**ORIGINAL ARTICLE**

Sulforaphane Accelerates Acetaldehyde Metabolism by Inducing Aldehyde Dehydrogenases: Relevance to Ethanol Intolerance

Yusuke Ushida\(^1,2\) and Paul Talalay\(^1,\ast\)

\(^1\)Lewis B. and Dorothy Cullman Chemoprevention Center, Department of Pharmacology and Molecular Sciences, Johns Hopkins University School of Medicine, Baltimore, MD 21205, USA and \(^2\)Research Institute, Kagome Co. Ltd., 17 Nishitomiyama, Nasushiobara, Tochigi 3292762, Japan.

*Corresponding author: Department of Pharmacology and Molecular Sciences, Johns Hopkins University School of Medicine, 725 N Wolfe Street, Baltimore, MD 21205, USA. Tel.:+1-410-955-3499; Fax:+1-410-502-6818; E-mail: ptalalay@jhmi.edu

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Abstract    —  Aims: Many East Asians are highly intolerant to even modest alcohol consumption. These individuals accumulate acetaldehyde, the primary metabolite of ethanol, because of a genetic polymorphism of aldehyde dehydrogenase (ALDH) which metabolizes acetaldehyde to nontoxic acetate. The aim of these studies is to upregulate ALDH by dietary means, thereby reducing acetaldehyde toxicity.  Methods: Sulforaphane [SF, 1-isothiocyanato-4-(methylsulfinyl)butane] derived from its glucosinolate precursor contained in cruciferous vegetables and related inducers of the Keap1/Nrf2/ARE pathway were assessed for their potencies to induce ALDH in murine hepatoma Hepa1c1c7 cells. Inducer potencies for ALDH were compared with those for NQO1, a prototypical cytoprotective enzyme present downstream of the Keap1/Nrf2/ARE pathway. SF (5 or 20 μmol/day) was fed to CD-1 mice for 7 days prior to a single administration of ethanol, and then ALDH induction in organs and pharmacokinetics of acetaldehyde was examined.  Results: In addition to SF, other electrophiles, including many Michael reaction acceptors, induce ALDH. Potencies of these agents as inducers parallel their activities in inducing NQO1, and are also dependent on Nrf2. In mice, in vivo, feeding of SF induced tissue ALDH and dramatically increased (doubled) the rate of elimination of acetaldehyde arising from the administration of ethanol.  Conclusion: SF and other edible phytochemicals may ameliorate the alcohol intolerance of individuals who are polymorphic with respect to ALDH.

INTRODUCTION

It is well known that many East Asians including Chinese, Japanese and Koreans are highly sensitive to alcohol, and even small doses of ethanol evoke the unpleasant effects of flushing, nausea, headache and tachycardia (Yoshida et al., 1984; Eng et al., 2007). Whereas modest consumption of ethanol is believed to be beneficial, large doses can cause many serious medical problems (Crabb et al., 2009). In the body, alcohol dehydrogenase (ADH) rapidly converts ethanol to its primary metabolite, acetaldehyde, which is mutagenic and carcinogenic, and is largely responsible for the abovementioned symptoms and associated health damage. Acetaldehyde is then further metabolized to nontoxic acetate by aldehyde dehydrogenase (ALDH), predominantly mitochondrial ALDH2 (Impraim et al., 1982). Polymorphism of ALDH is widespread among East Asians, in whom about 40% of the population have a mutation of ALDH2 (ALDH2*2) resulting in much reduced or absent enzyme activity and the accumulation of acetaldehyde. This paper describes dietary methods for inducing ALDHs to counteract the toxic effects of acetaldehyde accumulation.

ALDH polymorphism results in increased vulnerability to developing cancer and other serious diseases (Harada et al., 1981). Particularly, the risk of esophageal squamous cell (ESC) cancer, common among middle-aged men in Japan, is often associated with the polymorphism of ALDH2 (Brooks et al., 2009; Oze et al., 2011). Thus, the risk of ESC cancer is dramatically increased in individuals with ALDH2*2 who drink alcohol compared to those with normal type of ALDH2 (Yokoyama et al., 2003). Therefore, in addition to smoking, acetaldehyde accumulation after alcohol consumption contributes to carcinogenesis.

A recent population-based prospective cohort study of 38,700 middle-aged Japanese men (Yamaji et al., 2008) provided possible insight into protection against damage caused by over-consumption of alcohol. An increase in consumption of fruits and vegetables by 100 g/day reduced the hazard ratio for esophageal carcinoma by 11%, and importantly, higher intake of cruciferous vegetables was strongly associated with a significant further decrease in the risk by 56% (P < 0.02).

Many epidemiological studies have suggested that cruciferous vegetables have beneficial health effects because they contain glucosinolates that interact with various functional groups of proteins due to their electrophilic properties (Talalay et al., 2003; Higdon et al., 2007; Fahey et al., 2012). The isothiocyanate sulforaphane (SF) that was isolated from broccoli is a prominent example (Zhang et al., 1992). SF has attracted widespread attention for its role in protecting cells against carcinogens, by induction of a network of cytoprotective phase 2 enzymes and by suppressing inflammatory responses (Juge et al., 2007; Guerrero-Beltrán et al., 2010; Elbarbary and Elrod, 2011). Major chemoprotective effects of SF are mediated by the transcriptional upregulation of the Keap1/Nrf2/ARE pathway and other anti-inflammatory mechanisms that regulate COX2, iNOS and macrophage migration inhibitory factor (MIF) (Liu et al., 2008; Baird and Dinkova-Kostova, 2011; Healy et al., 2011; Suganuma et al., 2011). The Keap1/Nrf2/ARE pathway does not operate at its maximal capacity under basal conditions, but it can be induced by a wide variety of small molecules (Talalay et al., 1995, 2003; Dinkova-Kostova et al., 2010; Kessler et al., 2013). This strategy mobilizes natural compounds to protect cells against stress, and reduces the risk of developing cancer and chronic degenerative diseases. We establish here that ALDH expression is under major control of transcriptional factor Nrf2, and that ALDH activities can be substantially increased by SF and related inducers of the...
Keap1/Nrf2/ARE pathway in animal cells and organs, and mice in vivo. This strategy has the potential to protect humans who have low or absent ALDH activity and are intolerant to alcohol.

MATERIALS AND METHODS

Chemicals and materials
Sulforaphane was obtained from Santa Cruz Biotechnology (Santa Cruz, CA, USA). Other isothiocyanates were from LKT Laboratories (St. Paul, MN, USA). 4-(Rhamnopyranosyl)benzyl isothiocyanate from Moringa oleifera was a gift from J.W. Fahey. Triterpenoid TP-225 (Dinkova-Kostova et al., 2005) was a gift of M.B. Sporn (Department of Pharmacology and Toxicology, Dartmouth Medical School, Hanover, NH, USA). Celastrol was from Cayman Chemical (Ann Arbor, MI, USA). Bis(benzylidene)acetones, HBB-2 and HBB-4 were synthesized (Dinkova-Kostova et al., 1998). The tricyclic bis(cyano-enone), TBE-31, was synthesized by Tadashi Honda (Honda et al., 2007; Dinkova-Kostova et al., 2010), and was a gift from M. B. Sporn. Flavonoids were from Indofine Chemical Company (Hillsborough, NJ, USA).

Cell culture
All cell lines were grown in 5% CO₂ at 37°C. Murine hepatoma cell line, Hepa1c1c7, from the American Type Culture Collection was cultured in α-MEM supplemented with 10% (v/v) heat-inactivated fetal bovine serum (FBS). Mouse embryo fibroblasts (MEFs) derived from day 13.5 embryos of wild-type or Nrf2-knockout C57BL/6 mice were cultured in Iscove’s Modified Dulbecco’s Medium (with L-glutamine) supplemented with 10% (v/v) heat-inactivated FBS.

Animal experiments
All animal experiments were performed in compliance with National Institutes of Health Guidelines and those of the Animal Care and Use Committee of the Johns Hopkins University (MO11M123). First, 15 female, 8- to 9-week-old CD-1 mice (Charles River Laboratories, Wilmington, MA, USA) were used to assess the effects of dose of SF on enzyme activities and mRNA expression of ALDHs. All mice were fed a low inducer-containing diet (AIN-76A) for 7 days, and were then randomized to three groups, control, low- and high-SF groups (n = 5 in each group). They received basal diet, 5 or 20 µmol SF per 3 g diet, respectively. After 7 days, mice were euthanized and their livers, forestomachs, glandular stomachs and proximal small intestines were harvested, frozen in liquid N₂ and stored at −80°C until analysis. A small portion of each tissue was stored in RNA-stabilizing solution (RNALater, Sigma, St. Louis, MO, USA) at 4°C until total RNA extraction.

Second, 18 female CD-1 mice were acclimatized on the AIN76A, divided into two groups, control (n = 9) and SF (n = 9), and then received AIN76A or 20 µmol SF per 3 g AIN76A diet for 7 days, respectively. After fasting overnight, they were gavaged with 35% (v/v) ethanol (2.0 g ethanol/kg body weight). Before, and 0.5, 1, 2, 3, 4, and 6 h later, 20 µl of blood was collected by nicking the tail vein, and used to determine blood ethanol and acetaldehyde levels.

Assay of NAD(P)H-quinone acceptor oxidoreductase 1 activity
Hepa1c1c7 cells were seeded in 96-well plates at 10⁵ cells per well, grown for 24 h and then exposed to serial dilutions of inducers for 48 h. NAD(P)H-quinone acceptor oxidoreductase 1 (NQO1) activities were determined with menadione as substrate by the Prochaska assay (Prochaska and Santamaria, 1988; Fahey et al., 2004). Cytosolic/microsomal fractions of tissues were subjected to similar NQO1 assays.

Analysis of mRNA expression of ALDHs
Total RNA was extracted from Hepa1c1c7 cells that had been exposed to serial dilutions of inducers for 24 h, or from RNA-stabilized tissues from mice with TRZol reagent (Invitrogen, Grand Island, NY, USA), followed by reverse transcription into cDNA (iScript, Bio-Rad, Hercules, CA, USA). The cDNA was subjected to quantitative real-time PCR analysis by using SYBR Green fluorescence (POWER SYBR Mastermix, Applied Biosystems, Carlsbad, CA, USA) with 7000 Sequence Detection System (Applied Biosystems). All primers used in this study were designed based on previous reports (Levi et al., 2009). Relative expressions of individual mRNAs for ALDH were normalized to β-actin as endogenous
control, and the expression rate was calculated by the comparative ΔΔCt method.

Determinations of ethanol and acetaldehyde levels in mouse blood

These were determined enzymatically by modification of the method of Tottmar et al. (1978). Whole blood samples (20 µl) were obtained by incisions of mouse tail veins, and were immediately mixed with 200 µl of 4% (v/v) perchloric acid in sealed tubes. After incubation at 4°C for 10 min, the tubes were centrifuged at 3000 x g for 10 min, and the pH values of the supernatant fractions were adjusted to 7.5–8.0 by adding 20 µl of 3 M K₂CO₃ in new tubes. After removing precipitated perchlorate by centrifugation at 3000 x g for 10 min, supernatant fractions were stored in sealed tubes at 4°C until assayed.

Diluted supernatant fractions were added to each well of 96-well plates containing in a final volume of 200 µl: 0.5 M glycine-NaOH buffer (pH 9.0), 0.6 mM NAD and 53 units/ml of ADH (purified ADH from yeast, Sigma, St. Louis, MO, USA). Blood ethanol levels were calculated from the rate of NADH generation for 5 min measured with a microplate fluorometer (λₑₓ 340 nm and λₑₘ 460 nm) with ethanol standards.

Acetaldehyde was measured in 10-mm quartz fluorescence cuvettes in an assay mixture containing in a final volume of 2.33 ml: 50 mM sodium pyrophosphate (pH 8.8), 0.1 mM pyrazole, 0.1 mM NAD and 0.2 unit/ml of purified ALDH (potassium-activated from baker’s yeast, Sigma) with a luminolence spectrophotometer (Model LS 50, Perkin Elmer, Waltham, MA, USA). Before and 5 min after addition of 170 µl of the supernatant fraction, intensities were determined (λₑₓ 340 nm and λₑₘ 460 nm). The acetaldehyde level in blood was calculated from rate of change in fluorescence intensity by using acetaldehyde standard curves corresponding to ranges of 1.56–50 µM in blood.

Statistical analysis

All values are means ± SEM. Differences between groups were determined by Student’s t-test or Dunnett’s post hoc test after a one-way ANOVA.

RESULTS

Sulforaphane increases total ALDH activity in Hepa1c1c7 cells

We first measured the total ALDH activities of lysates of Hepa1c1c7 murine hepatoma cells with propionaldehyde as substrate. Treatment of these cells with a series of concentrations (0.3, 1.0 and 3.0 µM) of SF for 48 h induced total ALDH activity. Significant increases in activity were observed in cells exposed to 0.3 µM SF, similar to the concentration required to activate many Nrf2-dependent genes (Fig. 1A). These increases were both SF concentration- and time-dependent (Fig. 1B), but did not occur immediately, suggesting that SF induces ALDH transcriptionally but does not activate it directly.

Chemical structures and ALDH inducer potencies in Hepa1c1c7 cells

We assayed a wide range of compounds belonging to eight structurally very different chemical classes previously shown to be inducers of phase 2 cytoprotective genes (Table 1). Of 20 compounds examined, 15 chemical agents including isothiocyanates such as SF, flavonoids and triterpenoid Michael acceptors increased total ALDH specific activity in Hepa1c1c7 cells. Inducer potencies were expressed as concentrations required to double the basal specific enzyme activities (CD values).

Inducer potencies of compounds for ALDH and NQO1 in Hepa1c1c7 cells

Next, inducer potencies of the above-described compounds for ALDH and the prototypical phase 2 enzyme NQO1 were compared by determining CD values for inducing ALDH and NQO1 activities (Table 1). The CD values ranged from the most potent triterpenoid TP-225 (CD values of 0.0016 µM for ALDH and 0.00038 µM for NQO1) to the stilbene resveratrol, the least potent compound assessed in the present study. Interestingly, in Hepa1c1c7 cells the compounds were uniformly 5–10 times more potent as inducers of NQO1 than of ALDH. The reasons for these differences are unclear, but other studies (not shown) indicate that the relative potencies of
compounds vary greatly among cell types, and thus may be attributable to differences in the metabolism rather than fundamental molecular mechanisms of the inducers in different cells. The relationship of potencies for induction of ALDH and NQO1 was also analyzed by displaying the CD values of 15 compounds in Hepa1c1c7 cells as a double logarithmic plot (Fig. 2). A highly significant linear correlation was observed over more than five orders of magnitude of potency ($r^2 = 0.94$). This result strongly suggests that induction of ALDH by phase 2 inducers operates through the same mechanism as induction of NQO1, i.e. the Keap1/Nrf2/ARE pathway.

Participation of Nrf2 in induction of ALDH by SF
SF was a much less potent inducer of total ALDH in C57B/6 MEFs than in Hepa1c1c7 cells. Notably, ALDH activity increased dose-dependently upon treatment with SF in WT MEFs, whereas SF had no effect on ALDH induction in Nrf2$^{-/-}$ MEFs (Fig. 3), establishing that Nrf2 is clearly involved in the induction of ALDH by SF and probably by other inducers.

<table>
<thead>
<tr>
<th>Chemical class, compound and structure</th>
<th>CD, μM in Hepa1c1c7 cells</th>
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<tbody>
<tr>
<td></td>
<td>ALDH</td>
</tr>
<tr>
<td>Isothiocyanates</td>
<td></td>
</tr>
<tr>
<td>Sulfuraphane [1]</td>
<td>2.31</td>
</tr>
<tr>
<td>Erucin [2]</td>
<td>1.61</td>
</tr>
<tr>
<td>Iberin [3]</td>
<td>13.0</td>
</tr>
<tr>
<td>Benzyl isothiocyanate</td>
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</tr>
<tr>
<td>Phenethyl isothiocyanate</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Propyl isothiocyanate</td>
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<tr>
<td>Hexyl isothiocyanate</td>
<td>&gt;100</td>
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<tr>
<td>4-(Rhamnopyranosyloxy)benzyl-isothiocyanate; 4R8ITC [4]</td>
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</tr>
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<td>Steroids</td>
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<tr>
<td>Withaferin A [5]</td>
<td>1.98$^b$</td>
</tr>
<tr>
<td>Triterpenoids</td>
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<tr>
<td>2-Cyano-3,12-dioxyoleane-1,9(11)-dien -28-onitride; TP-225 [6]</td>
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<tr>
<td>Celastral [7]</td>
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<tr>
<td>Tricyclic (cyano enones)</td>
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<tr>
<td>Tricyclic bis(cyano-enone); TBE-31 [8]</td>
<td>0.032</td>
</tr>
<tr>
<td>Bis(benzyldienes)</td>
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<tr>
<td>Bis(2-hydroxybenzylidene)acetone; HBB-2</td>
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</tr>
<tr>
<td>Bis(4-hydroxybenzylidene)acetone; HBB-4 [9]</td>
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<td>Tectochrysin [12]</td>
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<td>Resveratrol [14]</td>
<td>121$^b$</td>
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<tr>
<td>Sesquiterpenes</td>
<td></td>
</tr>
<tr>
<td>Zerumbone [15]</td>
<td>3.53</td>
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</tbody>
</table>

$^a$Numbers in brackets are linked with Fig. 2.
$^b$Extrapolated values.

Effects of phase 2 inducers on individual ALDHs
Three representative phase 2 inducers with radically different structures (the isothiocyanate SF, the triterpenoid TP-225 and the flavonoid β-naphthoflavone) were examined for their capacities to induce individual ALDHs in Hepa1c1c7 cells, with special emphasis on cytosolic ALDH1A1 and mitochondrial ALDH2, which are principally involved in acetaldehyde metabolism. After 48 h, ALDH activities in both fractions were dose-dependently increased up to 3-fold (Fig. 4). Moreover, dose-dependent elevations of mRNA expression of Aldh1a1
and Aldh2 were observed in Hepa1c1c7 cells treated with the three compounds (not shown).

Antioxidant response element consensus sequences in ALDH genes
We examined whether the established antioxidant response element (ARE) core sequence present in phase 2 cytoprotective genes [RTGA(S/Y)nnnGCR (where R = A or G, S = C or G, Y = C or T and n = any nucleotide)] is also present in ALDH genes. Previous reports showed that induction of both Aldh1a1 and Aldh3a1 is probably mediated by the Keap1/Nrf2/ARE pathway because ARE core consensus sequences were identified in the 5-flanking region of their genes (Sreerama and Sládek, 2001; Abdullah et al., 2012). Search for the ARE core consensus sequences by the procedure of Abdullah et al. disclosed at least two perfectly matched (8/8) sequences within 2000-bp of 5-flanking region of Aldh2 (in the ENSEMBL mouse project website). These sequences, GTGACcagGCG and ATGAGacaGCA, are situated 82–92 bp and 1364–1374 bp upstream of the putative transcription start site, respectively. Both ARE sequences are categorized as class 4 enhancers because they do not contain embedded activator protein 1-binding sites TGASTCA (Hayes et al., 2010). Additionally, >10 similar sequences (scored 5/8-7/8) were found in the region, indicating that induction of Aldh2 as well as Aldh1a1 and Aldh3a1 is also likely to be mediated by the Keap1/Nrf2/ARE pathway.

Effects of SF on ALDH activities in mouse organs
To evaluate the potential of SF for inducing ALDH in vivo, we measured ALDH activities in cytosolic/microsomal and mitochondrial compartments and mRNA expression of ALDHs in liver, forestomach, glandular stomach and proximal small intestine of female CD-1 mice. The animals were fed SF...
levels of ALDH genes such as Aldh1a1, 2 and 3a1 in all organs examined, the basal expression levels of these genes varied considerably among organs (Table 2). Expression of Aldh1a1 and Aldh2 messengers was much higher in liver than in other organs, whereas that of Aldh3a1 was observed in both parts of stomach but only minimally in liver and proximal small intestine. In the liver, expression levels of Aldh1a1 and 2 were increased by 2.5- and 1.8-fold, respectively, which possibly contributed to increased ALDH activities in cytosolic/microsomal and mitochondrial fractions from mouse livers. In stomach, Aldh3a1 was strikingly induced by 2.3-fold (fore-stomach) and 6.5-fold (glandular stomach) as well as Aldh1a1 and 2, with lower expression in stomach than in liver. In agreement with cytosolic/microsomal ALDH activity, the highest induction of Aldh3a1 was observed in glandular stomach, which indicated that ALDH3A1 might largely reflect the activity in glandular stomach. In proximal small intestine, basal expression of ALDH genes was low, and induction was not prominent. These results suggest that SF is a highly potent inducer of ALDHs in vivo and protects against aldehyde toxicities by enhancing aldehyde metabolism.

**Effects of SF on blood ethanol and acetaldehyde levels in mice**

We measured changes in blood ethanol and acetaldehyde levels in CD-1 mice that were fed 20 µmol of SF per 3 g diet per day for 7 days before a single oral administration of ethanol (2.0 g/kg body weight).

In control mice, the blood ethanol and acetaldehyde levels were increased to about 30 mM and 22 µM at 1 to 2 h after ethanol gavage, respectively. Thereafter, ethanol levels fell rapidly, but acetaldehyde was still detectable in blood at 6 h after ethanol gavage (Fig. 6). Feeding SF for 7 days slightly affected the ethanol level only in the descending phase of the blood ethanol curve, and there was no significant difference between the area under the curve (AUC) of control and SF-fed mice. In contrast, prior feeding of SF markedly reduced the increase in blood acetaldehyde level by 30% in the ascending phase, and it remained at the lower level to the end of the experiment. Blood AUC for acetaldehyde was significantly lower in the SF-fed mice compared with those fed control diet. Pharmacokinetic analysis with a first order model showed that elimination of blood acetaldehyde was strongly accelerated in SF-fed compared with that in control mice with half-lives of 1.77 ± 0.12 and 3.43 ± 0.23 h, respectively (elimination rate...
constants, $k$: $0.40 \pm 0.03$ and $0.21 \pm 0.02$ h$^{-1}$, $P < 0.01$; initial blood levels, $C_0$: $32.38 \pm 2.4$ and $28.62 \pm 2.1$ µM, not significant). We conclude that doubling of the rate of acetaldehyde elimination by SF feeding results from enhancement of acetaldehyde metabolism through induction of ALDH in liver and other organs by SF.

**DISCUSSION**

Total ALDH activity was measured in cell homogenates to assess the potencies of SF and various other phase 2 inducers of ALDH. The human genome contains at least 17 genes that are members of ALDH superfamily (Vasiliou et al., 2004), and the total ALDH activity measured in the present study includes activities of multiple ALDH enzymes. We focused on enzyme activities of ALDH1A1 and 2 (coded by *Aldh1a1* and *Aldh2*) that are known to be principally responsible for metabolism of acetaldehyde in cytosol and mitochondria. Evaluation of 20 phase 2 inducers belonging to more than eight chemical classes demonstrated that their potencies for the induction of ALDH were correlated with those for the induction of NQO1. Additionally, increase of the total ALDH activity by SF was not observed in Nrf2$^{-/-}$ MEFs, which strongly suggests that induction of ALDHs is regulated by the Keap1/Nrf2/ARE pathway. These findings are in agreement with previous genomic and proteomic analyses with WT and Nrf2$^{-/-}$ mice (Lee et al., 2003; Cho et al., 2005; Shen et al., 2005; Nair et al., 2006; Kitteringham et al., 2010; Abdullah et al., 2012), in which up-regulations of the basal and induced expression levels of ALDH1A1 (*Aldh1a1*) and ALDH2 (*Aldh2*) in WT mice were consistently observed. Furthermore, a previous report in which markedly increased mortality associated with liver failure was observed in Nrf2$^{-/-}$ mice given ethanol doses that were tolerated by WT mice also supports our findings (Lamlé et al., 2008). Toxicity of acetaldehyde was postulated as one of the causes of serious damage in Nrf2$^{-/-}$ mice, because ALDH enzyme activity was significantly lower and consequently acetaldehyde levels in the liver were much higher in Nrf2$^{-/-}$ mice than in WT animals. In the present study, we confirmed that phase 2 inducers with different structures increased gene expressions of *Aldh1a1* and *Aldh2* in WT mice, and intake of SF increased ALDH activities in both cytosol and mitochondria in mouse livers concomitantly with gene expressions of *Aldh1a1* and *Aldh2*. In this connection, it will be of interest to examine the response to SF of mutant cells with *Aldh2* $+/-$, $+/-$ and $-/-$ genotypes.

![Fig. 6. Effects of SF on ethanol and acetaldehyde pharmacokinetics after single-dose ethanol administration.](https://academic.oup.com/alcalc/article-abstract/48/5/526/209660)
In conclusion, inductions of ALDHs including ALDH1A1 and ALDH2, as well as a network of phase 2 cytoprotective enzymes, are regulated by the Keap1/Nrf2/ARE pathway. It is therefore very likely that a variety of natural products will have the potential of protecting individuals who are alcohol intolerant against acetaldehyde toxicity (Talalay and Fahey, 2001).

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