Dietary Phytochemicals as Cancer Preventive Agents: Efficacy and Mechanisms

Yohei Shirakami1,2*, Hiroyasu Sakai1, Masaya Kubota1, Takahiro Kochi1 and Masahito Shimizu2

1Department of Informative Clinical Medicine, Gifu University Graduate School of Medicine, Gifu, Japan
2Department of Gastroenterology, Gifu University Graduate School of Medicine, Japan

Abstract

Despite significant advances in cancer therapeutic modalities, available anti-tumor drugs display limited efficacy and sometimes carry a risk of severe adverse side effect. Therefore, it is important to identify and develop cancer chemopreventive agents without toxicity. Epidemiological examinations in human populations and experimental rodent studies provide evidence that certain types of phytochemicals suppress development and growth of cancers at various organ sites. A number of clinical investigations have been also conducted and shown that dietary phytochemicals are able to inhibit tumorigenesis, indicating several phytochemicals are regarded as cancer chemopreventive agents. Epigallocatechin-3-gallate (EGCG), the major catechin in green tea, is considered as the most biologically active constituent in drinking tea with respect to inhibiting cell proliferation and inducing apoptosis in cancer cells. EGCG appears to directly target receptor tyrosine kinases with inhibiting activation of the receptors and down-stream signaling pathways. In addition, EGCG has improving effects against obesity and insulin resistance, which leads to suppressing the development of obesity-related malignancies. Other polyphenolic phytochemicals, including curcumin and resveratrol, are also reported to exert anti-cancer effect. In this review article, we summarize the potential of dietary phytochemicals as anti-cancer drugs and those possible mechanisms against cancer, especially chemopreventive effect of green tea catechins.

Keywords: Capsaicin; Chemoprevention; Chronic inflammation; Colorectal cancer; Curcumin; Genistein; Green tea catechin; Hepatocellular carcinoma; Obesity

Introduction

A number of epidemiological and experimental investigations have demonstrated an inverse relationship between the risk for some types of cancers and consumption of a diet which has a high content of fruits and vegetables [1,2]. These observations indicate that supplementation of nutritional component derived from fruits and vegetables can be useful for cancer prevention. Although these fruits and vegetables have been approved by researchers, especially epidemiologist, the specific components of these plant nutrients and the precise mechanisms of action for cancer prevention have not yet been fully understood. In recent studies, a number of specific phytochemicals, known as plant-derived and non-nutritive substances, have been identified which exert anti-cancer effects in various experimental systems [2]. Several mechanisms of action against cancer by these phytochemicals have been implicated, including antioxidant activity, trapping of oxygen radicals, induction of drug metabolizing and detoxifying enzymes, promotion of DNA repair, and modulating tumor-suppressor genes [3,4]. In addition to the mechanisms above, recent studies have revealed that several phytochemicals have an anti-cancer effect by regulating activities of various types of receptor tyrosine kinases (RTKs) and their downstream signaling pathways, which are associated with the expression of the genes involved in cell proliferation, angiogenesis, and apoptosis [2,5-8].

Among various types of phytochemicals, (-)-epigallocatechin gallate (EGCG) (Figure 1), the major biologically active component in green tea, appears to be one of the most potent polyphenols regarding inhibition of cell proliferation and induction of apoptosis in cancer cell lines [5,7,9]. EGCG have been reported to exert its anti-cancer efficacy by suppressing oxidative stress [9], inhibiting activation of several types of RTKs, regulating epigenetic modification, and modulating immune system [7,10-16]. In this review article, we summarize cancer chemopreventive effects of dietary phytochemicals, especially focusing on the mechanisms of EGCG against cancer. This review also mentions other phytochemicals, such as curcumin, capsaicin, and genistein, to possess anti-tumor activity and several clinical studies to examine the possibility of dietary phytochemicals as anti-cancer drugs. Although other phytochemicals, such as resveratrol and anthocyanin, have been reported as cancer preventive agents [17,18], ones from foods taken relatively often in daily life are chosen in this article.

Experimental Studies

Green tea catechins and EGCG

Tea is produced from the dried leaves of the tea plant Camellia sinensis and is one of the most widely consumed beverages in the world. It is demonstrated in many epidemiological studies that consumption of tea, especially green tea, is related to decreased incidence of many types of cancers [19]. A number of experimental studies in rodents have also indicated that green tea or its constituents suppress the development and the growth of cancers at various organ sites [9]. Green tea contains several types of catechins, such as EGCG, (-)-epigallocatechin (EGC), (-)-epicatechin-gallate (ECG), and (-)-epicatechin (EC). Among green tea catechins (GTCs), EGCG is considered as one of the major constituents and the most abundant and active constituent in terms

*Corresponding author: Yohei Shirakami, Department of Informative Clinical Medicine and Gastroenterology, Gifu University Graduate School of Medicine, 1-1 Yanagido, Gifu 501-1194, Japan, Tel: +81-58-230-6313; Fax: +81-58-230-6310; E-mail: ys2443@gifu-u.ac.jp

Received March 16, 2015; Accepted April 06, 2015; Published April 10, 2015


Copyright: © 2015 Shirakami Y, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.
of inhibiting cell proliferation and inducing apoptosis in cancer cells [20,21]. The chemical structure of EGCG is illustrated in Figure 1. GTCs, especially EGCG, have been extensively examined and reported to have various anti-cancer effects, including induction of apoptosis and cell-cycle arrest, inhibition of NF-κB and AP-1, suppression of cyclooxygenase-2 overexpression, modulation of immune system, regulation of epigenetic modification, and inhibition of activation of several types of RTKs [7,9-16]. Some of those anti-cancer mechanisms are shown below.

Apoptosis, known as programmed cell death, is considered to play an important role in the elimination of cancerous cells and to function as an essential protective mechanism against cancer [22]. Previous examinations have indicated that EGCG treatment induces cell-cycle arrest during the G1 phase via regulating expression of cyclin D1, cdk4, p21CIP1, and p27KIP1, and induces apoptosis through generation of reactive oxygen species and activation of caspase-3 and -9 [23]. EGCG administration increases the proportion of cells at the G1 phase, decrease cyclin D1 protein levels, and increase p21CIP1, and p27KIP1 proteins levels [12] in head and neck squamous carcinoma (HNSCC) cell lines. In addition, it is reported that treatment with EGCG and other tea polyphenols inhibits cellular growth of PC-9 human lung cancer cells through cell-cycle arrest during the G2/M phase [24]. Another study of the HT29 human colon cancer cell line, treatment with either EGCG alone or combination with other tea catechins was found to increase the number of cells during the G1 phase, induce apoptosis, decrease the levels of cyclin D1 and Bcl-XL protein, and increase caspase-3 and -9 activity [15]. In an in vivo examination of azoxymethan-induced colon carcinogenesis model using obese and diabetic mice, it is demonstrated that administration of EGCG suppresses colon neoplastic lesions and causes a significant decrease in the level of cyclin D1 protein in colonic mucosa [25]. These results suggest that green tea and its constituents, especially EGCG, exert anti-cancer effect by inducing cellular growth arrest and apoptosis through various mechanisms.

Nuclear factor-xB (NF-xB) is known as a transcriptional factor and closely associated with cancer development [20]. Masuda et al. [10] demonstrated that EGCG treatment inhibits NF-xB activation in H891 human HNSCC cells and MDA-MB-231 human breast cancer cells. Treatment with EGCG also down-regulates NF-xB by inducing kinase expression in PC-9 human lung cancer cells [24]. Nuclear translocation of NF-xB occurs during activation of NF-xB, which leads to suppression of apoptosis and the induction of cellular transformation, proliferation, invasion, metastasis, and inflammation. EGCG treatment is reported to inhibit not only NF-xB activity in human colon cancer cells [20], but also inhibit NF-xB nuclear translocation in A431 epidermoid carcinoma cells in a dose- and time-dependent manner [26]. Another transcription factor activator protein-1 (AP-1), which regulates gene expressions associated with apoptosis and proliferation, also appears to promote cellular proliferation via up-regulating cyclin D1 and down-regulating tumor-suppressor genes, such as p53, p21CIP1, and p16INK4a [20]. EGCG treatment inhibits AP-1 activation and cell transformation in mouse epidermal cell line JB6 [27] and Ras-activated AP-1 activity in the H-ras-transformed JB6 cell line [28]. It is also observed that EGCG treatment inhibits transcriptional activity of AP-1 and NF-xB promoters, as examined by reporter assay [14], and that treatment with either EGCG alone or combination with other tea catechins causes a dose-dependent inhibition of AP-1 luciferase reporter activity in human colon cancer cell line HT29 [15]. These results indicate that GTCs can inhibit both NF-xB and AP-1 activities, which appear to be a possible mechanism underlying the anti-cancer activity of green tea catechins.
Cyclooxygenase (COX) is a key regulatory enzyme for prostaglandin synthesis and is divided into two distinct genes, COX-1 and COX-2. While COX-1 is constitutively expressed in whole body, COX-2 expression is controlled by many factors, such as mitogens, tumor promoters, cytokines, and growth factors. In a variety of pre-malignant and malignant conditions, overexpression of COX-2 has been observed [29]. It is demonstrated that EGCG inhibits mitogen-stimulated COX-2 expression in human prostate carcinoma cells [30] and decrease COX-2 expression in human mammary and colon cancer cells [14,31]. Our research group has reported that oral administration of GTCs has an inhibitory effect on COX-2 expression in the colon epithelium in a rodent study using inflammation-related colon carcinogenesis model [32]. These observations suggest that GTCs may be a potential candidate for preventing various types of cancers, since development of an agent which inhibits COX-2 expression, preferably without affecting COX-1 expression, can be a promising strategy for cancer chemoprevention [33].

Consumption of green tea has been thought to enhance humoral and cell-mediated immunity, resulting in decreased risk of certain cancers [34]. Immunity is defined as the ability to fight against invading organisms or abnormal conditions in order to prevent the development of various diseases including infection and cancer [35]. Although inflammation is fundamental reaction of immune-system, inappropriate inflammation frequently becomes a cause of disease. It has been indicated that GTCs have anti-inflammatory efficacy with therapeutic potential, since a number of in vivo studies have shown that administration of green tea polyphenols decreases inflammation. Among those studies, Yang et al. [21] demonstrated that lipopolysaccharide-induced tumor necrosis factor (TNF) production is decreased by administration of green tea polyphenols. Similarly, our research group found that administration of GTCs decreases levels of various inflammatory cytokines, including TNF-α, in the colon mucosa and suppresses the development of inflammation-related colon carcinogenesis in a mouse model [32]. Supplementation of green tea and its constituents may have a beneficial effect on inflammatory disorders possibly by exerting anti-inflammatory action via inhibition of NF-κB activation [36]. Indoleamine 2, 3-dioxygenase (IDO) is a tryptophan catabolic enzyme and is considered to play an important role to induce immune tolerance [37]. Our research group found that EGCG treatment causes a significant decrease in IFN-γ-induced expression of IDO in human colon cancer cells in a dose-dependent manner [38]. EGCG also significantly inhibits IDO enzymatic activity by suppressing STAT activity [38]. In a rodent study investigating the effects of an IDO inhibitor 1-methyltryptophan (1-MT) and EGCG, it is revealed that both 1-MT and EGCG significantly suppress the development of AOM-induced colonic neoplastic lesions which have overexpression of IDO protein [39]. The study also demonstrates that both 1-MT and EGCG markedly inhibit the increase of IDO activity in the serum and stroma [39]. These findings suggest that EGCG exerts suppressive effect on cancer development presumably through inhibiting both the expression and function of IDO and that EGCG and IDO inhibitor 1-MT are potential anti-tumor agents as immune modulators for cancer chemoprevention.

Epigenetics is the study of the reversible heritable gene expression changes without alteration of DNA sequences. These changes are thought to play a significant role in the regulation of general gene expression and contribute to cancer development due to affecting histone modification and altering chromatin structure [40]. Epigenetic silencing of DNA-repairing and tumor-suppressor genes, which is frequently caused by hyper-methylation and occurs during early stages of carcinogenesis, is associated with various diseases including cancer [41]. Although it has been considered that the effects of EGCG on epigenetic alteration primarily attributes to DNA methylation in cancer cells, a previous study revealed that EGCG also functions as a histone modifier [42]. Treatment with EGCG inhibits the activity of DNA methyltransferase and subsequently induces cytosine-phosphate-guanine demethylation and reactivation of silenced tumor-suppressor genes, such as p16[INK4a], retinoic acid receptor-β (RARβ), and O6-methyl guanine-DNA methyltransferase in human esophageal cancer cells [43]. EGCG is also reported to partly promote demethylation of hypermethylated RARβ in breast cancer cells [40]. Other studies, however, have shown that EGCG treatment exhibits no significant changes in the extent of demethylation or the reactivation of methylation-silenced genes [44,45]. In addition, the results from several studies investigating the effects of EGCG on reactivation of silenced genes appear to be still inconclusive [46-48]. Among the studies, Morey et al. has reported that administration of green tea polyphenols neither inhibits prostate tumor progression nor promotes dose dependent alterations in DNA methylation status in a mouse model [47]. Further studies are required to provide evidence that EGCG or GTCs have efficacy on epigenetic alteration as a mechanism against cancer.

Receptor tyrosine kinases (RTKs), which play a pivotal role in cell proliferation and apoptosis, are possible targets of GTCs against cancer [7,49]. RTKs and their downstream signaling pathways, including Ras/ extracellular signal-regulated kinase (ERK) and phosphatidylinositol 3-kinase (PI3K)/Akt signaling pathways, regulate the expression of multiple target genes related to cell proliferation and apoptosis [50,51]. Due to binding of growth factors and cytokines as ligands to the extracellular domain of RTKs, it stimulates their tyrosine kinase activity and triggers phosphorylation of specific tyrosine residues [50,51]. The activation of cell-surface RTKs and their multiple downstream signaling play essential roles in various fundamental processes in normal cells. Pre-malignant and malignant cells often display inappropriate activation of RTKs through several mechanisms, such as gene mutation and overexpression [52,53]. The epidermal growth factor receptor (EGFR) family includes four members, namely EGFR (erbB1), HER2 (neu/erbB2), HER3 (neu/erbB3), and HER4 (neu/ erbB4), which belong to subclass I of the RTK superfamily. Insulin-like growth factor-1 receptor (IGF-1R) and vascular endothelial growth factor receptor (VEGFR) belong to other group of RTKs. Although approximately 20 different RTK classes have been identified, abnormalities in certain RTKs, especially EGFR, IGF-1R, and VEGFR2, are deeply associated with the acquisition of malignant properties [52-54]. This relationship indicates that EGFR and HER2 are therapeutic targets in cancer treatment, which is supported by preclinical and clinical evidence in lung and breast cancer [55]. GTCs have been shown to affect several RTKs in a beneficial manner. It is reported that administration of green tea polyphenols in drinking water at a 0.1% concentration inhibits the development of prostate cancer and metastatic lesions in rodent prostate cancer model [56]. This treatment leads to a decrease of insulin-like growth factor-1 (IGF-1) levels and restoration of IGF binding protein-3 (IGFBP-3) levels, which are associated with reduced levels of P38 and phosphorylated forms of Akt and ERK [56,57]. In azoxymethan-induced colon carcinogenesis model, similar experimental results were observed in which drinking EGCG induces down-regulated IGF-1 level and suppresses colon pre-malignant lesions [25]. In in vitro experiment using human colon cancer and hepatoma cells, treatment with EGCG decreases levels of IGF-1 and the activated form of IGF-1R protein, while increasing levels of IGFBP-3, suggesting that EGCG has inhibitory effect on the IGF/
IGF-1R axis [13,16]. The findings of anti-cancer effects of EGCG on the VEGF/VEGFR axis have been also reported in other studies. EGCG treatment inhibits VEGF production by down-regulating activation of signal transducer and activator of transcription (STAT)-3 and NF-xB in HNSCC and breast cancer cells [10]. In another study, treatment with EGCG inhibits phosphorylation of both VEGFR1 and VEGFR2 and induces apoptosis in B-cell chronic lymphocytic leukemia cells [58]. In addition, it is demonstrated that EGCG suppresses growth of xenografts on mice generated from HuH7 human hepatoma cells and SW837 human colon cancer cells through suppressing expression of VEGF and activation of VEGFR2, ERK, and Akt [59,60]. The effect of GTCs, including EGCG, on ErbB receptor family has been also well investigated and documented. EGCG treatment inhibits not only activation of EGFR and HER2 and their downstream signaling, but also activation of HER3 in various human cancer cell lines [10-12,15]. Researchers also found that treatment with EGCG alone or combination with other tea catechins down-regulates the levels of phosphorylated forms of EGFR and HER2, which leads to a decrease in the phosphorylation of ERK and Akt [15].

In addition to the direct effects of EGCG on certain types of RTKs at the cell surface, several studies have revealed that EGCG also has indirect effects on RTKs by targeting the lipid organization in soluble ordered plasma membrane domains known as “lipid rafts”. EGCG treatment alters the lipid rafts in human colon cancer cells and inhibits binding of the ligand epidermal growth factor (EGF) to EGFR and the subsequent receptor dimerization [61]. Alterations of lipid organization on the plasma membrane by EGCG induce the internalization of EGFR into endosomes with preventing ligands from binding to EGFR. The degradation of EGFR on cell surface following internalization appears to be induced by phosphorylation of the receptor at serine 1046/1047, which is associated with the activation of p38 MAPK caused by EGCG [62]. The findings suggest that this novel mechanism may be able to explain ubiquitous effects of EGCG on regulating various types of cell surface RTKs.

Curcumin: Curcumin is a polyphenol (chemical structure in Figure 1) and one of curcuminoids from yellow pigmented turmeric which is a rhizome of the herb Curcuma species. One of the most significant biological effects of curcumin is its anti-inflammatory property. Previous study has reported the property; curcumin is a potent NF-xB inhibitor in human myeloid effectors [11]. It inhibits binding of the ligand epidermal growth factor (EGF) to EGFR and the subsequent receptor dimerization [61]. Alterations of lipid organization on the plasma membrane by EGCG induce the internalization of EGFR into endosomes with preventing ligands from binding to EGFR. The degradation of EGFR on cell surface following internalization appears to be induced by phosphorylation of the receptor at serine 1046/1047, which is associated with the activation of p38 MAPK caused by EGCG [62]. The findings suggest that this novel mechanism may be able to explain ubiquitous effects of EGCG on regulating various types of cell surface RTKs.

Genistein: Genistein is a soy-derived compound isoflavone, is known as a phytoestrogen which has similar structure of estrogen. This phytochemical has diverse biological activities including cancer chemopreventive function. Its anti-cancer activities have been shown in rodent models as well as in various types of cancer cells through modulation of several signal transduction pathways [87]. Genistein is reported to inhibit TPA-induced c-fos expression, AP-1 activity, and ERK activity in human breast cancer cells [88]. Genistein also reduces IxB phosphorylation and inhibits nuclear translocation of NF-xB leading to decreased DNA binding and NF-xB activation in prostate cancer cells [89]. A recent examination has demonstrated that genistein inhibits cellular proliferation through inactivation of IGF1R/PI3K/Akt pathway and decrease of the ratio of anti-/pro-apoptotic protein levels in breast cancer cells [90]. In the transgenic mouse model for prostate cancer, supplementation of genistein significantly down-regulated activation of EGFR and IGF-1R, both are RTKs, and their downstream signaling [8].

Clinical interventional studies

Plenty of interventional studies and clinical trials to investigate cancer chemopreventive effects of dietary phytochemicals have been conducted. Among them, we here focus on the investigations of tea catechins, including GTCs and EGCG, and these are introduced and discussed below. The examinations using curcumin and genistein are also well documented and a detailed discussion can be found in


ISSN: 1948-593X JBB, an open access journal


excellent reviews from Shanmugam et al. [91] and Taylor et al. [92] respectively.

As described above, one potential mechanism underlying the chemopreventive effect of tea is anti-oxidant activity of GTCs. In a phase II randomized interventional trial examining the effect of drinking green tea on reducing DNA damage in heavy smokers, consumption of 4 cups/day of decaffeinated green tea for 4 months significantly decreases in levels of urinary 8-hydroxydeoxyguanosine (8-OHdG), a surrogate biomarker of oxidative DNA damage [93]. Another study, however, has shown no correlation between green tea consumption and lung cancer risk in smokers [94], suggesting that the anti-oxidant activities of green tea play a limited role in decreasing lung cancer risk and, therefore, the existence of an alternative mechanism by which green tea decreases the risk.

Several clinical trials have conducted to examine cancer chemopreventive effects of administrating tea catechins and/or EGCG. Among them, one interventional study has revealed that oral administration of mixed tea products significantly decreases the size of leukoplakia, a pre-malignant lesion in oral mucosa [95]. Another study has found that green tea extracts at a dose of 200 mg for 12 weeks can show therapeutic effect on human papilloma virus-infected cervical lesions which are considered as pre-cancerous lesions [96]. Interestingly, Bettuzzi et al. [97] has reported that oral administration of 600 mg/day of GTCs for 12 months is able to inhibit the progression of pathological lesion from high-grade prostate intraepithelial neoplasia (PIN) to prostate cancer in a randomized, double-blind, placebo-controlled trial. Following-up of the participants as a long-term research revealed that continued inhibition of development of prostate cancer from PIN even two years after initial treatment with GTCs [98]. These observations appear to provide evidence of the beneficial efficacies of GTCs on the prevention of human malignancies, although three other interventional studies investigating the effect of green tea against prostate cancer found no beneficial effects [99-101]. These three studies with negative results include patients with established malignancies of prostate, while only patients with pre-malignant lesions participate in the trial conducted by Bettuzzi et al. [97,98]. Therefore, the findings together suggest that treatment with GTCs is probably effective at very early stages of cancer development and that these phytochemicals should be considered as agents for chemoprevention.

Our research group has conducted a pilot study to investigate the effects of treatment with green tea extracts on the development of colorectal adenoma which is considered as a pre-cancerous lesion of the colon [102]. The participants in this trial are patients who had undergone endoscopic polypectomy to remove colorectal adenomas. It is found in the study that oral administration of 1.5 g/day of green tea extracts for 1 year significantly suppresses the development of colorectal adenomas compared to an untreated control group (Figure 2). The size of relapsed adenomas in the experimental group was

![Figure 2: A pilot study demonstrating the chemopreventive effect of green tea extract (GTE) on metachronous adenomas after endoscopic polypectomy. (A) Study design. The study included 136 participants who underwent endoscopic resection of one or more colorectal adenomas. Twelve months later, the participants received another total colonoscopy to confirm the absence of remaining endoscopically-detectable adenoma. The participants were then randomized into two groups while administering a daily green tea drinking; the GTE group (71 patients) was given three GTE tablets a day for 12 months and the control group (65 patients) received no supplement. After 12 months of GTE supplementation, a follow-up (end-point) colonoscopy was performed in 125 patients (60 in the GTE group and 65 in the control group) to check the presence of new adenomas. (B) Effects of the GTE supplementation on the incidence and the size of metachronous colorectal adenomas at the end-point colonoscopy. The incidence of adenomas was 15% (9 of 60) in the GTE group and 31% (20 of 65) in the control group. The size of relapsed adenomas was significantly smaller in the GTE group than that of the control group.](image-url)
significantly smaller compared to that of the untreated control group.

A study using GTCs in a high-risk group of individuals for hepatocellular carcinoma (HCC) has been conducted in a region where high exposure aflatoxin which is a risk factor for developing HCC. In this double-blinded and placebo-controlled phase IIA trial, administration of GTCs in these individuals, who are seropositive for both HBs-Ag and aflatoxin-albumin adducts, effectively decreases the levels of urinary 8-hydroxydeoxyguanosine, a surrogate marker of oxidative DNA damage [103]. Daily GTCs consumption also modulated aflatoxin biomarkers in this trial [104]. It is, however, not clear whether GTCs indeed prevent the development of HCC. In addition, HCC development is frequently associated with chronic inflammation and subsequent liver cirrhosis induced by a persistent infection with hepatitis viruses. Recent evidence also indicates that obesity and related metabolic abnormalities, especially insulin resistance, increase the risk for live cancer [105,106], while GTCs appear to exert anti-obesity and anti-diabetic activity [107,108]. Therefore, well-designed interventional clinical trials should be conducted to investigate whether GTCs are able to prevent the development of HCC in high-risk patients with viral liver cirrhosis and obesity.

Bioavailability, safety, tolerability, and pharmacokinetics

Since the bioavailability and plasma concentration are significantly important factors following consumption of phytochemicals, they must be considered when reviewing the findings of in vivo experimental and human clinical studies of the absorption, distribution, and metabolism of dietary phytochemicals [109]. Here, we review previous reports investigating the bioavailability of dietary phytochemicals, focusing on GTCs.

During absorption, polyphenols, including GTCs, are conjugated in the intestine first then in the liver. Methylation, sulfation, and glucuronidation are mainly involved in these reactions [110]. The bioavailability of GTCs in healthy subjects has been examined; consumption of 1.5 mM of EGC, ECG, and ECGG alone have the average plasma levels reach 5.0, 3.1, and 1.3 μM, respectively [111]. The peak plasma concentrations of EGCG are reached 1-2 h after oral administration, while the liver, lungs, and kidney contain no capsaicin at 8 h after oral gavage, while the liver, lungs, and kidney contain the highest concentrations of capsaicin in 2 h after administration [129]. Among those organs, the lung appears to metabolize capsaicin slower than other organ tissues [129,130], because a higher level of capsaicin can be detected in the lung from 1 h up to 8 h, while the liver, kidney, or serum contain no capsaicin at 8 h after oral gavage [129]. The safety of capsaicin has been demonstrated in both rats and humans [122].

Capsaicin is also known to have low bioavailability, which is associated with poor water solubility and a short half-life [126,127]. On the other hand, it has been reported that over 90% of capsaicin can be absorbed rapidly and reach the peak concentration at 1 h after administration in rats [128]. Another report has shown that capsaicin is detected in serum at 1 h after oral gavage, while the liver, lungs, and kidney contain the highest concentrations of capsaicin at 2 h after administration [129]. Among those organs, the lung appears to metabolize capsaicin slower than other organ tissues [129,130], because a higher level of capsaicin can be detected in the lung from 1 h up to 8 h, while the liver, kidney, or serum contain no capsaicin at 8 h after oral gavage [129]. The safety of capsaicin has been reported as well as being well-tolerated and no systemic toxicity [131].

A number of pharmacokinetic studies have shown that genistein has poor oral bioavailability and the concentrations in plasma and organ tissues following oral intake are far lower than that in in vitro experiment [132,133], although several clinical trials have demonstrated that genistein has favorable and beneficial effects on chemoprevention against certain types of cancers [92,134]. A previous rodent study shows that oral intake of curcumin results in 1% bioavailability in rat plasma [123,124]. In contrast to rodents, 2 g/kg, the same dosing in the study in rats above, of curcumin administered orally to humans leads to extremely low concentrations (0.006 ± 0.005 μg/mL at 1 h) in serum [122]. In a human clinical trial, the oral dose of 3.6 g curcumin resulted in plasma concentration of 11.1 nmol/L at 1 h after administration [125]. The study has reported that dose-limiting toxicity was not observed in human [125]. The safety of curcumin has also demonstrated in both rats and humans [122].

The safety of GTCs has been demonstrated in several studies; no adverse events are observed due to administration of tea polyphenols at doses ranging from 600 to 1800 mg/day [97,102,116,117]. In order to achieve high levels of tea catechins in serum and tissues, relatively high doses of GTCs are often employed in human interventional studies. Therefore, there have been a growing number of case reports of side effects in humans associated with consuming dietary supplements of green tea, with excess gas, upset stomach, nausea, heartburn, stomachache, abdominal pain, dizziness, headache, muscle pain, and hepatotoxicity, which have been reported with doses ranging from 700 to 2100 mg/day [117,119]. These adverse reactions, however, appear to be experienced in studies with supplementation of high doses of GTCs in pills or capsules rather than drinking green tea [120]. A report recently indicates that green tea extracts are able to inhibit certain types of microsomal cytochrome P450 (CYP), but may not contribute to drug-induced liver injury if a drug and green tea are administered simultaneously [121].

It has been revealed that curcumin has poor bioavailability due to its limited solubility in water. A previous study has found that a maximum serum level of 1.35 ± 0.23 μg/mL is observed at 0.83 h after oral administration of curcumin (2 g/kg) in rats [122]. Other studies show that oral intake of curcumin results in 1% bioavailability in rat plasma [123,124]. In contrast to rodents, 2 g/kg, the same dosing in the study in rats above, of curcumin administered orally to humans leads to extremely low concentrations (0.006 ± 0.005 μg/mL at 1 h) in serum [122]. In a human clinical trial, the oral dose of 3.6 g curcumin resulted in plasma concentration of 11.1 nmol/L at 1 h after administration [125]. The study has reported that dose-limiting toxicity was not observed in human [125]. The safety of curcumin has also demonstrated in both rats and humans [122].

Capsaicin is also known to have low bioavailability, which is associated with poor water solubility and a short half-life [126,127]. On the other hand, it has been reported that over 90% of capsaicin can be absorbed rapidly and reach the peak concentration at 1 h after administration in rats [128]. Another report has shown that capsaicin is detected in serum at 1 h after oral gavage, while the liver, lungs, and kidney contain the highest concentrations of capsaicin at 2 h after administration [129]. Among those organs, the lung appears to metabolize capsaicin slower than other organ tissues [129,130], because a higher level of capsaicin can be detected in the lung from 1 h up to 8 h, while the liver, kidney, or serum contain no capsaicin at 8 h after oral gavage [129]. The safety of capsaicin has been reported as well as being well-tolerated and no systemic toxicity [131].

A number of pharmacokinetic studies have shown that genistein has poor oral bioavailability and the concentrations in plasma and organ tissues following oral intake are far lower than that in in vitro experiment [132,133], although several clinical trials have demonstrated that genistein has favorable and beneficial effects on chemoprevention against certain types of cancers [92,134]. A previous rodent study shows that more than 80% of genistein is converted to glucuronides and sulfates after both intravenous and oral administrations at 20 mg/kg and that the absolute bioavailability is 23.4% [135]. Pharmacokinetic studies have shown that genistein has very long half-life (46 h) after oral administration and that different dose of genistein show no correlation of AUC, suggesting that there may be unknown mechanism of elimination and recycling system [135,136]. In human, genistein is extensively metabolized and the plasma level of unconjugated form is very low [137,138]. Several human clinical pharmacokinetic studies have revealed that the level of total genistein in plasma is within micro
molar range while the genistein aglycone, a biological active form compared to genistein conjugates, is in hundred nano molar range [138,139]. There were adverse events in a clinical trial using genistein 30 mg/day for 6 weeks, but all events, including gastrointestinal and cardiovascular, were mild and no patients aborted the protocol due to the events [134].

Recently, several formulations of phytochemicals have been prepared in order to enhance bioavailability and to obtain better permeability and resistance to metabolic processes. Those include nanoparticles, liposomes, micelles, and phospholipid complex [127,140,141]. Nanocurcumin indeed increases bioavailability of curcumin in animals as well as in humans. The pharmacokinetics of the formulation nanoemulsion curcumin have 10 fold increase in the AUC and 40-fold increase in the Cmax compared to curcumin in mice [142]. The colloidal nanoparticles showed more than 40-fold higher AUC than that of curcumin powder after oral administration in rats. The particles also resulted in 27-fold higher AUC than that of curcumin powder in healthy human volunteers, theracurmin (30 mg) when administered orally [143]. Capsaicin is also able to be encapsulated in liposome, which shows improved oral bioavailability [127].

Concluding Remarks

Treatment with dietary phytochemicals, including GTCs, appears to offer many potential clinical advantages compared to other traditional anti-cancer agents. Especially, tea catechins can offer the advantages, because it is in globally available beverages, is able to be isolated inexpensively, and is considered as safe agents based on the long history of consuming commonly. As previously discussed, numerous experiments of rodents and human interventional studies have observed no adverse events, even with administration of relatively high doses, although several studies have reported tea catechin-induced toxicity [116,119].

The results of epidemiological studies to examine the effects of green tea consumption on the risk of various human cancers are still inconclusive, although lots of studies of rodent carcinogenesis model have demonstrated significant cancer chemopreventive effects by administration of GTCs. This discrepancy is considered to be attributed to diverse confounding factors, such as variations in human genetics, lifestyle, and etiology of cancer, as well as in the quantity, quality, and type of tea [144]. Among these factors, the amount and type of drinking tea seem to affect the association between tea consumption and cancer risk reduction, because prospective cohort studies have indicated that daily consumption of at least 10 cups of tea, which is equivalent amount of 2.5 g green tea extract, is required for a cancer chemopreventive effect [145,146]. In addition, it is widely accepted that green tea is more effective to decrease a risk for cancer than black tea, possibly because of higher concentrations of tea catechins in green tea [144]. Other confounding factors, such as smoking, alcohol intake, and obesity, may be responsible for the inconsistent results among epidemiological studies to examine the anti-cancer effects of GTCs. For instance, smoking and alcohol intake are known to significantly affect the cancer development in esophagus and liver [147,148].

In order to obtain explicit and conclusive data regarding the chemopreventive effects of GTCs, or other dietary phytochemicals, on malignancies in various organ sites, carefully-conducted cohort studies with a large number of subjects should be performed and designed to remove any potential confounding factors as well.

Acknowledgment

This work was supported in part by Grants-in-Aid from the Ministry of Education, Science, Sports and Culture of Japan (No. 25460888 and 50632816), Grant-in-Aid for the 3rd Term Comprehensive 10-Year Strategy for Cancer Control from the Ministry of Health, Labor and Welfare of Japan, and the Takeda Science Foundation.

References


