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Chapter 8 Green Tea Catechins and Sport Performance

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8.1. INTRODUCTION

Green tea is brewed from the unfermented dried leaves of the plant *Camellia sinensis*. The predominant constituents of green tea are polyphenols belonging to the family of catechins, mainly (–)-epigalocatechin gallate (EGCG), with lesser amounts of catechin (C), epicatechin (EC), epigalocatechin (EGC) and epicatechin gallate (ECG). In addition, caffeine, theanine, theaflavins and phenolic acids such as gallic acid are present in smaller quantities (Cooper et al., 2005). A typical brewed green tea beverage (250 mL) contains 50–100 mg of catechins and 30–40 mg of caffeine. However, the concentration of bioactive compounds of green tea can vary widely according to preparation methods, that is, brewing time or water temperature (Rains et al., 2011). Therefore, standardised green tea extract (GTE) has been developed for research to provide uniform levels of green tea catechins (GTCs).

In recent years, many health benefits of consuming green tea have been reported, including the prevention of diseases associated with free radicals and reactive oxygen species, such as cancer, or cardiovascular and neurodegenerative diseases. In addition to the antioxidant properties of the catechins, their anti-diabetic, anti-bacterial, anti-inflammatory and anti-obesity activities also have been reported (Zaveri, 2006). The health benefits of green tea are mainly attributed to its anti-oxidant properties, including the ability of catechins to scavenge reactive oxygen species or chelate with metal ions (Kashima, 1999). In addition to antioxidant effects, GTCs have been purported to influence several molecular targets in signal transduction pathways associated with cell death and survival (Murase et al., 2002). However, it is not known so far whether these effects on molecular endpoints in signal transduction pathways are downstream events of the modulation of pro-oxidant/antioxidant balance in cells or if they result from direct action of the catechins on molecular targets, independent of antioxidant properties (Zaveri, 2006).

This chapter highlights the recent research on the efficacy and mechanisms of action of GTCs on body weight, fat metabolism and oxidative stress parameters, with particular interest in their application in healthy, physically active and trained individuals.

8.2. EFFECTS OF GTCs ON BODY WEIGHT

The majority of evidence associated with green tea consumption and health benefits come from epidemiological studies. In one of these studies in Taiwan (Wu et al., 2003), a lower percentage of total body fat, smaller waist circumference and decreased waist-to-hip ratio were observed in subjects with average habitual tea consumption of 434 mL/day for more than 10 years, compared to non-habitual tea drinkers. In accordance with the above are the results of experiments in rodent models, which demonstrated the reducing effects of tea catechins on dietary fat-induced weight gain and body fat mass (Hasegawa et al., 2003; Chen et al., 2009). The results of human intervention studies are inconsistent, however; they indicate that the presence of caffeine in green tea supplements appears to be necessary to see an effect of GTCs on weight loss (Manore, 2012). Phung et al. (2010) performed meta-analysis of 15 randomised clinical trials to characterise the relation between GTCs with or without caffeine and changes in anthropometric variables. In a majority of these reviewed studies, a habitual normal diet was maintained. The authors concluded that GTCs alone (caffeine-free) do not seem to alter positively anthropometric measurements. However, ingestion of GTCs with caffeine (about 12 weeks, total catechins 583–714 mg/day and caffeine ≤114 mg/day) is associated with a reduction in body weight (average –1.38 kg) or other anthropometric parameters (BMI and waist circumference) as compared to caffeine-matched controls (Phung et al., 2010).

It seems that ethnicity (Asian vs. Caucasian) may be a potential moderator of weight loss magnitude after green tea ingestion (Hursel et al., 2009). As reported in more recent reviews regarding studies with overweight or obese adults with duration 12–13 weeks (Jurgens et al., 2012), the mean weight loss in six studies conducted outside Japan was –0.04 kg, whereas in eight Japanese studies the weight loss ranged from –0.2 kg to –3.5 kg in favour of green tea preparations over controls. Indeed, in a 12-week clinical study in Taiwan (Tsai et al., 2009), performed on a group of 120 healthy overweight and obese persons, the average weight loss in individuals who ingested green tea amounted to 6.8 kg (vs. 0.8 kg in the control), and the average loss in body fat mass amounted to 7.6% in green tea consumers (vs. 0.5% decrease in the control). Smaller effects were obtained by Zhang et al. (2012) in a population of 118 Chinese adults with a high proportion of abdominal visceral fat. Those authors investigated the effects of ingestion of catechin-enriched green tea beverage for 12 weeks (609.3 mg catechins and 68.7 mg caffeine daily) or a control beverage (86.2 mg catechins and 40.4 mg caffeine daily), without any intervention of diet, on anthropometric parameters. After 12 weeks, a significant reduction in visceral fat, as well as body weight (–1.0 kg) and body fat (–0.7 kg) were observed by ingestion of catechin-enriched green tea, whereas no significant changes were seen in the control group (Zhang et al., 2012).

It must be emphasised that a number of factors, apart from ethnicity, may affect the results of GTC supplementation, such as the characteristics of the studied population (children, healthy adults or adults with overweight, obesity, hyperlipidemia or diabetes mellitus), doses and types of tea catechins used, and timing of tea catechin ingestion relative to meals (Phung et al., 2010). Additionally, it has been mentioned that the magnitude of habitual caffeine intake can also influence study results (Thielecke and Boschmann, 2009). Two studies examined the effects of GTCs on body weight maintenance after a period of weight loss in overweight and moderately obese male and female subjects. In a study by Kovacs et al. (2004), a 4-week weight loss period (with a very low caloric diet) was followed by a 13-week weight maintenance period in which the subjects (overweight or moderately obese) consumed their habitual diet and received green tea extract (total catechins 573 mg/day, of which 323 mg was EGCG, and caffeine 104 mg/day) or a placebo. No significant differences in body weight regain were observed between the green tea and placebo groups; however, in the green tea treatment, habitual high caffeine consumption (>300 mg/day) was associated with a higher weight regain compared with habitual low caffeine consumption (Kovacs et al., 2004). In another study by these authors (Westerterp-Plantenga et al., 2005), a green tea–caffeine mixture (270 mg EGCG + 150 mg caffeine per day) gave further significant reductions a in both body weight and body fat during a period of weight maintenance following a weight loss period, but only in low-level caffeine consumers, whereas no effect was seen in high-level caffeine consumers. These results confirm the hypothesis that high habitual caffeine intake may mask the beneficial effects of GTCs on weight loss and weight maintenance. In line with the above are also the results obtained by Diepvens et al. (2006), who investigated the effect of GTEs with added caffeine (1207 mg catechins + 237 mg caffeine a day) along with low-energy diet on body composition in moderate caffeine users (200–400 mg caffeine/day). In that study, no significant differences in rate of weight loss were observed between the placebo and GTE groups. Finally, it has been suggested that the effect of green tea preparation on weight loss or weight maintenance can be influenced by protein content in the diet. In a study by Hursel and Westerterp-Plantenga (2009), a green tea–caffeine mixture (270 mg EGCG + 150 mg caffeine/day, ingested in three doses before the meals) or a placebo were added to a high- or low-protein diet (four groups studied), during a 13-week period of weight maintenance after a weight loss period (4-week) in moderately obese subjects. Both green the tea–caffeine mixture and the high-protein diet improved weight maintenance independently through thermogenesis, fat oxidation and sparing fat-free mass. However, no synergistic effect between the green tea–caffeine mixture and the high-protein diet was found, most likely because of the formation of complexes and, in turn, a reduction in absorption (Hursel and Westerterp-Plantenga, 2009).

Few studies added GTCs to diet and exercise in a weight loss program. Meanwhile, theoretically, the administration of GTCs could have an additive effect on weight loss, above and beyond that caused by exercise alone. Shimotoyodome et al. (2005) reported that, in mice fed a high-fat diet, the combination of dietary GTE and regular exercise (treadmill running) had a greater effect on body weight gain and fat utilization than regular exercise alone.

Maki et al. (2009) compared the effects of a high-GTC-beverage (625 mg/d GTC + 39 mg caffeine) versus a control beverage (39 mg caffeine) on body composition and fat distribution in 132 overweight and obese adults during a 12-week weight loss programme (moderate-intensity exercise, ≥180 min/week). Although the percentage changes in fat mass did not differ between the GTC and control groups, greater percentage reductions in both total abdominal fat area (–7.7% vs. –0.3%) and subcutaneous abdominal fat area (–6.2% vs. 0.8%) were observed after GTC versus control beverage administration. In the latest double-blind and placebo-controlled study (Cardoso et al., 2013), a combination of green tea ingestion with resistance training (8 weeks) was examined in overweight and obese women. Green tea combined with resistance training decreased body fat as well as increased lean body mass and muscle strength, as compared to resistance training alone. However, in overweight and obese women undergoing regular endurance exercise (a 12-week programme: walking or running 3 times a week for 45 min at 75% HR_{max}), no additional changes in both body composition and abdominal fat, above those caused by the exercise, were observed after supplementation with EGCG alone (300 mg/day) (Hill et al., 2007). This observation confirms that GTCs without concomitant caffeine ingestion do not exert their weight-loss effect, and it may also indicate that the effect of GTCs might be due to the combination but not catechin alone (Phung et al., 2010).

In the available literature, as described above, most studies involved overweight and obese populations to evaluate the effects of green tea ingestion on weight loss. Very few reports concern the use of this supplement in weight loss programmes for athletes. Weight loss in athletes is motivated by a desire to optimise performance by improving the power–weight ratio, or for aesthetic reasons in leanness sport (Garthe et al., 2011). In sport divided by weight categories (e.g. combat sport such as wrestling, boxing, taekwondo and judo), the rationale for achieving rapid weight loss is to compete at the lowest possible weight class. Weight regulation for elite combat sport athletes is considered an important component of the athletes' mental preparation for competition (Pettersson et al., 2012). To achieve a rapid weight reduction, athletes use a variety of methods, such as reduced liquid ingestion, use of saunas, blouses and plastic suits, reduced energy intake, fasting one day prior to the weigh-in, reduced carbohydrate and fat intake or more aggressive actions such as vomiting and diuretics (Franchini et al., 2012). Weight regulation practices have been proven to negatively affect health parameters, including nutritional and hormonal status, immune function or psychological status, the latter related to dehydration or hypoglycemia (Pettersson et al., 2012). Despite the well-documented negative consequences of rapid weight loss on health status, the prevalence of aggressive and harmful procedures for rapid weight reduction is very high in most combat sport (Franchini et al., 2012).

It has been recommended that, on average, weight loss goals should be approximately 0.5–0.9 kg per week and should not exceed 1.5% of body weight loss per week. A higher rate of weight loss indicates dehydration or other restrictive or unsafe behaviours that can negatively affect performance and health (Turocy et al., 2011). To achieve a weight loss of 0.5–1.0 kg/week, an energy deficit corresponding to 500–1000 kcal/day is needed. However, reducing daily energy intake by 1000 kcal can compromise recovery and impair training adaptation in athletes, especially with an already low energy intake (American College of Sports Medicine, 2009). Garthe et al. (2011) compared the effects of 5–6% body weight loss at slow and fast rates (0.7% and 1.4% weekly, respectively) on changes in body composition and strength-and power-related performance in elite athletes. They found that the slower weight-loss intervention had more positive effects on lean body mass and performance than the faster weight-loss intervention (Garthe et al., 2011).

Only one study investigated the effect of tea catechins combined with caffeine on body weight and composition in athletes (Bajerska et al., 2010). In this study, wrestlers ingested GTE (509.9 mg EGCG and 36.9 mg caffeine daily), oolong tea extract (OTE: 172 mg EGCG and 138.2 mg caffeine daily) or a placebo (cellulose) for 6 weeks. The study was conducted during a pre-season conditioning programme, when the athletes were on regular diet (55% calories from carbohydrates, 25% from lipids and 15% from proteins). As compared to baseline levels, significant weight loss was observed after ingestion of both GTE (0.6 kg or 0.8%) and OTE (1.4 kg or 1.6%), but not with the placebo. Body weight reduction was accompanied by absolute fat loss (GTE: 1.3 kg, 8.6%; OTE: 1.9 kg, 8.0%). Surprisingly, only in the OTE group was absolute fat loss significant after 6 weeks, as compared to the baseline. However, changes in

relative fat mass (% body weight) during 6 weeks were significantly different in both intervention groups, as compared to the placebo (–1.5%, –1.7% and +0.4% for GTE, OTE and placebo, respectively). Although, in the above-mentioned study by Bajerska et al. (2010), no differences between GTE and OTE were observed regarding all parameters, more marked changes in the OTE group were probably due to the higher caffeine content.

Favourable effects of GTCs on body weight and body fat have been shown in a number of intervention trials with a dose of GTCs from 270 mg to 1200 mg/day (Rains et al., 2011). So far, however, an optimal dose of GTC has not yet been established (da Silva Pinto, 2013). Moreover, there is lack of data about the possible side effects, especially of high doses of GTC. Although GTE at a dose of 3.0 g/day (Freese et al., 1999) and EGCG in pure form at a dose of 800 mg (Chow et al., 2003) have been considered to be safe for humans, excessive amounts of GTC used for weight reduction may cause hepatic toxicity (Yang et al., 2011).

Taken together, ingestion of green tea extract rich in catechins and caffeine may be a successful and safe strategy for athletes to gradually lose weight, especially when combined with moderate energy restriction and increased energy expenditure. Additionally, supplementation with green tea catechin-enriched caffeine can improve weight maintenance after a period of weight loss. However, more studies are needed to confirm these effects and evaluate the dose and content of tea catechins and caffeine required to achieve expected results. Before evaluating precise recommendations to athletes, habitual caffeine use should be taken into account because there are convincing data that high habitual caffeine intake can blunt the beneficial effects of green tea supplements on body weight loss. Therefore, for high-level caffeine consumers (≥300 mg/day), a higher dose of tea catechins may be needed to obtain desirable results. Moreover, based on meta-analysis of intervention studies, it seems that the effects of a GTC–caffeine mixture may be more pronounced in Asian than Caucasian subjects. Finally, green tea extract may be an alternative strategy for intake of caffeine alone in high doses, because no change in heart rate or blood pressure was reported after green tea extract ingestion. In contrast, ingestion of high doses of caffeine (400 mg) has been related to side effects such as elevated systolic and diastolic blood pressure, anxiety, palpitation, headache and dizziness (Westerterp-Plantenga, 2010).

8.3. MECHANISMS OF ACTION OF GTCs ON WEIGHT LOSS

Both green tea catechins and caffeine are considered the two active substances contained in GTE that are responsible for weight loss. Several biological mechanisms of action by which green tea can help reduce body weight have been proposed, including decreased fat absorption, reduced adipocyte lipogenesis or increased thermogenesis and fat oxidation (Wolfram et al., 2006). As far back as in the 1970s (Borchardt and Huber, 1975), an *in vitro* study showed an inhibitory effect of GTCs on catechol-*o*-methyl-transferase (COMT), the enzyme that degrades norepinephrine. Among GTCs, EGCG and ECG have been found to be the most potent COMT inhibitors (Chen et al., 2005). As is well known, norepinephrine, being a neurotransmitter of the sympathetic nervous system, plays an important role in the control of thermogenesis and fat oxidation. Thus, catechins ingested by inhibiting COMT may cause an increase and a more prolonged effect of norepinephrine on thermogenesis and fat metabolism. (The inhibition of COMT by catechins allows norepinephrine to exert a prolonged influence on thermogenesis and fat metabolism.) In turn, caffeine can also exert a thermogenic effect, but through a different pathway: by inhibiting phosphodiesterases and prolonging the life of cyclic adenosine monophosphate (cAMP) in the cell (Shixian et al., 2006). Consequently, increased cAMP stimulates the sympathetic nerve system and activates hormone-sensitive lipase, which promotes lipolysis (Westerterp-Plantenga, 2010). It has been suggested that caffeine and GTCs may act additively or even synergistically to prolong the sympathetic stimulation of thermogenesis (Phung et al., 2010; Manore, 2012). As indicated by the meta-analysis of six short-term (24-h) studies (Hursel et al., 2011), both the catechin–caffeine mixture and caffeine alone have a significant effect on energy expenditure, in a dose-dependent manner. The dose–response effect on energy expenditure occurred with a mean increase of 0.53 kJ/mg for catechins and 0.44 kJ/mg for caffeine. However, as compared to a placebo, a stimulating effect on fat oxidation was observed only after the catechin–caffeine mixture ingestion, whereas no effect was seen after ingestion of caffeine alone (Hursel et al., 2011).

The greater effect of caffeine-containing GTE than that of an equivalent amount of caffeine on the metabolic rate was found in a study by Dulloo et al. (1999). In that study, sedentary healthy young men, whose mean BMI was 25.1 ± 1.2 kg/m^2, spent 24 h in a respiratory chamber three times, consuming on separate occasions: GTE (150 mg caffeine and 375 mg catechins provided daily, of which 270 mg was EGCG; ingested in three divided doses with the main meals), caffeine alone (150 mg/day) and the placebo. Compared to the placebo, a significant increase in 24-h energy expenditure (4%) and a significant decrease in 24-h respiratory quotient (RQ, from 0.88 to 0.85) were observed during treatment with GTE, whereas no significant changes in these parameters were found during treatment with caffeine alone or placebo (Dulloo et al., 1999). As a lack of differences between treatments in urinary nitrogen excretion (thus in the protein oxidation rate) was observed in a study by Dulloo et al. (1999), a lower RQ (ratio of expired CO_2 to inspired O_2) indicated higher fat oxidation because more O_2 is required in relationship to expired CO_2 during fat burning (the RQ of carbohydrate oxidation is 1:1 and fat is 0.7). The effect of increasing energy expenditure by 4% over 24 h increases the contribution of the thermogenesis component to the total energy expenditure (Dulloo et al., 1999). Typically, thermogenesis contributes 8–10% of the daily energy expenditure, so green tea extract ingestion could increase thermogenesis by 35–43% (75–100 kcal). Although it seems small for a single day, the long-term effects are significant (Bell and Goodrick, 2002).

A significant increase in total 24 h urinary norepinephrine excretion observed in a study by Dulloo et al. (1999) after GTE ingestion is consistent with the inhibiting effect of green tea on COMT and confirms the stimulatory effect of GTCs on sympathetically mediated thermogenesis and fat oxidation. It has been suggested that more positive results of studies with Asian subjects than studies with Caucasian subjects may be caused by differences in COMT enzyme activity between ethnic groups (Westerterp-Plantenga, 2010; Hursel et al., 2011). There is evidence that this difference is due to the COMT gene polymorphism, since Asian populations have a higher frequency of the thermostable, high-activity enzyme, $COMT^H$ allele (*Val/Val* polymorphism) opposite to the higher frequency of the thermolabile, low activity enzyme, $COMT^L$ allele (*Met/Met* polymorphism) in Caucasian populations (Palmatier et al., 1999).

8.4. GTCs AND SPORT PERFORMANCE

8.4.1. Effect of GTCs on Exercise Metabolism

As is well known, total energy expenditure is composed of three factors: resting metabolic rate, thermic effect of feeding (diet-induced thermogenesis) and thermic effect of physical activity (Shixian et al., 2006). In a study by Dulloo et al. (1999), the increase in daily energy expenditure during green tea treatment was due to a cumulative increase in postprandial thermogenesis in the diurnal period. However, in a more recent study (Lonac et al., 2011), no acute effect of EGCG alone (in total, seven capsules per 135 mg EGCG were consumed over 48 h; three capsules/day, and the final capsule was ingested 2 h before measurement) on a resting metabolic rate and thermic effect of feeding was observed in healthy young people with a normal BMI (average 24.6 ± 1.2 kg/m^2). It has also been purported that the effect of GTE could be greater under conditions of elevated sympathetic tone and norepinephrine release (i.e. higher activity of COMT) during higher activity levels (Dulloo et al., 1999). In fact, in healthy normal-weight, active men (with a mean BMI 23.9 ± 0.8), ingestion of GTE in a 24-h period before a 30-min cycling exercise at 60% VO_{2max} (total 890 mg polyphenols, in which 366 mg was EGCG, no caffeine) caused a 17% increase in both whole body fat oxidation and the contribution of fat oxidation to total energy expenditure, as compared to placebo (Venables et al., 2008). In another study (Ichinose et al., 2011), the hypothesis that endurance training in combination with GTE supplementation would further accelerate whole-body fat utilisation during exercise, compared with training alone, was investigated. To test it, healthy men were undergoing 10-week endurance training (cycling for 60 min/day at 60% VO_{2max}, 3 days/week). In that time, they ingested GTE (delivering daily 572.8 mg total catechins, of which 100.5 mg was EGCG, and 76.7 mg caffeine) or placebo + caffeine (77.6 mg/day). Before and after training, respiratory gas exchange was measured during 90 min exercise at 55% VO_{2max}. As a result of training combined with GTE supplementation, a significant decrease in the respiratory exchange ratio (RER; post-training: 0.816 vs. pre-training: 0.844) during exercise was seen, indicating an increase in the proportion of whole body fat utilisation during exercise.

Despite interaction between moderate-intensity training and GTE supplementation, no change in RER was observed after training alone (Ichinose et al., 2011). Moreover, in this study, increased fat oxidation during exercise in the GTE group only, without any change in the caffeine-matched placebo group, indicates that tea catechins were responsible mainly for enhancement of fat utilisation.

It has been suggested that increased fat oxidation during aerobic exercise could have a glycogen-sparing effect and consequently result in an improved endurance capacity (Jeukendrup et al., 1998). The results of animal studies (Murase et al., 2005, 2006) may confirm this hypothesis. In mice fed GTE for 10 weeks, lower RQ and a higher rate of fat oxidation (as determined by indirect calorimetry) were observed during swimming exercise to exhaustion, as compared to control mice (Murase et al., 2005). In addition, feeding with GTE increased ß-oxidation activity in skeletal muscles and free fatty acid concentration in plasma, as well as decreased plasma lactate concentration. An increase in lipid utilisation as a result of GTE ingestion contributed to improvement in endurance capacity, since prolonged swimming time to exhaustion was observed in animals fed GTE as compared to controls (by 8–24%). Furthermore, the effect of GTE on endurance performance was dose-dependent, and the catechin responsible for observed effects of GTE is, at least partially, EGCG (although the effects of EGCG appeared weak compared with those of GTE). Similarly, in the next study of this research group (Murase et al., 2006), a 10-week intake of catechin-rich GTE in mice, together with habitual exercise, improved running endurance (an increase in running time to exhaustion by 30%, as compared to control mice), and these effects were caused by increasing whole body lipid utilisation and sparing muscle glycogen content.

However, some human studies did not support the stimulating effect of GTE supplementation on fat oxidation during exercise (Eichenberger et al., 2009; Dean et al., 2009; Hodgson et al., 2013). In a double-blind crossover study by Eichenberger et al. (2009), healthy endurance-trained men ingested, for 21 days, GTE (159 mg catechins/day, of which 68 mg/day was EGCG, and only 28 mg caffeine/day) or placebo (corn starch). At the end of the respective supplementation period (both GTE and placebo), a submaximal cycling exercise (for 2 h at 50% W_{max}) was performed. GTE supplementation did not influence fat metabolism during exercise, as indicated by plasma fatty acids, 3-ß-hydroxybutyrate and triacylglycerol, or RER and energy expenditure (Eichenberger et al., 2009). It must be mentioned, however, that the dose of catechins used in this study was relatively low (159 mg catechins, which approximately corresponds to the content in two cups of green tea brew) in comparison to other studies; in these, the dose of catechins reached the equivalent of six to seven cups of green tea beverage (Ichinose et al., 2011) and even more—up to 10 cups (Venables et al., 2008). In another double-blind crossover study (Dean et al., 2009), male cyclists performed exercise (60 min of steady-state cycling at 60% VO_{2max}, immediately followed by a self-paced 40-km cycling time trial) three times: after EGCG (270 mg/day), after placebo and placebo + caffeine (3 mg/kg/day) ingestion over a 6-day period, and 1 h before exercise testing. The study found little benefit of EGCG on fat oxidation or cycling performance, unlike caffeine which enhanced cycling performance. Therefore, the positive effect of green tea on thermogenesis and fat oxidation may be attributed to an interaction between GTCs and caffeine on sympathetic activity rather than individual catechin components (Dean et al., 2009). In a more recent study (Hodgson et al., 2013) in healthy physically active men, the metabolic responses following 7-day GTE supplementation (1200 mg catechins + 240 mg caffeine/day consumed in two doses: before breakfast and dinner) at rest and during moderate-intensity exercise (60-min cycling at 56% VO_{2max}) were examined using gas and liquid chromatography-mass spectrometry. As indicated by metabolic profiling, GTE enhanced lipolysis and fat oxidation when compared to placebo, but only under resting conditions, whereas no effect of GTE was seen during exercise. Because the metabolic effects observed during exercise were largely attributed to acute ingestion of the last dose of green tea (for 2 h before exercise), the authors concluded that a single dose of GTE used may not be potent enough to stimulate further metabolism above that already upregulated by exercise. Moreover, the supplementation period in these two studies (Dean et al., 2009; Hodgson et al., 2013) seems to be too short (6–7 day) to exert an adaptive stimulating effect of GTE on exercise fat metabolism.

Unexpectedly, in the study by Hodgson et al. (2013), no increase in plasma norepinephrine was seen after GTE supplementation, not only during exercise, but particularly at rest when a stimulating effect of green tea on fat metabolism was observed. It questions COMT inhibition as a putative mechanism of action of GTE *in vivo*, and suggests that green tea could stimulate lipolysis via non-adrenergic mechanisms, including upregulation of lipid-metabolizing enzymes by attenuating nuclear factor-ƙB (NF- ƙB) activity (Hursel and Westerterp-Plantenga, 2010). It is generally assumed that NF-ƙB is a transcription factor regulating the expression of several genes which are important in such cellular responses as inflammation or growth (Yang et al., 2001). NF-ƙB has been cited as a typical redox-regulated factor and ROS have been claimed to be principal regulators of NF-ƙB activation in many situations (Powers and Jackson, 2008). For example, after hepatic warm ischaemia and reperfusion in rats, an increase in free radical formation was observed, with concomitant NF-ƙB activation and elevated pro-inflammatory cytokine production (Zhong et al., 2002). However, GTE prevented ischaemia–reperfusion injury to the liver. This protective effect of GTE was associated with decreased free radical formation, as well as inhibited NF-ƙB activation and, in turn, blunted cytokine production. Taking into account the pro-oxidant stimulation of NF-ƙB activation, and the fact that a number of diverse antioxidants are inhibitors of this signalling pathway, it is likely that GTCs inhibit NF-ƙB activation by scavenging free radicals (Zhong et al., 2002). Moreover, evidence indicates that the stimulating effect of GTCs on fat oxidation may be mediated by peroxisome proliferator-activated receptors. In high fat-fed mice treated with dietary EGCG for 16 weeks, increased expression of peroxisome proliferator-activated receptor α was observed in the skeletal muscles, as compared to high fat-fed controls (Sae-Tan et al., 2011). Therefore, GTCs, as antioxidants, can block the activation of NF-ƙB, which is no longer able to inhibit the peroxisome proliferator-activated receptor and the latter upregulates lipid-metabolising enzymes involved in fat oxidation (Hursel and Westerterp-Plantenga, 2010).

By contrast with animal studies (Murase et al., 2005, 2006), no improvements in endurance performance were observed after GTC consumption in all the above-mentioned human studies (Eichenberger et al., 2009; Dean et al., 2009; Ichinose et al., 2011), even if augmented fat oxidation was observed (Ichinose et al., 2011). So far, only one study in humans has reported an increase in sport performance after GTC ingestion (Richards et al., 2010). In this study, 19 healthy adults performed incremental cycling exercise until volitional fatigue twice, after placebo and EGCG consumption (7 capsules for 135 mg EGCG, in total 945 mg EGCG; 3 capsules/day were ingested over 48 h prior to exercise, and the last capsule was taken 2 h before exercise testing). Short-term ingestion of EGCG increased significantly VO_{2max} (this increase was observed in 14 out of 19 subjects); however, other physiological parameters (maximal values of RER, stroke volume, cardiac output, work rate and heart rate) were not affected by EGCG consumption (Richards et al., 2010). The authors tried to explain the mechanisms responsible for the increase in VO_{2max} after EGCG consumption. They speculated that EGCG may increase arterial–venous oxygen difference in skeletal muscles, since maximal cardiac output was not augmented as a result of EGCG ingestion. However, it was not supported with direct empirical data. Alternatively, uncoupling of mitochondrial respiration from ATP production by EGCG was suggested (Richards et al., 2010). Indeed, increased mRNA levels of different uncoupling proteins, which are considered to be implicated in thermogenesis and energy metabolism, were found in animal studies after green tea catechin supplementation (Nomura et al., 2008; Lee et al., 2009). As a result of EGCG ingestion, increased mRNA expression of uncoupling protein 2 in mouse liver was reported, whereas RQ during night was decreased, supporting a decreased lipogenesis and increased fat oxidation (Klaus et al., 2005). However, taking into account that no change in RER was found after EGCG ingestion in a study by Richards et al. (2010), it does not seem that the uncoupling mechanism could be responsible for the increase in VO_{2max} after consumption of EGCG. Similarly, it is unlikely that attenuation of norepinephrine degradation via inhibition of COMT could be the mechanism of EGCG action in the above-mentioned study, since not only RER but also maximal heart rate and stroke volume were not affected by EGCG ingestion. Finally, the possibility that tea catechins may impact VO_{2max} through its antioxidant properties was discussed (Richards et al., 2010). It has been mentioned that ROS bioactivity/oxidative stress can modulate cardiac responsiveness to ß-adrenergic receptor stimulation by the sympathoadrenal system (Mak and Newton, 2001). In accordance with the above, the intracoronary infusion of vitamin C as antioxidant augmented the

inotropic response to an exogenous ß-receptor agonist dobutamine in humans (Mak and Newton, 2001). Similarly, the thermogenic responsiveness to non-selective ß-adrenergic receptor stimulation was augmented after intravenous ascorbic acid administration (Bell et al., 2006). However, this effect was observed in sedentary but not in habitually aerobic exercising healthy adults. Thus, it does not seem that in endurance-trained persons, antioxidant administration could offer additional benefits over these caused by training alone since, as confirmed in a study by Bell et al. (2006), regular aerobic exercise alone increases thermogenic responsiveness to ß-adrenergic receptor stimulation. Although there is no information about the training status of subjects in the above-mentioned study, the mean value of VO_{2max} points rather to a low level. Therefore, it remains open whether GTC supplementation could increase VO_{2max} in trained athletes, especially via the above-suggested mechanisms.

8.4.2. GTCs and Exercise-Induced Oxidative Stress

The results of controlled interventional studies indicate that regular consumption of green tea (at least 0.6–1.5 L/day) may increase total antioxidant potential in plasma, reduce lipid/protein peroxidation and protect against DNA damage in healthy subjects (Ellinger et al., 2011). However, it seems that green tea ingestion may be effective when antioxidative/oxidative balance is impaired. Thus, these beneficial effects of green tea consumption occur more likely in subjects exposed to increased oxidative challenge, that is, cigarette smoke, benzene exposure and exhaustive exercise (Ellinger et al., 2011).

It is fairly well accepted that intense exercise, both aerobic and anaerobic, can induce an oxidative stress, a condition in which pro-oxidant production (including free radicals and other reactive oxygen and nitrogen species) overwhelms antioxidant defences. As a result, increased oxidative modifications of proteins, nucleic acid and lipids have been reported (Bloomer et al., 2007). Growing evidence indicates that reactive oxygen species can contribute to both the initiation and the progression of muscle fibre injury, which may lead to decreased muscle contractile ability and force production and, as a consequence, to impaired muscle performance (Bloomer, 2007). From the above point of view, much attention has been focused on the supporting endogenous antioxidant defence system by antioxidant supplementation as a strategy to reduce oxidative stress and muscle damage, as well as to improve exercise performance (Urso and Clarkson, 2003; Nikolaidis et al., 2012).

The effects of green tea ingestion on exercise-induced oxidative stress were studied for the first time in rats (Alessio et al., 2002). After green tea ingestion for 6.5 weeks, rats performed an acute running exercise. Green tea ingestion increased post-exercise levels of total antioxidants in plasma, as well as prevented exercise-induced lipid peroxidation in kidneys. Human studies confirmed a protective effect of GTCs against oxidative damage caused by exercise (Panza et al., 2008; Jówko et al., 2011). In a study by Panza et al. (2008), healthy men, involved in recreational weight training, performed intense resistance exercise twice: after 7-day ingestion of water and then after 7-day green tea intake (daily 600 mL brew, total phenol concentration 771 μg/mL). The exercise performed after control treatment increased both plasma creatine kinase activity (an indicator of muscle damage) and xanthine oxidase activity (the main source of free radicals in the ischaemia–reperfusion conditions), without any change in plasma lipid hydroperoxide levels (indicators of lipid peroxidation). However, as a result of green tea ingestion, increased antioxidant potential of plasma (i.e. increased concentrations of reduced glutathione, total polyphenols and ferric reducing ability of plasma) and decreased plasma lipid hydroperoxide (both at rest and post-exercise) were observed. Moreover, green tea intake prevented a post-exercise rise in plasma creatine kinase and xanthine oxidase activities (Panza et al., 2008). In our study (Jówko et al., 2011), physical education students were subjected to a 4-week strength training (focused on strength endurance development), in combination with placebo or GTE supplementation (daily 640 mg polyphenols, 500 mg of which were catechins). Moreover, the students completed an intense muscular endurance test (one set of bench press and back squat to exhaustion, at 60% one repetition maximum) twice: in the pre- and post-treatment periods. Resting values of both the total plasma polyphenols and the total antioxidant potential of plasma were elevated after GTE supplementation, as compared to placebo. Furthermore, GTE ingestion prevented the increase in plasma creatine kinase activity induced by the muscular endurance test, as well as the increase in

plasma hydroxyperoxides caused by the 4-week strength training. These results show that GTE supplementation can protect against oxidative damages induced by both single intense strength exercise and prolonged strength training, at least in previously untrained subjects (Jówko et al., 2011). However, in a more recent study (Jówko et al., 2012), no changes in oxidative stress parameters were seen after acute ingestion of GTE in professional soccer players. In that study, the athletes performed an intense strength exercise (3 sets of bench press and back squat to exhaustion, at 60% one-repetition maximum) 1.5 h following ingestion of GTE in a single dose (640 mg polyphenols). While total plasma polyphenols increased slightly after GTE ingestion, the total antioxidant potential of a plasma was unaffected by acute GTE intake. Furthermore, ingestion of a single dose of GTE did not affect both plasma lipid peroxidation levels and plasma creatine kinase activity. Thus, it is likely that the acute ingestion of GTCs may be insufficient to modify the antioxidant potential in plasma and a longer period of GTE supplementation is necessary to diminish the oxidative damages induced by intense exercise (Jówko et al., 2012). In our latest study (in press), we investigated the effect of GTE ingestion on blood markers of oxidative stress in sprint-trained athletes during their preparatory period. In this placebo-controlled crossover study, the athletes performed repeated a sprint test (4 × 15 s on a cycloergometer, separated by 1-min rest intervals) three times: at baseline, after a 4-week treatment with a placebo and following a 4-week treatment with GTE. Supplementation with GTE increased the total antioxidant potential of plasma at rest and prevented oxidative stress induced by the high-intensity repeated sprint test; but, conversely, no protection from exercise-induced muscle damage was found in sprinters as a result of GTE ingestion (unpublished). These results are in contrast to previous findings in non-athletes (Panza et al., 2008; Jówko et al., 2011) or endurance trained cyclists (Eichenberger et al., 2009), in whom a decrease in plasma creatine kinase activity was observed after GTC ingestion.

Finally, it does not seem that GTE supplementation could improve physical performance through attenuation of oxidative stress, since no changes in exercise parameters were noted after GTE intake in all the above-mentioned studies. On the contrary, there is growing evidence that decreasing free radical production through the use of excessive amounts of antioxidants could inhibit the signalling induced by reactive species, which are necessary to specific cellular adaptations to exercise (Gomez-Cabrera et al., 2005, 2008a). Indeed, there is clear evidence that redox-sensitive transcription factor NF-ƙB is activated with exercise leading to the upregulation of gene expression of antioxidant enzymes. Furthermore, this adaptation was abolished when production of ROS was prevented by allopurinol, which is known as an inhibitor of xanthine oxidase (Gomez-Cabrera et al., 2005). Although in our studies (Jówko et al., 2011; and unpublished data) GTE intake did not affect superoxide dismutase activity, it cannot be excluded that inhibition of NF-ƙB activation by high doses of GTCs could prevent a training-induced adaptive increase of other antioxidant enzyme activities. From the above point of view, the need for antioxidant supplementation for athletes on a well-balanced diet should be re-evaluated. However, in the case of a low intake of antioxidant nutrients, an antioxidant-rich diet appears to be a prudent recommendation (Panza et al., 2008). It may be a matter of concern for some athletes practising weight control sport and those who, for some reason, do not eat a well-balanced diet (Williams, 2004).

In addition, it appears that only moderate regular exercise can attenuate oxidative stress via mild generation of ROS, inducing hormesis-like effect, manifesting upregulation of antioxidant enzymes, repair enzymes and enzymes responsible for degradation of potentially harmful damaged molecules (Goto et al., 2007; Gomez-Cabrera et al., 2008a). These adaptive responses protect the body against more severe stresses in future (Ji et al., 2010). On the other hand, excessive generation of ROS by exhaustive exercise may be harmful to unprepared cells (Goto et al., 2007). Based on these data, antioxidant supplementation can be recommended to limit the effects of oxidative stress in athletes involved in heavy training (Williams 2004) or before competition (Gomez-Cabrera et al., 2008b). In a study by Margonis et al. (2007), severe resistance training decreased antioxidant potential in plasma and increased lipid peroxidation products in plasma and urine, and these changes were highly correlated with performance drop and training volume increase. Although in our study (unpublished) GTE supplementation did not attenuate exercise-induced muscle damage in sprinters during their preparatory period, it cannot be excluded, however, that these effects could be observed in terms of a more intense period of training. Thus, further studies are needed to evaluate whether chronic GTE supplementation may be beneficial in athletes during their competition period.

8.5. CONCLUSION

Consumption of GTCs has been shown to increase fat oxidation and energy expenditure, particularly if combined with caffeine. This effect was seen in both sedentary and physically active individuals during exercise. Thermogenic properties of green tea seem to be beyond that explained by its caffeine content. The mechanisms by which GTCs may stimulate fat oxidation and energy expenditure include, among others, inhibition of COMT and prolonged stimulation of the sympathetic nervous system by norepinephrine. Moreover, GTCs as antioxidants may block the activation of the oxidative stress-sensitive transcription factor NFκB and, in turn, activate peroxisome proliferator activated receptors that are important transcription factors for lipid metabolism. The above-mentioned mechanisms of action may explain the positive effect of green tea extract with caffeine on weight loss and on weight maintenance, which were found in a population of overweight and moderately obese individuals. However, these effects can be influenced by different modulators like ethnicity or habitual caffeine intake. Moreover, more studies are needed to evaluate the efficiency of GTC–caffeine mixture on body weight and body composition in non-obese individuals, with potential implications for body weight control in athletes. In addition, the optimal dose of GTCs, as well as side effects, especially of high doses of GTCs, has not yet been established so far.

As evidenced in animal studies, increased fat oxidation during aerobic exercise as a result of GTC ingestion could have a glycogen-sparing effect, which can result in an improvement of endurance capacity. However, these observations cannot be confirmed by human studies. Moreover, chronic but not acute ingestion of GTCs can increase the antioxidant potential in plasma and alleviate both oxidative stress and muscular damage induced by exhaustive exercise. However, taking into account that excessive intake of antioxidant supplements may hinder training adaptations, further studies with GTE supplementation are needed in regard to trained athletes, especially in the heavy training period. It is difficult to answer the question regarding whether athletes need antioxidant supplements to counter increases in oxidative stress from exercise. It is still unknown at what level of oxidative stress the potential benefits will outweigh the risks. Thus, more research is necessary to address these issues and to provide guidelines for recommendations to athletes.

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