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Inhibitory Effects of Oolong Tea Polyphenols on Pancreatic Lipase in Vitro

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Fifty-four polyphenols isolated from tea leaves were evaluated for their inhibitory activities against pancreatic lipase, the key enzyme of lipid absorption in the gut. (−)-Epigallocatechin 3-*O*-gallate (EGCG), which is one of major polyphenols in green tea, showed lipase inhibition with an IC_{50} of 0.349 μM. Moreover, flavan-3-ol digallate esters, such as (−)-epigallocatechin-3,5-digallate, showed higher activities of inhibition on lipase with an IC_{50} of 0.098 μM. On the other hand, nonesterified flavan-3-ols, such as (+)-catechin, (−)-epicatechin, (+)-gallocatechin, and (−)-epigallocatechin, showed zero and/or the lowest activities against pancreatic lipase (IC_{50} > 20 μM). These data suggested that the presence of galloyl moieties within the structure was required for enhancement of pancreatic lipase inhibition. It is well-known that flavan-3-ols are polymerized by polyphenol oxidase and/or heating in a manufacturing process of oolong tea. Oolonghomobisflavans A and B and oolongtheanin 3′-*O*-gallate, which are typical in oolong tea leaves, showed strong inhibitory activities with IC_{50} values of 0.048, 0.108, and 0.068 μM, respectively, even higher than that of EGCG. The oolong tea polymerized polyphenols (OTPP) were prepared for the assay from oolong tea extract, from which the preparation effectively subtracted the zero and/or less-active monomeric flavan-3-ols by preparative high-performance liquid chromatography. The weight-average molecular weight (Mw) and number-average molecular-weight (Mn) values of OTPP were 2017 and 903, respectively, by using gel permeation choromatography. OTPP showed a 5-fold stronger inhibition against pancreatic lipase (IC_{50} = 0.28 μg/mL) by comparison with that of the tannase-treated OTPP (IC_{50} = 1.38 μg/mL). These data suggested that the presence of galloyl moieties within their chemical structures and/or the polymerization of flavan-3-ols were required for enhancement of pancreatic lipase inhibition.

KEYWORDS: Oolong tea; flavan-3-ol; polymerized polyphenol; lipase inhibition

INTRODUCTION

Tea is the most popular beverage in the world (*1*). It has been well-known for a long time that three kinds of tea, i.e., green tea, oolong tea, and black tea, have beneficial effects on health. All types of tea are manufactured from the same plant species, *Camellia sinensis* L., but the preparation process for each one is different: oolong tea is semi-fermented, green tea is unfermented, and black tea is well fermented.

Tea polyphenols have been reported to have various biological and pharmacological functions, such as an anti-HIV effect (*2*) and antioxidative (*3*, *4*), antimutagenic (*5*), anticarcinogenic (*6*), antitopoisomerase (*7*), antiobesity (*8*), and hypocholesterolemic activities (*9*, *10*). Furthermore, it has been reported that the chemical structures of over 60 polyphenols from green tea (*11*, *12*), oolong tea (*13*−*15*), and black tea (*16*−*18*) were elucidated, and the relationship between the chemical structure and activity was evaluated for the antioxidative effect against lipid peroxidation by the ferric thiocyanate method in vitro (*19*).

Obesity is caused by the results of an imbalance between energy intake and expenditure. Excess energy is stored in fat cells that enlarge or increase in number. Moreover, obesity is a strong risk factor for various diseases, such as hypertension, hyperlipidemia, arteriosclerosis, and diabetes (*20*). Therefore, an effective way to prevent obesity is to inhibit fat absorption from intestine or increase metabolic rate and fat oxidation.

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Pancreatic lipase is a key enzyme for lipid absorption. It is well-known that dietary fat is not directly absorbed from the intestine unless it has been subjected to the action of pancreatic lipase. Thereby, to suppress weight gain, it would be effective to reduce fat absorption by lipase inhibition. Orlistat, a specific pancreatic lipase inhibitor, is clinically used for preventing obesity and hyperlipidemia (*21*). On the other hand, lipase inhibitory materials derived from natural products, such as chitosan (*22*), chondroitin sulfate, and the polyphenolic constituents of *Salacia reticulata* (*23*) and grape seed extract (*24*), have been reported previously.

Oolong tea is traditionally reported to prevent obesity and improve lipid metabolism, and it is assumed that habitual ingestion is effective to enhance the metabolic rates and lipid catabolism (*25*). Han et al. reported that the antiobesity action of oolong tea was due to the enhancing effect of caffeine on noradrenaline-induced lipolysis in adipose tissue and to the inhibitory action of teasaponin on pancreatic lipase activity (*26*). Teasaponins, such as teasaponin E1 and E2, showed lipase inhibitory effects, but the concentration of teasaponin of oolong tea was only 0.6% (*27*).

Oolong tea contains many varieties of polyphenols involved in oligomeric flavan-3-ols. Oolong tea polyphenols have inhibitory activities against some enzymes, such as glycosyltransferase of mutans streptococci (*28*). Therefore, it is expected that oolong tea polyphenols are effective for lipase inhibition and preventing obesity.

In the present study, the inhibitory effects of dimeric flavan-3-ols on pancreatic lipase and the structure−activity relationship were evaluated. Furthermore, the inhibitory activity of polymerized polyphenols prepared from oolong tea was examined.

MATERIALS AND METHODS

Chemicals. (+)-Catechin, (+)-gallocatechin, (−)-catechin gallate, (−)-gallocatechin gallate, (−)-epicatechin, (−)-epicatechin gallate, (−)-epigallocatechin, and (−)-epigallocatechin gallate were purchased from Funakoshi Co. Ltd. (Tokyo, Japan), and their purities were more than 98%. Oolongtheanin gallate and dehydrodicatechin A were enzymatically synthesized as described below. Oolong tea polymerized polyphenols (OTPP) were fractionated from oolong tea by HPLC. Other dimeric polyphenols used in this study had previously been isolated from green tea, oolong tea, and black tea (*11*−*18*). And purities of dimeric polyphenols were more than 90% in HPLC. The structures of the monomeric and dimeric polyphenols are shown in **Figure 1**. Tannase was purchased from Funakoshi Co. (Tokyo, Japan). Pancreatic lipase (type VI-S, from porcine pancreas) and 4-methylumbelliferyl oleate were purchased from Sigma Chemical Co. (St. Louis, MO). The other reagents were of analytical grade, and all solvents used were of HPLC grade (Nacalai Tesque Co., Kyoto, Japan).

Preparation of OTPP. Ten grams of oolong tea leaves was steeped in 1.5 L of boiling water for 5 min. After filtration, the extract was lyophilized, and the yield of the dry matter was about 20% of the weight of the leaves. The concentrations of flavanols (flavan-3-ols and flavan-3-ol gallate esters) in the extract were analyzed by HPLC with UV detection at 280 nm. The analysis was performed with a reversed-phase HPLC column (Develosil C30-UG-5, 4.6 mm × 150 mm, Nomura Chemical Co., Aichi, Japan) at 40 °C. Compounds were eluted (solvent A, 0.05% trifluoroacetic acid, 10% acetonitrile in water; solvent B, 0.05% trifluoroacetic acid, 80% acetonitrile in water) at a flow rate of 1 mL/min using a gradient program (solvent B content: isocratic elution of 0% for 5 min, gradient elution of 0−8% for 3 min, gradient elution of 8−10% for 3 min, isocratic elution of 10% for 9 min, gradient elution of 10−100% for 1 min, and isocratic elution of 100% for 9 min). The quantitative analysis of flavanols was made using standard calibration curves for authentic specimens using a 280 nm area, and OTPP was quantified using a calibration curve that was derived from polyphenols isolated from oolong tea by HPLC. The chromatograph of oolong tea extract is shown in **Figure 2**.

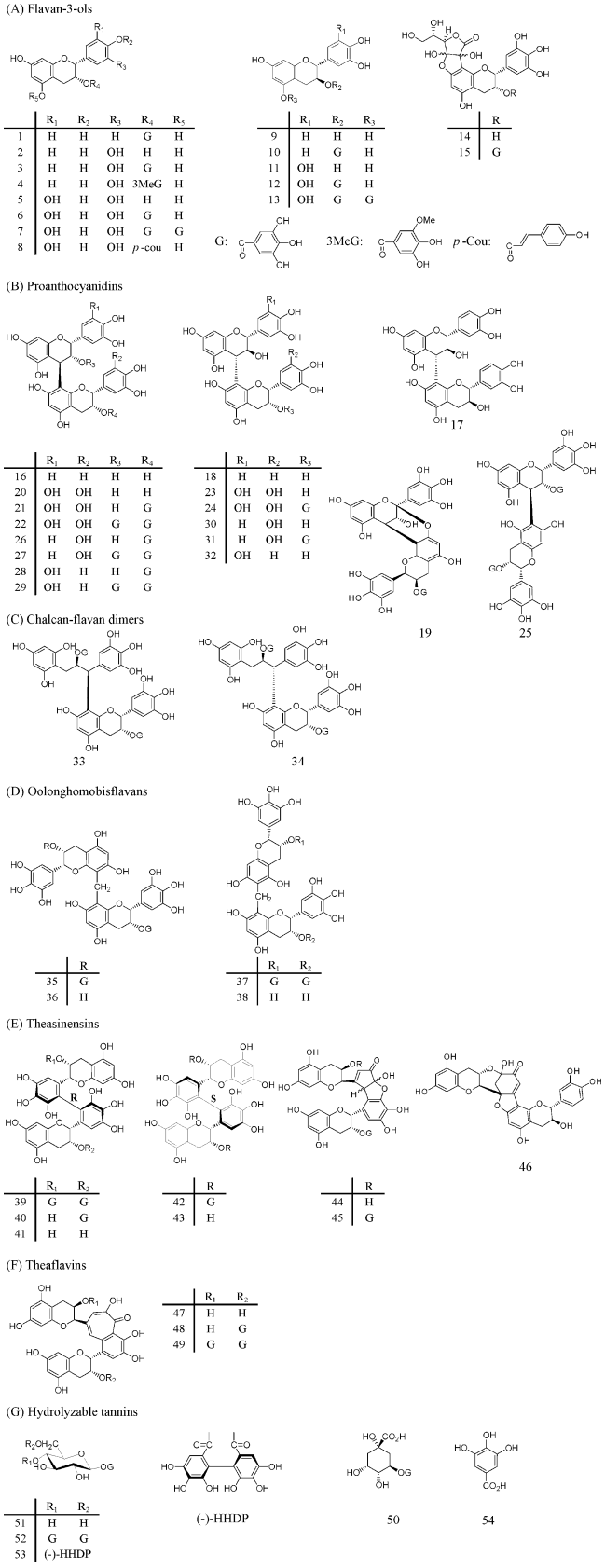

Figure 1. Structual formulas of the test compounds.

Gel Permeation Chromatography Analysis. The molecular weight of OTPP was estimated by gel permeation chromatography (GPC) with UV detection at 280 nm (*29*). OTPP was dissolved in tetrahydrofuran (THF) and applied to Shodex GPC columns KF-802.5 and KF-801 (8.0 mm × 300 mm, Showa Denko K.K., Tokyo, Japan) at 25 °C. The mobile phase was THF, and the flow rate was 0.8 mL/min. The

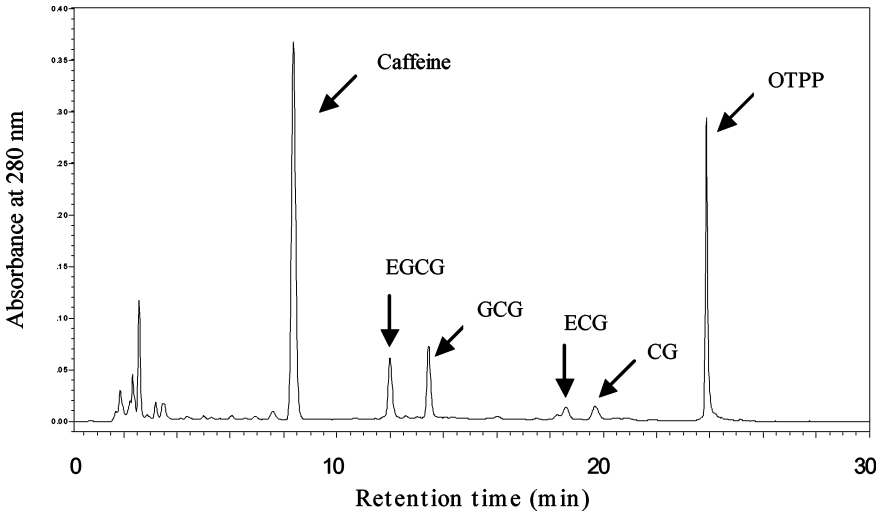

Figure 2. Reversed-phase HPLC chromatogram of oolong tea extract: EGCG, (–)-epigallocatechin 3-*O*-gallate; GCG, (–)-gallocatechin 3-*O*-gallate; ECG, (–)-epicatechin 3-*O*-gallate; CG, (–)-gallocatechin 3-*O*-gallate; OTPP, oolong tea polymerized polyphenols.

chromatogram was calibrated against standard polystyrenes (molecular weights 920, 2090, and 9860) and (+)-catechin (molecular weight 290).

Measurement of Pancreatic Lipase Activity. The pancreatic lipase activity was measured using 4-methylumbelliferyl oleate (4-MU oleate) as a substrate (*30*). Twenty-five microliters of a sample solution dissolved in water and 50 μL of a 0.1 mM 4-MU solution dissolved in a buffer consisting of 13 mM Tris-HCl, 150 mM NaCl, and 1.3 mM $CaCl_2$ (pH 8.0) were mixed in the well of a microtiter plate, and 25 μL of the lipase solution (50 U/mL) in the above buffer was then added to start the enzyme reaction. After incubation at 25 °C for 30 min, 0.1 mL of 0.1 M sodium citrate (pH 4.2) was added to stop the reaction. The amount of 4-methylumbelliferone released by lipase was measured with a fluorometrical microplate reader (Fluoroskan Ascent C Lab-Systems, Inc.) at an excitation wavelength of 355 nm and an emission wavelength of 460 nm. The IC_{50} of the test sample was obtained from the least-squares regression line of the plots of the logarithm of the sample concentration (log) versus the pancreatic lipase activity (%).

Preparation of Crude Polyphenol Oxidase Solution. Fresh leaves (600 g) of *C. sinensis cv.* Kyoken-129gou and polyamide (150 g) were homogenized in a 0.01 M potassium phosphate buffer (pH 7.0) under cooling. After removal of the insolubles by filtration through gauze, the solution was centrifuged (5000 rpm), and the supernatant was treated with acetone at −20 °C. The resulting precipitates were collected using an 8000 rpm centrifuge, dissolved in 600 mL of a 0.01 M citric acid−0.02 M potassium phosphate buffer (pH 5.6), and used for the enzymatic reaction of polyphenol oxidase.

Polyphenol Oxidase Reaction of Flavanols. EGCG (500 mg) was incubated in the above crude polyphenol oxidase solution (500 mL) at 32 °C for 3 h. To stop the reaction, 250 mL of 90% CH_3CN containing 1% TFA was added to the reaction mixture, and then the solution was diluted 4 times with H_2O and applied on an HP-20 column (400 mL, Mitsubishi Chemical Co., Ltd.). After washing with H_2O, catechins were eluted by 90% CH_3CN containing 0.1% TFA. The reactant was purified by prep-HPLC. The HPLC was accomplished with the use of an ODS column (Develosil ODS-UG-15/30, 500 mm × 50 mm, Nomura Chemical, Ltd.) with a flow rate of 32 mL/min and monitoring at $A = 280$ nm. The solvent systems used included a linear gradient elution for 100 min using 20−50% of solvent B (90% CH_3CN, 0.1% TFA in H_2O) in solvent A (0.1% TFA in H_2O). As a result of this chromatogram, 16 mg of oolongtheanin gallate was obtained.

(+)-Cathechin (100 mg) was incubated in the above crude enzyme solution (100 mL) at 32 °C for 3 h. To stop the reaction, 50 mL of 90% CH_3CN containing 1% TFA was added to the reaction mixture, and then the solution was diluted 4 times by H_2O and applied on HP-20. After washing with H_2O, catechins were eluted by 90% CH_3CN containing 0.1% TFA. The reactant was purified by HPLC using Develosil C30-UG-5 (250 mm × 20 mm, Nomura Chemical Co., Ltd.) with a flow rate of 6 mL/min and monitoring at $A = 280$ nm to give pure dehydrodicatechin A (2 mg). The solvent systems used included linear gradient elution for 60 min using 20−50% of solvent B (90% CH_3CN, 0.1% TFA in H_2O) in solvent A (0.1% TFA in H_2O).

Tannase Hydrolysis of OTPP. A solution of oolong tea polymerized polyphenols (2 mg) in 50% EtOH (1 mL) was dissolved in 9 mL of a 0.1 M potassium phosphate buffer (pH 5.5) and shaken with tannase (2 mg) at 25 °C for 18 h. The mixture was applied to Sep-pak C18 and washed with H_2O to remove gallic acid, tannase, and potassium phosphate and then eluted with 90% CH_3CN.

Spectroscopy. The structures of the products of flavan-3-ols dimerized by polyphenol oxidase were determined as briefly described below. NMR spectra (^1H NMR, ^{13}C NMR, $^1H\{^{13}C\}$-HSQC, $^1H\{^{13}C\}$-HMBC, TOCSY, and DQF-COSY) of the isolated products dissolved in CD_3OD were obtained on a DMX-750 spectrometer (Bruker Biospin). The mass spectra of the products were obtained using a nano ESI-Q-TOF MS equipped with a Z-spray ion source (Micromass, Manchester, UK) in both negative and positive modes. High-resolution FAB-MS of the products was recorded on a JMS-HX/HX110A system (JEOL) in the positive mode.

RESULTS AND DISCUSSION

Inhibitory Activities of Flavanols on Lipase. The tea polyphenols are classified into two groups: the primary polyphenols, including flavan-3-ols, proanthocyanidins, chalcan−flavan dimers, oolonghomobisflavans, and hydrolyzable tannins, which originally constitute tea leaves; and the secondary polyphenols, which are those compounds derived from primary polyphenols, specifically from flavan-3-ols, by polyphenol oxidases during self-fermentation, and include theasinensins and theaflavins isolated from semi- and well-fermented tea leaves such as oolong and black tea.

The inhibitory activities of 54 polyphenols on pancreatic lipase are shown in **Table 1**. Among monomeric polyphenols (flavan-3-ols) found in oolong tea, compounds such as EGCG (**6**) and GCG (**12**), which had an ester bond of gallic acid and pyrogallol type in the B ring of the structures, strongly inhibited lipase activity in vitro. Moreover, flavan-3-ol digallate esters, such as epigallocatechin-3,5-digallate (**7**) and gallocatechin-3,5-digallate (**13**), showed higher activities of inhibition on lipase with IC_{50}s of 0.098 and 0.213 μM. On the other hand, nonesterified flavan-3-ols, such as catechin (**9**) and gallocatechin (**11**), had little inhibitory potential ($IC_{50} > 20$ μM). As shown in **Figure 2**, the major compounds of oolong tea extract are EGCG, GCG, and caffeine, but caffeine did not show an inhibitory effect on lipase (data not shown).

Table 1. Inhibitory Effcts of Polyphenols on Pancreatic Lipase

polyphenol	IC_{50} (μM)
Flavan-3-ols	
(–)-epiafzelechin 3-*O*-gallate (**1**)	2.582
(–)-epicatechin (**2**)	>20
(–)-epicatechin 3-*O*-gallate (**3**)	0.452
(–)-epicatechin 3-*O*-(3′-*O*-methyl)gallate (**4**)	0.680
(–)-epigallocatechin (**5**)	>20
(–)-epigallocatechin 3-*O*-gallate (**6**)	0.349
(–)-epigallocatechin 3,5-di-*O*-gallate (**7**)	0.098
(–)-epigallocatechin 3-*O*-*p*-coumaroate (**8**)	0.885
(+)-catechin (**9**)	>20
(–)-catechin 3-*O*-gallate (**10**)	0.543
(+)-gallocatechin (**11**)	>20
(–)-gallocatechin 3-*O*-gallate (**12**)	0.437
(–)-gallocatechin 3,5-di-*O*-gallate (**13**)	0.213
8-C-ascorbyl (–)-epigallocatechin (**14**)	0.646
8-C-ascorbyl (–)-epigallocatechin 3-*O*-gallate (**15**)	0.791
Proanthocyanidins	
procyanidin B-2 (**16**)	7.958
procyanidin B-3 (**17**)	2.941
procyanidin B-4 (**18**)	>20
prodelphinidin A-2 3′-*O*-gallate (**19**)	0.171
prodelphinidin B-2 (**20**)	2.951
prodelphinidin B-2 3′-*O*-gallate (**21**)	1.969
prodelphinidin B-2 3,3′-di-*O*-gallate (**22**)	0.107
prodelphinidin B-4 (**23**)	6.230
prodelphinidin B-4 3′-*O*-gallate (**24**)	0.223
prodelphinidin B-5 3,3′-di-*O*-gallate (**25**)	0.558
(–)-epicatechin (4β-8)-(–)-epigallocatechin 3-*O*-gallate (**26**)	0.147
(–)-epicatechin 3-*O*-gallate (4β-8)-(–)-epigallocatechin 3-*O*-gallate (**27**)	0.846
(–)-epigallocatechin (4β-8)-(–)-epicatechin 3-*O*-gallate (**28**)	0.913
(–)-epigallocatechin 3-*O*-gallate (4β-8)-(–)-epicatechin 3-*O*-gallate (**29**)	0.612
(+)-catechin (4α-8)-(–)-epigallocatechin (**30**)	7.912
(+)-catechin (4α-8)-(–)-epigallocatechin 3-*O*-gallate (**31**)	0.174
(+)-gallocatechin (4α-8)-(–)-epicatechin (32)	2.862
Chalcan–Flavan Dimers	
assamicain A (**33**)	0.120
assamicain B (**34**)	0.186
Oolonghomobisflavans	
oolonghomobisflavan A (**35**)	0.048
monodesgalloyl oolonghomobisflavan A (**36**)	0.271
oolonghomobisflavan B (**37**)	0.108
didesgalloyl oolonghomobisflavan B (**38**)	2.083
Theasinensins	
theasinensin A (**39**)	0.142
theasinensin B (**40**)	0.276
theasinensin C (**41**)	>2
theasinensin D (**42**)	0.098
theasinensin E (**43**)	>2
oolongtheanin (**44**)	0.219
oolongtheanin 3′-*O*-gallate (**45**)	0.068
dehydrodicatechin A (**46**)	3.090
Theaflavins	
theaflavin (**47**)	0.106
theaflavin 3′-*O*-gallate (**48**)	0.112
theaflavin 3,3′-di-*O*-gallate (**49**)	0.092
Hydrolyzable Tannins	
theogallin (**50**)	>50
β-glucogallin (**51**)	>50
1,4,6-tri-*O*-galloyl-β-D-glucose (**52**)	1.226
strictinin (**53**)	0.472
gallic acid (**54**)	>50

Among the proanthocyanidins, prodelphinidins having gallate esters in their structures showed high activities, but procyanidins without gallate esters had lower activities than EGCG. On the other hand, there were dimeric compounds that showed weak activities even though they had two galloyl groups in the structures, such as epicatechin 3-*O*-gallate (4β-8)-epigallocatechin 3-*O*-gallate (**27**) and epigallocatechin 3-*O*-gallate (4β-8)-epicatechin 3-*O*-gallate (**29**), with IC_{50}s of 0.846 and 0.612 μM, respectively. Epicatechin (4β-8)-epigallocatechin 3-*O*-gallate (**26**) with an IC_{50} of 0.147 μM, the desgalloyl compound in the upper part of the dimeric structure, was more effective than **27**. Furthermore, the activity of epigallocatechin (4β-8)-epicatechin 3-*O*-gallate (**28**) with an IC_{50} of 0.913 μM was the same level as that of **29**. These data suggested that the EGCG moiety constructing the lowering unit of the dimeric structure was necessary for lipase inhibition in proanthocyanidin dimers.

Assamicains, oolonghomobisflavans, and theasinensins also had potent antilipase activity. Monodesgalloyl (**36**) or didesgalloyl (**38**) oolonghomobisflavans showed less activity than oolonghomobisflavan A (**35**) and B (**37**). The activity levels of theasinensins also depended on the number of galloyl groups within their molecular structures, such as oolongtheanin 3′-*O*-gallate (**45**) and theasinensin D (**42**) and A (**39**) with IC_{50}s of 0.068, 0.098, and 0.142 μM, respectively. Although catechin had no activity (IC_{50} > 20 μM), an inhibitory activity of dehydrodicatechin A (**46**), a dimeric compound of catechin, was markedly increased (IC_{50} = 3.09 μM). The relationship between the chemical structure and activity suggested that the inhibitory effects advanced with the dimerization of flavan-3-ol.

The inhibitory activity of oolonghomobisflavan A was strongest among assamicains, oolonghomobisflavans, and theasinensins. It is suggested that a methylene bridge linking the 8,8′-positions of two flavan units was responsible for the higher activities. It has been reported that oolonghomobisflavans were isolable from oolong tea but not from green tea or black tea; therefore, many active compounds, such as these, may only exist in oolong tea.

Theasinensins (**39**−**43**), which possess *R*- and *S*-forms (atropisomerism) in the biphenyl moiety, did not show any significant difference in activity; however, the activity increased with the number of additional galloyl groups in their molecules.

However, the activities of theaflavins did not depend on the number of the galloyl groups in the structure. The activity levels of theaflavins (**47**−**49**) were almost the same despite the difference in the galloyl number in their molecules. This finding suggested that a benzotropolone nucleus itself was important to the activity.

On the other hand, hydrolyzable tannins showed little activity, although many galloyl groups existed in their structures. Among the hydrolyzable tannins, strictinin, which had a hexahydroxydiphenoyl ester, showed the same level of activity as flavan-3-ol gallate esters. However, other hydrolyzable tannins possessed some galloyl groups (**51**−**53**) with little or zero activity. These data suggested that the intermolecular galloyl groups themselves were not essential for lipase inhibition activity.

GPC Analysis of OTPP. Oolong tea is produced from tea leaves via semifermentation and heating processes. In these processes, flavan-3-ols are complicatedly polymerized by polyphenol oxidase and/or heating. However, hydrophobic polymerized polyphenols, which are complexes of high molecular weight compounds, have not been purified from oolong tea. Hydrophobic polyphenols (OTPP) fractionated from oolong tea by reversed-phase HPLC are shown in **Figure 2**. The concentrations of major polyphenols, such as EGCG, GCG, ECG, CG, and OTPP in oolong tea extract were estimated as 0.8, 0.8, 0.3, 0.2, and 9.6% (w/w), respectively. OTPP were the complex of high molecular weight polyphenols by GPC analysis. The GPC of OTPP is shown in **Figure 3**. The weight-

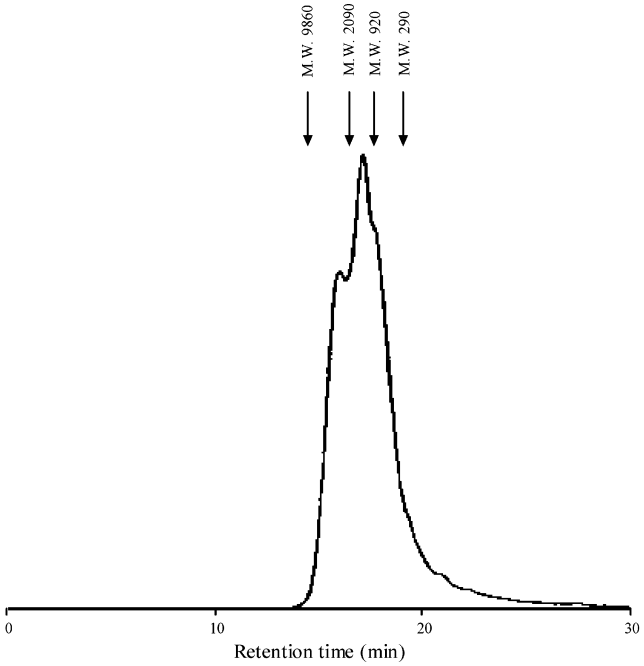

Figure 3. GPC analysis of oolong tea polymerized polyphenols. Arrows indicate elution points of each standard.

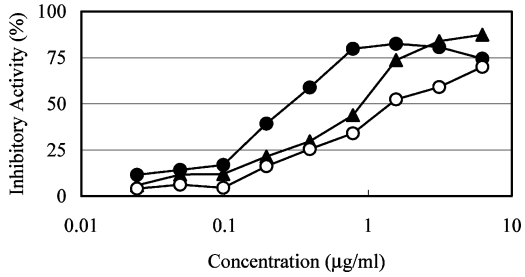

Figure 4. Inhibitory effects of polyphenols on pancreatic lipase: (●) oolong tea polymerized polyphenols (OTPP) derived from oolong tea extract, (▲) oolong tea, and (○) tannase-treated OTPP.

average molecular weight (Mw) and number-average molecular weight (Mn) values of OTPP were 2017 and 903, respectively.

Inhibitory Effect of OTPP on Lipase. The inhibitory activity of OTPP on lipase (IC_{50} = 0.28 μg/mL) was stronger than that of oolong tea (IC_{50} = 0.91 μg/mL), as shown in **Figure 4**. OTPP were major polyphenols contained in oolong tea as shown **Figure 2** and largely contributed to inhibit lipase.

It was also shown in **Figure 4** that the inhibitory activity of OTPP was significantly decreased by tannase treatment (IC_{50} = 1.38 μg/mL). In this experiment, some of the active compounds of oolong tea polyphenols were dimeric compounds of flavan-3-ol gallate esters, and the EGCG unit was important for potentiating the activity. To elucidate this point, the lipase inhibitory activity was examined after OTPP was hydrolyzed by tannase. The activity of OTPP hydrolyzed by tannase decreased but was not entirely diminished. These data suggested that the lipase inhibition potency of OTPP consisted of both the functional galloyl moieties in it and the oligomeric form of flavan-3-ols, since dehydrodicatechin A increased the inhibitory activity compared to the (+)-catechin monomer. Hamada et al. reported that the polymers derived from catechins in tea leaves were effective for increasing glucosyltransferase inhibitory activities (*31*).

In conclusion, flavan-3-ol gallate esters largely contributed to the inhibitory activity of oolong tea against pancreatic lipase. We demonstrated that the dimeric compounds of the flavan-3-ol gallate esters of EGCG and GCG, such as proanthocyanidins, oolonghomobisflavans, theasinensins, and theaflavins, were also more responsible for lipase inhibition than EGCG and GCG. Moreover, OTPP showed stronger inhibition against pancreatic lipase than oolong tea extract and tannase-treated OTPP. Our data suggested that the functional galloyl moieties in the structure and the polymerization of flavan-3-ol were needed for the expression of lipase inhibition.

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