

# Sulforaphane Glucosinolate Monograph



## Introduction

Intake of broccoli sprouts, a rich source of the glucosinolate glucoraphanin, has been associated with decreased incidence, multiplicity, and tumor growth in animal cancer models.<sup>1-3</sup> In 1992, Paul Talalay, MD, and colleagues at Johns Hopkins University identified the isothiocyanate, sulforaphane, a biologically active metabolite of glucoraphanin, as the compound in broccoli responsible for many of its health benefits.<sup>4</sup> Since that time, more than 500 studies have been conducted on the mechanisms and biological activity of sulforaphane and its precursor, glucoraphanin.<sup>5</sup> Glucoraphanin, also referred to as sulforaphane glucosinolate (SGS), is the most potent naturally-occurring inducer of phase 2 detoxification enzymes<sup>4,6</sup> and is an indirect, long-acting antioxidant.<sup>7-9</sup> Sulforaphane also exhibits broad-spectrum antimicrobial activity against numerous gram-positive and -negative bacteria,<sup>10</sup> most notably *Helicobacter pylori*.<sup>11</sup> In addition, sulforaphane possesses anti-inflammatory activity; it inhibits cytokine production in preclinical and clinical studies.<sup>12-14</sup> Sulforaphane's multiple molecular targets and promising early research have led to 15 clinical trials currently underway to assess its effects on various cancers, cardiovascular disease, upper airway inflammation, radiation dermatitis, and vascular health.<sup>15</sup>

## Biochemistry

Glucoraphanin is a glucosinolate found in high concentrations in the Mariner variety of broccoli (*Brassica oleracea italica*) and other members of the Brassica family.<sup>16</sup> All glucosinolates are comprised

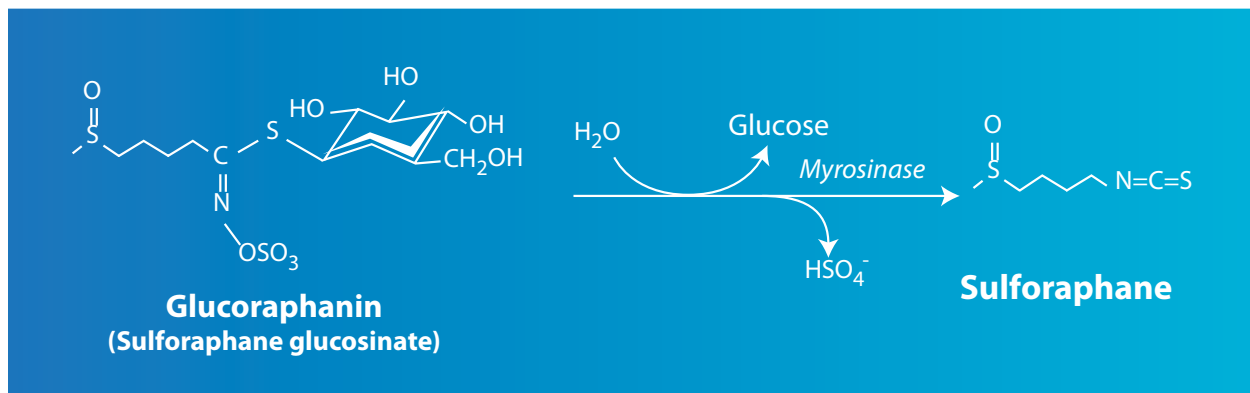
of a basic structure consisting of a  $\beta$ -D-thiogluco-  
 se group, a sulphonated oxime group, and an amino  
 acid-derived side chain.<sup>17</sup> Glucosinolates must be  
 enzymatically hydrolyzed to their associated  
 isothiocyanate to become active.<sup>18</sup> Sulforaphane  
 (molecular formula  $C_6H_{11}NOS_2$ ) is the biologically  
 active isothiocyanate produced when glucora-  
 phanin is metabolized by the enzyme myrosinase  
 (Figure 1).<sup>19</sup>

## Pharmacokinetics

Glucoraphanin in broccoli is enzymatically  
 hydrolyzed by myrosinase, an enzyme compart-  
 mentally separated from glucoraphanin in plant  
 cells. Myrosinase is released when the plant is  
 chewed or processed.<sup>20</sup> Heating broccoli partially  
 denatures and inactivates myrosinase, leaving the  
 glucoraphanin at least partially intact. In the gut of  
 healthy individuals any intact glucoraphanin is  
 then metabolized by myrosinase-producing  
 bacteria.<sup>21</sup> Because broccoli sprout or seed extracts  
 taken orally contain no myrosinase to hydrolyze  
 the glucoraphanin, transformation to sulforaphane  
 must be carried out by the gut microflora.<sup>22</sup> In  
 individuals with compromised intestinal flora and  
 low myrosinase activity, it is unclear if glucora-  
 phanin exerts the same systemic effects as  
 observed in individuals with normal intestinal  
 flora.<sup>23</sup>

Research in humans indicates approximately 74  
 percent of sulforaphane from broccoli extract is  
 absorbed in the jejunum.<sup>24</sup> After absorption,  
 sulforaphane is metabolized via the mercapturic  
 acid pathway.<sup>25,26</sup> Although this pathway involves a  
 complex interplay between the liver, small

Figure 1. Glucoraphanin Metabolism



intestine, and kidneys, the liver is thought to be the primary site of activity and is the site of sulforaphane conjugation to glutathione. Sulforaphane-glutathione conjugates are subsequently converted to cysteinyl-glycine, cysteine, and N-acetylcysteine conjugates in the kidneys or gut and then cycled back to the liver for acetylation. Of these conjugates, sulforaphane-N-acetylcysteine is the most prevalent.<sup>21</sup>

Upon absorption into the bloodstream, sulforaphane readily accumulates in tissue and exerts anticarcinogenic effects. In one human study, a single 200  $\mu\text{M}$  dose of sulforaphane from broccoli sprouts yielded peak plasma concentrations between 0.943 and 2.27  $\mu\text{mol/L}$  at one hour post feeding; the half life of sulforaphane was  $1.77 \pm 0.13$  hours.<sup>27</sup> A pilot study in eight healthy women undergoing reduction mammoplasty demonstrated a broccoli sprout extract containing 200  $\mu\text{M}$  sulforaphane given orally one hour prior to tissue removal resulted in average tissue uptake of  $1.45 \pm 1.12$  pmol/mg in the left breast and  $2.00 \pm 1.95$  pmol/mg in the right breast. Both detoxification enzyme genes for NADH quinone reductase (NQO1) and heme oxygenase-1 (HO-1) were measurable in the excised breast tissue, indicating cancer blocking activity after sulforaphane consumption.<sup>28</sup> Research in mice has also demonstrated colonic tissue uptake of sulforaphane after oral dosing, accompanied by a reduction in adenoma formation.<sup>29</sup> Excretion of sulforaphane conjugates in the urine is via first-order kinetics with metabolites being cleared from the body within 72 hours of dosing.<sup>27,30</sup>

**Key words:** sulforaphane, broccoli, glucoraphanin, SGS, isothiocyanate, *Crucera*, detoxification, detox, phase 2, phase II, *H. pylori*, *Helicobacter*, Brassica, cruciferous, chemoprotection, chemoprotectant, anticarcinogen, carcinogen, cancer, inflammation, Gilbert's syndrome, anti-inflammatory, antioxidant, Nrf2

### Mechanisms of Action Indirect Antioxidant and Carcinogen Detoxification

Sulforaphane is a pleiotropic molecule and a potent inducer of numerous nuclear factor erythroid-derived 2 (Nrf2)-dependent phase 2 enzymes involved in xenobiotic detoxification. Enzymes induced by sulforaphane include the antioxidant response element (ARE) targets: NQO1,<sup>4</sup>  $\gamma$ -glutamylcysteine synthetase (GGCS),<sup>31</sup> HO-1,<sup>32</sup> glutathione transferases (GST),<sup>33</sup> glucuronosyl transferases,<sup>34</sup> and epoxide hydrolases.<sup>35</sup> These enzymes are regulated by the Nrf2 transcription factor, which upon release from the Kelch-like ECH-associated protein 1 (KEAP1), binds to ARE sites in the enzymes' genes and upregulates carcinogen detoxification.<sup>36,37</sup> Other Nrf2-mediated effects of sulforaphane include inhibition of LDL oxidation,<sup>38</sup> inhibition of dopamine oxidation,<sup>39</sup> improvement of age-related TH1 immunity via restoration of redox equilibrium,<sup>40</sup> and reduction of oxidative stress caused by electrophilic carcinogens.<sup>41</sup> Sulforaphane also modulates phase 1 cytochrome p450 (CYP) enzymes by decreasing CYP1A1, CYP2B1/2, and CYP3A4 activity, thereby inhibiting the activation of procarcinogens and preventing the generation of DNA adducts during the initiation stage of cancer.<sup>42</sup> The overall net effect on phase 1 and 2 enzymes is an increase in metabolism and detoxification of chemical carcinogens.<sup>43</sup>

### Other Chemopreventive Mechanisms

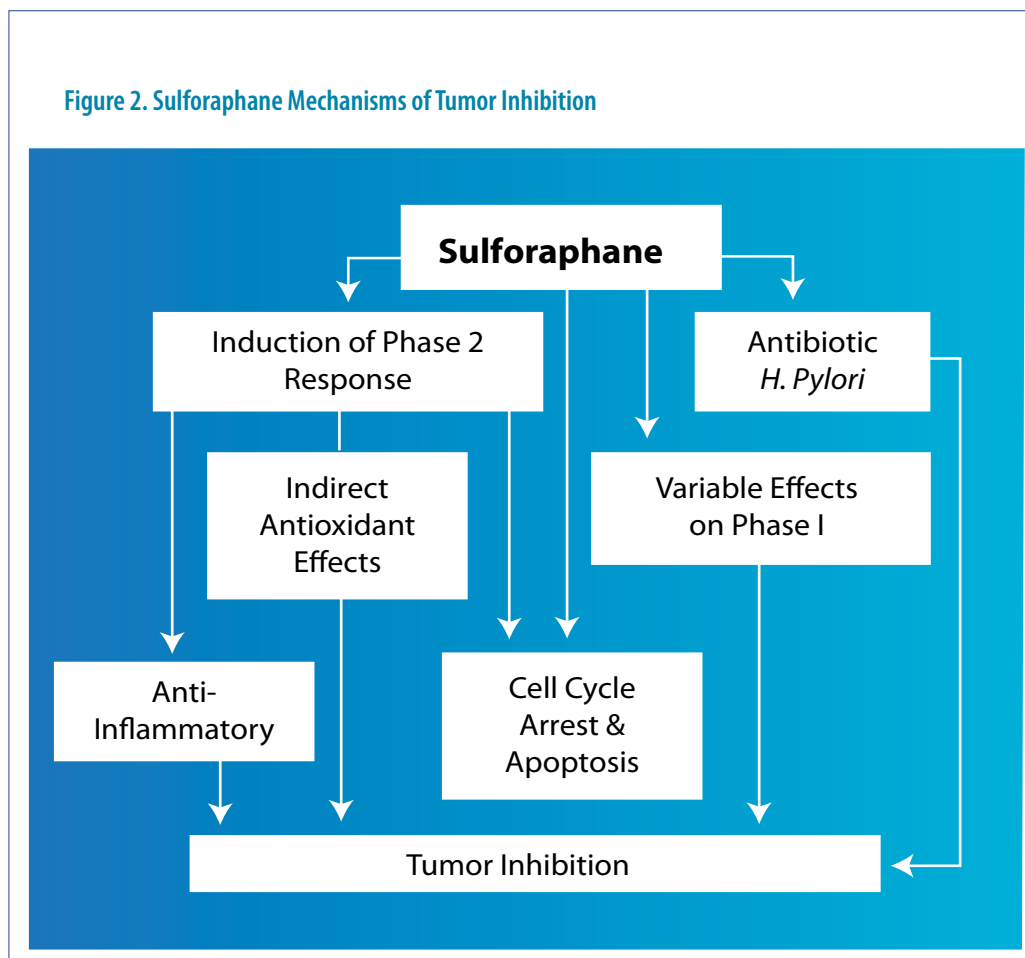
Sulforaphane exerts a direct effect on human cancer cells post-initiation. Research has demonstrated sulforaphane directly inhibits cell cycle progression, primarily via G<sub>2</sub>M arrest,<sup>44,45</sup> and induces apoptosis of cancer cells via caspase

activation, resulting in reduced tumor weight and volume both *in vitro* and in animal cancer models.<sup>45,46</sup> In human tissue samples, reductions in histone acetylation correlate with increased cancer grade and risk of cancer recurrence.<sup>47</sup> Studies show sulforaphane directly inhibits histone deacetylase (HDAC), which correlates with induction of G<sub>2</sub>M cell cycles arrest and apoptosis.<sup>48</sup> Sulforaphane also appears to upregulate apoptosis in cancer cells by modulating nuclear factor kappaB (NFκB) activity<sup>49</sup> and increasing mitochondrial reactive oxygen species, causing disruption of mitochondrial membrane potential and release of cytochrome C.<sup>50</sup> And finally, sulforaphane potently inhibits angiogenesis and metastasis of tumors by reducing microcapillary formation and inhibiting cell migration.<sup>51</sup> These effects were associated with down regulation of angiogenesis factors, including vascular endothelial growth factor (VEGF).<sup>52</sup> Figure 2 summarizes the tumor inhibition effects of sulforaphane.

### Miscellaneous Mechanisms

Sulforaphane's anti-inflammatory effects have been attributed to inhibition of pro-inflammatory signaling molecules and cytokines<sup>13</sup> such as NFκB, prostaglandin E2, and nitric oxide.<sup>12</sup> Sulforaphane also appears to reduce upper airway inflammation via increased phase 2 enzyme detoxification of air pollutants and pollen, apparently via decreased cellular oxidative stress, inhibition of inflammatory cytokine production, and decreased tissue inflammation.<sup>14</sup> *In vitro* research has also shown sulforaphane inhibits the production of interleukin and tumor necrosis factor-alpha (TNF-α) in rheumatoid T cells.<sup>53</sup> Sulforaphane exhibits broad-spectrum antimicrobial activity, inhibiting the growth of several gram-positive and -negative bacteria, including *E. coli* O157:H7, *Helicobacter pylori*, *Salmonella*, *Shigella*, *Staphylococcus aureus*, *Streptococcus pyogenes*, *Pseudomonas aeruginosa*, and *Cryptococcus neoformans*.<sup>10,11</sup>

Figure 2. Sulforaphane Mechanisms of Tumor Inhibition



## Clinical Indications

### Cancer

#### Preclinical and Animal Research

Numerous *in vitro* studies in human colon, leukemia, pancreatic, lung, and skin cancer cell lines have demonstrated sulforaphane's inhibitory effects on cell cycle arrest,<sup>45,54-56</sup> and research in human bladder<sup>57</sup> and prostate<sup>46</sup> cell lines has shown it increases apoptosis. Sulforaphane's ability to disrupt tubulin polymerization and inhibit mitosis has also been demonstrated in animal models of breast cancer.<sup>58,59</sup> Inhibition of histone deacetylase and increased apoptosis in human colon, prostate, and kidney cell lines has also been reported.<sup>48,60,61</sup>

In a pilot study involving three healthy volunteers (ages 18-55), a single daily dose of 68 g BroccoSprouts® (approximately 105 mg sulforaphane) significantly inhibited HDAC activity in peripheral blood mononuclear cell cultures three and six hours following consumption, suggesting sulforaphane may induce cell cycle arrest and apoptosis in humans.<sup>62</sup>

In mice with experimentally induced prostate cancer, 6  $\mu\text{mol}$  sulforaphane by oral gavage three times weekly from age six weeks onward decreased pulmonary metastasis incidence by 50 percent and multiplicity by 63 percent. Prostate tissue samples revealed decreased cellular proliferation and increased apoptosis when compared to control mice.<sup>63</sup> Tumor necrosis factor-related apoptosis-inducing ligand (TRAIL) induces apoptosis in a wide variety of cancer cells. In a mouse model of prostate cancer, tumor-bearing male mice were given sulforaphane (40 mg/kg), TRAIL (15 mg/kg) + sulforaphane (40 mg/kg), TRAIL alone (15 mg/kg), or vehicle at varying intervals for four weeks. Although either sulforaphane or TRAIL alone decreased tumor growth, the combination of sulforaphane and TRAIL was more effective, suggesting sulforaphane may have a potentiating effect on TRAIL. The sulforaphane-TRAIL combination also activated several caspases and was more effective at inhibiting markers of angiogenesis and metastasis than either agent alone.<sup>64</sup> Sulforaphane given to female breast cancer-bearing, non-obese, diabetic/severe combined immunodeficient (NOD/SCID) mice at a daily dose of 50 mg/kg for two weeks eliminated breast cancer stem cells *in vivo* and halted tumor growth.<sup>65</sup>

### Clinical Studies

The first direct observation of sulforaphane's inhibitory effect on cancer in humans was observed in 200 healthy adults (ages 25-65) from the Jiangsu Province of China, a region with a high rate of hepatocellular carcinoma due to excessive dietary aflatoxin exposure and chronic hepatitis B infection. The primary end-point of this blinded, placebo-controlled trial was to determine if drinking daily broccoli sprout infusions (containing 400  $\mu\text{mol}$  glucoraphanin) for two weeks could reduce urinary excretion of aflatoxin DNA adducts – indicators of DNA damage. A highly significant inverse association was observed for excretion of dithiocarbamates (isothiocyanate metabolites of glucoraphanin) and aflatoxin-DNA adducts in individuals treated with broccoli sprout infusions. An average of approximately 12 percent (range 1-45 percent) of the administered dose of broccoli sprout glucoraphanin was excreted as dithiocarbamates, with significant variability in excretion rates. The reason for this variation may be due to differences in enteric microflora composition, some individuals possibly having less myrosinase. Genetic polymorphisms of the glutathione S-transferase enzyme involved in glucoraphanin metabolism may also be partially responsible.<sup>66</sup>

### Cardiovascular Disease and Hypertension

Glucoraphanin and sulforaphane afford cardiovascular protection via their antioxidant and anti-inflammatory properties, resulting in reduced oxidative stress, improvement in lipid profiles, and decreased blood pressure. A phase 1 trial involving 12 cigarette smokers (six men and six women) investigated whether consuming 100 g fresh broccoli sprouts daily (glucoraphanin/sulforaphane content not specified) for one week impacted oxidative stress markers and cholesterol values. Cholesterol levels, plasma amino acids, natural killer cell activity, serum coenzyme Q10, and markers of oxidative stress – plasma phosphatidylcholine hydroperoxide (PCOOH), urinary 8-isoprostane, and urinary 8-hydroxydeoxyguanosine – were measured pre- and post-treatment. After only one week of broccoli sprout intake, all subjects demonstrated decreased serum total- and LDL-cholesterol levels and reductions in all oxidative stress markers; females also had significantly increased HDL-cholesterol levels.<sup>38</sup>

Animal research supports these findings. Studies on male and female spontaneously hypertensive rats on a glucoraphanin-enriched diet (equivalent to 27.3  $\mu\text{mol}$  sulforaphane per g dried sprouts)

showed decreased oxidative stress, lower blood pressure, and less renal and central nervous system inflammation in kidney and spinal cord tissue when compared to animals on glucoraphanin-free diets.<sup>67,68</sup>

### Upper Airway Inflammation

Airborne diesel exhaust particles appear to exacerbate lung and cardiovascular diseases by inducing oxidative stress.<sup>69</sup> Sulforaphane inhibits cytokine production in human airway epithelial cells exposed to diesel extract via induction of phase 2 enzyme genes NQO1 and glutathione-S-transferase M1.<sup>13</sup> In the first study to demonstrate oral sulforaphane upregulation of phase 2 antioxidant enzyme expression in the human airway, Reid et al administered BroccoSprouts® homogenates (BSH) to 57 healthy adult volunteers (average age 34) in a single-blind, dose-escalation (25, 50, 75, 100, 125, 150, 175, and 200 g), three-day trial. Analysis demonstrated a sulforaphane content of 0.283 μmol/mL BSH – the 175- and 200-mg doses delivering 89 and 102 μmol sulforaphane, respectively. Control subjects received a 200 g dose of alfalfa sprouts, containing negligible amounts of sulforaphane. Baseline nasal lavage and blood samples were collected from all participants and assessed for phase 2 enzyme expression. Subjects were assessed again one day after final dosing. Significant increases in glutathione-S-transferases, HO-1, and NQO1 were observed with the 200-g BSH dose compared to placebo. All doses were well tolerated and without serious side effects, although four subjects reported mild gastrointestinal events that did not require treatment.<sup>14</sup>

### *Helicobacter pylori* Infection

The role of *Helicobacter pylori* in development of stomach cancer is well established.<sup>70,71</sup> Animal research shows sulforaphane given to human gastric xenograft-bearing mice at a daily dose of 1.33 mg (equivalent to a 100-mg daily dose in humans) is strongly bacteriocidal and eradicates *H. pylori*.<sup>72</sup> Yanaka et al subsequently demonstrated glucoraphanin-rich three-day old broccoli sprouts (6 μmol glucoraphanin/g) given to *H. pylori*-infected female mice reduced gastric bacterial colonization, decreased mucosal TNF-α and interleukin-1β expression, decreased gastric inflammation, and prevented gastric atrophy. These effects were not observed in Nrf2-depleted mice, indicating the important role of Nrf2-dependent phase 2 enzyme induction by sulforaphane.<sup>73</sup>

In a human arm of the Yanaka study, 48 *H. pylori*-infected patients were divided into a broccoli sprout treatment group (n=25) or an alfalfa sprout placebo group (n=23). Those in the broccoli sprout group received 70 g sprouts daily, containing 6 μmol glucoraphanin/g, for eight weeks. Glucoraphanin feeding decreased breath test urease levels, *H. pylori* antigen, and pepsinogens I and II – markers of gastric colonization and inflammation. These results indicate broccoli sprouts as a source of glucoraphanin improve *H. pylori* infection sequelae and enhance chemoprotection from *H. pylori*-induced stomach tumors.<sup>73</sup> Two other clinical trials demonstrated the bacteriocidal<sup>74</sup> and chemoprotective properties of sulforaphane in individuals with *H. pylori* infection.<sup>75</sup>

### Gilbert's Syndrome

Gilbert's syndrome is characterized by genetic polymorphisms in the UDP-glucuronosyltransferase (UGT) enzymes, the primary one being UGT1A1\*28, which is involved in bilirubin glucuronidation. UGT polymorphisms can manifest as benign unconjugated hyperbilirubinemia, associated with reduced hepatic conjugation, and may increase cancer risk in this population.<sup>76</sup> In an observational study of 191 nonsmoking volunteers (ages 19-40) consuming 0-4 servings of cruciferous vegetables daily, there was a statistically significant inverse association between the UGT1A1 gene/Cruciferae interaction and total, direct, and indirect bilirubin measurements. Sulforaphane from cruciferous vegetables has been shown to induce UGT1A1 activity, resulting in greater bilirubin conjugation and clearance and possibly mitigating the increased cancer risk.<sup>77</sup>

### Rheumatoid Arthritis

Rheumatoid arthritis (RA) involves a tumor-like expansion of the synovium characterized by hyperproliferation of synoviocytes, infiltration of T and B cells, and increases in interleukin (IL) -6, -8, and -17. RA treatment involves suppression of synoviocyte proliferation and cytokine production.<sup>78</sup> Due to the “tumor-like” attributes of synoviocytes and their role in RA progression, Kong et al investigated the effect of sulforaphane on synoviocyte apoptosis in a mouse model of RA. Sulforaphane was administered peritoneally to male mice at concentrations of 12.8, 63.8, and 318.8 mg/mL/kg every other day for five weeks. Sulforaphane decreased synoviocyte survival up to 51 percent compared to baseline, significantly decreased IL-17 and TNF-α, and repressed the

proliferative response in polymorphonuclear cells to baseline levels. Histological examination revealed less inflammation, synovial hyperplasia, and bone destruction in mice treated with sulforaphane compared to the control group.<sup>53</sup>

### Macular Degeneration

Oxidative stress in the retinal pigmented epithelial (RPE) cell layer is associated with age-related macular degeneration, the leading cause of blindness in the elderly.<sup>79</sup> *In vitro* and animal research demonstrates that sulforaphane protects RPE cells from photo-oxidative damage; the degree of protection correlated with basal levels of glutathione and NADH quinone reductase.<sup>9,80</sup>

### Neurological Conditions

*In vitro* and animal research indicates sulforaphane treatment of various neuronal cell lines (neuroblastoma, astrocyte, and primary cortical neurons) protects against neuronal injury caused by oxidative stress and inflammation. This is accomplished via activation of Nrf2/ARE-mediated detoxification enzymes and results in increased intracellular glutathione levels and reduced rates of apoptosis.<sup>81-84</sup> These studies indicate sulforaphane may protect against the types of neuronal injury found in Parkinson's and Alzheimer's diseases.

### Side Effects and Toxicity

Several studies have been conducted to assess the safety of sulforaphane in humans. A randomized, placebo-controlled, double-blind study showed broccoli sprout extracts were without significant side effects at doses of 25 and 100  $\mu\text{mol}$  glucoraphanin for seven days.<sup>85</sup> Another randomized, placebo-controlled study involving 200 healthy adults consuming broccoli sprout infusions daily for two weeks (400  $\mu\text{mol}$  or approximately 175 mg glucoraphanin) showed no adverse effects.<sup>66</sup> In a dose escalation safety study, broccoli sprout extracts containing sulforaphane doses as high as 340 nmol were topically applied three consecutive times to forearm skin. Researchers reported significant induction of phase II enzyme activity in biopsied tissue without any adverse reactions.<sup>86</sup>

### Dosage

Based on available research, typical dosage for broccoli sprout and seed extracts is 50-100 mg sulforaphane glucosinolate daily in divided doses.

### Warnings and Contraindications

Sulforaphane and glucoraphanin from broccoli, broccoli sprouts, and broccoli seeds has a good safety profile with no known contraindications or drug interactions.

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