Delivery of Tea Polyphenols to the Oral Cavity by Green Tea Leaves and Black Tea Extract

Mao-Jung Lee,† Joshua D. Lambert,† Saitela Prabhu,† Xiaofeng Meng,† Hong Lu,† Pius Maliakal,† Chi-Tang Ho,‡ and Chung S. Yang†

†Department of Chemical Biology, Ernest Mario School of Pharmacy, Rutgers, The State University of New Jersey, New Brunswick, New Jersey, and ‡Department of Food Science, Cook College, Rutgers, The State University of New Jersey, New Brunswick, New Jersey

Abstract
Catechins and theaflavins, polyphenolic compounds derived from tea (Camellia sinensis, fam. Theaceae), have been reported to have a wide range of biological activities including prevention of tooth decay and oral cancer. The present study was undertaken to determine the usefulness of green tea leaves and black tea extract for the delivery of catechins and theaflavins to the oral cavity. After holding either green tea leaves (2 g) or brewed black tea (2 g of black tea leaves in 100 ml) in the mouth for 2–5 min and thoroughly rinsing the mouth, high concentrations of catechins (Cmax = 131.0–2.2 μM) and theaflavins (Cmax = 1.8–0.6 μM) were observed in saliva in the 1st hour. Whereas there was significant interindividual variation in the peak levels of catechins and theaflavins, the overall kinetic profile was similar, with t1/2 = 25–44 min and 49–76 min for catechins and theaflavins, respectively (average coefficient of variation in t1/2 was 23.4%). In addition to the parent catechin and theaflavin peaks, five unidentified peaks were also observed in saliva after black tea treatment. Hydrolysis of theaflavin gallates, apparently by salivary esterases, was observed in vitro and in vivo. These results indicate that tea leaves can be used as a convenient, slow-release source of catechins and theaflavins and provide information for the possible use of tea in the prevention of oral cancer and dental caries.

Introduction
Tea, made from the leaves of Camellia sinensis (fam. Theaceae), is one of the most popular beverages worldwide. Green tea is prepared from fresh tea leaves that are pan-fried or steamed and dried to inactivate enzymes. Chemically, this beverage is characterized by the presence of the polyphenolic catechins including: (−)epigallocatechin-3-gallate (EGCG), (−)epigallocatechin (EGC), (−)epicatechin-3-gallate (ECG), and (−)epicatechin (Fig. 1). Black tea is prepared by crushing withered tea leaves and allowing enzyme-mediated oxidation, commonly referred to as fermentation, to occur, leading to the formation of oligomers such as theaflavins (Fig. 1) and polymers known as thearubigins. Oolong tea is a partially fermented product that contains considerable amounts of catechins and oligomerized catechins (1).

A number of beneficial effects have been attributed to tea consumption, including the prevention of oral cancer and tooth decay (2, 3). In several animal experiments and human trials, green tea and black tea have been shown to significantly reduce plaque scores and caries index (4–8). Although tea polyphenols have been shown to have anticancer activity in vitro and oral cancer preventive activity in animal models (9, 10), epidemiological evidence for oral cancer prevention has been sparse and inconclusive. For example, a population-based, case–control study in Denmark has found no association between tea consumption and the development of oral squamous cell cancer (11). On the other hand, preliminary results from an intervention study have shown that oral and topical administration of a tea preparation significantly reduced the size of oral lesions and the incidence of micronucleated oral mucosa cells in leukoplakia patients compared with a nontreated group (12).

To demonstrate the effectiveness of tea and tea components as cancer preventive agents, investigators need carefully designed intervention studies. To accomplish this, a clear understanding of the bioavailability of the tea components is essential. Previous work in our laboratory has shown that after drinking brewed green tea (1.2 g of tea solids in 200 ml hot water), salivary levels of EGC and EGCG reach 11–44 μg/ml (37–147 μM) and 5–22 μg/ml (10–44 μM) at 20 min, respectively in human volunteers (13). These levels were two orders of magnitude greater than the plasma levels after a similar dose of tea (78 and 223 ng/ml for EGC and EGCG, respectively; Ref. 14). In practical application, chewing or holding tea leaves or extract in the mouth might be a convenient and economical method of sustained delivery of catechins and black tea polyphenols to the oral cavity.

We explored these ideas in this study and report herein the salivary levels of catechins and theaflavins achieved by holding green tea leaves or black tea extract in the mouth. These data should aid in designing proper intervention studies on the effectiveness of green and black tea in the prevention of oral cancer and tooth decay.

Materials and Methods

Chemicals and Reagents. EGCG, epicatechin, ECG, β-D-glucuronidase (G-7896, EC 3.2.1.31, from Escherichia coli with 9 × 10⁶ units/g solid), and sulfatase (S-9754, EC 3.1.6.1, from Abalone entrails with 2.3 × 10⁶ units/g solid) were
purchased from Sigma Chemical Co. (St. Louis, MO). Green tea leaves and black tea solids (lyophilized extract) were provided by Anhui Agricultural University (Anhui, China); EGCG and theaflavins were provided by Unilever Best Food Co. (Englewood, NJ). The mixture of theaflavin contained the following (per g): theaflavin (TF, 202 mg) theaflavin-3-gallate (TF-3-G, 331 mg), theaflavin-3'-gallate (TF-3'-G, 156 mg), and theaflavin-3,3’-digallate (TFdiG, 311 mg).

Stock solutions of EGCG, EGC, ECG, epicatechin, and theaflavins (10 μg/ml catechins and 100 μg/ml theaflavins) were made in 0.2% ascorbic acid-0.005% EDTA solution and stored at −80°C. These standards were stable for up to 6 months. Other reagents and high-performance liquid chromatography (HPLC) solvents were of the highest grade commercially available.

**Holding of Tea and Sample Collection.** The protocol for human subjects in these studies was approved by the Institutional Review Board for the Protection of Human Subjects (Protocol no. 92-034) at Rutgers University (Piscataway, NJ). Volunteers between 25 and 50 years of age who did not smoke, drink alcohol, nor drink tea for at least two days before the start of this study were selected. After thoroughly brushing their teeth, four volunteers gently chewed 2 g of green tea leaves in the mouth for 5 min. The leaves were voided, and the subjects immediately rinsed their mouths vigorously 10 times with 50 ml water for a period of 2 min. Unstimulated saliva was collected in tubes containing 20 μl of ascorbic acid-EDTA solution [0.4 mM NaH₂PO₄ buffer containing 20% ascorbic acid and 0.1% EDTA (pH 3.6)] before holding green tea leaves and black tea solids (lyophilized extract) were procured from Sigma Chemical Co. (St. Louis, MO). Green tea leaves and black tea solids (lyophilized extract) were procured from Sigma Chemical Co. (St. Louis, MO).

**Stability of Theaflavins.** The pH stability of the theaflavins was determined by dissolving 0.25 mg of theaflavins in 10 ml 50 mM sodium phosphate buffer (pH 3.3) were incubated at 4°C, 25°C, and 37°C for 0, 1, 8, and 24 h and were analyzed as above.

To determine whether salivary esterases removed the galloyl group from gallated theaflavins, 5 ml of saliva were collected as above, were combined with 10 mg of TFdiG, and were incubated at 37°C. Aliquots were removed at 0–240 min, were diluted 100 times with 30% acetonitrile and 100 μl of ascorbic acid/EDTA solution, and were analyzed by HPLC.

**Analysis of Tea Polyphenols.** Samples were analyzed on a HPLC system composed of an ESA Model 465 refrigerated autosampler, two ESA Model 580 dual piston pumps, and an ESA 5500 coulochem electrode array system. A Supelcosil C18 reversed-phase column (150 mm × 4.6 mm inner diameter; Supelco Co., Bellefonte, PA) was used for all applications. The column and coulochem electrode array system detector were housed in a temperature-regulated compartment maintained at 35°C. The autosampler was maintained at 6°C. For binary gradient elution, mobile phase A consisted of 1.75% acetonitrile and 0.12% tetrahydrofuran in 30 mM NaH₂PO₄ (pH 3.35), and mobile phase B consisted of 58.5% acetonitrile and 12.5% tetrahydrofuran in 15 mM NaH₂PO₄ (pH 3.45). The flow rate was maintained at 1 ml/min, and the eluent was monitored by coulochem electrode array system with potential settings at −100, 100, 300, and 500 mV. Gradient conditions were the same as those previously reported with the following modification (15).

For simultaneous analysis of both catechins and theaflavins, the mobile phase began with a 7-min isocratic phase of 96% A and 4% B, followed by progressive, linear increases in B to 17% at 25 min, 30% at 31 min, 44% at 50 min, 50% at 55 min, and 98% at 62 min. The mobile phase was maintained at 98% B for 5 min and then was re-equilibrated to 4% at 67.5 min.

**Results**

**Analysis of Tea Polyphenols.** After subjects held 2 g of tea leaves in their mouths for 5 min, participants rinsed their mouths 10 times with 50 ml of distilled water, saliva samples were collected, and catechin levels were determined. Rinsing the mouth 10 times was found to be necessary to remove unabsorbed tea components (data not shown). Initial experiments conducted without tooth-brushing before the start of the experiment resulted in significant variation in the levels of tea polyphenols (data not shown). The addition of tooth-brushing eliminated this variation. HPLC analysis demonstrated the presence of not only the parental catechin compounds but also three unknown peaks (gA, gB, gC; Fig. 2A). Peaks gA and gC have been previously detected, although the identity of all of the peaks remains unknown (13). The retention times of EGC, epicatechin, EGCG, and ECG were 12.5, 24, 28.5, and 36 min, respectively. An analysis of blank saliva revealed no interfering or comigrating peaks compared with either the green tea leaf or black tea extract group (data not shown).

Similarly, HPLC analysis of saliva after black tea extract was held in the mouth revealed good separation of all catechin and theaflavin peaks (Fig. 2B). The retention times of EGC, epicatechin, EGCG, and ECG were 8, 16, 21.5, and 33 min, respectively; TF, TF-3-G, TF-3’-G, and TFdiG eluted at 41, 44, 45.5, and 46.5 min, respectively. In addition to the catechin and theaflavin peaks, five unknown peaks (ba–bE) were observed (Fig. 2B). Whereas peak bb was found in the tea solution, peaks ba, bc, bd, and bE were formed over the time course of the
Salivary Levels of Tea Polyphenols.

The efficiency of chewing tea leaves in the mouth for extracting catechins was compared with that of successively boiling the leaves for 10 min in 200 ml of water. It was interesting to note that chewing 2 g of green tea leaves in the mouth for 20 min extracted EGCG, ECG, and epicatechin from the leaf matrix as effectively as boiling green tea leaves in 200 ml of water for four 10-min periods (Table 1). A G peak was not observed when the leaves were boiled and are apparently formed during the chewing process.

Initially, it was hypothesized that chewing green tea leaves would result in a higher salivary level of catechins compared with holding the leaves without chewing. Chewing did lead to an increase in the peak levels of catechins in the saliva of 2–4-fold (Table 2). However, in some subjects, at later time points, there was a second increase in the concentration of the catechins (Fig. 3A). In experiments to accurately determine the kinetics of the catechins in the saliva, however, we elected to have the subjects hold the leaves in their mouths without chewing.

Salivary levels of catechins after holding tea leaves in the mouth without chewing were maximal in the first 10 min and decreased in a time-dependent manner (Fig. 3B). EGC and EGCG were found in the highest concentrations (39 ± 31 and 31 ± 21 µg/ml, respectively). The t₁/₂ for the catechins was 34–44 min (Table 2). The unknown peaks gA and gC, but not gB, increased as a function of time, reaching a maximal level (estimated Cmax = 2.5–4.0 µg/ml) at 50 and 22 min, respectively, followed by a time-dependent decrease (Fig. 3C). For cA, cB, and cC, the t₁/₂ was 34.8 ± 2.6, 29.5 ± 2.6, and 26.5 ± 13 min, respectively.

Salivary Levels of Black Tea Polyphenols. Similar experiments were attempted using black tea leaves; however, it was observed that black tea leaves were too brittle and that particles of black tea leaves remained in the mouth even 60 min after vigorous rinsing. This led to variable levels of tea polyphenols in the saliva. The experiments, therefore, were conducted using black tea extract. The composition of black tea extract was determined by boiling 2 g of leaves in 100 ml of water for 10 min before decanting off the liquid. An aliquot was combined

The catechin extraction efficiency of chewing green tea leaves was compared with that of boiling an equal amount of tea leaves in water. Green tea leaves (2 g) were gently chewed for 20 min. The leaves were voided (5–10 ml of saliva), and the subjects washed the mouth vigorously 10 times with water (total volume = 350 ml) in a 2-min period. The leaves and washouts were combined and centrifuged. The clear supernatant was then diluted and analyzed by high-performance liquid chromatography (HPLC).

Experiment. These peaks are currently being identified by liquid chromatography/mass spectrometry and nuclear magnetic resonance. The concentrations of peaks gA–gC and bA–bE were estimated by assuming that the compounds had similar electrochemical properties to the catechins and theaflavins, respectively. Peak heights were compared with the peak heights of standards of known concentration.

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Salivary levels of tea polyphenols after placing tea in the mouth. A, levels of catechins in the saliva of one subject over the course of the experiment after gentle chewing of green tea leaves for 5 min. Salivary levels (B) of catechins or unknown peaks (C) over the course of the experiment after the holding of green tea leaves. Salivary levels of catechins (D), theaflavins (E), or unknown peaks (F) over the course of the experiment after the holding of black tea extract. All of the samples were collected after voiding tea leaves or solution and after washing of the mouth vigorously for 2 min with water. Detection at 100 mV.

Fig. 4. Stability of theaflavins as a function of pH. Incubations were in 50 mM sodium phosphate buffer. With 0.25 mg of theaflavins, pH 6.5 (A), pH 7.0 (B), pH 7.5 (C), pH 9.0 (D).

Table 3  Levels of catechins and theaflavins in black tea solutions and elimination half-lives after holding black tea extract in the mouth for 2 min

<table>
<thead>
<tr>
<th>Compound</th>
<th>Black tea extract (µg/ml)</th>
<th>Peak level (µg/ml)</th>
<th>$t_{1/2}$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGCG</td>
<td>74.0</td>
<td>0.33–1.9</td>
<td>30.4 ± 5.6</td>
</tr>
<tr>
<td>ECG</td>
<td>36.7</td>
<td>0.25–1.6</td>
<td>24.9 ± 3.4</td>
</tr>
<tr>
<td>EGC</td>
<td>19.3</td>
<td>0.45–2.8</td>
<td>31.2 ± 1.9</td>
</tr>
<tr>
<td>Epicatechin</td>
<td>16.0</td>
<td>0.20–2.5</td>
<td>27.6 ± 8.1</td>
</tr>
<tr>
<td>TF</td>
<td>24.6</td>
<td>0.10–0.80</td>
<td>60.1 ± 46.0</td>
</tr>
<tr>
<td>TF-3-G</td>
<td>29.3</td>
<td>0.50–2.6</td>
<td>48.5 ± 31.2</td>
</tr>
<tr>
<td>TF-3'-G</td>
<td>21.3</td>
<td>0.05–0.6</td>
<td>75.8 ± 73.5</td>
</tr>
<tr>
<td>TFDiG</td>
<td>40.7</td>
<td>0.34–2.0</td>
<td>67.9 ± 65.1</td>
</tr>
</tbody>
</table>

$^a$ These data were obtained from the same experiment shown in Fig. 3, D–F.

Discussion

In previous studies, we have shown that oral consumption of green tea, or holding brewed green tea in the mouth, results in
salivary tea catechin levels that are two orders of magnitude greater than plasma levels from similar doses of tea (13). Here we show that high salivary levels of tea polyphenols can be achieved by holding either green tea leaves or black tea extract in the mouth. Whereas there is significant interindividual variation, holding green tea leaves in the mouth results in a higher $C_{\text{max}}$ (2.0–80 µg/ml) and longer $t_{1/2}$ (33.6–43.9 min) compared with previous results ($C_{\text{max}} = 1.8–44$ µg/ml; $t_{1/2} = 11–15$ min; Ref. 13).

Initially, it was hypothesized that chewing green tea leaves would result in the higher salivary levels of catechins compared with holding the leaves without chewing. Chewing did lead to an increase in the peak levels of catechins in the saliva of 2–4-fold (Table 2). However in some subjects, at later time points, there was a second increase in the concentration of the catechins (Fig. 3A). This increase may be the result of a decrease in the volume of saliva produced after long periods of chewing tea leaves. When subjects consumed large volumes of water immediately before the start of the experiment, these later increases were not observed (data not shown). It is also possible that tea leaf particles become trapped in the spaces between the teeth. These fine particles may get into the saliva samples at later time points and affect the measurements of catechin levels. For practical application, chewing tea leaves may be more efficient for delivering high concentrations of tea catechins to the oral mucosa. In experiments to accurately determine the kinetics of the catechins in the saliva, however, we elected to have the subjects hold the leaves in their mouths without chewing.

Holding pure theaflavins (0.18 mg/ml) in the mouth results in 10–20-fold higher salivary levels of these compounds than did holding black tea extract, which has a similar concentration of theaflavins: there was no effect on elimination kinetics. There results may indicate that other components in black tea interfere with the transfer of theaflavins from the solution into the saliva and the oral mucosa.

In addition to the theaflavin and catechin peaks, we observed several unknown peaks in saliva after holding green tea leaves or black tea extract in the mouth. Compounds gC, bA, and bC–bE were not present in the tea leaves or black tea extract and appeared to form while the leaves were held in the mouth; compound gA was present in the green tea leaves and increased in the saliva over time before decreasing because of elimination. On the basis of comparisons with pure catechin and theaflavin standards, these peaks reached high ng/ml to low µg/ml levels and may represent metabolites created in the oral milieu by either human enzyme systems or oral microflora. Additional experiments are needed to identify these peaks and determine their origin. The concentrations of these compounds can then be accurately measured by comparison with standards. When pure theaflavins were held in the mouth, compounds bA–bE were not observed, indicating that the compounds are derived from some component of black tea other than theaflavins. Moreover, because the identity of these compounds remains unknown, we cannot comment on their potential contribution to the biological effects of green or black tea in the oral cavity.

The present study also demonstrates that chewing green tea leaves is as effective at extracting EGCG, epicatechin, and ECG from the leaf matrix as is repeatedly boiling the leaves. Previously, Khalif et al. (17) reported that the growth of cell lines derived from oral leukoplakia patients and oral cancer patients was inhibited by EGCG after a 5-day treatment, with $IC_{50}$ equal to 8–18 µM. Treatment with EGCG, EGC, or epicatechin, at concentrations of 80 µM, also resulted in growth inhibition of oral squamous cell carcinoma cells (10). These concentrations are within the range achievable in the saliva by holding (2–131 µM) or chewing (12–260 µM) green tea leaves. Although a single administration of these concentrations of tea polyphenols is probably not sufficient to elicit an anticancer effect, it is possible that, by holding tea leaves in the mouth regularly over the course of a day, effective levels of catechins or theaflavins could be maintained in the oral cavity. The salivary levels presented in this report were measured after the leaves were voided from the mouth. The amount of EGCG available to oral mucosa when the tea is still in the mouth should be similar to the saliva washout (9.8 mM) or black tea extract (162 µM). The total concentration of theaflavins in the black tea extract was 161 µM. These data support the potential usefulness of holding tea leaves in the mouth as a means of oral cancer prevention.

In the present study, we also studied the stability of theaflavins. Our purpose was two-fold. First, we wanted to establish that these compounds were stable under our experimental conditions and would not degrade during analysis. Theaflavins are stable under acidic conditions and in the presence of ascorbic acid. Second, the stability of theaflavins in the oral cavity and gastrointestinal tract may affect the bioavailability of these compounds. Theaflavins have been shown previously to have very low bioavailability. Mulder et al. (18) found that the maximum plasma concentration of theaflavins was 1 ng/ml in volunteers after oral ingestion of 700 mg of theaflavins (equivalent to 30 cups of black tea). We demonstrate that the theaflavins are stable under acidic conditions ($\text{pH 6.5}$) but degrade at neutral and basic $\text{pH}$ ($\text{pH > 7.0}$). The $\text{pH}$ of the oral cavity is usually 7.0–7.4 and it is expected that under physiological conditions, some degradation of theaflavins will occur. Once the compounds enter the gastric environment, they are probably stable. We have observed that theaflavins are stable in simulated gastric juice ($\text{pH 1.7}$) at $37^\circ \text{C}$ for greater than 4 h (data not shown). Likewise, the slightly acidic ($\text{pH 6.4}$) and largely anaerobic environment of the small intestine disfavors theaflavin degradation (19). In the colon, however, the $\text{pH}$ becomes more basic ($\text{pH = 8.0}$), and the potential for degradation may arise, but the low oxygen tension disfavors oxidative degradation of theaflavins. On the basis of our results, the low bioavailability of theaflavins is probably not due to $\text{pH}$ or temperature-dependent degradation in the gastrointestinal tract. In contrast, the low bioavailability of these compounds is probably due to the high molecular weight and large polar surface area of these compounds (20). The hydroxyl groups on theaflavins likely form a large hydration shell that gives the compounds greater apparent surface area and prevents movement through the plasma membrane (21).

In summary, this report demonstrates that holding green tea leaves or black tea extract in the mouth represents a method to achieve locally high levels of tea polyphenols. Black tea leaves proved to be too brittle and resulted in the deposition of plant material in the mouth, which confounded attempts at determining theaflavin and catechin levels in this study. Similarly, chewing green tea leaves resulted in significant variation in the data but higher levels of catechins than holding tea leaves. In practical application, however, chewing or holding green or black tea leaves probably results in the most effective delivery of these compounds to the oral cavity, and is the most convenient and economical sustained delivery system. Development of sustained release products such as chewing gum may aid in the esthetic acceptance and standardization of tea polyphenol delivery. The data presented here should prove useful in designing quality intervention trials to determine the effective-
ness of tea as an oral cancer preventive and anticariogenic substance.

References