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Estimation of total antioxidant capacity from diet and supplements in US adults

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Abstract

Given the importance of dietary antioxidants in reducing the risks of chronic diseases, the present study aimed to estimate the intake of total antioxidant capacity (TAC) from diet and dietary supplements of US adults. We utilised the US Department of Agriculture flavonoid and proanthocyanidin databases, dietary supplement data and food consumption data of 4391 US adults aged 19 + years in the National Health and Nutrition Examination Survey 2001–2. In order to convert the intake data of individual antioxidant compounds to TAC values, the vitamin C equivalent (VCE) of forty-three antioxidant nutrients measured previously was also applied. Daily TAC averaged 503·3 mg VCE/d (approximately 75 % from diet and 25 % from supplements). The energy-adjusted daily TAC level from diet and supplements was higher in women (except for carotenoids), older adults, Caucasian (except for carotenoids), non-alcohol consumers (for vitamin E and proanthocyanidins), subjects with higher income (except for carotenoids) and higher exercise levels than their counterparts ($P<0·05$). TAC was positively associated with daily consumption of fruits and fruit juices, vegetables and vegetable products, beverages, wines and teas ($P<0·001$). Teas, dietary supplements, and fruits and fruit juices were the major sources of dietary TAC of the US population (28, 25 and 17 %, respectively), while the contribution of vegetables and vegetable products to TAC was minimal (< 2 %). The present study indicates that antioxidant intake from various diet and supplements contributes to TAC status. TAC levels are different in sociodemographic subgroups of the US population. The relationship between TAC intake and risks of chronic disease warrants further investigation.

Key words: Antioxidants: Vitamin C equivalents: Diet recall: Sociodemographic subgroups

Consumption of fruits and vegetables has been associated with a low incidence and mortality rate of various degenerative diseases including CVD[1–3] and cancer[4,5]. It is not known which dietary constituents are responsible for this association, but it is often assumed that antioxidants play a significant role in this respect. Plant foods contain a variety of compounds with antioxidant activity, including ascorbic acid, tocopherols, carotenoids and phytochemicals such as flavonoids and procyanidins. Since any single antioxidant may not reflect the total antioxidant power of food, the concept of total antioxidant capacity (TAC) has been introduced[6]. TAC considers the cumulative/synergistic and protective activities of all the antioxidants present in food or body fluids, thus providing an integrated parameter rather than the simple sum of measurable antioxidants.

Recently, the applicability and scientific appropriateness of the TAC concept have been debated due to the fact that plasma TAC may be affected by plasma protein, uric acid and antioxidant enzymes rather than by antioxidant nutrients and their metabolites directly originating from diets[7]. Also, dietary TAC does not reflect bioavailability as determined by absorption and excretion. Furthermore, the successful application of this tool is highly dependent on the completeness and validity of dietary intake data as well as on the accuracy

Abbreviations: ABTS, 2,2′-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid; DR, diet recall; NHANES, National Health and Nutrition Examination Survey; ORAC, oxygen radical absorbance capacity; PA, proanthocyanidin; TAC, total antioxidant capacity; USDA, US Department of Agriculture; VCE, vitamin C equivalents.

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of food composition data. Nevertheless, dietary TAC still has a great potential for clinical and public health applications since it exclusively provides the sum of protective activities of dietary antioxidants.

Our research group has recently estimated antioxidant intakes of the US population from diet and dietary supplements by creatively utilising the US Department of Agriculture (USDA) flavonoid databases, food consumption data and dietary supplement data in the National Health and Nutrition Examination Survey (NHANES) 1999–2002[8–10]. To expand our knowledge on the contribution of diets to TAC, a dietary TAC database of the US population has been developed and validated for future application in human antioxidant research[11]. However, there is no documentation on the assessment of dietary TAC of a free-living US population due to the limited information of valid antioxidant intake data and measured TAC levels of diverse food items[11]. Therefore, the present study aimed to provide the baseline dietary TAC estimation of US adults and sociodemographic subgroups as a premise in order to build the foundation for further investigation of disease prevention and health improvement.

Participants and methods

Study population

Individuals aged 19 years and older among the NHANES 2001–2 participants[12] and having reliable and complete diet recall (DR)[13] data as coded by the National Center for Health Statistics[14] were included in the present study (n 4391). Participants (n 698) with unreliable and incomplete DR were excluded from the study. There were no significant differences in major outcome variables between included and excluded participants. The NHANES has been conducted by the National Center for Health Statistics to obtain nationally representative information on the health and nutritional status of the US population since the 1970s. All interviewed persons were invited to the mobile examination centre, where the 24 h DR (midnight to midnight) and questionnaires on dietary supplement use were administered. Written informed consent was obtained from all participants or proxies, and the survey protocol was approved by the Research Ethics Review Board of the National Center for Health Statistics.

Description of datasets

Details of the datasets used in the present study have been reported in our recent publication[10]. Briefly, we created one flavonoid database from two different datasets released in recent years: the USDA database for the flavonoid content of selected foods (2007 update)[15] and the USDA–Iowa State University database on the isoflavone content of foods (2008 update)[16]. The combined flavonoid database consisted of twenty-four flavonoid compounds: flavonols (quercetin, kaempferol, myricetin and isorhamnetin), flavones (luteolin and apigenin), flavanones (eriodictyol, hesperetin and naringenin), flavan-3-ols (catechin, epicatechin, theaflavin and thearubigin), anthocyanidins (cyanidin, delphinidin, malvidin, pelargonidin, peonidin and petunidin) and isoflavones (daidzein, genistein, glycitein, biochanin A and formononetin). In order to improve the coverage of the estimated flavonoid intake, we expanded the flavonoid database according to the pre-established protocol that has been described extensively in a separate publication[10]. The USDA proanthocyanidin (PA) database[17] released in 2004 complements the USDA flavonoid and isoflavone databases. It contains analytical data generated by the Arkansas Children's Nutrition Center as well as other published analytical data. The PA database includes the food composition data of 205 selected food items for the following PA: monomers, dimers, trimers, 4–6 mers (tetramers, pentamers and hexamers), 7–10 mers (heptamers, octamers, nonamers and decamers) and polymers (degree of polymerisation >10).

Estimation of antioxidant intakes from diet

The calculation of dietary antioxidant intake has been described in detail in our preliminary study[10]. In summary, we matched the NHANES food consumption data with the USDA flavonoid database following the same procedure: (1) conversion of food items in NHANES dietary recalls to USDA standard reference codes using the food recipe book and food description data file for NHANES food codes; (2) weight adjustment using moisture content; (3) code modification using the USDA food unit conversion search program; (4) linking food intake data with the flavonoid database. Daily individual flavonoid intake from selected foods was determined by multiplying the content of individual flavonoids (mg aglycone equivalents/100 g food) by the daily consumption (g/d) of the selected food item. Estimated total intake of individual flavonoids was the sum of individual flavonoid intakes from all food sources reported in the 24 h DR. Total flavonoid intake was determined by the summation of the total intake of individual flavonoids. Data on individual participant's daily dietary intakes of antioxidant vitamins are available in the NHANES 2001–2[12,18].

Estimation of antioxidant intakes from supplements

A dietary supplement is defined by the Dietary Supplement Health and Education Act of 1994 as 'a product (other than tobacco) intended to supplement the diet that bears or contains one or more of the following dietary ingredients: a vitamin, a mineral, an herb or other botanical, an amino acid or a dietary substance for use by man to supplement the diet by increasing the dietary intake, or a concentrate, metabolite, constituent, extract, or combination of the above ingredients'. The data on dietary supplement use in the NHANES 2001–2 enable investigators to estimate the individual vitamin and mineral intake from dietary supplement use. They provided information about the participants' dietary supplement usage, including supplement counts, supplement records, supplement information, ingredient information and blend information[12]. To calculate the intakes of antioxidant nutrients from the supplement, vitamin C, vitamin E, carotenes, Se and flavonoids were selected from the ingredient information

file. Next, the nutrient composition table of supplements containing the antioxidants was made using the supplement information file. The antioxidant intakes from the supplements were calculated using the supplement counts file, supplement records file and the nutrient composition table of supplements. Participants in the NHANES 2001–2 were questioned specifically about their use of vitamin and mineral supplements. Even though the NHANES dietary supplement data provides comprehensive information on nutrient intake status of the US population from various dietary supplements, limited information is available on flavonoid composition in those products. Furthermore, flavonoid intake from supplements was reported to be less than 2% in US adults[6]. Therefore, flavonoid intake from supplements was not included in the present study. Consequently, the present study includes carotenoids, vitamin C and vitamin E from supplements to estimate the total antioxidant intakes.

Analyses of antioxidant capacity of antioxidants

Antioxidant power of individual antioxidant nutrients expressed as vitamin C equivalents (VCE) measured by the 2,2′-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid (ABTS) assay has been documented in our previous study[11]. Concisely, antioxidant capacities of forty-three major antioxidant nutrients were measured by the ABTS assay conducted according to Kim *et al.*[19,20]. These antioxidants include thirty flavonoids (isorhamnetin, eriodictyol, theaflavin, theaflavin 3-gallate, theaflavin 3′-gallate, theaflavin 3,3′-digallate, petunidin, glycitein, quercetin, kaempferol, myricetin, luteolin, apigenin, hesperetin, naringenin, (+)-catechin, (+)-gallocatechin, (−)-epicatechin, (−)-epigallocatechin, (−)-epicatechin 3-gallate, (−)-epigallocatechin 3-gallate, cyanidin, delphinidin, malvidin, pelargonidin, peonidin, daidzein, genistein, biochanin A and formononetin), four PA (dimers and trimers), six carotenoids (α-carotene, β-carotene, β-cryptoxanthin, lutein, lycopene and zeaxanthin), vitamin E (α-tocopherol and γ-tocopherol) and vitamin C.

Estimation of total antioxidant capacity from diet and supplements

Individual antioxidant intake from diet and supplements was determined by multiplying the content of the individual antioxidants (flavonoids, PA, carotenoids, vitamin C and vitamin E) by the daily consumption of each selected food item. The sum of the individual antioxidant intakes was then calculated by summarising individual antioxidant levels from all food sources reported by 24 h DR and dietary supplement use[21]. Antioxidant capacity of each antioxidant consumed daily was calculated by multiplying the consumption data of each antioxidant by its respective antioxidant capacity. TAC from diet and dietary supplements was assessed by summing individual antioxidant capacity and then adjusted by daily total intake and energy intake, which was adjusted to TAC per 4184 kJ (1000 kcal). The US adults were subgrouped by sociodemographic and lifestyle variables: age (19–30, 31–50, 51–70 and 70 + years); sex; ethnicity (non-Hispanic white, non-Hispanic black, Mexican-American, others); BMI (≤20, 20–25, 25–30 and >30 kg/m^2); poverty income ratios (<1·85, ≥1·85); alcohol consumption (yes or no to 'at least twelve drinks/year'); current smoking (yes or no to 'current smoking' and 'smoked cigarettes, cigars or pipes and/or used chewing tobacco or snuff at least once during the past 30 d'); exercise levels (0, T1, T2 and T3). The exercise levels were expressed as the metabolic equivalent score calculated by combining the intensity level of the leisure-time activities reported, mean duration and frequency.

Statistical analyses

All statistical analyses were carried out with SAS software, release 8.1, 2000 (SAS Institute, Cary, NC, USA) and the Survey Data Analysis for multi-stage sample designs professional software package (SUDAAN, release 8.0.2, 2003; Research Triangle Institute, Raleigh, NC, USA). Sample weights were applied to all analyses to account for the unequal probability of selection, non-coverage and non-response bias resulting from oversampling of low-income persons, adolescents, the elderly, African-Americans and Mexican-Americans.

The variables on individual and total antioxidant intakes were not normally distributed and they were not normally distributed even after any transformation. However, non-parametric methods could not be used in the analyses since SUDAAN does not work for those methods. Arithmetic means of dietary TAC intake from the daily diet and supplements of subpopulations grouped by sociodemographic and lifestyle variables were determined. Standard error of the means was calculated by the linearisation (Taylor series) variance estimation method for population parameters by SUDAAN. Student's *t* test and ANOVA were used to compare means for interval scale variables and to test overall differences of TAC intakes by sociodemographic and lifestyle variables such as sex, income, smoking, etc. The trends of TAC intakes by weight of specific food groups consumed were tested using linear contrasts after adjustment for sex, age, ethnicity and total energy intake. The χ^2 test was applied for assessing the distributions of categorical variables. Multivariate linear regression analyses were performed to determine the extent to which energy-adjusted TAC intake was explained by dietary behaviours and other sociodemographic factors. The contribution of each food group to the daily TAC was calculated as the ratio of the antioxidant intake from that food group to the total intake from all foods. Values in the tables are presented as means with their standard errors.

Results

Daily total antioxidant capacity intake from diet and supplements

Individual antioxidant capacities from diet, supplements and TAC are shown in Table 1. Daily TAC level averages 503·3 mg VCE/d, approximately 75% from diet and 25% from supplements. Vitamin C and flavonoids are the top two sources contributing to TAC (41 and 39%, respectively).

When total energy was adjusted, daily individual antioxidant capacity levels from diet and supplements increased with age in both men and women (P for trend $<0{\cdot}05$; except for carotenoids in men), with income (P for trend $<0{\cdot}05$; except for carotenoids) and exercise level (P for trend $<0{\cdot}05$). Energy-adjusted individual antioxidant capacity was higher in women ($P<0{\cdot}05$; except for carotenoids) and in Caucasians ($P<0{\cdot}05$; except for carotenoids) than in their counterparts. Alcohol consumers had higher TAC levels from PA than non-consumers ($P<0{\cdot}05$). In addition, energy-adjusted TAC from diet and supplements were higher in women ($P<0{\cdot}001$), older adults ($P<0{\cdot}001$), Caucasians ($P<0{\cdot}001$) and those with higher income level ($P<0{\cdot}001$) and higher exercise level than in their counterparts ($P<0{\cdot}001$). Alcohol consumption and smoking did not seem to be related to TAC levels. BMI had a weaker association with TAC ($P=0{\cdot}100$) compared with the sociodemographic factors.

Estimated total antioxidant capacity by food group consumption

The consumption of specific food or food groups in relation to daily TAC was investigated by testing TAC levels in non-consumers and tertiles of consumers by major food groups (Table 2). After adjusting for sex, age, ethnicity and total energy intake, TAC levels were positively associated with the daily consumption of fruits and fruit juices, vegetables and vegetable products, beverages, wines and teas ($P<0{\cdot}001$), whereas bread and grain foods were not related to TAC levels ($P=0{\cdot}724$).

Major total antioxidant capacity sources consumed in US adults

Teas, dietary supplements, fruits and fruit juices, and wines were the major food or food groups of TAC based on the 24 h DR (28, 25, 17 and 5 %, respectively), while vegetables and vegetable products only account for less than 2 %. Fig. 1 elucidates the percentage of the major sources contributing to TAC and the corresponding TAC values. The food list of the major TAC sources is presented in Table 3.

Discussion

Antioxidants found in fruits and vegetables have been assumed to be responsible for the inverse association between higher consumption of these foods and lower risks of chronic diseases[22], while singly administered antioxidant interventions failed to support the promising causal relationship[23–26]. Instead of exploring the 'quenching' power of single antioxidants, recently, the concept of TAC has been introduced to express the total synergistic potential of antioxidants for investigating the health effects in food[6]. TAC from diet was found to be inversely and independently related to the plasma concentration of high-sensitive C-reactive protein concentration in Italian adults[27], and positively associated with adiponenctin levels by a Greek team[28]. Also, it was suggested to be potentially an early estimate of the risk of metabolic syndrome features in Spanish people[29].

A few analytical methods have been developed to measure the synergistic potential of individual food items, differing for scavenging various free radicals and for measuring different endpoints[30]. The commonly used methods include Trolox equivalent antioxidant capacity[31], oxygen radical absorbance capacity (ORAC)[32], total radical-trapping antioxidant parameters[33], ferric-reducing antioxidant power[34], 1,1-diphenyl-2-picrylhydrazyl[35] and ABTS[36] assays[37]. Among these methods, the ABTS assay developed by Kim *et al.*[38] and expressed in VCE antioxidant capacity was used in the present study to estimate TAC. The ABTS (VCE antioxidant capacity) assay utilises quantitative concepts in reference to the familiar vitamin C to measure both hydrophilic and lipophilic antioxidant activities, and its weight-based expression enables researchers to link weight-based food consumption data to estimate TAC[38].

DR[39] and FFQ[30,40] have been commonly used to assess dietary TAC by summation of known TAC values of different food items measured by total radical-trapping antioxidant parameters or ORAC, which, to large extent, depends on the ORAC or total radical-trapping antioxidant parameter food datasets limited to the species and amounts of fruits and vegetables. Although, in 2007, the USDA released an ORAC dataset of 277 selected food items based on a meta-analysis[41], it is unlikely to be used in different countries because of various food availability and nutrient fortification laws. Since it is impractical to measure the TAC of every food that each individual person consumes, we creatively estimated the dietary TAC theoretically by summation of antioxidant capacities of individual antioxidants consumed/d. This theoretical TAC of foods has been proven to be positively correlated with the different TAC values determined analytically by ABTS and 1,1-diphenyl-2-picrylhydrazyl assays and with TAC values from matched forty-four food items from the USDA ORAC database[11]. To our best knowledge, this is the first time such a method has been used to estimate dietary TAC of US adults. This approach to calculate dietary TAC would not be limited by specific food items, whose antioxidant capacity has to be measured in advance.

Daily TAC of 503·3 mg VCE in the present study is lower than what we reported previously in 2005 based on experimental data from fruits and vegetables purchased locally in the New York area (591 mg VCE)[21]. In the present study, antioxidants from both diet and supplements played pivotal roles in the daily TAC of US adults. Individual antioxidant contributions to TAC were in the following order: vitamin C > flavonoids > proanthocyanins > vitamin E > carotenoids. TAC from supplements took account for almost one-fourth of TAC, and particularly more than half of vitamin C contribution to TAC was from supplements, indicating that supplementation is a major source for vitamin C intake in US adults. These results were in accordance with the previous report that about 48 % of US adults take at least one supplement/d and that vitamin C intake from supplements are higher than that from diet[10]. Dietary phenolic

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Table 1. Total antioxidant capacity (TAC) from diet and supplements of US adults aged 19 + years and its subgroups by sociodemographic and lifestyle factors in the National Health and Nutrition Examination Survey 2001–2

(Mean values with their standard errors)

		Vitamin C† (mg VCE/d)						Vitamin E (mg VCE/d)					
		Diet		Suppl		Total		Diet		Suppl		Total	
	Stratified sample (*n*)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Sex													
Men	2247	103·2	4·8	96·1	9·7	199·3***	11·4	2·2	0·1	10·5	1·0	12·8***	1·0
Women	2144	84·2	2·2	125·1	12·6	209·3	12·5	1·7	0·1	15·3	1·1	17·1	1·1
Age (years)													
19–30	946	102·1	6·2	49·1	5·8	151·2***	10·0	2·0	0·0	3·4	0·5	5·4***	0·5
31–50	1466	89·5	5·5	97·7	12·8	187·2	12·8	2·0	0·1	9·2	1·1	11·2	1·0
51–70	1228	96·6	4·1	164·2	20·9	260·8	21·6	2·0	0·1	22·3	2·0	24·3	2·0
70 +	751	96·6	3·6	147·7	14·5	233·8	14·6	1·6	0·1	23·1	1·7	24·8	1·7
Ethnicity													
Non-Hispanic white	2302	89·3	3·5	131·5	12·4	220·8**	13·1	2·0	0·1	15·4	1·1	17·4***	1·1
Non-Hispanic black	849	100·8	6·9	40·8	5·9	141·6	8·5	1·8	0·1	6·5	1·0	8·3	1·0
Mexican-American	942	114·8	3·8	45·3	7·7	160·1	7·8	1·9	0·0	4·8	0·7	6·6	0·7
Others	298	104·4	6·4	67·5	13·2	171·9	16·3	1·7	0·1	6·3	1·3	8·1	1·3
BMI (kg/m^2)													
≤ 20	248	93·6	8·5	85·6	25·3	179·2	27·9	1·9	0·1	11·4	3·7	13·3	3·7
20 to ≤25	1181	105·2	4·1	127·9	20·6	233·0	21·2	2·1	0·1	14·2	1·7	16·3	1·7
25 to ≤30	1530	89·2	3·3	112·3	7·9	201·4	8·2	1·9	0·0	12·5	0·9	14·4	0·9
> 30	1248	88·4	4·3	100·7	11·3	189·1	13·0	2·0	0·1	12·8	1·3	14·8	1·3
PIR‡													
< 1·0	695	89·0	3·4	51·6	8·7	140·6***	9·8	2·0	0·1	5·6	1·2	7·3***	1·2
1·0–1·3	411	82·2	9·7	55·8	11·0	137·9	16·7	1·7	0·1	8·3	2·1	9·9	2·1
1·3–1·85	530	78·5	5·6	60·6	10·9	139·1	12·2	1·8	0·1	11·0	1·8	12·8	1·8
≥ 1·85	2467	98·9	3·4	133·8	14·1	232·7	13·9	2·1	0·1	14·7	1·0	16·8	1·0
Alcohol consumption§													
No	1231	94·8	4·4	105·9	11·4	200·8	12·3	1·9	0·1	14·7	1·5	16·6*	1·5
Yes	2766	92·3	3·4	117·1	12·9	209·4	13·0	2·0	0·1	13·0	1·1	15·0	1·1
Current smoking‖													
No	2085	102·5	2·6	109·0	7·0	211·5	8·4	2·0	0·1	13·6	1·1	15·6	1·1
Yes	2080	83·8	4·6	116·0	15·4	199·7	15·5	1·9	0·1	12·8	1·1	14·7	1·1
Exercise level¶													
0	1473	75·5	3·8	67·0	9·0	142·4**	9·4	1·7	0·1	9·4	0·9	11·1**	0·9
T1	838	84·9	4·7	123·7	20·4	208·6	21·8	2·0	0·1	10·8	1·3	12·8	1·3
T2	835	107·0	4·8	127·2	16·4	234·1	16·5	2·1	0·1	16·8	1·4	18·9	1·5
T3	886	112·0	5·2	140·4	15·8	252·5	16·8	2·2	0·1	15·2	1·7	17·4	1·6

Table 1. *Continued*

	Carotenoids (mg VCE/d)						Flavonoids (mg VCE/d)		PA (mg VCE/d)		TAC (mg VCE/d)					
	Diet		Suppl		Total		Diet		Diet		Diet		Suppl		Total	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Sex																
Men	5·5	0·3	0·1	0·0	5·6	0·3	210·7**	14·3	92·9**	6·9	414·6	21·0	106·7	10·3	521·3***	23·9
Women	3·9	0·2	0·1	0·0	3·9	0·2	178·4	10·2	77·3	4·5	345·4	14·8	140·5	13·2	485·9	19·2
Age (years)																
19–30	5·3	0·6	0·1	0·0	5·3*	0·6	168·6***	16·9	72·7**	7·5	350·6	23·8	52·5	6·1	403·2***	23·0
31–50	4·6	0·3	0·1	0·0	4·7	0·3	200·4	12·3	92·2	6·3	388·7	18·2	107·0	13·4	495·7	24·2
51–70	4·8	0·3	0·1	0·0	4·9	0·3	219·1	18·2	90·7	8·4	413·2	26·6	186·6	22·0	599·8	41·0
70 +	3·6	0·3	0·1	0·0	3·7	0·3	157·8	13·8	65·3	6·3	314·4	19·2	171·0	15·2	485·4	27·1
Ethnicity																
Non-Hispanic white	4·9	0·3	0·1	0·0	5·0	0·3	213·5**	14·8	94·5***	7·0	404·2	21·9	147·0	13·0	551·2***	26·0
Non-Hispanic black	3·8	0·3	0·1	0·0	3·8	0·3	136·2	8·0	61·3	4·0	303·9	15·7	47·3	6·7	351·2	14·5
Mexican-American	4·7	0·3	0·1	0·0	4·7	0·2	128·1	5·9	49·7	2·6	299·1	7·3	50·1	8·2	349·2	11·6
Others	4·1	0·4	0·1	0·0	4·2	0·4	150·6	19·6	59·6	5·8	320·4	28·0	73·9	14·1	394·3	35·8
BMI (kg/m^2)																
≤ 20	5·0	0·9	0·1	0·0	5·0	0·9	175·0	28·8	86·0	13·3	361·5	44·0	97·0	28·1	458·5*	58·7
20 to ≤25	4·8	0·4	0·1	0·0	4·9	0·4	198·2	17·3	86·2	7·1	396·4	23·9	142·2	21·8	538·6	33·6
25 to ≤30	4·6	0·3	0·1	0·0	4·7	0·3	214·7	15·3	95·6	7·6	406·0	21·5	124·8	8·7	530·7	22·8
> 30	4·8	0·4	0·1	0·0	4·9	0·4	176·3	13·0	73·9	5·8	345·3	16·8	113·7	11·5	459·0	15·6
PIR‡																
< 1·0	4·6	0·4	0·1	0·0	4·6	0·4	138·3**	16·4	59·5*	5·7	293·0	19·9	57·3	8·9	350·3***	21·7
1·0–1·3	4·3	0·6	0·1	0·0	4·4	0·6	151·1	15·9	63·2	6·2	302·5	23·0	64·1	12·9	366·5	29·7
1·3–1·85	4·6	0·5	0·1	0·0	4·7	0·4	146·7	20·6	73·8	12·6	305·5	35·2	71·7	12·1	377·2	39·1
≥ 1·85	4·8	0·3	0·1	0·0	4·9	0·3	214·4	13·0	93·6	6·3	413·7	19·1	148·6	14·7	562·3	21·9
Alcohol consumption§																
No	4·5	0·5	0·1	0·0	4·6	0·5	159·3	12·5	59·9**	3·3	320·4	13·0	120·8	12·0	441·1	20·0
Yes	4·7	0·2	0·1	0·0	4·8	0·2	211·6	12·9	95·8	6·5	406·4	18·8	130·2	13·7	536·6	23·3
Current smoking‖																
No	5·0	0·3	0·1	0·0	5·1	0·3	199·8	14·2	82·7	5·8	392·0	19·8	122·7	7·4	514·7	23·3
Yes	4·4	0·2	0·1	0·0	4·5	0·2	192·2	13·8	88·6	7·0	370·9	20·9	128·8	16·1	499·8	26·7
Exercise level¶																
0	4·1	0·3	0·1	0·0	4·2*	0·3	169·9**	10·6	73·0**	4·2	324·2	15·0	76·4	9·6	400·5***	11·6
T1	4·6	0·5	0·1	0·0	4·7	0·5	186·2	18·7	87·0	8·4	364·6	25·6	134·6	20·6	499·2	32·6
T2	5·2	0·3	0·1	0·0	5·3	0·3	203·4	13·3	87·4	7·1	405·0	19·6	144·1	16·9	549·1	26·1
T3	5·1	0·3	0·1	0·0	5·2	0·3	225·7	18·9	98·2	8·3	443·3	27·7	155·7	16·9	599·0	33·2

VCE, vitamin C equivalents; Suppl, supplements; PA, proanthocyanidins; PIR, poverty income ratio; MET, metabolic equivalent.

P values are for overall differences by the *t* test or ANOVA among males and females, age subgroups, ethnicities, income levels, alcohol consumption, smoking and exercise levels after adjusting for total energy intake: $^*P<0{\cdot}05$, $^{**}P<0{\cdot}01$, $^{***}P<0{\cdot}001$.

† Antioxidant capacities of nutrients are expressed as mg VCE/d.

‡ Ratio of the median family income: poverty index. A PIR ≤1·30 is required to be eligible for food assistance programs.

§ Yes meant to consume twelve alcoholic beverages or more per year.

‖ Yes meant to have smoked cigarettes, cigars, pipes, or used chewing tobacco or snuff at least once during the past 30 d.

¶ Exercise levels, expressed on the MET score, were calculated by combining the intensity level of the leisure-time activities reported, mean duration and frequency.

Table 2. Dietary total antioxidant capacity (TAC) of US adults aged 19 + years by food or food group consumption: National Health and Nutrition Examination Survey 2001–2

(Mean values with their standard errors)

	Non-consumers*		T1†		T2†		T3†		
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	*P*‡
Fruits and fruit juices (g/d)									
Range (g/d)	0		≤124·5		≤300·81		>300·81		
Subjects (*n*)	1485		969		970		967		
TAC from total food intake (mg VCE/d)	287·5	24·8	342·5	21·2	386·0	16·1	567·2	22·7	0·000
Vegetables and vegetable products (g/d)									
Range (g/d)	0		≤124·4		≤267·4		>267·4		
Subjects (*n*)	363		1341		1346		1341		
TAC from total food intake (mg VCE/d)	270·8	31·2	292·4	15·8	386·2	26·3	482·9	23·9	0·001
Bread and grain foods (g/d)									
Range (g/d)	0		≤592		≤1230		>1230		
Subjects (*n*)	87		1433		1437		1434		
TAC from total food intake (mg VCE/d)	341·0	72·3	328·5	18·9	391·0	15·6	419·2	25·5	0·724
Beverages§ (g/d)									
Range (g/d)	0		≤121·4		≤223·0		>223·0		
Subjects (*n*)	282		1373		1368		1368		
TAC from total food intake (mg VCE/d)	246·7	12·1	258·0	7·3	333·8	17·3	518·7	29·2	<0·001
Wines (g/d)									
Range (g/d)	0		≤33·0		≤206·5		>206·5		
Subjects (*n*)	4048		115		117		111		
TAC from total food intake (mg VCE/d)	354·50	15·0	312·5	30·5	566·0	60·6	944·0	32·4	0·000
Teas (g/d)									
Range (g/d)	0		≤309·3		≤593·8		>593·8		
Subjects (*n*)	3443		327		306		315		
TAC from total food intake (mg VCE/d)	240·3	9·8	364·3	23·8	615·3	20	1345·5	52·5	0·000

* All subjects who did not consume the food in 24 h dietary recalls were proposed as group 'non-consumers' and all consumers were divided into tertiles by the amount of consumption.
† T1, T2 and T3 refer to the first, second and third tertiles among the consumers of food or food group.
‡ Adjusted for sex, age, ethnicity and total energy intake.
§ Beverages include other drinks except wines, teas and fruit juices.

phytochemicals, such as flavonoids and PA, provided relatively high TAC (39 and 17 %, respectively), while those kinds of supplements which were expressed as the total amount of flavonoid and PA intakes regardless of the subcategories consumed accounted for so little (<2 %) and they were not included in the present study. The major sources of the phenolics in US diets were from fruits than from vegetables[21], black and green teas, red wines and cocoa[42,43]. The significant contribution of flavonoids to TAC was similar to the previous findings that flavonoid consumption from diet was two times more than vitamin C intake[10]. On the TAC database, flavonoids also have higher antioxidant capacities than other antioxidant vitamins[11]. Vitamin E and carotenoids took a very small part in TAC, which was attributed to their lower existence and their relatively lower antioxidant capacities[11].

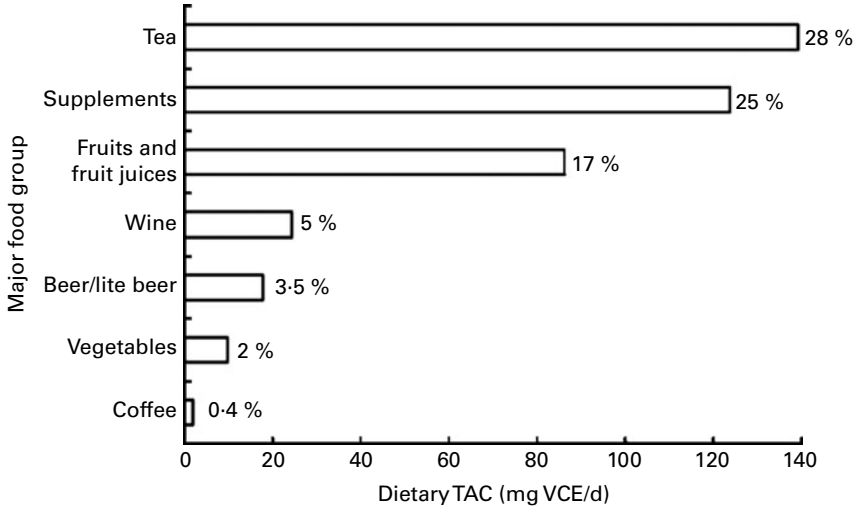

Fig. 1. Major sources of dietary total antioxidant capacity (TAC) in the US population aged 19 + years: the National Health and Nutrition Examination Survey 2001–2, including the dietary TAC value of the major food groups and the percentage the food group contributes to the TAC. VCE, vitamin C equivalents.

Table 3. Top major food items contributing to dietary total antioxidant capacity (TAC) in 19 + years US adults

Rank	Food groups	Dietary TAC (mg VCE/d)	%*	Cum%†
1	Tea‡	139·2	27·6	27·6
2	Vitamin C supplement	110·8	22·0	49·6
3	Orange juice§	27·0	5·4	55·0
4	Wine (table and dry)	24·4	4·8	59·8
5	Beer‖	17·8	3·5	63·3
6	Vitamin E supplement	13·0	2·6	65·9
7	Banana (raw)	7·3	1·5	67·4
8	Blueberries (raw)	5·9	1·2	68·6
9	Orange (raw)	5·4	1·1	69·7
10	Apple (raw)	5·0	1·0	70·7
11	Fruit drink¶	4·6	0·9	71·6
12	Strawberries (raw)	3·2	0·6	72·2
13	Apple juice	3·1	0·6	72·8
14	Cranberry juice drink with vitamin C added	2·8	0·6	73·4
15	Tomato (raw)	2·7	0·5	73·9
16	White potato**	2·5	0·5	74·4
17	Grapefruit (raw)	2·3	0·5	74·9
18	Plum (raw)	2·3	0·5	75·4
19	Orange drink††	2·1	0·4	75·8
20	Coffee (made from ground and regular)	1·9	0·4	76·2
21	Peach (raw)	1·9	0·4	76·6
22	Cantaloupe (muskmelon, raw)	1·8	0·4	77·0
23	Grapefruit juice (canned, bottled or in a carton, unsweetened)	1·8	0·4	77·4
24	Chili con carne with beans	1·8	0·4	77·8
25	Pear (raw)	1·6	0·3	78·1
26	Onions (mature and raw)	1·6	0·3	78·4
27	Broccoli (cooked, from fresh and fat not added in cooking)	1·6	0·3	78·7
28	Lemonade	1·6	0·3	79·0
29	Cherries (sweet, raw; Queen Anne, Bing)	1·4	0·3	79·3
30	Grapes (raw, NS as to type)	1·4	0·3	79·6

VCE, vitamin C equivalents; Cum%, cumulative percentage; NS, not specified.
* The percentage of the food item contributing to dietary TAC.
† Cum% of the food items contributing to dietary TAC.
‡ Includes tea, leaf, unsweetened; tea, leaf, pre-sweetened with sugar; tea, NS as to type, unsweetened; tea, NS as to type, pre-sweetened with sugar; tea, NS as to type, pre-sweetened, NS as to sweetener; tea, leaf, pre-sweetened with low-energy sweetener; tea, NS as to type, pre-sweetened with low-energy sweetener; tea, leaf, decaffeinated, unsweetened; tea, leaf, pre-sweetened, NS as to sweetener.
§ Includes orange juice, canned, bottled or in a carton, unsweetened; orange juice, frozen, unsweetened (reconstituted with water).
‖ Includes regular beer and lite beer.
¶ Includes fruit punch, fruit drink, or fruitade, with vitamin C added; fruit-flavoured drink, made from sweetened powdered mix (fortified with vitamin C); fruit juice drink, not fully specified.
** Includes white potato, French fries, from frozen, deep fried; white potato, chips.
†† Includes orange drink and orangeade with vitamin C added; orange breakfast drink.

TAC and individual antioxidant TAC from diet or supplements differed among sociodemographic subgroups. Energy-adjusted TAC of individual antioxidants increased with age, income and exercise levels except for carotenoids. This result was slightly different from the antioxidant intake estimation study[10], in which flavonoids present no trend. The discrepancy was probably attributed to the fact that the low antioxidant capacity of carotenoids weakened their contribution to the whole diet, particularly in men, while the high antioxidant capacity of flavonoids strengthened their role in scavenging free radicals. One of the serious public concerns related to smoking is the lower consumption of vitamin C, vitamin E and carotenes by smokers[10]. The present study, however, did not find any differences of TAC intake between smokers and non-smokers, which may stem from the lower antioxidant capacities possessed by these three nutrients. Although many studies have proved that smoking causes smokers to be subject to higher oxidative stress than their counterpart, based on our studies, smoking people did not intend to consume more antioxidants to counteract the adverse damage from smoking, which, indeed, needs public and self concern to increase the corresponding consumption of the antioxidant-rich foods or supplements. Energy-adjusted TAC indicated the similar trend to the TAC of the individual antioxidants, that is, higher in men, older adults, Caucasians and those with higher income level and exercise level.

Consumption of fruits and fruit juices, vegetables and vegetable products, beverages, wines and teas was positively associated with dietary TAC (Table 2). Although the previous studies have reported that fruits and fruit juices, and vegetables have been identified as major sources of antioxidant vitamins[44], vitamins did not contribute the most to the TAC from food. Vitamin C, the most abundant vitamin, was found to only account for less than 15% of antioxidant capacities in most fruits except for kiwi fruit and honeydew melon[21], whereas flavonoids were the predominant sources. Particularly, anthocyanins, with a high antioxidant potential among flavonoids, are abundant in many deep-coloured fruits and vegetables[45,46] and in red wine[10,46]. Tea was demonstrated to be the major source of flavan-3-ols and flavonols, both of which accounted for over 90% of total flavonoids[47]. These findings suggested that the food items

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possessing high proportional flavonoids would contribute most to the dietary TAC.

We identified the major food sources of dietary TAC as tea, supplements, fruits and fruit juices and wines, while vegetables and vegetable products account for little antioxidant potential in the US diet. One previous study has implicated that only 21 % of US adults drink tea daily, while fruits and fruit juices, were consumed by almost 80 % of US adults[47]; the various abundances of flavonoids and vitamins prompt tea to have a stronger free-radical scavenging power. The prevalent consumption of supplements in US adults drives them to be a major contributor of TAC. Vegetables and vegetable products account for a tiny part of the TAC in the US diet, and potatoes, onions and broccoli were the top three dietary TAC contributors among different vegetables (Table 3). The findings about vegetable contribution were different from two previous TAC estimations based on FFQ, which found vegetables to be the main contributors to TAC intake in the Italian and Swedish population[48,49]. The comparison probably raised the public concern that food selection based on TAC may modify the lifestyles or health conditions in US populations.

To our best knowledge, the present study is the first to document the baseline dietary TAC levels in the free-living US populations on a large scale. It provides a general insight of the real 'quenching' power of antioxidants and broadens our horizon to assess the antioxidant functions. However, there are some limitations. First, the lack of some antioxidant intake data or antioxidant capacity values limits our investigation, such as Se, whose antioxidant capacity was difficult to measure. Second, the NHANES food consumption data were based on a 24 h DR that might not be accurately presenting the usual US diet. Third, our study focuses on the dietary data without considering the bioavailability or metabolism of the antioxidants. Dietary TAC is not an 'intrinsic' parameter for the human body; however, several studies have found that it was potentially related to some biomarkers of chronic diseases[27,29].

The present study as a prerequisite for the future investigation of the association between the antioxidant status in humans and the risks of chronic diseases may advance the understanding of establishing the recommended dietary antioxidant intake in US populations for promoting the public health. Additionally, consumption of vegetables and fruits has been proved to decrease the risks of chronic diseases, though, whether antioxidants play the pivotal role warrants more investigation. Furthermore, the modulation of dietary TAC on plasma TAC or the role of antioxidant-rich diets on plasma antioxidant status is still debatable, which may be attributed to the homeostatic mechanisms of regulation, the various bioavailability of different antioxidants and the methods used for measuring biological antioxidant status or TAC. Importantly, on the journey of researching the dietary or physiological antioxidant status or their potential power for fighting against oxidative stress and therefore chronic diseases, considering antioxidants as a whole group, that is, as TAC, instead of individual nutrients, is a better direction.

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