1 to day 2 in crossings and rearings, respectively. Crossing is defined as the number of lines crossed by the animal in the arena. Rearing means the number of times the animal stood in erect posture. CD represents the control group; 3%Co, the group supplemented with 3% brewed coffee; 6%Co, the group supplemented with 6% brewed coffee; 0.04%Ca, the group supplemented with 0.04% caffeine; and 0.08%Ca, the group supplemented with 0.08% caffeine.

Table 1
Diet ingestion and body weight gain in the rats.

Days						
	21	35	50	65	80	95
Food consumption (g)						
CD	3.12 ± 0.41	14.45 ± 0.35	22.05 ± 0.52	24.63 ± 0.65	24.07 ± 0.51	23.74 ± 0.52
3%Co	3.77 ± 0.46	14.23 ± 0.58	23.08 ± 0.53	25.48 ± 0.79	25.79 ± 0.56	23.47 ± 0.65
6%Co	3.79 ± 0.61	14.21 ± 0.45	22.79 ± 0.69	24.86 ± 0.89	25.32 ± 0.85	24.18 ± 0.69
0.04%Ca	3.69 ± 0.45	13.79 ± 0.40	22.11 ± 0.57	23.93 ± 0.55	24.51 ± 0.42	23.63 ± 0.53
0.08%Ca	3.89 ± 0.46	13.78 ± 0.37	22.50 ± 0.53	24.32 ± 0.67	24.67 ± 0.69	24.95 ± 0.57
Body weight (g)						
CD	48.66 ± 1.12	125.16 ± 2.39	230.48 ± 4.55	316.24 ± 6.55	370.41 ± 7.11	395.21 ± 7.95
3%Co	49.44 ± 1.14	123.83 ± 2.70	231.97 ± 4.02	322.38 ± 6.71	383.91 ± 7.79	408.87 ± 8.22
6%Co	48.01 ± 1.21	121.07 ± 2.23	225.94 ± 3.67	312.82 ± 7.13	374.85 ± 7.90	398.11 ± 7.90
0.04%Ca	47.75 ± 1.19	120.60 ± 2.17	225.01 ± 4.47	312.44 ± 5.22	378.54 ± 6.15	394.61 ± 7.13
0.08%Ca	48.77 ± 0.93	123.22 ± 2.50	225.37 ± 4.86	319.50 ± 5.34	374.94 ± 6.77	403.09 ± 7.26

All values are mean ± SEM (n = 16). Although food consumption was assessed every couple of days and body-weight was assessed weekly, this table depicts six chosen periods (days 21, 35, 50, 65, 80 and 95) in order to show the time evolution of coffee/caffeine consumption per body weight along the experiment. No statistical difference was observed among the groups on the same day (column) according to ANOVA and Duncan test (P<0.05). CD fed lab chow; 3%Co fed 3% brewed coffee supplemented diet; 6%Co fed 6% brewed coffee supplemented diet; 0.04%Ca fed 0.04% caffeine supplemented diet, and 0.08%Ca fed 0.08% caffeine supplemented diet. The estimated caffeine intake in these animals was about 20 and 40 mg/kg per day, for the 3%Co–0.04%Ca and 6%Co–0.08%Ca treatments, respectively.
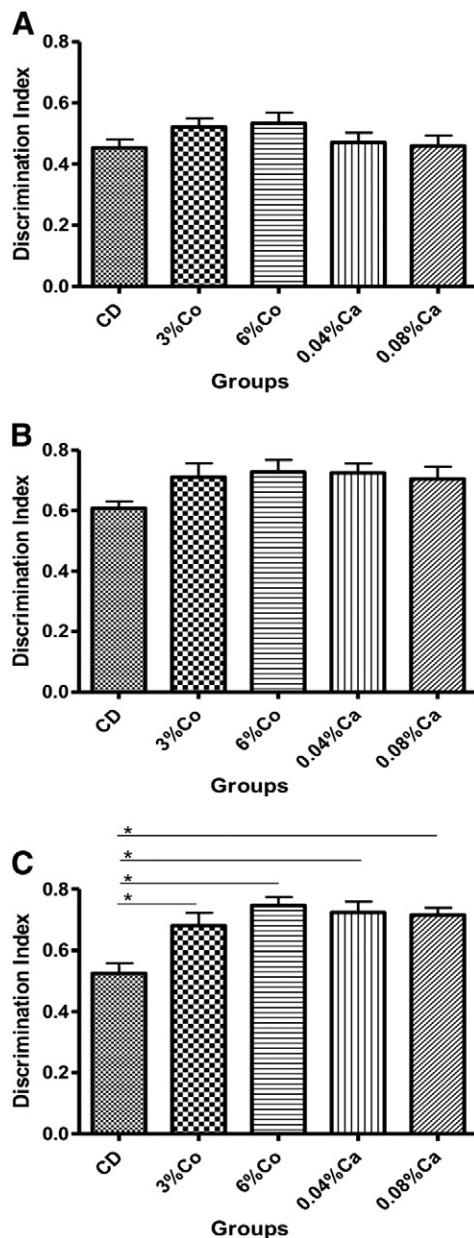
Fig. 1. Effect of daily coffee or caffeine ingestion in (A) sample phase, (B) test phase after 90 min and (C) test phase after 24 h of object recognition memory task. The discrimination index was calculated as the time spent by each animal exploring the novel object divided by the total time spent exploring both objects. Values are presented as the mean ± SEM (n = 16). CD represents the control diet; 3%Co, the group supplemented with 3% brewed coffee; 6%Co, the group supplemented with 6% brewed coffee; 0.04%Ca, the group supplemented with 0.04% caffeine; and 0.08%Ca, the group supplemented with 0.08% caffeine. *p < 0.05 (ANOVA and Bonferroni test).

day (lower number of crossings and rearings) (P < 0.05), demonstrating the intactness of non-associative memory.

Neither coffee nor caffeine affected the total time of exploration in both objects during the sample phase (data not shown). Fig. 1 shows the performance of the groups in the sample and tests phases. There was no statistical difference in the discrimination of objects between the control group and groups supplemented with coffee or caffeine during the test phase carried out after 90 min. However, in the test phase performed after 24 h, the groups that ingested coffee (3% or 6%) or caffeine (0.04% or 0.08%) diet performed better (higher discrimination index) than did the control group.

The influence of coffee or caffeine on the cerebral antioxidant system was also assessed. The results are summarized in Table 3. A

decrease in the content of TBARS (38%) in rats that ingested coffee or caffeine in the diet was observed. On the other hand, coffee 6% and caffeine 0.08% increased the GSH content by 60%. Diet supplementation with coffee or caffeine, as compared to the control group, induced a significant increase (56%) in GR activity but did not affect the GPx activity. Furthermore, an increase of 54% in superoxide dismutase (SOD) activity in the groups fed a diet supplemented with 6% coffee extract or caffeine could be observed.

4. Discussion

To evaluate the effect of chronic coffee ingestion on the cognitive function and antioxidant system modulation, the animals received a diet supplemented with brewed coffee (3% and 6%), and the corresponding doses of 0.04% and 0.08% caffeine after weaning. These diets were administered daily over the experimental life of the animals. According to prior studies conducted by our research group (Silva-Oliveira et al., 2010), and confirmed in this study, the addition of coffee or caffeine to the rat's diet did not alter food intake nor did it have any observable impact on the body weight of all groups studied.

The concentrations of 3% and 6% of coffee in the diet were based on the literature (Huber et al., 2003; Turesky et al., 2003) and on data from our research group that showed that the intake of coffee/caffeine in this concentration range is capable to produce physiological and metabolic effects in different biological systems of rats, without toxic effects. However, these doses of coffee and caffeine used in this experimental animal model study were raised according to daily human consumption. The estimated caffeine intake in these animals was approximately 20 and 40 mg/kg/day, for the 3% and 6% coffee groups, respectively. By contrast, the estimated intake of caffeine in humans drinking 2 cups of coffee daily is approximately 4 mg caffeine/kg body weight, whereas for heavy coffee drinkers the amount may reach 15 mg/kg (Turesky et al., 2003). But it is important to consider, in addition to body weight, the rate of caffeine metabolism, which is faster in rats than in humans, see pharmaco-kinectis studies from Fredholm et al. (1999) for details. The caffeine dose chosen (4 mg/kg/day) is also based on the report from van Gelder et al. (2007) who found best protection in elderly cognition decline by drinking 3 cups of coffee per day (375 ml/day), which is around 255 mg/day of caffeine for an approximate body weight of 60–70 kg.

The effects of coffee's individual components on learning and memory have been reported in different animal models; however the results of these studies are contradictory (Costa et al., 2008a, 2008b; Kwon et al., 2010; Myoung-Eun et al., 2007; Soellner et al., 2009). Most examined the acute effects of these components. Thus, the long-term effects of coffee consumption on the central nervous system of mice have been poorly characterized. Functional interactions among components can increase or decrease individual actions. Therefore, this study focused on the effects of coffee consumption over the experimental life of the animals, which can better reflect an overall human consumption.

Our results showed that coffee (3% or 6%) or caffeine (0.04% or 0.08%) groups presented a better consolidation of long-term memory than did the control group. Costa et al. (2008a, 2008b) also showed that caffeine treatment, when compared to the control group, increases the object discrimination index, reinforcing its positive effects on short-term and long-term memories. In addition, caffeine administration during the adult life of mice prevented the age-associated decline in recognition memory of objects. Moreover, aged animals treated with caffeine showed a similar performance to adult animals in the novel preference task (Costa et al., 2008b).

The results obtained in the open field test showed that diet supplementation with coffee or caffeine had no effect on the locomotor and exploratory activities of animals, i.e., improvement in the cognitive performance of the animals by the ingestion of coffee or

Table 3
Effect of daily coffee or caffeine ingestion on the endogenous antioxidant system of the brain.

	TBARS (nmol TBA/mg prot)	GSH (nmol GSH/mg prot)	GPx (μmol NADPH/min/mg prot)	GR (μmol NADPH/min/mg prot)	SOD (U/mg prot)
CD	2.37 ± 0.22	7.55 ± 0.67	10.28 ± 0.99	31.23 ± 3.20	1.56 ± 0.09
3%Co	1.33 ± 0.07 [*]	8.44 ± 0.68	9.96 ± 0.77	47.20 ± 3.76 [*]	1.73 ± 0.13
6%Co	1.31 ± 0.08 [*]	12.66 ± 0.52 [*]	12.01 ± 1.01	47.55 ± 4.56 [*]	2.29 ± 0.18 [*]
0.04%Ca	1.48 ± 0.09 [*]	9.88 ± 0.55	10.55 ± 0.72	49.76 ± 1.66 [*]	2.52 ± 0.25 [*]
0.08%Ca	1.79 ± 0.12 [*]	11.99 ± 1.13 [*]	12.30 ± 1.01	50.58 ± 4.97 [*]	2.42 ± 0.20 [*]

All values are mean $\pm$ SEM (n = 8). The antioxidant system was evaluated by determining the activities (normalized by mg of total protein) of glutathione (GSH), glutathione peroxidase (GPx), glutathione reductase (GR) and superoxide dismutase (SOD), as well as the lipid peroxidation and reduced glutathione content (TBARS). CD represents the control group; 3%Co, the group supplemented with 3% brewed coffee; 6%Co, the group supplemented with 6% brewed coffee; 0.04%Ca, the group supplemented with 0.04% caffeine; and 0.08%Ca, the group supplemented with 0.08% caffeine. *indicates statistical difference (p<0.05—ANOVA and Duncan test) between groups for each biochemical analysis.

caffeine was not accompanied by an increase in sensory and motor functions of the animals. Moreover, all experimental groups showed lower locomotor and exploratory activities on the second day (lower number of crossings and rearings), demonstrating an intactness of non-associative memory. Arendash et al. (2006), in a study of the chronic administration of caffeine (four to eight months of age) in transgenic mice used as models for Alzheimer's disease, also presented similar results. Caffeine showed a cognitive protection in multiple tests involving a variety of cognitive domains, such as spatial memory, working memory, and identification. These cognitive benefits of the long-term administration of caffeine showed no significant side effects in sensory and motor functions or in the level of anxiety, which can be affected by the acute administration of caffeine. Therefore, it can be concluded that the chronic consumption of moderate doses of coffee/caffeine does indeed have beneficial effects on cognition without altering sensory and motor functions.

Furthermore, our results demonstrated that the beneficial effects of chronic caffeine administration in the cognitive performance of adults and aged animals (Angelucci et al., 1999; Costa et al., 2008a, 2008b; Dall'igna et al., 2007) could also be observed with brewed coffee. Those data point to caffeine as an important component responsible for the protective role of coffee. Caffeine acts on the central nervous system as an antagonist of adenosine receptors. Although the blockade of A_1 and A_{2A} adenosine receptors has been attributed primarily to the psychoactive effects of caffeine, recent studies have shown that neuroprotection appears to be due mainly to the blockade of A_{2A} receptors (Dall'igna et al., 2003; Cunha, 2005). Though the density of A_{2A} receptors is more prevalent in the striatum, lower density in the hippocampus does not imply a lesser role in the information processing in this region of the brain. A recent study showed that long-term potentiation dependent on N-methyl-D-aspartate (NMDA) receptors depends on adenosine A_{2A} postsynaptic activation (Rebola et al., 2008). Similarly, the prevention of cognitive decline and the improvement in this performance due to caffeine in animals are often reproduced by selective A_{2A} antagonists, but not by A_1 antagonists (Cunha et al., 2008; Prediger et al., 2005). In addition, the genetic and pharmacological blockade of A_{2A} receptors prevents memory impairment in a rodent model of Alzheimer's disease (Canas et al., 2009). Thus, taken altogether, these data further substantiate the effects of caffeine targeting A_{2A} rather than A_1 receptors; although the actions of the remaining components of coffee ingestion on memory cannot be readily discarded.

The present work showed that chronic coffee and caffeine ingestion modulated the antioxidant system in rat brains. This effect may well be involved in the mechanism by which coffee consumption improves the capability of learning and memorization in animals. Pathological events, such as oxidative stress due to high generation of free radicals, with a subsequent increase in the oxidative modification of lipids, proteins, and nucleic acids, contribute significantly to a loss in the cognitive function (Bishop et al., 2010; Head, 2009; Martin and Grotewiel, 2006). Thus, daily coffee intake, because of its protective effect on the endogenous antioxidant system, can also result in a beneficial effect on learning and memory.

The chronic consumption of coffee in this study decreased the lipid peroxidation of the membranes; increased the concentration of glutathione, a potent endogenous antioxidant; and increased the activity of two antioxidant enzymes, glutathione reductase and superoxide dismutase. Undoubtedly, these beneficial effects of coffee on antioxidant properties are partly due to caffeine, as has been demonstrated in this study and in previous studies (Inkielewicz-Stepniak and Czarnowski, 2010; Nobre et al., 2010; Noschang et al., 2009; Prasanthi et al., 2010). It has been demonstrated that the adenosine receptors, the main molecular target of caffeine, are involved in the regulation of ROS production, affecting the genesis and impact of free radicals in neuronal and others biological systems (Agostinho et al., 2000; Almeida et al., 2003; Thakur et al., 2010). However, the importance of other coffee components in the beverage's antioxidant capacity should not be discarded. Coffee phenolic compounds, such as caffeic acid and chlorogenic acid, showed beneficial effects on the attenuation of oxidative stress (Cho et al., 2009; Huang et al., 2004; Lee and Zhu, 2006). Kahweol and cafestol, two coffee diterpenes, also contain antioxidant properties, especially in the glutathione homeostasis (Huber et al., 2002, 2003; Lee and Jeong, 2007). Therefore, the protective action of caffeine against oxidative stress is most likely modulated in coffee by the biological activity of other beverage compounds, making coffee an important protective food against oxidative damage and associated cognitive decline.

References

Agostinho P, Caseiro P, Rego AC, Duarte EP, Cunha RA, Oliveira CR. Adenosine modulation of D-[3H]aspartate release in cultured retina cells exposed to oxidative stress. Neurochem Int 2000;36:255–65.

Almeida AA, Farah A, Silva DA, Nunan EA, Glória MB. Antibacterial activity of coffee extracts and selected coffee chemical compounds against enterobacteria. J Agric Food Chem 2006;54:8738–43.

Almeida CG, de Mendonça A, Cunha RA, Ribeiro JA. Adenosine promotes neuronal recovery from reactive oxygen species induced lesion in rat hippocampal slices. Neurosci Lett 2003;339:127–30.

Angelucci MEM, Vital MABF, Cesário C, Zadusky CR, Rosalen PL, Da Cunha C. The effect of caffeine in animal models of learning and memory. Eur J Pharmacol 1999;373: 135–40.

Arendash GW, Schleif W, Rezai-Zadeh K, Jackson EK, Zacharia LC, Cracchiolo JR, et al. Caffeine protects Alzheimer's mice against cognitive impairment and reduces brain ß-amyloid production. Neuroscience 2006;142:941–52.

Bertaina-Anglade V, Enjuanes E, Morillon D, Drieu LA, Rochelle C. The object recognition task in rats and mice: a simple and rapid model in safety pharmacology to detect amnesic properties of a new chemical entity. J Pharmacol Toxicol Methods 2006;54:99–105.

Bishop NA, Lu T, Yanker BA. Neural mechanisms of ageing and cognitive decline. Nature 2010;464:529–35.

Canas PM, Porciúncula LO, Cunha GM, Silva CG, Machado NJ, Oliveira JM, et al. Adenosine A_{2A} receptor blockade prevents synaptotoxicity and memory dysfunction caused by beta-amyloid peptides via p38 mitogen-activated protein kinase pathway. J Neurosci 2009;29:14741–51.

Carlberg I, Mannervik B. Purification and characterization of the flavoenzyme glutathione reductase from rat liver. J Biol Chem 1975;250:5475–80.

Cavin C, Holzhaeuser D, Scharf G, Constable A, Huber WW, Schilter B. Cafestol and kahweol, two coffee specific diterpenes with anticarcinogenic activity. Food Chem Toxicol 2002;40:1155–63.

Cho ES, Jang YJ, Hwang MK, Kang NJ, Lee K, Lee HJ. Attenuation of oxidative neuronal cell death by coffee phenolic phytochemicals. Mutat Res 2009;661:18–24.

Costa MS, Botton PH, Mioranzza S, Ardis AN, Moreira JD, Souza DO, et al. Caffeine improves adult mice performance in the object recognition task and increases BDNF and TrkB independent on phospho-CREB immunocontent in the hippocampus. Neurochem Int 2008a;53:89–94.

Costa MS, Botton PH, Mioranzza S, Souza DO, Porciuncula LO. Caffeine prevents age-associated recognition memory decline and changes brain-derived neurotrophic factor and tyrosine kinase receptor (trkb) content in mice. Neuroscience 2008b;153:1071–8.

Cunha GMA, Canas PM, Melo CS, Hockemeyer J, Muller CE, Oliveira CR, et al. Adenosine A$_{2A}$ receptor blockade prevents memory dysfunction caused by β-amyloid peptides but not by scopolamine or MK-801. Exp Neurol 2008;210:776–81.

Cunha RA. Neuroprotection by adenosine in the brain: from A(1) receptor activation to A(2A) receptor blockade. Purinergic Signal 2005;1:111–34.

Cunha RA, Agostinho PM. Chronic caffeine consumption prevents memory disturbance in different animal models of memory decline. J Alzheimers Dis 2010;20: 95–116.

Dall'igna OP, Porciuncula LO, Souza DO, Cunha RA, Iara DR. Neuroprotection by caffeine and adenosine A$_{2A}$ receptor blockade of beta-amyloid neurotoxicity. Br J Pharmacol 2003;138:1207–9.

Dall'igna OP, Fett P, Gomes MW, Souza DO, Cunha RA, Iara DR. Caffeine and adenosine A$_{2A}$ receptor antagonists prevent β-amyloid (25–35)-induced cognitive deficits in mice. Experim Neurol 2007;203:241–5.

Ennaceur A, Delacour J. A new one-trial test for neurobiological studies of memory in rats. 1:Behavioral data. Behav Brain Res 1988;31:47–59.

Fredholm BB, Battig K, Holmen J, Nehlig A, Zvartau EE. Actions of caffeine in the brain with special reference to factors that contribute to its widespread use. Pharmacol Rev 1999;51:83–133.

Halliwell B, Gutteridge JMC. Oxygen radicals in the nervous system. Trends Neurosci 1985;8:22–6.

Hartree EF. Determination of protein: a modification of the Lowry method that gives a linear photometric response. Anal Biochem 1972;48:422–7.

Head E. Oxidative damage and cognitive dysfunction: antioxidant treatments to promote healthy brain aging. Neurochem Res 2009;34:670–8.

Herraiz T, Chaparro C. Human monoamine oxidase enzyme inhibition by coffee and beta-carbolines norharman and harman isolated from coffee. Life Sci 2006;78: 795–802.

Huang J, Paulis T, May JM. Antioxidant effects of dihydrocaffeic acid in human EA.hy926 endothelial cells. J Nutr Biochem 2004;15:722–9.

Huber WW, Scharf G, Rossmanith W, Prutomersky S, Grasl-Kraupp B, Peter B, et al. The coffee components kahweol and cafestol induce gamma-glutamylcysteine synthetase, the rate limiting enzyme of chemoprotective glutathione synthesis, in several organs of the rat. Arch Toxicol 2002;75:685–94.

Huber WW, Scharf G, Nagel G, Prustomersky S, Schulte-hermann R, Kaina B. Coffee and its chemopreventive components kahweol and cafestol increase the activity of O-metilguanine-DNA methyltransferase in rat liver-comparison with phase II xenobiotic metabolism. Mutat Res 2003;522:57–68.

Hwang YP, Jeong HG. The coffee diterpene kahweol induces heme oxygenase-1 via the PI3K and p38/Nrf2 pathway to protect human dopaminergic neurons from 6-hydroxydopamine-derived oxidative stress. FEBS Lett 2008;582:2655–62.

Inkielewicz-Stepniak I, Czarnowski W. Oxidative stress parameters in rats exposed to fluoride and caffeine. Food Chem Toxicol 2010;48:1607–11.

Kwon SH, Lee HK, Kim JA, Hong SI, Kim HC, Jo TH, et al. Neuroprotective effects of chlorogenic acid on scopolamine-induced amnesia via anti-acetylcholinesterase and anti-oxidative activities in mice. Eur J Pharmacol 2010;649:210–7.

Lee WJ, Zhu BT. Inhibition of DNA methylation by caffeic acid and chlorogenic acid, two common catechol-containing coffee polyphenols. Carcinogenesis 2006;27: 269–77.

Lee KJ, Jeong HG. Protective effects of kahweol and cafestol against hydrogen peroxide-induced oxidative stress and DNA damage. Toxicol Lett 2007;173:80–7.

Lowry OH, Rosebrough NJ, Farr AL, Randal RJ. Protein measurement with the Folin phenol reagent. J Biol Chem 1951;193:265–75.

Marklund S, Marklund G. Involvement of the superoxide anion radical in the autoxidation of pyrogallol and a convenient assay for superoxide dismutase. Eur J Biochem 1974;47:469–74.

Martin I, Grotewiel MS. Oxidative damage and age-related functional declines. Mech Ageing Dev 2006;127:411–23.

Matés JM, Sánchez-Jiménez F. Antioxidant enzymes and their implications in pathophysiologic processes. Front Biosci 1999;4:339–45.

Myoung-Eun H, Kyu-Hyun P, Sun-Yong B, Bong-Seon K, Jae-Bong K, Hak-Jin K, et al. Inhibitory effects of caffeine on hippocampal neurogenesis and function. Biochem Biophys Res Commun 2007;356:976–80.

Natella F, Nardini M, Giannetti I, Dattilo C, Scaccini C. Coffee drinking influences plasma antioxidant capacity in humans. J Agric Food Chem 2002;50:6211–6.

Nardi AE, Lopes FL, Freire RC, Veras AB, Nascimento I, Valença AM, et al. Panic disorder and social anxiety disorder subtypes in a caffeine challenge test. Psychiatry Res 2009;169:149–53.

Nobre HVJ, Cunha GM, de Vasconcelos LM, Magalhães HI, Oliveira Neto RN, Maia FD, et al. Caffeine and CSC, adenosine A2A antagonists, offer neuroprotection against 6-OHDA-induced neurotoxicity in rat mesencephalic cells. Neurochem Int 2010;56: 51–8.

Noschang CG, Krolow R, Pettenuzzo LF, Ávila MC, Fachin A, Arcego D, et al. Interactions between chronic stress and chronic consumption of caffeine on the enzymatic antioxidant system. Neurochem Res 2009;34:1568–74.

Paglia DE, Valentine WN. Studies on the quantitative and qualitative characterization of erythrocyte glutathione peroxidase. J Lab Clin Med 1967;70:158–69.

Paterson LM, Wilson SJ, Nutt DJ, Hutson PH, Ivarsson M. Characterisation of the effects of caffeine on sleep in the rat: a potential model of sleep disruption. J Psychopharmacol 2009;23:475–86.

Prasanthi JR, Dasari B, Marwarha G, Larson T, Chen X, Geiger JD, et al. Caffeine protects against oxidative stress and Alzheimer's disease-like pathology in rabbit hippocampus induced by cholesterol-enriched diet. Free Radic Biol Med 2010;49: 1212–20.

Prediger RD, Fernandes D, Takahashi RN. Blockade of adenosine A$_{2A}$ receptors reverses short-term social memory impairments in spontaneously hypertensive rats. Behav Brain Res 2005;159:197–205.

Rebola N, Lujan R, Cunha RA, Mulle C. Adenosine A$_{2A}$ receptors are essential for long-term potentiation of NMDA-EPSCs at hippocampal mossy fiber synapses. Neuron 2008;57:121–34.

Ritchie K, Carriere I, De Mendonca A, Portet F, Dartigues JF, Rouaud O. The neuroprotective effects of caffeine: a prospective population study (the Three City Study). Neurology 2007;69:536–45.

Santos C, Lunet N, Azevedo A, de Mendonça A, Ritchie K, Barros H. Caffeine intake is associated with a lower risk of cognitive decline: a cohort study from Portugal. J Alzheimers Dis 2010;20:175–85.

Shi X, Dalal NS, Jain AC. Antioxidant behavior of caffeine: efficient scavenging of hydroxyl radicals. Food Chem Toxicol 1991;29:1–6.

Silva-Oliveira EM, Fernandes PA, Moraes-Santos T. Effect of coffee on chemical hepatocarcinogenesis in rats. Nutr Cancer 2010;62:336–42.

Soellner DE, Grandys T, Nunez JL. Chronic prenatal caffeine exposure impairs novel object recognition and radial arm maze behaviors in adult rats. Behav Brain Res 2009;205:191–9.

Thakur S, Du J, Hourani S, Ledent C, Li JM. Inactivation of adenosine A$_{2A}$ receptor attenuates basal and angiotensin II-induced ROS production by Nox2 in endothelial cells. J Biol Chem 2010;285:40104–13.

Tietze F. Enzymic method of quantitative determination of nanogram amount of total and oxidized glutathione. Anal Biochem 1969;27:502–25.

Turesky RJ, Richoz J, Constable A, Curtis KD, Dingley KH, Turteltaub KW. The effects of coffee on enzymes involved in metabolism of the dietary carcinogen 2-amino-1-methyl-6-phenylimidazo [4,5-b]pyridine in rats. Chem Biol Interact 2003;145: 251–65.

van Gelder BM, Buijsse B, Tijhuis M, Kalmijn S, Giampaoli S, Nissinen A, et al. Coffee consumption is inversely associated with cognitive decline in elderly European men: the FINE StudyCoffee consumption and cognitive decline. Eur J Clin Nutr 2007;61:226–32.

Weinert BT, Timinas PS. Invited review: theories of aging. J Appl Physiol 2003;95: 1706–16.

Yagi K. Assay for blood plasma or serum. Methods Enzymol 1984;105:328–31.