Effects of xenobiotics on total antioxidant capacity

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ABSTRACT
The objective of this article was to review the effects of xenobiotics on total antioxidant capacity (TAC). Measurement of TAC is appropriate for evaluation of the total antioxidant defenses of blood, cells, and different kinds of tissues and organs. TAC is reduced by alcoholism, smoking, and exposure to radiation, herbicides, carbon monoxide, carbon tetrachloride, lead, arsenic, mercury, cadmium, aluminum, and other toxic elements. The test is also an important tool in evaluating environmental and occupational exposure.

KEY WORDS: total antioxidant capacity; free radicals; GSH; trolox; xenobiotics; smoking; alcohol

Introduction
The involvement of unstable free radicals and reactive species from oxygen (ROS), nitrogen (RNS), and chlorine in cell and tissue damage is well established (Vladimirov & Proskurnina, 2010; Ferrari, 2000).

A free radical (FR) is any molecule that has one or more incomplete orbitals. A FR can gain electrons, oxidizing another atom/molecule or lose them, thus reducing an element. Some reactive oxygen species (ROS) are FR [superoxide anion (O$_2^{•−}$)], hydroxyl radical (•OH), nitric oxide (NO$^{•}$), peroxynitrite (ONOO$^{−}$), though others are not [hydrogen peroxide (H$_2$O$_2$), singlet oxygen (1O$_2$)] (Halliwell, 2011).

FR, ROS and RNS have been associated with more than a hundred diseases or pathophysiological events since they cause changes of lipids (lipid peroxidation), proteins (protein peroxidation), nucleic acids (DNA or RNA oxidation), and carbohydrates (glycosylation) (Vladimirov & Proskurnina 2010; Ferrari et al., 2009).

Since the 1960’s, many research groups have been evaluating oxidative and nitrosative stress and the antioxidant defenses by measuring the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), glutathione reductase (GSH) and glutathione peroxidase (GPx). As a consequence of oxidative phosphorylation, 3–5% of oxygen in converted to the free radical superoxide anion (O$_2^{•−}$) by mitochondria. As a further step, SOD and GPx convert O$_2^{•−}$ into hydrogen peroxide (H$_2$O$_2$). However, as H$_2$O$_2$ is also a toxic reactive oxygen species, it should also be modified to innocuous water and atomic oxygen by the enzyme CAT.

Since 1993 many interesting tests have been proposed in order to measure the total antioxidant capacity (TAC) of a biological sample (blood, saliva, urine, feces), food or vegetable extract or of living tissues and organs (Cao et al., 1993; Miller et al., 1993; Benzie & Strain, 1996; Ferrari, 2008). Yet these TAC tests measure only hydrophilic antioxidants and they are strongly influenced by the uric acid in the sample.

Although the evaluation of tissue/organ total antioxidant capacity per se is not sufficient to assess the level of oxidative/nitrosative stress, it is valuable since it provides a gross estimation of how the body can react against oxidative and nitrosative injuries (Filho et al., 2007; Constantini & Verhulst, 2009).

The aim of this article was to review the health effects of several xenobiotics and environmental hazards on TAC of living organisms, especially mammals and man.

Total antioxidant capacity and pharmaceuticals
Xenobiotic is any factor, substance or element, exogenous to the organism (alcohol, drugs, environmental and occupational contaminants, pesticides, smoking, heavy
metals). Many xenobiotics can be toxic to cells, tissues and organs, constituting environmental and occupational health problems.

In order to know if a therapeutic drug can preserve or consume the antioxidants of a patient, TAC determination is done in medicinal drugs. Thus the perioperative anesthetics dopamine (1080±16 mmol ET/L), dobutamine (80±16 mmol ET/L), and noradrenaline (62±16 mmol ET/L) were found to present higher TAC values (Mantle et al., 2000). However, the antioxidant response to occupational exposure to anesthetic gases is different. Human exposure to these gases increased mononuclear leukocyte DNA damage and oxidative stress and reduced TAC of operating room workers (Baysal et al., 2009). Measured by TAC, captopril used as antihypertensive drug has also antioxidant activity (Benzie & Tomlinson, 1998), and so have fluvastatin and simvastatin, commonly used in treatment of hypercholesterolemic patients (Franzoni et al., 2003). Another statin, atorvastatin, has also been found to enhance plasmatic TAC and decrease oxidative stress in coronary artery disease dislipidemic patients (Buyukhatipoglu et al., 2010). Natural flavonoids like pomiferin also protected rats against ischemic-reperfusion kidney injury by decreasing lipid peroxidation and GPx, and improving the SOD and TAC levels (Bartošíková et al., 2010).

Paracetamol administration induced liver damage associated with increased lipid peroxidation, decreased catalase, GSH, and total thiols (Ashok-Kumar et al., 2010). Oral intake of paracetamol over 14 days was associated with a drastic reduction of blood TAC in healthy subjects (Nuttal et al., 2003). In a similar manner, administration of the cyclooxygenase inhibitor indometacin induced depletion of GSH, stomach epithelium mucin, and total antioxidant capacity, concomitantly increasing lipid and protein peroxidation in gastric mucosa of mice (Adhikary et al., 2011).

**Effects of chemical poisoning on TAC**

Carbon tetrachloride (CCl₄), one of the most potent liver toxins, presents a toxicological dose-response effect characterized by oxidative stress and lipid peroxidation events that induce reduction of liver TAC, liver degeneration, necrosis and fibrosis (Dianzani & Ugazio, 1973; Ugazio et al., 1973; Hassan et al., 2003; Mahmoud & Hijazi 2007; Wu et al., 2008).

Many heavy metals and other inorganic elements can contaminate the environment, causing bioaccumulation in plants and animals, intoxication in birds and other animals, including humans. The most important pathological mechanism is metal-induced oxidative stress which affects bivalves molluscs, aquatic insects, fishes, birds, and humans (Taylor, 2009; Xie et al., 2009; Zheng et al., 2011; Koivula & Eeva, 2010; Verlekar & Chaliny, 2008; Guilherme et al., 2008; Kobal et al., 2008). The toxicity effects of contaminating elements or compounds are presented in Table 1.

Lead exposure was associated with hypertension, higher activation of angiotensin-converting enzyme, increased levels of lipid peroxidation, and lower levels of nitric oxide and total antioxidant capacity (Alghasham et al., 2011).

As metallothionines (MTs) are important metal-scavenging proteins protecting cells against cadmium, mercury, zinc and copper cytotoxicity (Kang, 2006; Aschner et al., 2006; Agarwal et al., 2010), newer studies are important to address the potential of MTs to improve cell and tissue TAC in patients.

**Alcohol, oxidative stress and total antioxidant capacity**

Moderate alcohol drinking can increase TAC, whereas daily and higher ingestion of alcoholic beverages reduce blood TAC (Brighenti et al., 2005) reinforcing the knowledge that chronic alcohol intake contributes to oxidative stress, lipid peroxidation, mitochondrial damage and failure, depletion of GSH cytosolic stores, liver injury and hepatocyte apoptosis (Liu, 2004; Cederbaum et al., 2009). Lung injury due to alcoholism is in part derived from a proinflammatory reaction and an intense oxidative stress linked to depletion of GSH stores (Burnham et al., 2003; Boé et al., 2009). Alcoholic patients presented with lower SOD and GPx activities and higher values of lipid peroxidation yet normal CAT activity (Huang et al., 2009). After alcohol conversion to acetaldehyde, lipid peroxidation reactions are triggered; further, alcohol metabolism in hepatic microsomal systems is also associated with increased production of reactive oxygen species (Pisa et al., 2010). This is in accordance with other studies in which there was no significant change in plasma TAC after alcohol drinking (Bhardwaj et al., 2008).

**Occupational and environmental xenobiotics: effects on TAC**

**Smoking and depletion of total antioxidant capacity**

Environmental pollutants can also affect TAC. In a study in Lodz, Poland, smokers presented lower plasma TAC values in comparison to non-smokers (Goraca & Skibska, 2005; Goraca & Skibska, 2006). It is very important to note that among smokers urinary TAC was not a biomarker of oxidative/nitrosative stress, but 8-hydroxy-2′-deoxyguanosine, a DNA oxidation product, and the advanced glycation end products from oxidation of carbohydrates were both excellent urinary oxidative stress biomarkers in healthy smokers (Campos et al., 2011). This could be explained by the presence of many antioxidants in urine (e.g. uric acid), which prevent depletion of TAC (Benzie & Strain, 1996; Rice-Evans, 2000). Nicotine administration to rats had many deleterious effects such as DNA oxidative damage, induction of proinflammatory cytokines (TNF-α and IL-1β) and decrease of TAC in urogenital organs (Toklu et al., 2010). Smoking has been also related
to increased lipid peroxidation and reduced SOD, CAT, GSH and GST levels in kidneys and liver (Ramesh et al., 2010). In the same study, GPx activity decreased in the liver but increased in the kidney of rats exposed to smoking. Among healthy young adult smokers, two tests of TAC and GSH levels were reduced compared to non-smoking subjects, whereas lipid peroxidation and oxidized LDL cholesterol were found to be increased in smokers compared to controls (Bloomer, 2007). The effect of smoking during pregnancy was studied in plasma, kidneys, brain, liver and lungs of rats. The authors found reduced TAC levels in liver, kidneys and brain of non-pregnant rats, whereas increased TAC was recorded in the lungs of this group. In the same study, in pregnant rats exposed to cigarette smoking, reduced TAC was observed in kidneys and increased TAC values in lungs and brain with no significant change of TAC in liver and plasma (Florek et al., 2009). Periodontitis patients presented higher levels of lipid peroxidation associated with lower levels of TAC and smoking enhanced this deleterious effect (Guentsch et al., 2008). A closely related study also found correlation between reduced levels of TAC and the presence of gingivitis and periodontitis in smokers compared to non-smokers (Al-Bayati et al., 2011). Another interesting study reported that smoking was associated with increased lipid peroxidation levels in mothers and their fetuses and decreased TAC in both groups (Chelchowska et al., 2011). This explains the reduced TAC in patients with chronic obstructive pulmonary disease (COPD), an effect that was not associated with disease severity (Rahman, 2000).

**Table 1. Effects of chemical elements or compounds on total antioxidant capacity.**

| Element or compound | Effect | Reference |
|---------------------|--------|-----------|
| **Aluminum**        | Lipid peroxidation, ↑CAT, ↓GPx | Ozkaya et al. (2010) |
|                     | Lipid peroxidation, ↓CAT, ↓SOD, ↓GPx in brain | Shati et al. (2011) |
|                     | Lipid peroxidation, ↓CAT, ↓GST, ↓GSH and induced degeneration and death of testis and sperm | Youssef and Salama (2009) |
| **Arsenic**         | ↑Free radicals, ↓GSH, impairment of glucose metabolism; Oxidative stress and ↓TAC | Flora (2009) |
|                     |       | Wu et al. (2001) |
| **Cadmium**         | Oxidative stress-induced nephrotoxicity and neurotoxicity; ↑Free radicals in liver; ↑ lipid peroxidation and GPx, ↓GSH; inhibited CAT | Flora (2009) |
|                     |       | Son et al. (2009) |
|                     |       | Eybl and Kotyzová (2010) |
| **Carbon tetrachloride (CCl4)** | ↑Free radicals and lipid peroxidation in liver; ↓TAC in liver; induces liver necrosis and fibrosis; ↑GSH; ↓GSH; inhibited CAT | Hassan et al. (2003); Mahmoud and Hijazi (2007); Wu et al., (2008) |
| **Cobalt**          | Oxidative stress-induced heart damage | Flora (2009) |
| **Copper**          | ↓TAC and ↓NOS causing mitochondrial failure and death of neurons and astrocytes | Reddy et al. (2008) |
| **Lead**            | Preferential accumulation in hippocampus, thalamus, parietal cortex, and striatum, inducing Villeda-Hernández et al. (2001) | Bennett et al. (2007) |
|                     | lipid peroxidation | Nehru and Kanwar (2004) |
|                     | Increased expression of SOD and CAT to counteract the oxidative stress and ↑ lipid peroxidation in hippocampus and cerebellum | Chen et al. (2000) |
|                     | N-acetyl-cysteine improve TAC of brain decreasing lipid peroxidation damage by lead | Alghasham et al. (2011) |
|                     | ↑Nitric oxide causing hypertension and neuronal mitochondrial impairment | Payal et al. (2009) |
|                     | ↑ Lipid peroxidation and ↓ GST, CAT and SOD in bone of rats | |
| **Manganese**       | ↑Oxidative stress, ↑ LDL oxidation, ↑DNA oxidation and ↓TAC | Komatsu et al. (2009) |
| **Mercury**         | Oxidative stress in brain, kidney and liver; liver and kidney damage; ↓SOD, ↓GPx, ↓GSH; ↑Oxidative stress; ↑Lipid peroxidation; ↓Sperm motility | Agarwal et al. (2010); Rao and Gangadharan (2008) |
| **Nicotine**        | DNA oxidation and ↓TAC | Toklu et al. (2010) |
| **Ozone**           | ↓TAC | Bocci et al. (1998) |

**Occupational hazards and TAC**

In a study of a Taipei population group, Taiwan, exposure to arsenic was found to induce oxidative stress along with an inverse association between arsenic blood levels and TAC (Wu et al., 2001). Exposure to ozone (O₃) can also reduce plasma TAC by 20% (Bocci et al., 1998). Another interesting study showed drastic reduction of plasma TAC among bricklayers exposed to cement and related materials (Pournourmohammadi et al., 2008). Workers exposed to dust from tobacco leaves presented reductions in TAC from 15.5% to 31% (Swami et al., 2006).

Nevertheless, there are some pollutants that do not cause changes in TAC. In carbon monoxide poisoning from incomplete combustion of fossils, despite intense production of carboxyhemoglobin and peroxidative products, the exposed patients did not reveal significant changes in blood TAC (Kavakli et al., 2011). Due to inhibition of the mitochondrial-membrane complex IV system, CO poisoning causes hypoxia, lipid peroxidation, and neurological sequelae (Garrabou et al., 2011). Similar mechanisms are operative in exposure to herbicides. Picloram and triclopyr herbicides diminished cell viability and decreased expression of neuroprotective genes and mitochondrial electron transport genes in neurons (Reddy et al., 2011). Administration of the insecticide triazophos induced lipid peroxidation and glutathione-S-transferase activity (GST) with subsequent depletion of GSH and TAC, resulting in progressive liver degeneration (Jain et al., 2010).

Radiation exposure induced inflammation, increased oxidative stress and decreased TAC values in human
lymphocytes (Lee et al., 2010). It has been suggested that TAC levels were inversely correlated with cytogenetic radiation-induced damage in man, which means that antioxidant capacity is a protective factor against radiation hazard effects (Köteles et al., 2001).

It is important to note that depending on the type and intensity of exposure, TAC levels can be enhanced, not reduced, since cells and tissues can react by the hormesis response producing more heat shock proteins (HSPs) and activating the nuclear antioxidant response element which is further responsible for the increase in TAC levels. This could explain why exposure to magnetic fields has been correlated to increased TAC levels in male workers (Sirmatel et al., 2007). Nevertheless, other studies which evaluated the effects of magnetic fields on antioxidant response reported increased oxidative stress, and lipid peroxidation and decreased TAC in rat brains, especially in aged animals (Akdag et al., 2010; Falone et al., 2008). Exposure to low-frequency magnetic-field induced depletion of GSH and TAC associated with increased levels of lipid peroxidation and production of reactive oxygen species in liver and heart, depending on timing and distance from the field (Canseven et al., 2008; Goraca et al., 2010).

Exposure to elektromagnetic radiation of 900MHz from mobile phones induced lipid peroxidation in the hippocampus and brain cortex of rats as well as oxidative stress and histopathological changes in the rats’ endometrium, effects which were reversed by antioxidants (Köylü et al., 2006; Guney et al., 2007). Further studies should address the question whether radiation frequency from cell phones can induce oxidative/nitrosative stress and depletion of TAC in human subjects.

It should be noted that the techniques for determination of TAC in blood and biological fluids are still very recent. Thus potential clinical correlations between TAC and disease are yet in progress. Similarly, in many pathophysiological conditions the relationship with TAC levels has yet to be established. In a study with different degrees of injury, there was no correlation between plasma TAC levels and severity of lesions in patients with burns (Farriol et al., 2003). Borisenkov et al. (2007) revealed that TAC of saliva was increasing during the period from 3 AM to 7 AM, and presented but small changes between that TAC of saliva was increasing during the period from 3 AM to 7 AM, and presented but small changes between 3 AM to 7 AM, and presented but small changes between

Conclusions
Alcohol, smoking, heavy metals and toxic elements, some pesticides, some occupational exposures, and elektromagnetic and nuclear radiations can decrease TAC, rendering subjects less resistant to oxidative and nitrosative injuries and subsequent diseases. More research is needed to address the role of antioxidant supplementation in xenobiotic exposure and disease prevention.

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