Vitamin C selectively kills KRAS and BRAF mutant colorectal cancer cells by targeting GAPDH

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More than half of human colorectal cancers (CRCs) carry either KRAS or BRAF mutations and are often refractory to approved targeted therapies. We found that cultured human CRC cells harboring KRAS or BRAF mutations are selectively killed when exposed to high levels of vitamin C. This effect is due to increased uptake of the oxidized form of vitamin C, dehydroascorbate (DHA), via the GLUT1 glucose transporter. Increased DHA uptake causes oxidative stress at intracellular DHA is reduced to vitamin C, depleting glutathione. Thus, reactive oxygen species accumulate and inactivate glyceraldehyde 3-phosphate dehydrogenase (GAPDH). Inhibition of GAPDH in highly glycolytic KRAS or BRAF mutant cells leads to an energetic crisis and cell death not seen in KRAS and BRAF wild-type cells. High-dose vitamin C impairs tumor growth in Apc/KrasG12D mutant mice. These results provide a mechanistic rationale for exploring the therapeutic use of vitamin C for CRCs with KRAS or BRAF mutations.

VITAMIN C RESEARCH

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phosphate-buffered saline (PBS; vehicle control) for 3 to 4 weeks, at which point control mice had to be killed because of tumor size. Vitamin C treatment significantly reduced tumor growth relative to vehicle control treatment (Fig. 2B). KRAS and BRAF wild-type isogenic HCT116 and VACO432 cell lines cannot form xenograft tumors in mice. To directly test the impact of KRAS mutation on the sensitivity of tumors to vitamin C treatment, we generated a transgenic model of intestinal cancer, driven by either Apc mutation, or combined Apc and KRAS (G12D) mutations. Compound mutant mice were generated by crossing available Apc mutant, LSL-KrasG12D (15), and Lgr5-EGFP-CreERT2 (16) animals, enabling intestinal restricted alteration of Apc and Kras. Tumors were induced with a single ip injection of low-dose tamoxifen (20 mg/kg) and treated daily thereafter with high-dose vitamin C (ip, 4 g/kg) for 5 to 7 weeks. Whereas Apclox/lox mice showed no difference in polyo burden after vitamin C treatment, Apclox/lox/KrasG12D mice had significantly fewer and smaller small intestine polyps (76 versus 165 in control group), confirming that vitamin C selectively affected Kras mutant tumors (Fig. 2C and fig. S9). Consistent with experiments in CRC lines, tumors from Apclox/lox/KrasG12D mice showed higher GLUT1 expression and greater vitamin C uptake than did tumors from Apclox/lox mice (Fig. 2, D and E, and fig. S10).

To investigate the mechanism by which vitamin C is selectively toxic to KRAS and BRAF mutant cells, we used liquid chromatography–tandem mass spectrometry (LC-MS/MS)–based metabolomics to profile metabolic changes after vitamin C treatment (17). In untreated KRAS and BRAF mutant lines, the relative intracellular metabolite levels of glycolysis and the nonoxidative arm of the pentose phosphate pathway (PPP) were increased relative to their isogenic wild-type counterparts (fig. S11). Addition of a MEK1/2 (MAPK kinase) inhibitor to the parental KRAS or BRAF mutant cells also decreased glycolytic and PPP metabolite levels, indicating that the increased metabolite levels were driven by oncogene-induced MAPK activity (fig. S12) (18). Notably, within 1 hour of vitamin C treatment, the metabolic profile of the mutant cells changed markedly.

Glycolytic intermediates upstream of glyceraldehyde 3-phosphate dehydrogenase (GAPDH) accumulated while those downstream were depleted, which suggests that GAPDH was inhibited (Fig. 3A and fig. S13). Also, oxidative PPP metabolites increased (Fig. 3A and fig. S13), indicating that GAPDH was inhibited (Fig. 3A and fig. S13). Thus, vitamin C treatment decreased ATP levels, with a concomitant increase in adenosine monophosphate (AMP) levels (fig. S12 and fig. S15). Accordingly, vitamin C induced a significant drop in ATP levels, with a concomitant increase in adenosine monophosphate (AMP) levels (fig. S12 and fig. S15). Within 1 hour, AMP-activated protein kinase (AMPK), a marker for energy stress, was activated; activation was strongest in the mutant lines (Fig. 3F). The cell-permeable reducing agent and glutathione precursor N-acetylcysteine (NAC) rescued both AMPK activation and cell death in the mutant lines (Fig. 3, F and G). Consistent with the in

Fig. 1. KRAS and BRAF mutant cells predominantly take up DHA, the oxidized form of vitamin C, via GLUT1. (A) DHA, but not vitamin C, is transported into CRC cells via GLUT1. [14C]Vitamin C was added to the culture media (2 mM glucose) for 30 min, followed by measurement of scintillation counts per minute (CPM) per microgram of protein input. Treating cells with GSH or STF31 (GLUT1 inhibitor) significantly reduced vitamin C uptake in all cases when compared to no GSH or STF31 treatment. One-way analysis of variance (ANOVA) followed by Dunnett’s posttest for multiple comparisons. *P < 0.01, **P < 0.001, n = 3. (B) [14C]Vitamin C uptake was monitored in 2 mM glucose and signal normalized to total protein. P, parental cells; WT-GLUT1, exogenously expressed GLUT1 in wild-type cells; GLUT1 KO, GLUT1 knockout cells. Asterisks indicate significant decreases in vitamin C uptake of wild-type or GLUT1 KO cells relative to the parental lines, KRAS or BRAF mutant cells (MUT), and WT-GLUT1. One-way ANOVA followed by Dunnett’s posttest. *P < 0.01, n = 3. (C) LC/MS analysis of intracellular vitamin C and DHA in KRAS or BRAF isogenic cell lines derived from HCT116 and VACO432, respectively. Cells were treated with 1 mM (HCT116) or 2 mM (VACO432) vitamin C for 1 hour before extracting vitamin C and DHA (Student’s t test, n = 6). All data represent means ± SD.
in vitro results, supplementing drinking water with NAC over the course of vitamin C treatment abolished the ability of vitamin C to reduce xenograft growth (Fig. 3H). Similarly, pyruvate and oxaloacetate, both of which can enter the TCA cycle and thus provide ATP, rescued energy stress and cell death, as did Trolox (a water-soluble analog of the antioxidant vitamin E) (Fig. 3G and fig. S16, B and C). Rotenone, a complex I inhibitor, attenuated the ability of pyruvate to rescue vitamin C-induced cytotoxicity (fig. S17), indicating that the lack of mitochondrial substrates caused by glycolytic inhibition also contributes to ATP depletion in mutant cells (27).

We next sought to determine the mechanism by which vitamin C inhibits GAPDH. GAPDH is known to have an active-site cysteine (Cys152) that is targeted by ROS (22). The active-site cysteine can undergo reversible S-glutathionylation in which the oxidized cysteine forms a mixed disulfide with GSH (Cys-GSH), or undergo further irreversible oxidations that include sulfonic acid (Cys-SO_{3}H) (23, 24). Both cases result in loss of GAPDH activity. We measured GAPDH S-glutathionylation after vitamin C treatment by immunoprecipitating endogenous GAPDH and blotted with an antibody that recognizes S-glutathionylation under nonreducing conditions. In both KRAS and BRAF mutant lines, GAPDH S-glutathionylation levels were higher in vitamin C–treated cells than in vehicle-treated cells by a factor of 2 to 3 (Fig. 4A). However, GAPDH sulfonylation was not detected with a GAPDH-SO_{3}H antibody (Fig. 4B). GAPDH activity was assayed in lysates of vitamin C–treated cells to confirm inhibition by S-glutathionylation (fig. S18). Treatment with vitamin C for 1 hour decreased GAPDH activity by 50% in both KRAS and BRAF mutant cells. Combining NAC with vitamin C fully rescued GAPDH activity (fig. S18).

We reasoned that the 50% reduction in GAPDH activity after vitamin C treatment could be explained by S-glutathionylation (Fig. 4A). However, given that the GAPDH substrates were added to the lysates to perform the activity assay, and in light of the striking accumulation (by as much as a factor of 19) of the GAPDH substrate glyceraldehyde-3-phosphate (G3P) (Fig. 3A and fig. S13), we suspected that additional mechanisms may contribute to GAPDH inhibition. This led us to examine the levels of the NAD^{+} substrate required for GAPDH-dependent oxidation of G3P.

![Figure 2](http://science.sciencemag.org/)

**Fig. 2.** Vitamin C is selectively toxic to cells with mutant KRAS or BRAF alleles. (A) Cell viability assay in 2 mM glucose or 2 mM glucose plus GSH (PBS) after cells were plated at a low density. Values were normalized to vehicle control. Parental (P) and KRAS or BRAF mutant cells were significantly more sensitive than wild-type cells in the presence of vitamin C. One-way ANOVA with Dunnett’s posttest. *P < 0.0001, n = 3. (B) HCT116 (KRAS: G13D/+ or VACO432 (BRAF; V600E/+)) cells were injected subcutaneously into the flank of 6- to 8-week-old female athymic nude mice (G13D, Gly-to-Asp mutations at codon 13; V600E, Val-to-Glu mutations at codon 600). After 7 to 10 days, mice were randomly divided into two groups. One group was treated with freshly prepared vitamin C in 400 μL of PBS (4 g/kg) twice a day via ip injection (HCT116, n = 6; VACO432, n = 6). Control group mice were treated with PBS with the same dosing schedule (HCT116, n = 4; VACO432, n = 7). Tumor sizes were measured two or three times per week in an unblinded manner. Experiments were repeated twice independently. (C) At 7 weeks of age, Apc^{flox/flox} mice and Apc^{flox/flox}/LSL-Kras^{G12D} mice were treated with a single ip injection of low-dose tamoxifen (20 mg/kg) to activate the stem cell–specific Cre and facilitate loss of Apc and activation of the Kras G12D allele. Three weeks after tamoxifen injection, Apc^{flox/flox} mice (male, 9 female) and Apc^{flox/flox}/LSL-Kras^{G12D} mice (7 male, 9 female) were divided into two groups [vitamin C (4 g/kg) or PBS] and treated daily with ip injections (five or six times per week). As a result of weight loss and the increased level of fecal occult blood as measured by the Hemoccult II SENSA test, all Apc^{flox/flox} mice were killed at 6 weeks after treatment. Apc^{flox/flox}/LSL-Kras^{G12D} male mice were killed at 5 weeks after treatment and Apc^{flox/flox}/LSL-Kras^{G12D} female mice were killed at 7 weeks after treatment; average polyp numbers in the PBS group for female and male mice were similar. Apc^{flox/flox}/LSL-Kras^{G12D} male mice experiments were repeated twice. Polyp numbers and volumes were determined in whole-mount tissue after methylene blue staining, using a dissecting microscope in an unblinded manner. (D) Immunoblots of GLUT1 protein, phospho-ERK1/2, and total ERK in tumors from Apc^{flox/flox} mice (n = 4) and Apc^{flox/flox}/LSL-Kras^{G12D} mice (n = 4). Two separate polyps per mouse (pairs) were used for immunoblots. In E., normal intestinal epithelial cells. (E) Absolute amounts of intracellular vitamin C were measured in tumors derived from Apc^{flox/flox} mice and Apc^{flox/flox}/LSL-Kras^{G12D} mice treated with either vitamin C (4 g/kg) or PBS. Samples were harvested 1 hour after treatment. Two-way ANOVA (P = 0.0002) followed by Tukey’s test for multiple comparisons. All data represent means ± SD; n.s., not significant.
Fig. 3. Vitamin C inhibits glycolysis, thereby depleting ATP and selectively killing KRAS and BRAF mutant cells. (A) Heat map depicting significantly changed glycolytic and pentose phosphate pathway (PPP) metabolite levels in mutant cells after 1 hour of vitamin C (VC) or vehicle (CON) treatment, as analyzed by LC-MS/MS. Red, increase; blue, decrease; TCA, tricarboxylic acid cycle. (B) Relative ratios of reduced to oxidized glutathione (GSH/GSSG) in KRAS and BRAF isogenic cell lines determined by LC-MS/MS as in (A). The ratio was significantly decreased after vitamin C treatment in KRAS or BRAF mutant cells as well as wild-type cells (Student’s t test, *P < 0.002, n = 3), but the extent was greater in the mutant cells than in the wild-type cells. (C) Relative ATP levels were determined in KRAS or BRAF mutant cells relative to wild-type cells was abolished this effect (two-way ANOVA). (D) The extracellular acidification rate (ECAR) was monitored in HCT116 and VACO432 cells, respectively. All data represent means ± SD.

(F) Cells were treated with vitamin C alone or combined with NAC for 1 hour before immunoblotting for Thr172 phosphorylation (p-AMPK) or total AMPK (t-AMPK). (G) Cells were treated with NAC alone (30 mM in drinking water), vitamin C plus NAC, or PBS twice a day via ip injection. Tumor sizes were measured once per week in an unblinded manner. Experiments were repeated twice independently. Relative to PBS, vitamin C treatment alone significantly decreased tumor growth (P < 0.0001, n = 3). (H) Eight-week-old female athymic nude mice with subcutaneous tumors from parental HCT116 cells were treated with vitamin C alone (4 g/kg), NAC alone (30 mM in drinking water), vitamin C plus NAC, or PBS twice a day via ip injection. Tumor sizes were measured once per week in an unblinded manner. Experiments were repeated twice independently. Relative to PBS, vitamin C treatment alone significantly decreased tumor growth (P = 0.016), but adding NAC to the vitamin C treatment abolished this effect (P = 0.845). Mixed effect analysis followed by Tukey’s posttest. *P < 0.001, n = 3.
endogenous ROS inhibits GAPDH by both post-

phosphorylated H2AX, total H2AX, and β-actin on lysates from cells treated with vehicle (CON) or vitamin C for 1 hour. (D) Cells were treated with vitamin C alone (0.125 mM) or vitamin C plus 10 μM olaparib (VC + PARPi) or 1 mM β-nicotinamide mononucleotide (VC + NMN). Viability after 48 hours of treatment was measured using a CellTiter-Glo assay and normalized to untreated controls. Asterisks indicate significant differences relative to KRAS or BRAF mutant cells treated with vitamin C alone. Two-way ANOVA followed by Tukey’s test. *P < 0.01, **P < 0.001, n = 3. (E) Schematic showing how vitamin C selectively kills KRAS or BRAF mutant cells.

In contrast to G3P levels, intracellular NAD⁺ levels were significantly diminished after vitamin C treatment (fig. S19). PARP activation due to ROS-induced DNA damage consumes NAD⁺ to form adenosine diphosphate (ADP)-ribose polymers on acceptor proteins. We observed PARP activation and phosphorylation of H2AX, a marker of DNA damage, shortly after vitamin C treatment (Fig. 4C); this finding suggests that PARP activation may diminish NAD⁺ levels, thereby further inhibiting GAPDH activity by depleting substrate availability (25). To investigate whether PARP activation or NAD⁺ depletion contributes to vitamin C–induced cytotoxicity in KRAS and BRAF mutant cells, we treated cells with a PARP inhibitor, olaparib, or a cell-permeable NAD⁺ precursor, nicotinamide mononucleotide (NMN), before vitamin C treatment. Cell viability after vitamin C treatment was partially rescued by inhibiting PARP or supplementing with NMN (Fig. 4D). Taken together, these results indicate that in KRAS and BRAF mutant cells vitamin C–induced endogenous ROS inhibits GAPDH by both post-

translational modifications and NAD⁺ depletion, ultimately leading to an energetic crisis and cell death (Fig. 4E).

High-dose vitamin C cancer therapy has a controversial history. Although some early clinical studies indicated that vitamin C had antitumor activity (26, 27), others have shown little effect (28, 29). Recent studies suggest that the contradictory clinical data may be explained, at least in part, by differences in administration route: the millimolar vitamin C plasma concentrations cytotoxic to cancer cells are only achievable via intravenous administration, not via oral administration (30, 31). Given these findings, a growing number of phase I and phase II clinical trials are reevaluating intravenous infusion of vitamin C to treat various cancers (12, 13, 32, 33). However, despite the previous studies demonstrating that high-dose vitamin C is cytotoxic to cancer cells in vitro (34–36) and that it delays tumor growth in xenograft models (37, 38), the mechanism by which vitamin C kills cancer cells while sparing normal cells has been unclear. Our findings address this fundamental question by suggesting that the oxidized form of vitamin C, DHA, is the pharmacologically active agent, and that the selective toxicity of vitamin C to tumor cells stems from high GLUT1 expression combined with KRAS or BRAF oncogene-induced glycolytic addiction. Although it is unclear whether the results we have observed in our cell culture and mouse studies will translate to human cancer, our findings on the mechanism of action of vitamin C may warrant future investigation in clinical trials.

REFERENCES AND NOTES
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Materials and Methods
Figs. S1 to S19
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Getting all stressed out by vitamin C

Few experimental cancer therapies have incited as much debate as vitamin C. Yet the mechanistic effect of vitamin C on cancer cells is still poorly understood. Yun et al. studied human colorectal cancer cells with KRAS or BRAF mutations and found that they "handle" vitamin C in a different way than other cells, ultimately to their detriment (see the Perspective by Reczek and Chandel). Because a certain receptor is up-regulated in the mutant cells, they take up the oxidized form of vitamin C (dehydroascorbate). This leads to oxidative stress, inactivation of a glycolytic enzyme required by the mutant cells for growth, and finally cell death. Whether the selective toxicity of vitamin C to these mutant cells can be exploited therapeutically remains unclear.

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