Distribution of Catechins, Theaflavins, Caffeine, and Theobromine in 77 Teas Consumed in the United States

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ABSTRACT: To help define the composition of commercial teas consumed in the United States, we have developed and validated an high-performance liquid chromatography (HPLC) method to analyze levels of catechins, theaflavins, and alkaloids in 77 commercial black, green, specialty (brown rice, white, oolong), and herbal teas extracted with hot water to simulate home use. The following 13 compounds were separated in a single analysis on an Inertsil ODS-3v column with acetonitrile/potassium dihydrogen phosphate as the mobile phase: (–)-epigallocatechin, (+)-catechin, (–)-epicatechin, (–)-epigallocatechin-3-gallate, (–)-gallocatechin-3-gallate, (–)-epicatechin-3-gallate, (–)-catechin-3-gallate, theaflavin, theaflavin-3-gallate, theaflavin-3′-gallate, theaflavin-3, 3′-digallate, caffeine, and theobromine. The data show that (1) extraction time from 3 min to 20 min did not significantly affect measured levels of tea compounds and (2) there was a wide variation in the composition of the tea compounds both within each tea category and among categories: black teas contained both theaflavins and catechins, green and white teas contained catechins and trace amounts of theaflavins, herbal teas contained very low amounts of all tea compounds. A statistical profile of the distribution of catechins, theaflavins, caffeine, and theobromine in the evaluated teas offers consumers a choice of teas containing high levels of health-promoting compounds.

Keywords: HPLC, catechins, theaflavins, caffeine, theobromine, teas, *Camelia sinensis*

Introduction

Plants, including tea leaves from *Camelia sinensis* (Beecher 2003), produce secondary metabolites, organic compounds that are involved in the defense of the plants against invading pathogens, including insects, bacteria, fungi, and viruses. In the case of tea leaves, these metabolites include polyphenolic catechins and theaflavins and the alkaloids caffeine and theobromine. Commercial teas can be classified into several major categories: unfermented green, semi-fermented oolong, and fully fermented black. Inactivation of phenol oxidases in green tea prevents oxidations of the catechins, whereas phenolase-catalyzed oxidation of catechins in green tea results in the formation of dimeric theaflavins and polymeric thearubigins, which impart the black color to black tea (Schwimmer 1981; Bonoli and others 2003; Sang and others 2004; Shahidi and Naczk 2004). White tea is produced only in a province of China from tip buds of a special tea plant. Herbal teas are derived from plants other than *Camelia sinensis*.

Depending on the stereochemical configuration of the of the 3′, 4′-dihydroxyphenyl and hydroxyl groups at the 2- and 3-positions of the C-ring, tea catechins can exist as 2 geometrical isomers: *trans*-catechins and *cis*-epicatechins (Figure 1). Each of the isomers, in turn, exists as 2 optical isomers: (+)-catechin and (–)-catechin and (+)-epicatechin and (–)-epicatechin, respectively. (–)-Catechin can be modified by esterification with gallic acid to form (–)-catechin-3-gallate, epicatechin-3-gallate, (–)-epigallocatechin-3-gallate, and (–)-gallocatechin-3-gallate, respectively. Oxidative coupling of different catechins forms the 4 theaflavins.

Antioxidative tea components are reported to have beneficial protective effects against cancers (Michels and others 2005), cholesterol (Maron and others 2003; Vinson and others 2004), cerebral damage (Suzuki and others 2004), diabetes (Vinson and Zhang 2005), smoking (Schwarz and others 2005), and pathogenic bacteria (Yoda and others 2004; Friedman and others 2005). Green and black teas also contain the central nervous system stimulant caffeine and the diuretics/vasodilators theobromine (Fisone and others 2004) and theophylline (Fernandez and others 2002). Black teas also contain the polymeric thearubigin pigments of undefined structure (Menet and others 2004). A need exists to relate the composition of commercial teas to beneficial effects.

A wide variety of extraction conditions and analysis methods have been used resulting in a wide variety in measured concentrations of tea compounds. Previous studies include the following observations:

Lee and Ong (2000) measured 4 catechins and theaflavins (extracted with boiling water and incubated at 90 °C for 30 min) in 8 teas sold in Singapore using high-performance liquid chromatography (HPLC) and electrophoresis. The mobile phase used consisted of acetonitrile/trifluoroacetic acid. Although the analysis by electrophoresis was faster, it was only 1/5 as sensitive as HPLC.

Lin and others (Lin and others 2003) used an isocratic HPLC procedure with a mobile phase consisting of ethanol/H_2O/formic acid to determine caffeine and 5 catechins in 31 Taiwanese tea leaves and tea flowers. Some of the flowers extracted with 75% ethanol at 60 °C for 30 min contained greater amounts of total catechins than

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did extracts obtained with boiling water for 30 min and others contained lower amounts.

Khokhar and Magnusdottir (Khokhar and Magnusdottir 2002) used HPLC with acetonitrile as the eluent to determine the content of 5 catechins and caffeine in 4 black, 3 green, and 6 fruit teas (extracted in boiling water for 5 min) consumed in the U.K. The amount of catechins and caffeine extracted in water increased in the range 60 °C to 100°C and was greatest at 100 °C for 5 min. The total catechin content ranged from 5.6 to 47.5 mg/g in black teas and from 51.5 to 84.3 mg/g in green teas. The estimated dietary intake of total tea catechins was 92.7 mg/d from black teas and 405.5 mg/d from green teas. The range for caffeine was from 92 to 146 mg/d.

Fernandez and others (Fernandez and others 2002) used HPLC with water/acetonitrile/formic acid as the mobile phase to measure catechin and xanthine profiles of 13 green and 42 black and red teas (extracted with 60:40 acetonitrile/water at room temperature for 1 h) originating from China, Japan, Kenya, India, and Sri Lanka. Their results suggest that catechin, gallic acid, and the methyl-xanthine content may be used to differentiate the geographic origin of specific teas.

Cabrera and others (Cabrera and others 2003), using an HPLC method with a photodiode array detector, measured 4 catechins and caffeine levels in 15 black, green, and oolong teas sold in Spain (extracted with 80% methanol for 3 h and then twice more with 80% methanol containing 0.15% HCl for 3 h). They observed a wide variation in the content of catechins among these teas. Red teas had the lowest levels.

Analysis by HPLC-MS of catechins, theaflavins, and purine alkaloids in Indonesian green and black tea infusions extracted with boiling water for 3 min (Del Rio and others 2004) gave the following results for green tea (in mg/L): total catechins, 4572; theobromine, 57; caffeine, 866; total theaflavins, 0. The values for black tea were 26, 224, 25, and 541, respectively.

In related studies, Sakakibara and others (2003) extracted polyphenols from vegetables, fruits, and teas with 90% methanol/0.5% acetic acid; Zhu and others (2004) analyzed tea compounds by GS-MS after steeping the tea leaves in water at 80 °C for 30 min; and Bonoli and others (2003) extracted teas with boiling water for 5 min.

Other studies describe the analysis of tea polyphenols by HPLC with different detectors (Beecher and others 1999; Lee and others 2000) by micellar electrokinetic chromatography (Bonoli and others 2003), as well as by mass spectrometry (Menet and others 2004) and by HPLC/electrospray-mass spectrometry (Zhu and others 2004). Using UV spectroscopy, we previously showed that (–)-catechin and (–)-epigallocatechin resisted degradation at high pH (Friedman and Jürgens 2000). Catechins added to dough also resisted heat-degradation during the bread baking (Wang and Zhou 2004).

Units used to report results from analyses of teas include: mg/g dry wt of tea, % of dry matter (DM) (Leung and others 2001), μmol/100 g tea leaves (Sakakibara and others 2003), mg/L of tea infusions (Del Rio and others 2004), μg/mL of canned tea drinks (Fernandez and others 2002; Bonoli and others 2003), gallic acid equivalents (GAE) for total phenolics, and epicatechin equivalents (ECE) for total flavonoids (Rechner and others 2002; Lee and others 2003; Stevanato and others 2004).

As the previously cited studies show, a plethora of solvents, temperatures, and times have been used to extract tea leaves before analysis. Therefore, comparison of data from studies using different extraction methods may not always be justified. There is an urgent need to standardize extraction/analysis methods and units of measurement, preferably extraction with boiling water for 5 min to simulate home use of teas, analysis by HPLC, and units that report the results in mg/g of original weight of tea or as mg/L for tea infusions and commercial tea drinks.

The main objectives of this study were (1) to validate a new HPLC method for the analysis of 13 tea compounds (7 catechins, 4 theaflavins, and the alkaloids caffeine and theobromine) in a single run; and (2) to compare the levels of tea constituents extracted with hot water under conditions that would simulate what would be present in the teas prepared by consumers.

Materials and Methods

Materials

Black, green, specialty, and herbal teas were purchased in local markets and restaurants in the Albany-San Francisco area of California and from the The Stash Tea Co. (Portland, Oreg., U.S.A.). (–)-Epigallocatechin, (+)-catechin, (–)-epicatechin, (–)-epigallocatechin gallate, (–)-gallocatechin gallate, (–)-epicatechin gallate, (–)-catechin gallate, caffeine, and theobromine were obtained from Sigma (St. Louis, Mo., U.S.A.). Theaflavin, theaflavin-3-gallate, theaflavin-3′-gallate, and theaflavin-3, 3′-digallate were obtained from Wako (Osaka, Japan). HPLC-grade solvents were filtered through a 0.45-μm membrane (Millipore, Bedford, Mass., U.S.A.) and degassed in an ultrasonic bath before use.

Extraction and analysis of teas

For extraction with distilled water, each tea sample (about 1.5 g) was placed into a 250-mL flask to which was added 250 mL of water previously brought to the boiling point. The sample was then stirred slowly with a magnetic stirrer for 5 min, cooled, and centrifuged at 18000 × *g* for 10 min at 1 °C. The supernatant was filtered on a 0.45-μm Millipore nylon filter before analysis. The same procedure was used to determine the effect of extraction time (3, 5, 10, 15, or 20 min) on the levels of extracted tea compounds.

HPLC was carried out on a Hitachi liquid chromatograph model 665-II equipped with an Autosampler (model 655A-40). The stainless-steel column (250 mm × 4.0 mm inner dia) was packed with Inertsil ODS-3v (5-μm particle diameter) (GL Sciences, Tokyo Japan). The column temperature was maintained constant with a Shimadzu column oven CTO-10vp (Shimadzu, Kyoto, Japan). The gradient system consisted of a mixture of acetonitrile and 20 m*M* KH_2PO_4. The flow rate was 1 mL/min at a column temperature of 30 °C. A Shimadzu photo diode array UV-VIS detector (model SPD-10Avp) was set from 200 to 700 nm. The tea extract (10 μL) was injected directly into the column. Analyses, each in triplicate, were carried out with 3 extracts prepared from 3 different tea bags for each sample.

The initial composition of the mobile phase consisting of 7% acetonitrile (A) and of 93% of 20 m*M* KH_2PO_4 (B) (v/v) was maintained for 6 min. Solvent A was then increased linearly to 10% in 20 min, 15% in 25 min, 20% in 30 min, and 25% in 45 min to 70 min. Programming was then continued in the isocratic mode as follows: 40% A in 70.1 to 75.0 min and 7% A in 76.1 to 90.1 min (1 cycle ends).

Identification and quantification was accomplished by comparing integrated chromatographic peak areas from the test samples to peak areas of known amounts of standard compounds using the Hitachi Chromato-integrator model D-2500. Each peak was identified by comparing the retention times and absorption spectra of unknowns to those of standards. Identification was confirmed by spiking sample peaks with respective standards. Because cooling the infusions during centrifugation may result in precipitation of some material, what is being measured is the recovery of the compounds during centrifugation and filtration steps needed to prepare the samples for HPLC analysis.

For tests of recoveries of spiked samples, tea extracts were analyzed before and after addition of known amounts of standard compound. Recovery (%) = (concentration of each compound in spiked sample)/(concentration of endogenous compound + spike) × 100.

Statistical analysis

The square root or log transformation was used to stabilize the variances before 1-way analyses of variance between teas among the respective sums of 7 catechins, 4 theaflavins, and 11 catechins and theaflavins. Zeros were deleted (and data values <1 for caffeine) from the 1-way analyses (ANOVA) because they would result in a negative bias of the error variance estimates. Dunnett's 1-tailed test was used to test for decreases from the 10th highest ranked tea.

Results and Discussion

Analytical aspects

The HPLC-UV detection method was adapted, after extensive experimentation to optimize the analyses, from previously described procedures for the separation of potato and tomato glycoalkaloids (Friedman and others 2003; Kozukue and others 2004). Examination of the dependence of retention times of mixtures of standards on column temperature in the range 20 °C to 40 °C indicated that a column temperature of 30 °C resulted in optimum separation of chromatographic peaks. The mobile phase, consisting of mixtures of acetonitrile and 20 m*M* potassium dihydrogen phosphate and programmed in linear/isocratic modes, successfully separated all 13 catechins, theaflavins, caffeine, and theobromine (Figure 1 and 2). The method responded linearly over the concentration range shown in Table 1. The retention (elution) times ranged from 7.86 min for theobromine to 63.10 min for theaflavin-3, 3′-digallate. The limits of detection (LOD) ranged from 1.95 ng for theobromine to 12.58 ng for (+)-catechin. Recoveries from extracts spiked with authentic standards were quantitative for caffeine

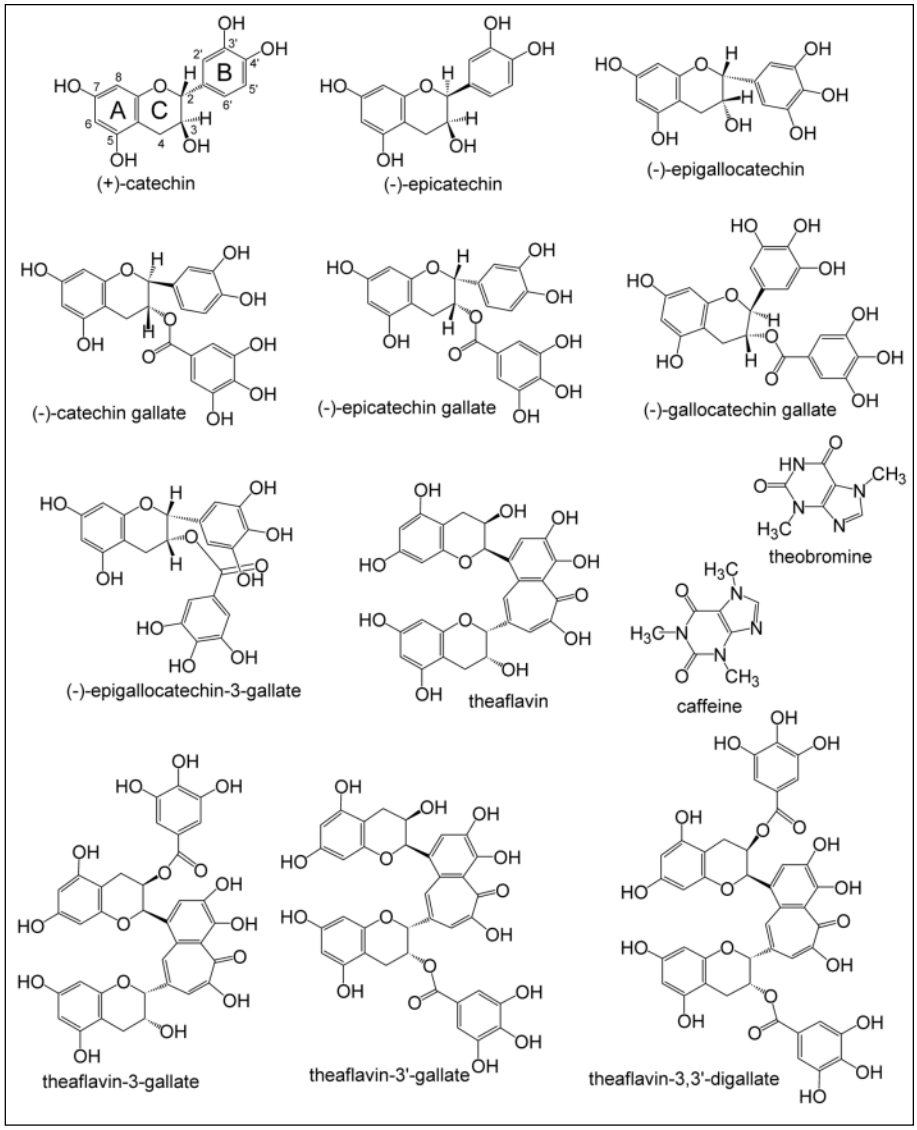

Figure 1—Structures of catechins, theaflavins, and alkaloids evaluated in this study gallate

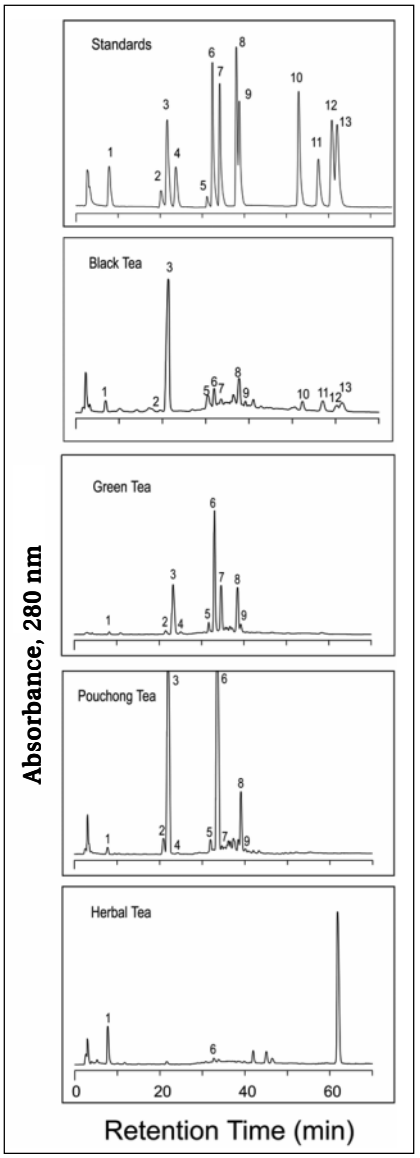

Figure 2—High-performance liquid chromatography (HPLC) chromatograms with UV detection at 280 nm of a mixture of 13 standards listed in Table 1 and of selected teas. Peak 1, theobromine; 2, (–)-epigallocatechin; 3, caffeine; 4, (+)-catechin; 5, (–)-epicatechin; 6, (–)-epigallocatechin gallate; 7, (–)-gallocatechin gallate; 8, (–)-epicatechin gallate; 9, (–)-catechin gallate; 10, theaflavin; 11, theaflavin 3-gallate; 12, theaflavin 3'-gallate; 13, theaflavin 3,3'-digallate

Table 1—High-performance liquid chromatography (HPLC) of standards listed in order of elution: retention times, limits of detection, tests for linearity, and recoveries after spiking of tea

Compound	Retention times on HPLC column (min)	Limits of detection (ng)	Linearity range[a] (ng)	Recovery after spiking (%)
Theobromine	7.86 ± 0.03	1.95	0-800	101.3 ± 2.6
(–)-Epigallocatechin (EGC)	20.62 ± 0.03	14.64	0-800	82.4 ± 1.2
Caffeine	22.35 ± 0.01	2.40	0-800	99.8 ± 1.7
(+)-Catechin (C)	24.23 ± 0.06	12.58	0-2000	91.9 ± 1.5
(–)-Epicatechin (EC)	31.06 ± 0.08	3.03	0-1500	82.4 ± 2.6
(–)-Epigallocatechin-3-gallate (EGCG)	32.70 ± 0.06	4.61	0-1500	79.6 ± 4.6
(–)-Gallocatechin gallate (GCG)	34.35 ± 0.08	5.95	0-2500	92.3 ± 5.3
(–)-Epicatechin gallate (ECG)	38.30 ± 0.07	6.50	0-5500	99.6 ± 0.7
(–)-Catechin gallate (CG)	39.04 ± 0.05	1.36	0-3300	103.8 ± 1.3
Theaflavin (TF)	53.34 ± 0.01	6.03	0-3300	74.2 ± 2.1
Theaflavin-3-gallate (TF3G)	58.27 ± 0.22	5.85	0-1400	86.6 ± 1.0
Theaflavin-3′-gallate (TF3′G)	61.60 ± 0.28	5.15	0-1800	81.8 ± 1.2
Theaflavin-3,3′-digallate (TF3,3′G)	63.10 ± 0.65	6.78	0-1800	89.1 ± 1.4

[a]Range of linear plots of concentration versus peak area in mvolts; $n = 3$; $r^2 = 0.99$ for all 13 plots.

Table 2—Teas and their sources

	Tea name	Company name
Black teas		
1	Orange Spice Tea	Safeway, Inc.
2	Earl Grey Tea	Safeway, Inc.
3	Classic Wissotzky Tea	Wissotzky Tea Co., Israel
4	Ten Ren Black Tea	Ten Ren Tea Co., Taipei
5	Sweet-Touch-Nee Orange Pekoe & Pekoe Cut Black Tea	Consolidated Tea, N.Y., U.S.A.
6	Forrelli Apple Cinnamon Tea	Pure Ceylon Tea, Switzerland
7	Maxwell House Orange Pekoe, Pekoe and Cut Black Tea	Kraft Foods Inc.
8	Tai Mahal Indian Assam Tea	Wissotzky Tea Co., Israel
9	Earl Grey	R. C. Bigelow, Inc, U.S.A.
10	Orange Pekoe and Pekoe Cut Black	Lipton Tea Co.
11	English Breakfast Tea	Twinings of London, England
12	English Teatime	R. C. Bigelow, Inc, U.S.A.
13	Ceylon Orange Pekoe Tea	Twinings of London, England
14	Gold Genuine Ceylon Tea Blend	Wissotzky Tea Co.
15	Original India Spice (100% Natural Chai Tea)	Celestial Seasonings
16	Exotica Osmanthus	The Stash Tea Co., Oregon
17	English Breakfast Black	The Stash Tea Co., Oregon
18	Orange Spice Black	The Stash Tea Co., Oregon
19	Earl Grey Black & Green, Organic	The Stash Tea Co., Oregon
20	Earl Grey Black	The Stash Tea Co., Oregon
21	Lemon Spice Green (and Black)	The Stash Tea Co., Oregon
22	Nilgiri Black	The Stash Tea Co., Oregon
23	Exotica Assam Breakfast	The Stash Tea Co., Oregon
24	Breakfast Blend, Organic	The Stash Tea Co., Oregon
25	Exotica Reserve Blend	The Stash Tea Co., Oregon
26	Darjeeling Black	The Stash Tea Co., Oregon
27	Exotica Ceylon Estate Earl Grey	The Stash Tea Co., Oregon
28	Darjeeling Spring	The Stash Tea Co., Oregon
29	Exotica Golden Darjeeling	The Stash Tea Co., Oregon
30	Kopili Assam Black	The Stash Tea Co., Oregon
31	Darjeeling Summer	The Stash Tea Co., Oregon
32	Darjeeling Black, Organic	The Stash Tea Co., Oregon
Green teas		
33	Green Tea with Roasted Brown Rice Tea (Decaf. Genmai-cha)	YamaMOTOYama of America
34	Green Tea (Orange, Passionfruit, & Jasmine)	Lipton Tea Co.
35	Organic Green Tea	YamaMOTOYama of America
36	Jasmine Tea	Ten Ren Tea Co., Taipei
37	Green Tea	Celestial Seasonings, USA
38	Organic Moroccan Mint Green Tea	Green Restaurant, San Francisco
39	Green Tea	YamaMOTOYama of America
40	Green Tea & Herbal Infusion	The Reincarnation of Tea (Zen)
41	Kukicha	The Stash Tea Co., Oregon
42	Japanese Green Tea	Midori Tea & Ginseng Co., New York (Product of China)
43	Organic Jasmine Green Tea	Green Restaurant, San Francisco
44	Green Tea (100% Natural)	Lipton Tea Co.
45	Premium Green, Decaffeinated	The Stash Tea Co., Oregon
46	China Green Tea	Herb Enterprise, San Francisco

(continues on next page)

Table 2—Teas and their sources *(continued from page 4)*

Tea name		Company name
Green teas		
47	Organic Green Tea (with an Essence of Peach)	Green Restaurant, San Francisco
48	Green Tea	Ten Ren Tea Co., Taipei
49	Moroccan Mint Green	The Stash Tea Co., Oregon
50	Jasmine Blossom Green	The Stash Tea Co., Oregon
51	Exotica Dragonwell Green	The Stash Tea Co., Oregon
52	Premium Green	The Stash Tea Co., Oregon
53	Sencha Japanese Green Tea	Peet's Coffee and Tea, California
54	Green Organic	The Stash Tea Co., Oregon
55	Sushi Bar Mild Green	The Stash Tea Co., Oregon
56	Darjeeling Green, Organic	The Stash Tea Co., Oregon
Specialty teas		
57	Roasted Tea (Hoji-cha)	YamaMOTOYama of America
58	Brown Rice Tea (Genmai-cha)	YamaMOTOYama of America
59	Pu-erh Oolong	The Stash Tea Co., Oregon
60	White Tea	Ten Ren Tea Co., Taipei
61	Oolong Tea	Ten Ren Tea Co., Taipei
62	Pouchong Tea	Ten Ren Tea Co., Taipei
63	Chinese Jasmine Tea	Madys Tea Co., San Francisco
64	Fusion Red & White	The Stash Tea Co., Oregon
65	Jasmin Tea	Tenfu Tea Industry Co., China
66	China Oolong	The Stash Tea Co., Oregon
67	Exotica China White	The Stash Tea Co., Oregon
68	Exotica Champagne Oolong	The Stash Tea Co., Oregon
69	Fusion Green & White	The Stash Tea Co., Oregon
70	Exotica Silver Jasmine	The Stash Tea Co., Oregon
Herbal teas		
71	Orange & Spice Herb Tea	R. C. Bigelow, Inc., U.S.A.
72	Chamomile Tea	Safeway, Inc.
73	Wild Raspberry Herbal	The Stash Tea Co., Oregon
74	Chamomile Herbal	The Stash Tea Co., Oregon
75	Evening Delight Tea	Safeway, Inc.
76	Peppermint Tea	Safeway, Inc.
77	Peppermint Herbal	The Stash Tea Co., Oregon

and theobromine and ranged from 79.6% to 103.8% for the catechins and from 74.2% to 89.1% for the theaflavins. See also earlier comment regarding recovery. These observations demonstrate both the sensitivity and utility of the analyses. The LOD values and recoveries were of the same order reported by other investigators mentioned subsequently.

Catechin, theaflavin, caffeine, and theobromine content of teas

Figure 3 shows that varying the extraction from 3 to 20 min did not significantly influence the levels of all tea compounds. We selected a time of 5 min for the water extractions of the 77 teas listed in Table 2 to represent as closely as possible the time used to prepare tea infusions in the home. To facilitate comparisons, the sums of the concentrations of the 7 catechins and 4 theaflavins calculated from the individual values listed in Table 3 are illustrated in Figure 4 and 5 in terms of bar graphs. A subset of 10 teas containing the highest amounts of catechins, theaflavins, caffeine, and theobromine was selected to define a statistical profile for all teas (see footnotes to Table 3).

For the 32 black teas, the sum of all catechins and theaflavins extracted with water under the conditions studied here ranged (in mg of compound/g dry tea) from 6.5 to 72.5. With few exceptions, the black teas contained both catechins and theaflavins. For the 24 green teas, the corresponding ranges are 4.4 to 100.0. These values are for

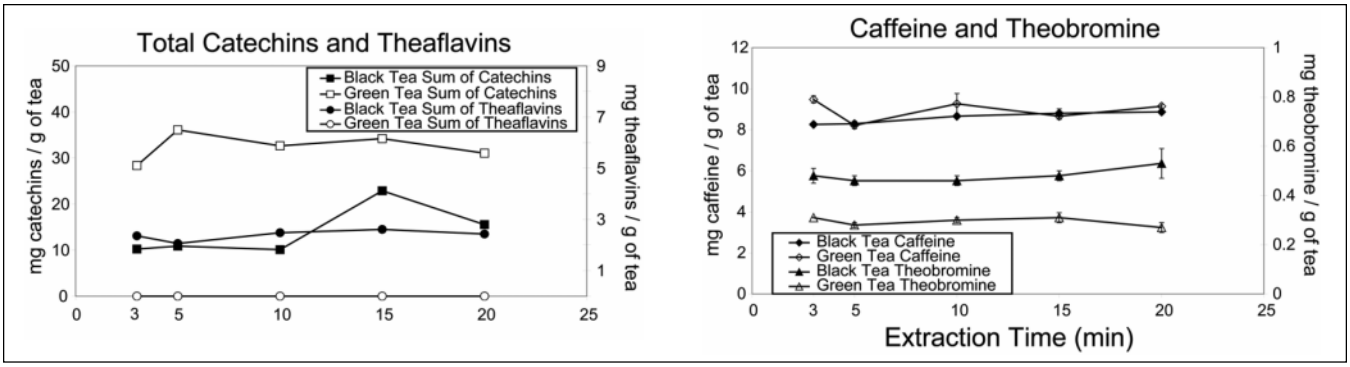

Figure 3—Effect of extraction time on levels of tea compounds in Lipton Orange Pekoe and Pekoe Cut Black Tea (nr 10) and Ten Ren Green Tea (nr 48) analyzed by high-performance liquid chromatography (HPLC)

Table 3—Content of 7 individual catechins, their sum (total CATS), 4 theaflavins, their sum (total TFS), sum of 7 catechins and 4 theaflavins (total flavonoids, FLAV), theobromine (Theo), and caffeine in black, green, specialty, and herbal teas

No	EGC	C	EC	EGCG	GCG	ECG	CG	Total CATS	TF	TF3G	TF3′G	TF33′G	Total TFS	Total FLAV	Theo	Caffeine
Black																
1	nd	nd	0.4±0.08	1.9±0.14	1.2±0.23	1.9±0.27	nd	5.4	0.1±0.08	0.3±0.03	0.2±0.03	0.5±0.04	1.1	6.5	0.2±0.03	3.5±0.28
2	0.7±0.31	0.6±0.14	1.2±0.28	0.9±0.16	0.9±0.03	1.7±0.39	0.2±0.05	6.2	0.4±0.10	0.4±0.08	0.1±0.03	0.6±0.06	1.5	7.7	0.5±0.15b	6.1±0.78
3	nd	nd	0.4±0.11	2.1±0.63	1.3±0.17	3.9±0.32	0.02±0	7.7	1.2±0.09	0.8±0.03	0.3±0.04	0.7±0.01	3.0	10.7	0.4±0.06	8.2±0.16
4	nd	nd	0.4±0.01	0.6±0.02	3.0±0.24	7.0±1.70	nd	11.0	0.2±0.01	0.2±0.03	0.1±0	0.2±0.02	0.7	11.7	0.4±0.01	9.6±0.17
5	nd	nd	0.6±0.34	3.2±0.16	1.2±0.14	4.7±0.29	nd	9.7	0.7±0.14	0.6±0.06	0.2±0.03	0.5±0.05	2.0	11.7	0.5±0.02	8.6±0.29
6	nd	nd	0.5±0.08	2.0±0.07	2.5±0.14	4.7±0.32	nd	9.7	0.4±0.10	0.5±0.07	0.1±0.03	1.4±0.14	2.4	12.1	0.6±0.01	9.5±0.22
7	1.0±0.67	0.9±0.09	0.6±0.41	1.9±0.08	1.5±0.17	3.6±0.04	0.5±0.11	10.0	0.7±0.19	0.6±0.19	0.1±0.03	0.7±0.02	2.1b	12.1	0.4±0.27	8.5±0.23
8	1.2±0.80	1.6±0.00	1.3±1.00	1.4±0.07	1.4±0.92	2.4±0.28	0.4±0.13	9.7	0.6±0.13	0.8±0.04	0.3±0.01	1.3±0.05	3.0	12.7	1.1±0.03	11.3±0.1
9	nd	nd	0.6±0.03	3.7±0.16	2.1±0.15	4.9±0.49	0.1±0.10	11.4	0.4±0.08	0.4±0.09	0.1±0.03	0.5±0.02	1.4	12.8	0.9±0.02c	11.4±0.2
10	nd	nd	0.7±0.19	2.4±0.13	3.3±0.51	4.5±0.23	nd	10.9	0.6±0.01	0.7±0.04	0.2±0.02	0.6±0.05	2.1	13.0	0.5±0.02	8.3±0.13
11	1. 7±0.13	nd	0.8±0.20	1.5±0.25	1.8±0.16	4.5±0.37	0.6±0.10	10.9	0.9±0.10	1.0±0.05	0.3±0.02	1.1±0.06	3.3	14.2	0.6±0.01	9.4±0.05
12	0.1±0.02	nd	0.3±0.06	4.9±1.09	2.0±1.36	5.3±0.45	nd	12.6	0.4±0.06	0.6±0.01	0.2±0.01	0.7±0.05	1.9	14.5	1.0±0.01	10.8±0.1
13	0.1±0.04	nd	0.8±0.18	2.1±0.37	4.2±0.35	4.8±0.08	0.01±0	12.0	0.9±0.09	1.1±0.2	0.3±0.01	1.1±0.07	3.4	15.4	0.7±0.01	9.0±0.37
14	nd	nd	0.5±0.32	4.3±1.34	5.4±1.21	6.5±1.48	nd	16.7	0.8±0.02	0.9±0.18	0.3±0.05	1.0±0.19	3.0	19.7	0.6±0.11	11.2±2.1
15	2.0±0.49	0.5±0.16	6.3±0.11	0.5±0.05	1.4±0.03	4.2±0.85	1.5±1.13	16.4	5.4±1.34	0.01±0	0.2±0.03	0.4±0.02	6.0b	22.4	tr	7.4±0.65
16	2.2±0.05	3.7±0.63	0.9±0.01	9.9±0.02	3.7±0.16	7.8±0.04	0.6±0.01	28.8	0.2±0.01	0.2±0.03	0.1±0	0.5±0.02	1.0	29.8	1.2±0.03	21.4±0.5c
17	3.4±1.16	3.0±0.94	2.3±0.14	6.6±0.53	2.4±0.31	10.1±2.5	0.7±0.05	28.5	1.2±0.01	1.6±0.08	0.6±0.02	2.0±0.04	5.4b	33.9	2.4±0.16b	22.3±0b
18	1.9±0.67	3.0±0.08	1.7±0.18	6.0±0	1.5±0.14	10.8±0.2	1.0±0.37	25.9	1.2±0	1.4±0.06	0.4±0	5.8±0.09	8.8b	34.7	1.8±0.05	15.4±0.7
19	2.8±0.11	4.3±0.13	2.3±0.03	9.0±0.68	1.8±0.02	11.0±0.3	0.8±0.02	32.0	1.2±0.01	1.4±0	0.5±0.01	1.2±0.02	4.3b	36.3	1.4±0.01	18.0±0.1
20	6.4±0	5.0±0.07	2.1±0.05	5.2±0.16	2.3±0.07	10.0±0.2	0.7±0	31.7	1.0±0.01	1.6±0.04	0.6±0	1.8±0.09	5.0	36.7	2.1±0.02b	19.9±0.4
21	3.4±0	2.8±0.19	1.4±0.01	12.9±0.3	2.9±0.01	11.7±0	0.4±0.01	33.5	0.6±0	0.6±0.02	0.8±0.03	0.6±0.03	2.6	38.1	1.3±0	15.0±0.3
22	2.3±0.03	8.1±0.50	2.4±0.03	6.1±0.01	1.9±0.03	11.8±0.5	0.6±0.02	33.2	1.2±0.01	1.5±0.03	0. 6±0	1.8±0.02	5.1b	38.3	2.5±0.13b	20.2±0.9
23	2.3±0.09	7.1±0.43	2.6±0.12	9.5±0.07	1.6±0	16.1±0.2	0.5±0.02	39.7	1.2±0.05	2.1±0.05	0.9±0.02	3.0±0.04	7.2b	46.9	2.6±0.05b	24.3±0.3b
24	2.5±0.09	7.4±0.19	2.5±0.07	12.7±0.9	2.1±0.11	14.5±0.6	0.6±0.01	42.3	1.7±0.08	1.3±0.05	0.6±0.03	1.5±0.02	5.1b	47.4	1.4±0.03	19.7±0.6
25	3.0±0.04	4.6±0.06	2.3±0.04	16.9±0.1	4.1±0.02	16.8±0.4	0.5±0.01	48.2	0.8±0.05	1.1±0.04	0.4±0.01	1.4±0.05	3.7c	51.9	2.7±0.09b	21.9±0.4
26	4.2±0.22	0.8±0.10	1.4±0.04	27.0±0.8	4.2±0.04	20.2±0.5	0.4±0.02	58.2	0.7±0.02	0.4±0.02	0.2±0.02	0.5±0.03	1.8	60.0	0.1±0.04	21.3±0.7c
27	10.3±0.20	2.7±0	4.3±0.06	23.0±0.1	1.1±0.10	20.6±0.5	0.5±0.01	62.5c	nd	nd	nd	nd	0	62.5	1.3±0.01	17.7±0.1
28	4.1±0.30	1.2±0.07	2.0±0	28.4±0.7	4.4±0.18	22.9±0.6	0.4±0.01	63.4c	0.7±0.01	0.4±0.01	0.1±0	0.4±0.02	1.6	65.0	1.9±0.05b	20.8±0.2c
29	5.2±0.00	1.7±0.01	2.3±0.01	28.2±0.2	3.2±0.06	24.2±0.3	0.7±0.01	65.5b	nd	nd	nd	nd	0	65.5c	1.1±0	22.0±0.3b
30	2.3±0.10	6.7±0.06	4.2±0.03	13.3±0.4	6.7±0.13	24.4±0.5	1.3±0.06	58.9	0.8±0.11	1.8±0.02	0.8±0.01	3.5±0.07	6.9b	65.8b	3.2±0.03b	26.7±0.5b
31	5.1±0.19	4.9±0.09	2.2±0.08	26.8±0.8	3.0±0.23	20.9±0.8	0.1±0.01	63.0c	0.8±0.01	0.6±0.04	0.3±0.02	6.4±0.28	8.1b	71.1	1.6±0.10c	22.8±0.8b
32	3.1±0.02	5.3±0.05	4.1±0.24	23.5±0.2	6.1±0.26	26.8±0.6	0.6±0	69.5b	0.9±0.03	0.8±0	0.2±0.01	1.1±0.03	3.0	72.5b	1.8±0.01b	21.8±0.1b
Green																
33	0.6±0.11	nd	0.1±0.02	2.2±0.10	0.3±0.10	1.2±0.16	nd	4.4	nd	nd	nd	nd	0	4.4	0.04±0	0.3±0.03
34	0.1±0	nd	0.5±0.14	7.3±0.95	0.02±0.01	3.1±0.52	0.03±0.01	11.1	0.2±0.02	nd	nd	nd	0.2	11.1	0.1±0.03	4.0±0.46
35	0.1±0.04	nd	0.6±0.05	9.1±0.61	1.1±0.78	3.3±0.31	nd	14.2	nd	nd	nd	nd	0	14.2	0.1±0.01	3.3±0.19
36	1.8±0.50	1.0±0.29	0.4±0.16	8.8±0.70	0.4±0.24	5.8±0.20	nd	18.2	nd	nd	nd	nd	0	18.2	0.4±0.02	5.2±0.11
37	nd	nd	0.7±0.01	13.8±0.6	0.8±0.05	4.0±0.10	nd	19.3	nd	nd	nd	nd	0	19.3	0.7±0.02	6.0±0.05
38	1.9±0.50	0.1±0.01	0.7±0.05	8.9±0.09	1.8±0.14	6.5±0.54	nd	19.9	nd	nd	nd	nd	0	19.9	0.5±0.04	5.1±0.12
39	nd	0.6±0.03	0.8±0.04	14.0±0.5	1.0±0.11	4.5±0.24	nd	20.9	nd	nd	nd	nd	0	20.9	0.2±0.05	5.6±0.07
40	0.1±0	nd	0.4±0.01	15.7±0.4	0.8±0.03	5.5±0.65	nd	22.5	nd	nd	nd	nd	0	22.5	0.3±0.01	7.8±0.10
41	1.1±0.04	3.5±0.07	0.5±0.01	7.4±0.07	6.3±0.18	5.0±0.04	0.1±0.01	23.9	nd	nd	nd	nd	0	23.9	1.1±0.01	12.5±0.1
42	0.1±0.03	nd	1.0±0.20	17.4±1.1	1.4±0.07	5.8±0.44	nd	25.7	nd	nd	nd	nd	0	25.7	0.3±0.02	8.8±0.11

(continues on next page)

Table 3—Content of 7 individual catechins, their sum (total CATS), 4 theaflavins, their sum (total TFS), sum of 7 catechins and 4 theaflavins (total flavonoids, FLAV), theobromine (Theo), and caffeine in black, green, specialty, and herbal teas ***(continued from page 6)***

No	EGC	C	EC	EGCG	GCG	ECG	CG	Total CATS	TF	TF3G	TF3′G	TF33′G	Total TFS	Total FLAV	Theo	Caffeine
Green																
43	nd	nd	0.9±0.16	18.3±1.2	1.1±0.11	5.7±0.29	nd	26.0	nd	nd	nd	nd	0	26.0	0.3±0.11	9.5±0.41
44	nd	nd	1.3±0.02	18.4±1.5	0.8±0.14	8.3±0.54	0.02±0	28.8	nd	nd	nd	nd	0	28.8	0.3±0.02	8.2±0.07
45	4.8±0.09	4.4±0.05	0.8±0.02	13.5±0.2	2.7±0.01	6.0±0.12	0.3±0	32.5	nd	nd	nd	nd	0	32.5	0.6±0.02	3.8±0.13
46	0.1±0.08	nd	0.7±0.02	18.3±0.6	5.7±0.47	8.9±0.45	nd	33.7	nd	nd	nd	nd	0	33.7	0.3±0.01	10.1±0.1
47	0.2±0	nd	0.9±0.15	24.4±1.0	0.3±0.04	10.2±1.0	nd	36.0	nd	nd	nd	nd	0	36.0	1.1±0.01	10.6±0.1
48	0.1±0	2.0±0.05	1.5±0.07	19.4±0.9	1.2±0.04	12.0±1.0	nd	36.2	nd	nd	nd	nd	0	36.2	0.3±0.01	8.2±0.16
49	1.0±0.03	33.2±0.4	1.3±0.11	6.7±0.37	3.2±0.11	7.7±0.19	0.4±0.24	53.5	nd	nd	nd	nd	0	53.5	tr	tr
50	6.4±2.17	6.2±0.02	0.9±0.05	29.4±3.1	5.0±1.17	15.9±1.7	0.3±0.04	64.1c	nd	nd	nd	nd	0	64.1	1.1±0	18.7±0.1
51	0.7±0.01	7.9±0.06	1.1±0	43.6±0.5	1.7±0.01	19.2±0.3	0.2±0.01	74.4b	nd	nd	nd	nd	0	74.4b	1.7±0.01b	23.9±0.1b
52	13.6±0.8	2.0±0.09	0.9±0.09	38.4±0.4	5.1±0.09	15.9±0.2	0.1±0.01	76.0b	nd	nd	nd	nd	0	76.0b	0.8±0.02	15.1±0.1
53	14.2±0.02	4.0±0.75	2.4±0.47	35.7±1.1	5.4±0.41	14.3±1.0	0.2±0.01	76.2b	nd	nd	nd	nd	0	76.2b	0.6±0	16.7±0.1
54	13.9±5.2	1.7±0.01	1.7±0.45	41.8±8.4	2.4±1.08	18.6±2.2	0.1±0.01	80.2b	nd	nd	nd	nd	0	80.2b	0.8±0.18	13.5±3.0
55	13.8±0.5	5.8±0.20	2.6±0.04	41.2±0.5	5.1±0.13	18.4±0.2	0.2±0	87.1b	nd	nd	nd	nd	0	87.1b	0.8±0.02	14.0±0.1
56	8.1±0.30	5.1±0.29	1.9±0.06	53.6±1.7	3.9±0.03	27.1±0.6	0.3±0.01	100.0b	nd	nd	nd	nd	0	100.0b	1.9±0b	22.1±1.0c
Specialty																
57	0.2±0.01	nd	0.1±0.08	1.0±0.18	1.5±0.24	0.5±0.08	0.1±0.02	3.4	nd	nd	nd	nd	0	3.4	0.1±0.01	2.7±0.16
58	nd	nd	0.3±0.04	4.5±0.23	0.4±0.16	1.9±0.18	nd	7.1	nd	nd	nd	nd	0	7.1	0.1±0	2.1±0.07
59	tr	1.5±0.17	0.4±0.01	2.1±0.03	1.7±0.05	1.3±0.07	0.3±0.02	7.3	nd	nd	nd	nd	0	7.3	1.3±0	20.8±0.1c
60	0.3±0.13	tr	0.5±0.39	6.8±2.01	0.7±0.48	5.4±1.42	nd	13.7	nd	nd	nd	nd	0	13.7	0.3±0.07	6.1±1.46
61	nd	0.6±0.26	0.5±0.02	12.3±0.2	0.6±0.05	3.9±0.07	nd	17.9	nd	nd	nd	nd	0	17.9	0.2±0.01	8.3±0.12
62	nd	0.3±0.03	0.5±0.14	12.3±0.2	0.6±0.07	4.8±0.26	nd	18.5	nd	nd	nd	nd	0	18.5	0.3±0.01	6.2±0.21
63	nd	0.1±0.03	0.6±0.10	13.9±0.1	0.1±0.01	8.0±0.73	nd	22.7	nd	nd	nd	nd	0	22.7	0.3±0	8.7±0.09
64	1.6±0.04	2.3±0.01	1.1±0.01	11.4±0.1	4.8±0.01	9.1±0	0.02±0	30.3	nd	nd	nd	nd	0	30.3	0.6±0.04	9.6±0.21
65	nd	nd	1.5±0.36	22.1±0.5	1.6±0.3	14.9±0.8	nd	40.1	nd	nd	nd	nd	0	40.1	0.6±0.01	10.5±0.2
66	5.7±0.29	5.7±0.16	2.5±0.01	23.2±0.04	3.5±0.2	2.2±0.04	2.3±0.07	45.0	nd	nd	nd	nd	0	45.0	0.9±0	16.7±0.2
67	2.1±0.16	4.2±0.07	1.3±0.05	30.4±1.1	2.9±0.08	19.2±0.7	0.4±0.02	60.5	nd	nd	nd	nd	0	60.5	1.3±0.02	29.7±0.4b
68	2.9±0.58	0.8±0.01	1.1±0.17	37.5±0.1	4.4±1.11	18.2±0.3	0.5±0.13	65.4b	nd	nd	nd	nd	0	65.4c	0.7±0.10	27.7±0.1b
69	5.8±0.25	6.2±0.09	2.5±0.03	33.5±0.4	2.7±0.04	16.1±0.2	0.2±0	67.0	nd	nd	nd	nd	0	67.0b	1.4±0.02	19.4±0.5
70	6.1±0.17	7.9±0.36	2.9±0.11	36.3±0.2	2.7±0.17	26.9±0.1	0.3±0.02	83.1b	nd	nd	nd	nd	0	83.1b	1.6±0.06c	23.4±0.2b
Herbal																
71	0.1±0	nd	0.1±0.03	0.2±0	0.5±0.08	0.3±0.19	nd	1.2	nd	nd	nd	nd	0	1.2	0.9±0.71	0.1±0
72	nd	nd	nd	0.5±0.13	0.3±0.04	0.8±0.2	nd	1.6	nd	nd	nd	nd	0	1.6	0.02±0	nd
73	tr	1.4±0.36	0.2±0.01	0.7±0.01	0.6±0.04	0.4±0.01	0.2±0.02	3.5	nd	nd	nd	nd	0	3.5	0.6±0.04	tr
74	nd	nd	0.2±0.01	2.1±0.01	0.9±0.12	1.8±0.39	0.3±0.01	5.3	nd	nd	nd	nd	0	5.3	nd	nd
75	nd	nd	0.3±0.02	0.2±0.01	0.1±0.01	5.7±0.67	1.2±0.12	7.5	nd	nd	nd	nd	0	7.5	0.01±0	0.2±0.01
76	nd	nd	nd	nd	nd	6.2±1.97	1.5±0.04	7.7	nd	nd	nd	nd	0	7.7	0.02±0.01	nd
77	0.8±0.39	1.0±0.26	nd	nd	nd	24.6±0.5	nd	26.4	nd	nd	nd	nd	0	26.4	nd	nd

[a]Numbers in 1st column correspond to teas listed in Table 2; values in mg/g ± SD (n = 3); nd = not detected. All values have been rounded off to 1 decimal point.
[b]Top 10 highest values.
[c]Not significantly < the 10th highest mean at $P > 0.05$ using Dunnett's test. Those without superscripts are significantly < 10th highest ($P < 0.05$).

catechins only because the green teas contained no theaflavins. For the 14 specialty teas, the corresponding ranges are 3.4 to 83.1. These values are for catechins only because the specialty teas contained no theaflavins. For the 7 herbal teas, the corresponding ranges are 1.2 to 26.4. These teas contained no or very low amounts of theaflavins.

These results demonstrate that the measured catechin content of green teas varied about 6-fold. For the sum of catechins and theaflavins, the variation was about 11-fold. For the specialty teas, the corresponding variations are 25-fold. Herbal teas contained low amounts or no catechins or theaflavins.

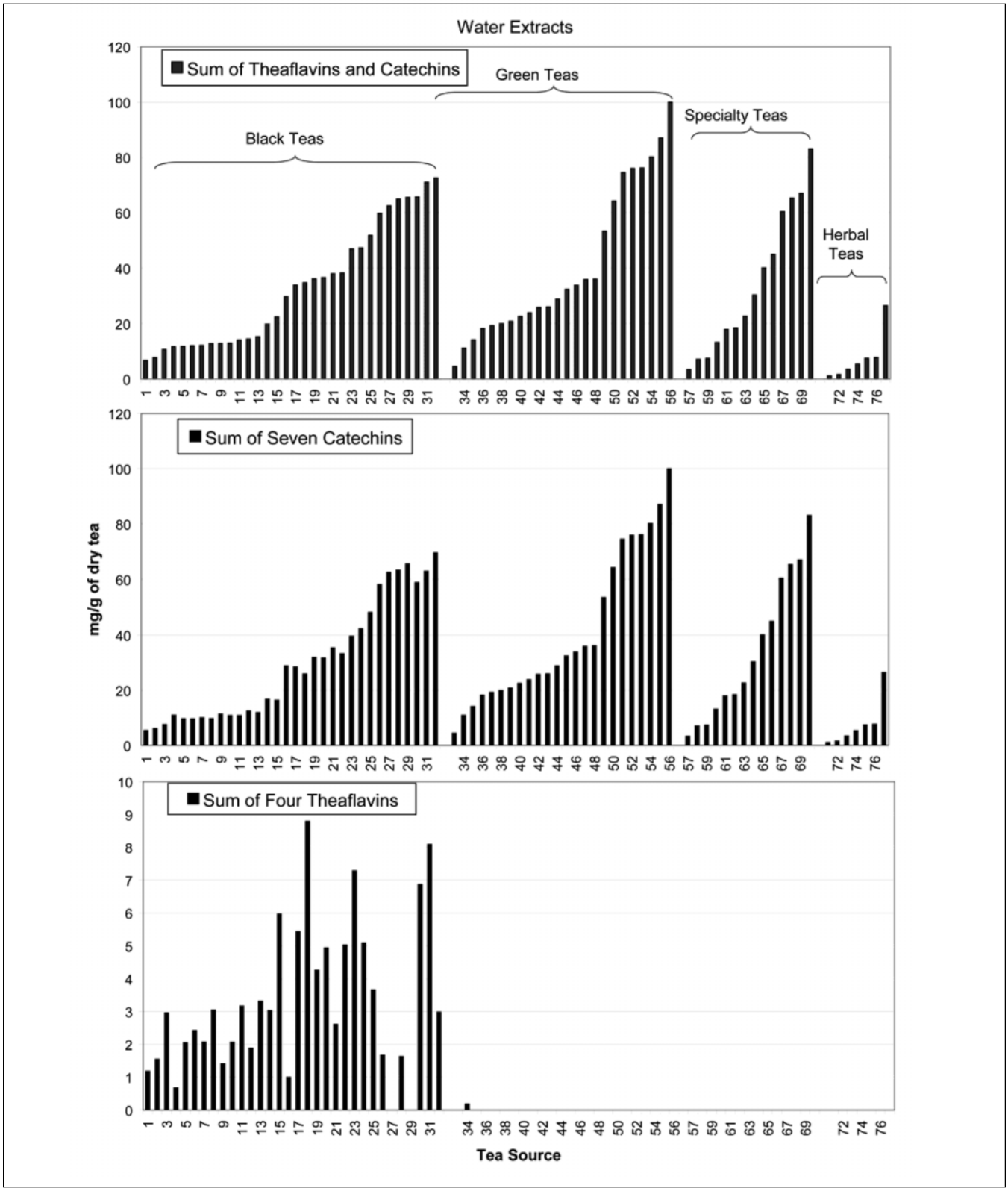

Figure 4—Bar graphs of tea catechin and theaflavin levels extracted with water based on data listed in Table 3

The variability in the levels of caffeine among the teas was much narrower than that of catechins and theaflavins. The content of theobromine is on average about 1/10 that of caffeine. Its distribution in teas showed much greater variability than that of caffeine. Herbal teas contained little or no caffeine or theobromine.

The data on various tea categories complement and extend the information on the composition of teas outlined earlier. Our results suggest that the consumer may be able to select teas containing high levels of beneficial catechins and theaflavins and avoid those containing low amounts of these compounds. However, it needs to be emphasized that we do not know whether the biological activities of individual tea compounds consumed in pure form differ from those exhibited by the same compound in teas, where there is the possibility of additive, synergistic (Morre and others 2003), and antagonistic interactions among the different tea constituents. Moreover, because black teas contain high levels of theaflavins and varying levels of catechins, while green teas contain high amounts of catechins and no theaflavins, consumption of both tea types may produce greater health benefits than consumption of either black or green teas alone. Because health effects may depend on the type of tea consumed and because there is a lack of composition data on individual teas consumed in different parts of the world, there is a need to know the catechin and theaflavin content of teas (Khokhar and Magnusdottir 2002). The results of this study on the composition of 77 teas consumed in the United States extend efforts designed to meet this very need (Peterson and others 2004).

A major aim of this study was to discover teas with high levels of catechins and theaflavins. The 10 green teas with the highest content of catechins (64 to 100 mg/g) were as follows: Darjeeling Green Organic (highest value), Sushi Bar Mild Green, Green Organic; Sencha Japanese Green; Premium Green, Exotica Dragonwell Green; Darjeeling Black Organic, Exotica Golden Darjeeling, Jasmine Blossom Green, and Darjeeling Summer.

The following 10 black teas had the highest amounts of theaflavins (3.7 to 8.8 mg/g): Orange Spice Black (highest value), Darjeeling Summer, Exotica Assam Breakfast, Kopili Assam Black, Original India Spice, English Breakfast Black, Breakfast Blend Organic, Nilgiri Black, Earl Grey Black, Earl Grey Black & Green Organic, and Exotica Reserve Blend.

The water extracts of the following 10 black teas contained the highest total (sum) of catechins and theaflavins (46.9 to 72.5 mg/g): Darjeeling Black Organic (highest value), Darjeeling Summer, Kopili Assam Black, Exotica Golden Darjeeling, Darjeeling Spring, Exotica Ceylon Estate Earl Grey, Darjeeling Black, Exotica Reserve Blend, Breakfast Blend Organic, and Exotica Assam Breakfast.

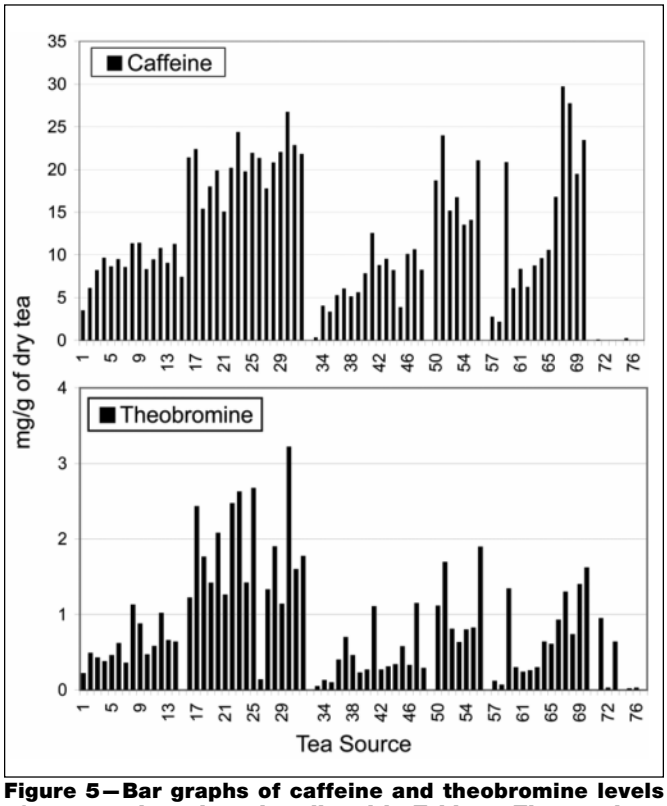

Figure 5—Bar graphs of caffeine and theobromine levels of teas are based on data listed in Table 3. The numbers shown on the horizontal axis correspond to the names of the teas listed in Table 2.

Conclusions

The results we obtained in this study extend our knowledge about the composition of a large number of teas consumed in the United States and allow the consumer to select tea brands with the highest content of beneficial compounds. Because a variety of factors including agricultural practices, geographical origin, postharvest processing, and brewing methods are all reported to influence the nature and amounts of flavonoids in teas (Fernandez and others 2002; Beecher 2003; Peterson and others 2004), labeling teas for catechin and theaflavin content may benefit tea consumers.

Acknowledgments

We thank Dr. Bruce Mackey for statistical analysis, Carol E. Levin for assistance with the preparation of the manuscript, and Journal reviewers for constructive comments.

We dedicate this study to Dr. Sigmund Schwimmer in honor his election to the ARS Hall of Fame in recognition of pioneering contributions to food enzymology (Schwimmer 1981).

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