ABSTRACT: Dietary antioxidants may help to supplement the body antioxidant defenses in handling free radicals. Studies on different food sources to discover their antioxidant property have received considerable attention since 1960s. However, the majority of these studies were from epidemiological studies and in vitro experiments. There are much fewer in vivo studies on the bioavailability of consumed antioxidants. Bioavailability of antioxidants is important, as the in vitro data cannot be simply extrapolated to the physiological situation. Hence, it is not convinced that dietary antioxidants can act as supplemental free radical scavengers to the body. Carotenoids and flavonoids are among the most extensively studied phytochemicals and were first reported to have antioxidant effects in the late 1970s and mid-1980s, respectively. The present review summarizes the existing bibliography over the last few decades on bioavailability studies of carotenoids and flavonoids, both in human and in rodents. Those findings well implied that it is extremely necessary to increase the bioavailability study of antioxidants so as to demonstrate direct absorption of antioxidants in vivo and, thus enable a more definite conclusion to be drawn on the beneficial effects that dietary antioxidants may have on the body.

KEYWORDS: Absorption, Antioxidant, Bioavailability, Carotenoids, Flavonoids, Free radicals.

INTRODUCTION

Antioxidants, compounds that scavenge free radicals (Halliwell and Gutteridge, 1984), have become increasingly popular as shown by a quadruple increase in published articles on antioxidants in the last decade (Huang et al., 2005). Halliwell (1994) proposed that dietary antioxidants could augment the ability of human body to counteract ill effects of free radicals, produced exogenously and endogenously.

To date, mounting efforts have been channeled to identify natural sources and foods ranging from beverages, oils, fruits, vegetables to herbal plants, for their antioxidant properties (Dragland et al., 2003; Pellegrini et al., 2003). At the same time, many antioxidant screening assays are constantly being developed and improved to screen a myriad of foods as well as biological samples, as summarized by Huang et al. (2005). In vitro experiments and epidemiological studies have also been extensively carried out to ascertain the alleged antioxidant property of plants and foods. In contrast, in vivo animal studies of dietary antioxidants are relatively scarce.

Clearly, while in vitro experiments cannot be adequately extrapolated to human situation, epidemiological studies do not reveal bioavailability of dietary antioxidants. Thus, in vivo studies, especially bioavailability studies of antioxidants are of particularly important to answer whether these dietary antioxidants are absorbed into the body and, thus are as effective in vivo as observed in vitro. Inability to absorb these antioxidants or not being absorbed to a significant extent would suggest that the observed antioxidant effects in vitro are by no means relevant. The present review summarizes the bioavailability studies of antioxidants carried out so far, focusing mainly on flavonoids and carotenoids as two of the major classes of antioxidants, which are well proven potent antioxidants in vitro. Animals do not synthesize flavonoids and carotenoids, unlike vitamin A, C and E. Flavonoids are widely distributed in nature and in foods, while carotenoids are natural pigments synthesized by plants and microorganisms. Most importantly, these antioxidants are found predominantly in foods consumed everyday. It is thus intuitively thought that by taking flavonoids- and carotenoids-rich foods, they can act as supplemental antioxidants. Consequently, their bioavailability has always been overlooked. Of the different classes of carotenoids, discussion will be focused on β-carotene since it is not only the most common carotenoid in fruits and vegetables, but also the most studied carotenoid.
values. TRAP is an assay which measures antioxidant capacity of an unknown sample, expresses as trolox equivalence, on protection of a fluorescence probe (uses as substrate) from peroxyl radical oxidation (Huang et al., 2005).

Flavonoids, a major subclass of polyphenols, are responsible for the antioxidant effect (Myara et al., 1993). Various flavonoids-contained food types and sources can be found in the review article by Beecher (2003). The most commonly consumed flavonoids differ from country to country as a reflection of different dietary habits. In Asian country such as Japan, intakes of isoflavones is higher than other flavonoids subclasses, while in Holland, due to the high consumption of tea, catechins have been the most consumed flavonoids. Generally, flavonols remain the most widely consumed flavonoids since they are found nearly ubiquitously in foods (Beecher, 2003).

Intake of flavonoids, comprising mainly quercetin and kaempferol, is associated with lower mortality rate from coronary heart disease (Hertog et al., 1993a; Hertog et al., 1995). These findings provide support for the in vitro study of de Whalley and colleagues (1990) that showed that various aglycone flavonoids protect low-density lipoprotein (LDL) against oxidation by macrophages by inhibiting the generation of hydroperoxides and oxidation of α-tocopherol in the lipoproteins. In vitro study by Viana et al. (1996) also showed that flavonoids, similar to vitamin C, were able to prevent LDL oxidation. One interesting point made was that both flavonoids and vitamin C are only effective if they are present in the early stage of the oxidation process, before endogenous antioxidants, such as vitamin E is consumed. Besides that, flavonoids act as selective inhibitors to lipoxygenase and cyclooxygenase, where both are indirectly involved in the oxidation of LDL (Steinberg et al., 1989; Laughton et al., 1991).

Carotenoids such as β-carotene and lycopene are potent antioxidants where both are efficient singlet oxygen quenchers, which can prevent lipid peroxidation (Krinsky, 1991). Carotenoids in certain animal models have been shown to act as cancer chemopreventive agents (Nagasawa et al., 1995; Kim et al., 1997; Sharoni et al., 1997) and anti-atherosclerotic agents (Shaish et al., 1995). In the Zutphen Elderly study by Keli et al. (1996), high intake of β-carotene over a period of 10 years lowered all stroke risk by 46%. A significant inverse relationship was also found between 10 years intake of flavonoids and stroke incidence with a 73% lower risk of stroke.

Figure 1 shows the general structures of various compounds discuss in this paper and other commonly found antioxidants.
A. Flavonoids

1. Flavonols

Quercetin as a flavonol that is naturally present in glycosylated form. It is probably not absorbed directly from the intestine but undergoes hydrolysis before absorption (Manach et al., 1995). A study conducted by Hollman et al. (1995) who recruited healthy ileostomy subjects, showed that quercetin glucosides were absorbed better than their aglycones and speculated that the intestinal sugar carriers were involved in the absorption of flavonoids. Following this, a comparative study carried out by de Vries et al. (2001) showed that red wine is a poor source of quercetin as compared to onions. They hypothesized that it may be due to the fact that quercetin glucosides, rich in the onions, are absorbed better than quercetin rutinosides found in red wine. Although quercetin is suggested to be absorbed intact, quercetin glucosides or the native forms of quercetin are not seen in plasma (Sesink et al., 2001). The absorbed quercetin undergoes metabolism to form conjugates by glucuronidation and sulfation in the caecal wall and liver, respectively (Morand et al., 1998). Circulating metabolites that have been identified include glucurono-sulfo conjugates of isorhamnetin (3'-O-CH₃-glucuronide) and quercetin, glucuronides of quercetin and, to a lesser extent, their methoxylated forms. In addition, isorhamnetin and tamarixetin were also found in the urine (Manach et al., 1996; Morand et al., 1998).

2. Anthocyanins

Anthocyanins are potent antioxidants widely distributed in fruits, vegetables and red wine, and occur in nature as glycosides (Milbury et al., 2002). Cao et al. (2001) and Netzel et al. (2001) were among the earliest to report on bioavailability of anthocyanins. It was reported that the consumed anthocyanins were excreted unchanged in the urine (Cao et al., 2001; Netzel et al., 2001; Felgines et al., 2002). Milbury et al. (2002) showed that anthocyanins were not only detected as glycosides in both plasma and urine samples, the elimination of plasma anthocyanins from elderberry followed first-order kinetics, and appeared in the urine within 4 h after consumption of anthocyanins. Differences in bioavailability of both aglycones and sugar-conjugated forms of anthocyanins suggest that sugar is an important determinant in anthocyanins absorption and excretion (McGhie et al., 2003). This suggestion was supported by Bitsch et al. (2004) in a comparative study on bioavailability of anthocyanins from red grape juice and red wine. Anthocyanins from red grape juice were more bioavailable than anthocyanins from red wine, which thus implied that sugar content of the ingested red grape juice would have elevated the anthocyanins absorption via co-transport with intestinal sodium-dependent glucose transporter (SGLT-1). As such, absorption of anthocyanins from red grape juice that involves active transport seems to be more efficient than from the red wine. Nevertheless, Frank et al. (2003) had earlier reported that pharmacokinetics parameters derived from plasma and urine for red grape juice showed higher variability compared to red wine. In addition, bioavailability of anthocyanins was low when low levels of red grape juice and red wine were consumed, as was demonstrated from the increased rate of their urinary excretion. In contrast to the anthocyanins found in the above fruits, interesting findings were reported by Felgines et al. (2003). They showed that besides pelargonidin-3-glucoside, the native forms of anthocyanins from strawberry, glucuroconjugates and sulfoconjugates forms of anthocyanins were excreted in the urine. The immediate analyses of collected urine samples without storing may have contributed to these results. As explained by Felgine et al. (2003), the processes of freezing and thawing would have either degraded or retained the metabolites in the precipitate, thus causing the metabolites to have escaped detection.

3. Flavanones

Of the different classes of flavonoids, flavanones are most abundantly found in citrus fruits (Beecher, 2003); naringin and hesperidin are the primary compounds present in grape fruits and orange respectively. Unlike anthocyanins, which are most probably absorbed intact, flavanones such as rutin, hesperidin, naringin and narirutin, which contain rutinoses or neohesperidases, are hydrolyzed by intestinal enzymes such as α-rhamnosidases and β-glucosidases, prior to absorption (Bokkenheuser et al., 1987). Oral administration of naringin was completely hydrolysed to naringenin and rapidly conjugated to its glucuronides, which appeared in the urine 2 h post-ingestion (Fuhr and Kummert, 1995). Circulating forms of hesperetin were mainly glucuronides and to a lesser extent, as sulphoglucuronides (Manach et al., 2003). Administration of multiple-dose of combined grape fruits and orange juices enabled the detection of aglycones naringenin and hesperitin in the urine within 6 h of the first dose at recovery levels of 7% and 24% respectively (Ameer et al., 1996). In addition, intake of commercial orange juice providing 444 mg/L hesperidin and 96.4 mg/L narirutin resulted in the metabolites of flavanones being detected in the plasma after 3 h, peak between 5 and 7 h before returning to the baseline at 24 h (Manach et al., 2003). However, bioavailability of flavanones from grape fruits and orange juices may not be as great since flavanones displayed short half-life and high interindividual variations (Erlund et al., 2001).

4. Isoflavones

Bioavailability studies of isoflavones in human and rats gave comparable findings. According to Sottili et al. (2002), isoflavone glycosides are not absorbed intact, and hydrolysis of their sugar moiety by β-glucosidase is essential before absorption by nonionic passive diffusion from the jejunum. Circulating and urinary forms of isoflavones are glucuronide and sulfate conjugates. Zheng et al. (2004) reported that upon consumption, isoflavone aglucons were more rapidly absorbed than the isoflavone glucosides. Despite slow absorption of isoflavone glucosides, both isoflavones have equal total bioavailability.
Bioavailability of flavonoids and carotenoids

It was shown that daidzein is more bioavailable than genistein, as reflected in its significantly higher urinary recovery than genistein (Xu et al., 1994; King, 1998). Genistein was excreted mainly into the bile (Sfakianos et al., 1997). Daidzein upon hydrolysis would release its glucoside, which has been identified as a precursor to equol. Both daidzein and equol were detected as monoglucuronide conjugates in human urine (Axelson et al., 1984). As suggested by King (1998), the lower level of equol recovery, which is a bacterial metabolite product of daidzein, than 4-ethyl-phenol of genistein, indicated greater resistance of daidzein to hydrolysis, which may thus contribute to its higher bioavailability than the latter. Furthermore, Xu et al. (1995) had earlier reported that the intestinal half-life of daidzein might be longer than that of genistein.

On the other hand, rapid gut transit time (GTT) coupled with a low faecal isoflavones degradation as observed in Asian women suggested greater genistein bioavailability (Zheng et al., 2003). Gender however, has no influence on plasma, urinary and faecal concentration of isoflavones, as well as their metabolites, except that men have significantly higher concentration of O-desmethylangolensin (O-DMA). Besides that, except for higher β-glucosidase activity, chronic soy consumption does not increase faecal β-glucuronidase activity (Wiseman et al., 2004). Bioavailability of isoflavones was not affected by short-term increased of fat and protein in the diet, but may be affected in the long run. In addition, different food sources of isoflavones will not affect absorption and bioavailability of isoflavones (Xu et al., 2000).

5. Catechins

Tea is by far the most well known beverage that has been claimed to have high antioxidants activity. In humans, absorption of catechins occur within 6 h after oral administration and are excreted in the urine mostly in conjugated forms within 24 h. Unchanged catechins appeared in the urine 6 h post-treatment and accounted for 18.6 % of the administered dose at 48 h faecal collection (Das, 1971). Warden et al. (2001) provided further evidence that catechins are bioavailable. The study demonstrated that following ingestion of black tea, significant increment of epigallocatechin (EGC), epicatechin (EC) and epigallocatechin-3-gallate (EGCG) were detected in the plasma. However, catechins underwent considerable metabolism or degradation in the gastrointestinal tract and after absorption, only 1.68 % of the ingested catechins were found in human plasma, urine and faeces. Bioavailability of gallated catechins was lower than the non-gallated forms. In rat, catechin and EC were rapidly absorbed, probably from the upper portion of the digestive tract, distributed in the plasma and excreted in the urine within 24 h. EC was more efficiently absorbed from the gastrointestinal tract when compared to catechin and its metabolites and, EC was shown to peak in the plasma within 1 h post-administration. While primary metabolites of catechin in the plasma were glucuronide in the non-methylated forms, EC produced non-methylated forms of glucuronide and sulfoglucuronide, and 3'-O-methylated forms of sulfate (Baba et al., 2001). Interestingly, Vaidyanathan and Walle (2002) reported that EC does not undergo glucuronidation in human liver and small intestine. Instead, EC was conjugated with sulfate via sulfotransferase (SULT1A1) in the cytosol of liver cells, and both SULT1A1 and SULT1A3 in the small intestine. Rats on the other hand, were able to efficiently metabolised EC to glucuronide and sulfate conjugates.

As the most abundant polyphenol in green tea, EGCG however was slowly absorbed as compared to EGC and EC following intragastric (i.g.) administration of decaffeinated green tea (DGT) in rat. Furthermore, EGCG displayed low bioavailability whether it was consumed from DGT or as pure EGCG, and was excreted mainly through the bile. Administration of EGCG (i.g.) or intravenous (i.v.) showed that EGCG from the DGT is more bioavailable than pure EGCG (Chen et al., 1997). Similarly, a human study conducted by Lee et al. (2002) reported that EGCG has poor bioavailability after ingestion of green tea solid. EGCG was mostly present in the free form in the plasma while EGC and EC were present mainly in the conjugated forms. The conjugated forms of EGC and EC were excreted in the urine within 8 h. In contrast, a high degree of conjugated EGCG was observed in the plasma of mice, which is different from human studies (Lambert et al., 2003).

B. Carotenoids

In order to understand the kinetics and mechanisms of β-carotene absorption, Hollander and Ruble Jr. (1978) proposed that the initial uptake of β-carotene is via passive diffusion. Absorption was increased by acidification of the luminal contents or decreased thickness of the unstirred water layer. The absorption rate of β-carotene was also increased by the addition of fatty acids (Dimitrov et al., 1988). However, it is reported recently by Borel et al. (2005) that the absorption of certain carotenoids is mediated by scavenger receptor, and not by passive diffusion. Roodenburg et al. (2000) had demonstrated earlier that except for lutein esters, vitamin E, α-carotene and β-carotene do not require higher amount of fat (3-5 g) to obtain optimal intestinal absorption. These results however, are different from studies by Brown and colleagues (2004). Brown et al. (2004) showed that dietary fat is necessary to facilitate carotenoids absorption. Ingestion of fat-free salad dressing produced negligible amount of α-carotene, β-carotene and lycopene in the chylomicron whilst these carotenoids concentrations increased tremendously when salad dressing containing 28 g canola oil was consumed. Nevertheless, the supplements were prepared differently in both studies; the former incorporated purified carotenoids into low- and high-fat spread while the latter measured bioavailability of carotenoids from vegetables. In order to explain this, Brown et al. (2004) suggested that the amount of dietary fat requires for optimal carotenoids absorption is influenced by food matrix or the carotenoids content, or both.

Bioavailability studies of β-carotene in humans showed great interindividual variation (Dimitrov et al., 1988; Brown et al., 1989; Mathews-Roth, 1990; Nierenberg et al., 1991; Carugh
and Hooper, 1994; Borel et al., 1998). Apparently, the variability is mainly due to interindividual differences in the efficiency of intestinal absorption and in the chylomicron metabolism (Borel et al., 1998). Nierenberg et al. (1991) pointed out that following oral supplementation of 50 mg of β-carotene/d for a year, the mean dietary of β-carotene increased to 4.0 mg/d from the baseline of 3.8 mg/d, which is less than 1% of the amount given, is a result of high interindividual variation. They showed that although the median plasma concentration increased from the initial value of 335 nmol/L to 3163 nmol/L a year later, a large median change was observed, with changes in the plasma β-carotene concentration ranged from -313 to +16 090 nmol/L. They thus suggested that the initial plasma β-carotene concentration could be used as an indicator to predict response to β-carotene supplementation. This suggestion was made based on a report from Brown et al. (1989) who observed that subjects who have poor β-carotene absorption from dietary sources will also poorly absorb supplemented pure β-carotene. In contrast to β-carotene, baseline plasma levels of lutein and lycopene do affect the relative increased of their levels after supplementation, but depleted subjects are expected to have a greater increased of plasma carotenoids concentrations (Riso et al., 2004).

According to Brown et al. (1989), β-carotene is slowly absorbed and the maximum concentration was only observed between 24-48 h post-dose. Purified β-carotene is more efficiently absorbed than if a similar amount is present in vegetables (Huang et al., 2000). It is generally agreed that long-term intake of carotenoids is the key to maintain high level of carotenoids in the plasma (Paetau et al., 1998; Bugianesi et al., 2004; Thurmann et al., 2005). Regular intake of carotenoids-contained foods can leads to a progressive increase in plasma carotenoids concentration or maintain the steady-state profile of plasma carotenoids (Rock et al., 1992; Riso et al., 2004). Therefore, although intake of large doses of β-carotene at 180 mg per day has been shown to cause the plasma β-carotene concentration to reach plateau in 1.5 to 4 weeks, fluctuation in the concentration still occurred thereafter (Mathews-Roth, 1990). Consumes a diet of low carotenoids for 2 weeks will cause a 60% decline of β-carotene, α-carotene and lycopene in the plasma (Carugh and Hooper, 1994). A non-linear decline in the plasma levels suggests that there are two pools of carotenoids in the body; one that is rapidly responsive to changes in carotenoids intake and one that is more resistant to depletion and may represent tissue stores (Micozzi, et al., 1992; Rock et al., 1992).

While most studies determined β-carotene absorption by measuring its plasma concentration, chylomicron has been suggested to be a more appropriate model to study intestinal absorption kinetics of carotenoids (van Vliet et al., 1995). Measuring lycopene concentration in the chylomicron showed that lycopene bioavailability following tomato paste consumption was significantly higher than that from fresh tomatoes (Gartner et al., 1997). Plasma concentrations of naringenin and chlorogenic acid increased significantly from ingestion of cooked cherry tomatoes, but not fresh cherry tomatoes (Bugianesi et al., 2004). Mechanical disruption of cells during tomato paste preparation that extracts lycopene into the lipophilic phase, may have contributed to its higher absorption (Gartner et al., 1997). Moreover, bioavailability of carrots is improved by processing such as chopping and heating (Molldrem et al., 2004). Daily intake of processed carrots and spinach, both contain about 9.3 mg of β-carotene, for a 4-week period, produced a three times higher absorption of β-carotene as reflected in its plasma level than from the raw forms (Micozzi, et al., 1992; Rock et al., 1998).

There are exceptions however, that processing is not required for fresh-frozen watermelon juice as it produces comparable lycopene level to canned tomato juice after three weeks of consumption (Edwards et al., 2003). Antioxidant activity of carotenoids and flavonoids from fresh lettuce, as measured by TRAP assay, was higher compared to lettuce that was stored at 5°C under modified-atmosphere packaging (MAP) conditions (Serafini et al., 2002). TRAP is based on the protection afforded by plasma or other substrates against the decay of a fluorescent target during a controlled peroxidation reaction (Ghiselli et al., 1995). In the study by Serafini and colleagues (2002), plasma or lettuce extract was added to the reaction mixture and determined their TRAP values. TRAP was expressed as μmol peroxidyl radicals trapped per liter plasma or per gram lettuce. Unlike MAP-storage lettuce that does not preserve their antioxidants, leading to an overall decrease of its in vitro antioxidants capacity, fresh lettuce ingestion increased plasma levels of caffeic acid, p-coumaric acid, quercetin, vitamin C and β-carotene. However, except for vitamin C, these flavonoids and β-carotene were unable to increase plasma antioxidants capacity. It is not clear whether ingestion of the 250 g fresh lettuce containing 26.7 mg vitamin C has contributed to the increased of antioxidant activity, since Serafini et al. (2002) suggested that the effect comes from factors other than the original compounds present in the food matrix.

Absorption of β-carotene is faster than lutein. Carotenoids interact with each other and the pharmacokinetics of both lutein and β-carotene have been shown to be affected when present together (Micozzi et al., 1992; Kostic et al., 1995). However, the interactions do not affect the individual concentration in the plasma (Tyssandier et al., 2002; Riso et al., 2004; Thurmann et al., 2005). Besides that, it was found that lutein from yellow carrots is more bioavailable than is β-carotene from orange carrots. Beside lutein, yellow carrots also contained 40% of β-carotene that remained at constant concentration throughout the study. It was suggested that there could be many pools of lutein in the body as evidenced by faster depletion of serum lutein when peak concentration was high but slower depletion when peak concentration was low (Molldrem et al., 2004).

Table 1 shows the flavonoids and carotenoids content found in selected food sources while Table 2 lists the design of bioavailability studies carried out on dietary antioxidants.
Table 1. Flavonoids and carotenoids content (mg/serving) in fresh vegetables, fruits and beverages

<table>
<thead>
<tr>
<th>Food source</th>
<th>Content of flavonoids and carotenoids (mg/serving)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flavonols</td>
</tr>
<tr>
<td>Tomato: 100g, 400g*</td>
<td>0.5</td>
</tr>
<tr>
<td>Lettuce: 100g, 48g^</td>
<td>1</td>
</tr>
<tr>
<td>Onion: 20g</td>
<td>7</td>
</tr>
<tr>
<td>Yellow carrots: 100g</td>
<td></td>
</tr>
<tr>
<td>Broccoli: 600g</td>
<td></td>
</tr>
<tr>
<td>Spinach: 150g</td>
<td></td>
</tr>
<tr>
<td>Apple: 200g</td>
<td>7</td>
</tr>
<tr>
<td>Cherry: 50g</td>
<td>1</td>
</tr>
<tr>
<td>Strawberry: 100g</td>
<td>13</td>
</tr>
<tr>
<td>Orange juice: 100ml</td>
<td></td>
</tr>
<tr>
<td>Black tea: 200ml</td>
<td>8</td>
</tr>
<tr>
<td>Dark chocolate: 20g</td>
<td></td>
</tr>
</tbody>
</table>
### Table 2A. Summary of the human models adopted for bioavailability study of dietary flavonoids

<table>
<thead>
<tr>
<th>Dietary flavonoids</th>
<th>Model</th>
<th>Design of study</th>
<th>Sample collected</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Human subjects.</td>
<td>Ingested single oral dose of red wine or red grape juice.</td>
<td>Urine.</td>
<td>Frank et al. (2003).</td>
</tr>
<tr>
<td></td>
<td>Human subjects.</td>
<td>Study consisted of 4 parts, each separated by at least 8 wk. Study required consumed single dose of pure naringin, single dose of pure naringen and hesperidin, grape fruit juice and orange juice co-administered, and 1 pound of grape fruit.</td>
<td>Blood and urine.</td>
<td>Ameer et al. (1996).</td>
</tr>
<tr>
<td></td>
<td>Female human subjects.</td>
<td>Received single dose of isoal flavones in soybean milk as part of a liquid diet in 3 feeding days, each separated by a 2 wk washout period.</td>
<td>Blood, urine and faeces.</td>
<td>Xu et al. (1994) and Xu et al. (1995).</td>
</tr>
<tr>
<td></td>
<td>Female human subjects.</td>
<td>Three servings of isoal flavones per day from soymilk powder reconstituted with distilled water; or fed with 4 types of soybean foods.</td>
<td>Blood, urine and faeces.</td>
<td>Xu et al. (2000).</td>
</tr>
<tr>
<td></td>
<td>Human subjects.</td>
<td>Ingested single oral dose of green tea solids dissolved in warm water; ingested pure EGCG dissolved in water; received single oral dose of DGT dissolved in water. Each succeeding experiment was conducted after a 1 wk washout period.</td>
<td>Blood and urine.</td>
<td>Lee et al. (2002).</td>
</tr>
</tbody>
</table>
### Table 2B. Summary of the human models adopted for bioavailability study of dietary carotenoids

<table>
<thead>
<tr>
<th>Model</th>
<th>Design of study</th>
<th>Sample collected</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human subjects.</td>
<td>Consumed lutein or β-carotene capsule or the combination for 5 wk each, with a 10 d equilibration period in between.</td>
<td>Blood.</td>
<td>Kostic et al. (1995).</td>
</tr>
<tr>
<td>Human subjects.</td>
<td>Ingested lycopene-rich tomato juice, lycopene capsules or lycopene beards for 4 wk each, with self-selected diets. Each treatment was separated by a 6 wk washout period.</td>
<td>Blood.</td>
<td>Paetau et al. (1998).</td>
</tr>
<tr>
<td>Female human subjects.</td>
<td>Consumed defined dose of β-carotene daily either from raw or thermally processed vegetables in a two 4 wk treatments, separate by a 4 wk washout period.</td>
<td>Blood.</td>
<td>Rock et al. (1998).</td>
</tr>
<tr>
<td>Female human subjects.</td>
<td>Intake of 35 g tomato puree daily for 14 consecutive days.</td>
<td>Blood.</td>
<td>Pellegretti et al. (2000).</td>
</tr>
<tr>
<td>Human subjects.</td>
<td>During the two 7d experimental periods which was 5 wk apart, subjects consumed a low- or high-fat spread supplemented with either vitamin E or α-tocopherol-β-carotene or lutein esters.</td>
<td>Blood.</td>
<td>Roedenburg et al. (2000).</td>
</tr>
<tr>
<td>Female human subjects.</td>
<td>Consumed 5 different combinations of tomato, spinach, lutein pills and lycopene pills, each for 3 wk followed by a 3 wk washout period before proceed to the next treatment.</td>
<td>Blood.</td>
<td>Tysstander et al. (2002).</td>
</tr>
<tr>
<td>Human subjects.</td>
<td>Consumed yellow carrots, white carrots or a lutein supplement in oil. Each treatment lasted for 7 d and was followed by a 7 d washout period.</td>
<td>Blood.</td>
<td>Mollfeld et al. (2004).</td>
</tr>
<tr>
<td>Female human subjects.</td>
<td>Intake of spinach diet for 21 d; consumed spinach -tomato diet for the next 21 d. Finally, both supplements were consumed with olive oil. Each treatment followed a 2 wk washout period.</td>
<td>Blood.</td>
<td>Rizzo et al. (2004).</td>
</tr>
<tr>
<td>Human subjects.</td>
<td>Received daily oral dose of lutein beardslets for 42 d. Xanthophylls concentration was monitored.</td>
<td>Blood.</td>
<td>Thurmann et al. (2005).</td>
</tr>
</tbody>
</table>
### Table 2C. Summary of the animal models adopted for bioavailability study of dietary carotenoids

<table>
<thead>
<tr>
<th>Dietary antioxidants</th>
<th>Model</th>
<th>Design of study</th>
<th>Sample collected</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Flavonoids</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Flavanones</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>5. Catechin</td>
<td>Male Sprague Dawley rats.</td>
<td>EGGG or DGT was administered either i.v. or i.g.</td>
<td>Liver, kidneys, lungs, blood and intestine.</td>
<td>Chen et al. (1997).</td>
</tr>
<tr>
<td></td>
<td>Male Sprague Dawley rats.</td>
<td>Catechin, EC or mixture of the two was suspended in de-ionized water and administered orally.</td>
<td>Blood and urine.</td>
<td>Baba et al. (2001).</td>
</tr>
<tr>
<td></td>
<td>Male CF-1 mice.</td>
<td>Administered single dose of EGGG dissolved in NaCl via i.v. or i.g.</td>
<td>Blood, urine, faeces, lungs, liver, spleen, kidneys, colon, small intestine, prostate and brain.</td>
<td>Lambert et al. (2003).</td>
</tr>
</tbody>
</table>

NA: Not available.

### Table 3. Mode of absorption of different classes of flavonoids and carotenoids

<table>
<thead>
<tr>
<th>Antioxidants</th>
<th>Proposed mode of absorption</th>
<th>Proposed absorption site</th>
<th>Enzymatic activity prior absorption</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Flavonols: Quercetin</td>
<td>Active transport via sodium-dependent glucose transporter (SGLT-1)</td>
<td>Jejunum*</td>
<td>No suggestion</td>
<td>No suggestion</td>
</tr>
<tr>
<td>2. Anthocyanins: cyanidin-3-glucoside*, pelargonidin-3-glucoside*</td>
<td>Active transport via SGLT-1</td>
<td>No suggestion</td>
<td>No suggestion</td>
<td>No suggestion</td>
</tr>
<tr>
<td>3. Flavonones: nasturtin, herperidin</td>
<td>Passive diffusion**</td>
<td>Jejunum*</td>
<td>No suggestion</td>
<td>No suggestion</td>
</tr>
<tr>
<td>5. Catechins: total catechins</td>
<td>Passive diffusion</td>
<td>No suggestion</td>
<td>No suggestion</td>
<td>No suggestion</td>
</tr>
<tr>
<td>B. Carotenoids</td>
<td>Passive diffusion</td>
<td>Jejunum and ileum</td>
<td>β-carotene 15, 15'-monooxygenase*</td>
<td>No suggestion</td>
</tr>
<tr>
<td>1. Carotenone β-carotene</td>
<td>Passive diffusion</td>
<td>Jejunum and ileum</td>
<td>Bβ-carotene 15, 15'-monooxygenase*</td>
<td>No suggestion</td>
</tr>
<tr>
<td>2. Lycopene</td>
<td>Passive diffusion</td>
<td>Jejunum and ileum</td>
<td>Bβ-carotene 15, 15'-monooxygenase*</td>
<td>No suggestion</td>
</tr>
<tr>
<td>3. Xanthophylls: lutein</td>
<td>Passive diffusion</td>
<td>Jejunum and ileum</td>
<td>Bβ-carotene 15, 15'-monooxygenase*</td>
<td>No suggestion</td>
</tr>
</tbody>
</table>
DISCUSSIONS

A. Flavonoids

By now, studies suggest flavonoids to be absorbed by two distinct modes of action. However, understanding on the absorption mechanism of quercetin has not been improved by these findings. On the one hand, it is suggested that upon ingestion, flavonoid glycosides are hydrolysed to flavonoid aglycone by bacterial enzymes present at the lower part of ileum and caecum, or by lactase phlorizin hydratase that is located at the intestinal brush border membrane (Bokkenheuser et al., 1987; Day et al., 2000). Alternatively, glycosides are absorbed directly from the intestine via sodium-dependent glucose transporter (SGLT-1) (Hollman et al., 1999). Even so, studies by Sesink et al. (2001) clearly showed that quercetin glucosides are not present in the plasma after consumption of quercetin-3-glucosides or quercetin-4'-glucosides, but were appeared as quercetin glucuronides. They thus suggested that quercetin glucosides were hydrolysed and the aglycone conjugated during passage from the intestinal lumen to the peripheral circulation. It was not determined where the hydrolysis and the subsequent conjugation would have taken place. In short, irrespective of which mechanism is involved, no native quercetin or only traces of native quercetin can be found in the plasma (Manach et al., 1995; Manach et al., 1996; Manach et al., 1999; Graefe et al., 2001; Sesink et al., 2001). This nonetheless raises question as to how potent these glucuronidated quercetin are as antioxidants as compared to their native forms?

Although it is still unclear which mechanism of absorption predominates or represents the real situations, the presence of glucuro-, sulfo- and methylated forms of quercetin as metabolites in the systemic circulation is unequivocal (Manach et al., 1995; Manach et al., 1996; Morand et al., 1998; de Vries et al., 2001; Sesink et al., 2001). These metabolites of quercetin are bound strongly to albumin, and showed capability to shift the absorbance profile comparably to that of the native quercetin (Manach et al., 1995). Doubtful as to whether this complex will exert the same antioxidant effect as other water and lipid soluble antioxidants, Morand et al. (1998) showed that quercetin glucuronides and sulfates were able to delay the Cu²⁺-induced oxidation of lipoprotein, but with only one-half of the magnitude of inhibition to that measured with their aglycone. In other words, metabolites of quercetin retain their antioxidant property but with less potency, and albumin may have indirectly reduced antioxidant property of quercetin.

Kroon et al. (2004) pointed out that while conventional drugs prepared at pharmacological doses are delivered in their active forms in target tissues, polyphenols delivered through human diets are present at low doses, which in most cases do not escape first-pass metabolism (Williamson, 2002). If polyphenols are not absorbed intact, the processes of hydrolysis and conjugation will produce metabolites that would have different physiological behaviors compare to their native forms. Therefore, it is extremely important to identify plasma polyphenols and defining their biological activities. Following this, in order to make in vitro data more relevant to the physiological situations, it is probably a prerequisite to first identify and then use the conjugates found in vivo as substrate in the in vitro designed bioavailability or pharmacological studies. Plasma polyphenols that have been identified so far can be found in the review article by Kroon et al. (2004).

With regards to the differences in absorption mechanisms described above, study design proves to be crucial to understand the topic under investigation. Studies from Hollman et al. (1995) and Walle et al. (2000) who employed healthy ileostomy subjects and collected the ileostomy effluent to determine absorption mechanism of quercetin however, showed sharp contrasting results. Hollman et al. (1995) who defined absorption as oral intake of quercetin minus ileostomy excretion and the degradation process suggested that quercetin is absorbed intact. Unconvincing with the results, Walle et al. (2000) repeated the study but measured intake of quercetin and their elimination using molecularly specific High Performance Lipid Chromatography (HPLC) methodology and reported that quercetin needs to be hydrolysed prior to its absorption.

Apart from this, it is noteworthy that most of the flavonoids are obtained from plant foods, not from capsules or tablets. As such, interaction between quercetin that is found ubiquitously in plants with other flavonoids can affect bioavailability of the respective compounds. Interaction between quercetin and catechin has received considerable attention. Co-administration of quercetin and catechin in rats has demonstrated decreased bioavailability of both flavonoids (Silberberg et al., 2005). It was suggested that a competitive interaction between quercetin and catechin had occurred which thus led to a reduction in intestinal absorption of both compounds. Therefore, care must be taken when interpreting data obtained from purified compounds as not to overlook the complicated chemical reactions and their eventual effects on the compounds bioavailability.

Unlike quercetin, there is less debate and confusion on catechins absorption but it was suggested that catechins displayed low bioavailability (Chen et al., 1997; Warden et al., 2001). Effect of drug interaction on bioavailability has also been studied for catechins. Piperine was found to increase bioavailability of EGCG, probably by inhibiting small intestinal glucuronidation of EGCG and reduced gastrointestinal transit of EGCG (Lambert et al., 2004). Besides that, tartaric acid also enhanced bioavailability of wine polyphenols (Yamashita et al., 2002).

It has already been often stated that the conjugated or sugar-bound forms of flavonoids present in foods cannot be absorbed from the intestines. Only flavonoids hydrolysed by intestinal microorganisms will enable the absorption of aglycones (Kuhnau, 1976; Bokkenheuser et al., 1987; Hertog and Hollman, 1996; Morand et al., 1998). However, this is not the case for anthocyanins. As was mentioned in the previous section, anthocyanins from food sources were mostly absorbed intact where the unchanged forms were detected in the urine (Cao et al., 2001; Nettel et al., 2001; Milbury et al., 2002; Frank et al., 2003; Mcghie et al., 2003; Bitsch et al., 2004). It was suggested that the observed absorption mechanism was probably due to
the sugar content in the fruits. Similar to quercetin glycosides, the absorption could thus happen via the intestinal brush border SGLT-1 (Bitsch et al., 2004). However, straightforward as it might seem, the presence of sugar content in strawberry does not result in the production of unchanged anthocyanins in the urine. In fact, five metabolites were detected. Felgines et al. (2003) reasoned that two possible pathways are responsible for the formation of these metabolites. Because jejunum is able to hydrolyse cyanidin-3-glucoside to cyanidin aglycone, it is possible that pelargonidin-3-glucoside was hydrolysed to aglycone and then rapidly glucuronidated in the intestine (Tsuda et al., 1999; Felgines et al., 2003). On the other hand, pelargonidin-3-glucoside serves as a substrate for UDP-glucose dehydrogenase to form pelargonidin-3-glucuronide (Wu et al., 2002). As for sulfoconjugate, pelargonidin-3-glucoside may first be hydrolysed to aglycone then conjugated in the intestine (Felgines et al., 2003). From here, it can be inferred that differences in molecular structures are important determinants to the compounds’ eventual fate (McGhie et al., 2003).

Anthocyanins when compared to other flavonoids, displayed very low bioavailability, as reflected in the urinary excretion of total anthocyanins. Except for anthocyanins from strawberry that accounted for 1.8 % of the ingested amount, anthocyanins from other fruits mentioned here corresponded to less than 0.7 % of the administered dose (Netzel et al., 2001; Felgines et al., 2002; Felgines et al., 2003; Frank et al., 2003; Bitsch et al., 2004).

As suggested above, differences in molecular structures will determine how the flavonoids are absorbed and metabolised. Both flavanones and isoflavones are not absorbed intact. The mechanism of absorption proposed so far for both of these classes of compounds are well accepted and give no conflicting information. Due to the different mode of absorption and metabolism, both flavonones and isoflavones are expected to have different bioavailability as compared to anthocyanins. In fact, anthocyanins have been shown to have lower bioavailability than flavanones and isoflavones (Xu et al., 1994; Xu et al., 1995; Amer et al., 1996; King, 1998; Erlund et al., 2001; Zheng et al., 2003; Wiseman et al., 2004; Zheng et al., 2004).

Because of the metabolism process, the hydrolysed or conjugated flavonoids have generated huge concern on their antioxidants property in the body. Hence, it is interesting to learn that equol has higher antioxidants activity than its parent compound (Hodgson et al., 1996; Arora et al., 1998). Equol protects hairless mouse from skin carcinogenesis (Widyarini et al., 2005), inhibits bone loss in ovariectomised mice (Fujikawa et al., 2004) and inhibits prostate growth in male rats (Lund et al., 2004). However, only 30-50 % of the adult populations who consume soy products on a daily basis are equol producers (Rowland et al., 2000; Setchell et al., 2002; Setchell et al., 2003). High equol producers are at a lower risk for breast cancer than low equol producers (Yamamoto et al., 2003). Lumbar spine bone mineral density (BMD) of equol producers was 2.4 % higher than the control group, whereas there were no changes in BMD in the non-equol producers after a 2-year intervention with isoflavones (Lydeking-Olsen et al., 2002). Meanwhile, cholesterol-lowering effect of soy is independent of equol producer status (Greany et al., 2004). Obviously, variability in equol production lies heavily on the presence of intestinal bacteria. It was reported that young infants with underdeveloped gut microflora and germ-free animals do not produce equol (Cruz et al., 1994; Bowey et al., 2003). Besides that, a possible involvement of several types of bacteria in daidzein metabolism (Atkinson et al., 2004) further increases interindividual variability. Since equol appears to be a potent antioxidant and has extensive beneficial effects, it is probably suitable to work on identifying the specific equol-producing gut microflora and activating them so as to maximize the antioxidant effect of isoflavones.

### B. Carotenoids

It was reported that purified β-carotene is far better absorbed than β-carotene from food (Brown et al., 1989; Micozzi et al., 1992). According to Micozzi et al. (1992), intake of 272 g carrots which corresponded to 29 mg β-carotene, produced only 18 % changed in the plasma concentration of β-carotene compared to that produced by subjects taking 30 mg capsulated β-carotene. Purified β-carotene has also been often used to obtain data for bioavailability evaluation study (Hollander and Ruble Jr., 1978; Dimitrov et al., 1988; Mathews-Roth, 1990; Nierenberg et al., 1991). However, when compared to the capsulated β-carotene, vegetables make a cheaper and more convenient source for β-carotene, besides other carotenoids, and other phytochemicals present in the vegetables.

Following its low bioavailability, there were suggestions that processing will enhance β-carotene absorption. Since carotenoids are compartmentalized within plastids, disruption of the plant matrix via homogenization or heating will promote release of carotenoids and incorporate the compounds into the mixed micelles, making it accessible for absorption (Brown et al., 2004). Lycopene serum concentration was significantly higher from ingestion of tomato paste than from fresh tomatoes (Gartner et al., 1997). Bioavailability of β-carotene and lutein from processed carrots were higher than from raw carrots (Moldrem et al., 2004). Although heat treatment has been reported to promote isomerization of β-carotene from trans to cis forms, which are less bioavailable, cis-β-carotene does not negate the enhanced absorption of β-carotene of cooked spinach and carrots (Rock et al., 1998).

Different plant matrix affects bioavailability of carotenoids. For example, broccoli and green peas that contain 10 times lower β-carotene levels than β-carotene than the whole leaf and chopped spinach, induced a greater increase in plasma β-carotene levels (van het Hof et al., 1999a). In another study, β-carotene was shown to be more bioavailable than lycopene after intake of orange fruits, and also induced a higher plasma responses than β-carotene from dark-green, leafy vegetables and carrots (de Pee et al., 1998), where β-carotene displayed lower bioavailability than lutein following intake of spinach (de Pee et al., 1998; Castenmiller et al., 1999). The differences in bioavailability of carotenoids between fruits and vegetables can be explained by their presence in different food matrix. It was suggested by de Pee et al. (1998)
that because β-carotene is dissolved in oil droplets in the chromoplasts of fruits compared to β-carotene that is found in the chloroplasts of vegetables, incorporation of β-carotene into the fat micelles for absorption has been made easier. Disruption of the spinach matrix has later been found to increase bioavailability of β-carotene, but give no effect on bioavailability of lutein (Castenmiller et al., 1999).

Dietary fat facilitates β-carotene absorption. Besides chylomicron, endogenous fat may play a role in β-carotene absorption (Dimitrov et al., 1988). There was no absolute amount of fat suggested to optimally enhance its absorption as it depends on the size and composition of the associated meal. However, it has been shown that not all types of fat will enhance bioavailability of carotenoids. Consumption of low dose (3 g/d) of a non-absorbable, synthetic fat analogue, sucrose polyester (SPE) simultaneously with carotenoids, significantly reduced plasma concentrations of carotenoids when compared to the baseline value. The reduction was largest for β-carotene and lycopene at 20% and 38% respectively, and increased of SPE concentration to 12.4 g/d produced a 34% and 52% reduction in the plasma levels for β-carotene and lycopene (Westrake and van het Hof, 1995). High intake of olestra, another type of sucrose polyester at 18 g/d, also caused an average of 27% reduction in the serum carotenoids levels compared to the baseline value. Koonsvitsky et al. (1997) suggested that the effect of olestra on carotenoids absorption is most prominent if both components are taken concurrently. In short, although a sufficient amount of fat can facilitate carotenoids absorption (Brown et al., 2004), any intention to use fat to increase bioavailability of carotenoids needs careful study.

On the other hand, a rapid decline in plasma levels when individual consume a low carotenoid diet suggests that regular consumption of carotenoids-contained foods is necessary to maintain plasma levels of these compounds (Rock et al., 1992; Carugh and Hooper, 1994). Overall, with low bioavailability in nature, antioxidant effect of carotenoids from food seems to be minimal when compare to their capsulated forms. However, it may still be an important food source for other biologically active compounds that are not present in the purified carotenoids (Micozzi et al., 1992).

Although it is generally perceived that higher intakes of fruits and vegetables rich in β-carotene will reduces the risk of cancer, clinical trials carried out by three different groups of researchers demonstrated that β-carotene produced no such effect (The Alpha-tocopherol, beta carotene cancer prevention study group, 1994; Hennekens et al., 1996; Omenn et al., 1996). In fact, men who received β-carotene were found to have higher mortality rate from lung cancer and cardiovascular disease (The Alpha-tocopherol, beta carotene cancer prevention study group, 1994; Omenn et al., 1996). These findings were later justified by Feskanich and co-workers (2000), who showed that fruits and vegetables do have moderately lowering effect on lung cancer risk in women, but not in men. The observed effect comes from cruciferous vegetables, citrus fruits and foods high in total carotenoids but not individual foods or food group. Since inverse association was only found following high total carotenoids intake and not high intakes of β-carotene (Michaud et al., 2000), it was suggested that due to the complex interactions between substances in fruits and vegetables, a longer study period is required before antioxidant effects from foods become more noticeable (Feskanich et al., 2000). All in all, in the case of pharmacological versus physiological doses and, failure to measure smoking characteristics or smoking histories of subjects assigned to the studies may have resulted to the differences reported here, where past and present smoking behavior affects the potency of β-carotene in lowering lung cancer risk.

Before closing the discussion section, it is important to bear in mind that the increase of antioxidants level or their metabolites in plasma and urine do not necessarily mean the increase of antioxidants activity in the body. Other than Serafini et al. (2002) who reported that the increase of plasma β-carotene does not modify plasma antioxidant capacity significantly, Pellegrini et al. (2000) showed that although daily intake of 25.0 g tomato puree for 14 d (contains 7.0 mg of lycopene and 0.25 mg of β-carotene) did increase lycopene and β-carotene plasma concentrations, it gave no significant changes in the antioxidant capacity of plasma as evaluated through the TRAP assay. Experiments by Sharoni et al. (1997) showed that both lycopene and β-carotene were absorbed into the blood, liver, mammary gland, and mammary tumors. However, only tomato oleoresin-treated and not β-carotene-treated rats were protected from the mammary cancer. Therefore, besides a dire need to increase effort in bioavailability study of dietary antioxidants, screening of biological samples for their antioxidant capacity utilizing some of the well established antioxidant assays such as Trolox Equivalent Antioxidant Capacity (TEAC) and Oxygen Radical Absorbance Capacity (ORAC) assays eventually, seem to be a must do procedure.

CONCLUSION

Great interindividual variations among study subjects were reported in many of the studies conducted, both in flavonoids and carotenoids bioavailability studies. Although variations can be simply due to differences in gastrointestinal microflora, as was suggested by Erlund et al. (2001), other unclear, probably inherent factors may interplay, such as gender differences that have not been stressed. For example, high interindividual variations can been seen from isoflavones bioavailability studies which involved 76 subjects but not in studies involving 7 and 25 subjects respectively (Xu et al., 1995; Wiseman et al., 2004; Zheng et al., 2004), which also indicate that sample size may not be the main cause of variations.

In view of the unforeseen discrepancy and difficulties in human studies, as can be inferred from the report by Feskanich et al. (2000) on β-carotene, animal can be adopted for flavonoids bioavailability studies. Notwithstanding of the inability to directly relate findings to human situations, in vivo animal models are ideal models for preliminary studies. Inbred animals give higher homogeneity and less complexity than a human model. Besides that, considering the core of bioavailability is absorption, direct assessment on intestinal absorption offers a more straightforward
way to study the efficacy of dietary antioxidant. And this is more feasible to be carried out in animal.

Despite this, animal models are not good model for carotenoids bioavailability study. Researches conducted to test the effectiveness of carotenoids against mammary carcinogenesis have not been consistent. Rodents showed poor absorption and low levels of carotenoids in target tissues (Moon and Constantinou, 1997) where rats receiving intra-peritoneal (i.p.) injection of β-carotene (10 mg/kg) showed no protection against the development of mammary cancer (Sharoni et al., 1997). In contrast, rats injected Intraperitoneally with lycopene-enriched tomato olesoresin (10 mg/kg) developed significantly fewer tumors and the tumor area was smaller as compared to the untreated rats. It was also pointed out by Paiva and Russell (1999) that most animals do not absorb or metabolize carotenoids similarly to humans. This may be accounted for the lack of information on carotenoids absorption mechanism, given that human models are more frequently used. In other words, there is an urgent need to design or develop suitable model for carotenoids bioavailability study. A summary of the proposed mode of absorption for flavonoids and carotenoids is presented in Table 3.

In conclusion, by studying the pharmacokinetics data reported in 97 bioavailability studies, bioavailability of the different classes of polyphenols were compared and ranked as followed: isoflavones, catechins, flavanones, quercetin and the anthocyanins (Manach et al., 2005). For carotenoids, researches on non-purified carotenoids suggest that bioavailability of lutein is higher than β-carotene and α-carotene, while bioavailability of lycopene is probably the lowest (Micozzi et al., 1992; Gartner et al., 1997; van het Hof et al., 1999b; Brown et al., 2004; Molldrem et al., 2004).

REFERENCES


bioavailability of flavonoids and carotenoids


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