(3-Chloroacetyl)-indole, a novel allosteric AKT inhibitor suppresses colon cancer growth in vitro and in vivo

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ABSTRACT

Indole-3-carbinol (I3C) is produced in *Brassica* vegetables such as broccoli and cabbage and has been shown to inhibit proliferation and induce apoptosis in various cancer cells, including breast, prostate, colon, and leukemia. However, only high doses of I3C were shown to inhibit cell proliferation (IC$_{50}$ = 200–300 μM). Our goal here was to develop a more potent antitumor agent by modifying the structure of I3C. We created I3C derivatives and found that (3-chloroacetyl)-indole (3CAI) more strongly inhibited colon cancer cell growth compared to I3C. Additionally, by screening 85 kinases in a competitive kinase assay, we found that 3CAI was a specific AKT inhibitor. AKT is a serine/threonine kinase that plays a pivotal role in promoting transformation and chemoresistance by inducing proliferation and inhibiting apoptosis. Therefore, AKT is regarded as a critical target for cancer therapy. 3ICA, a derivative of I3C, is a potent and specific AKT inhibitor. This compound showed significant inhibition of AKT in an *in vitro* kinase assay and suppressed
expression of AKT direct downstream targets such as mTOR and GSK3β as well as
induced growth inhibition and apoptosis in colon cancer cells. Additionally, oral
administration of this potent AKT inhibitor suppressed cancer cell growth in an in vivo
xenograft mouse model.

Introduction

Indole-3-carbinol (I3C), a natural product found in broccoli and cabbage, has
chemopreventive properties such as anti-proliferative and pro-apoptosis activities against
various cancers (1, 2). I3C reportedly targets a broad range of signaling pathways involved
in cell cycle regulation and survival, including those mediated by AKT, nuclear factor-κB
(NF-κB), Bcl-2, mitogen activated protein kinases (MAPKs), cyclin-dependent kinase
(CDK) inhibitors and cyclin D1 in vitro (3-5). It is also reported to protect against
chemically-induced carcinogenesis in vivo (6-8). These previous studies suggest that many
dietary plants produce unique compounds that could be a source of starting molecules from
which to synthetically develop new chemotherapeutic molecules with potent anti-cancer
properties.
AKT/PKB is a serine/threonine kinase that belongs to the AGC family of kinases (9). Three members, AKT1, AKT2 and AKT3, have been identified and are composed of a conserved N-terminal pleckstrin homology (PH) domain, a central catalytic domain and a C-terminal regulatory hydrophobic motif (HM). The PH domain directs AKT translocation from the cytosol to the plasma membrane by binding to the membrane lipids phosphatidylinositide-3,4-P2 and 3,4,5-P3, which are products of phosphatidylinositide-3-kinase (PI3K). The AKT kinases are activated by phosphorylation of a threonine residue (Thr308) in the activation loop and a serine residue (Ser473) in the COOH-terminal activation domain (10, 11). The PI3K/AKT pathway regulates many cellular functions through a wide range of downstream targets, including the tuberous sclerosis complex 2 (TSC2), which negatively regulates the mammalian target of rapamycin (mTOR).

Phosphorylation of TSC2 by AKT releases mTOR activity, which can stimulate protein synthesis in response to nutrients as well as regulate cell growth (12, 13). Another major substrate of AKT is glycogen synthesis kinase 3β (GSK3β), which is inactivated by AKT phosphorylation leading to increased glycogen synthesis during glucose metabolism following insulin stimulation (14, 15).
The PI3K signaling pathway is genetically altered in numerous types of cancers. For example, activating mutations of PIK3CA or mutations of PTEN are found in tumors of the colon, breast, brain, prostate, stomach and many other organs (16). AKTs are good candidates for mediating PI3K-dependent cell survival responses. Indeed, AKT activation and overexpression are often associated with resistance to chemotherapy or radiotherapy and dominant-negative mutants of AKT enhance the cytotoxicity of chemotherapeutic agents (17-19). In contrast, only a few AKT inhibitors have been identified (20). Thus, development of AKT inhibitors should be useful in clinical cancer therapy. Herein we report that the I3C, (3-chloroacetyl)-indole (3CAI) is a potent allosteric and specific AKT inhibitor, which exerts efficacy in vitro and in vivo.

Materials and Methods

Reagents

I3C (purity: 95%) was purchased from Sigma-Aldrich (St Louis, MO). 3CAI (purity: 95%), 5-methoxy-3CAI (purity: 95%), 5-fluoro-3CAI (purity: 95%) and 2-(4-(2-hydroxyethyl)piperazin-1-yl)-1-(5-methoxy-1H-indol-3-yl)ethanone) (purity: 95%) were purchased from InterBioScreen (Moscow, Russia). CNBr-Sepharose 4B beads were
purchased from GE Healthcare (Piscataway, NJ). The active AKTs, active MEK1, active JNK1, active ERK1 human recombinant protein, histone H2B and H2AX for kinase assays were purchased from Millipore (Temecula, CA). The active TOPK human recombinant protein for the kinase assay was purchased from SignalChem (Richmond, BC). PI3K was obtained from Upstate Biotechnology (Lake placid, NY). AKT, p-AKT (Thr308), mTOR, p-mTOR (Ser2448), GSK3β, p-GSK3β (Ser9), Bad, Bcl2 and p-ASK1 (Ser83) and CDKN1A antibodies were purchased from Cell Signaling Technology (Beverly, MA). Antibodies to detect p53 and β-actin were purchased from Santa Cruz Biotechnology (Santa Cruz, CA). LY294002 was purchased from Gibco BRL (Grand Island, NY). AKT inhibitor VIII was purchased from Merck KGaA (Darmstadt, Germany).

**Synthesis of 3CAI**

3CAI (purity: 95%) was synthesized as described (21) and purity and structure were analyzed using HPLC and NMR.

**Cell culture**

All cell lines were purchased from American Type Culture Collection (ATCC) and were
cytogenetically tested and authenticated before the cells were frozen. Each vial of frozen cells was thawed and maintained in culture for a maximum of 8 weeks. Enough frozen vials were available for each cell line to ensure that all cell-based experiments were conducted on cells that had been tested and in culture for 8 weeks or less. HCT116 and HT29 human colon cancer cells were cultured in McCoy’s 5A medium supplemented with 10% fetal bovine serum (FBS; Atlanta Biologicals, Lawrenceville, GA) and 1% antibiotic-antimycotic.

**Molecular modeling**

The crystal structure of the pleckstrin homology (PH) domain of AKT1 was obtained from the RCSB Protein Data Bank, PDB entry 1UNQ (22), which is a complex structure of the AKT1 PH domain and Ins(1,3,4,5)P4 and has an atomic resolution of 0.98 Å. The crystal structure was prepared using the Protein Preparation Wizard in Maestro v.9.2. Hydrogens were added to the protein structure consistent with a pH of 7. All water molecules in the crystal structure were removed. Then the crystal structure was minimized with an RMSD cutoff value of 0.3 Å. The structure of the AKT2 PH domain used in this study was modeled with the template structure of 1UNQ using Prime v.3.0. Energy grids for docking
were computed for each protein structure using default settings in Glide v.5.7. 3CAI was prepared using LigPrep v.2.5 and then was docked into the PH domains of AKT1 and 2 with Glide extra precision (XP) mode.

**Anchorage independent cell growth**

Cells (8 × 10³ per well) suspended in complete growth medium (McCoy’s 5A supplemented with 10% FBS and 1% antibiotics) were added to 0.6% agar with different doses of each compound in a base layer and a top layer of 0.3% agar. The cultures were maintained at 37°C in a 5% CO₂ incubator for 3 weeks and then colonies were counted under a microscope using the Image-Pro Plus software (v. 4) program (Media Cybernetics).

**Western blot analysis**

Cell lysates were prepared with RIPA buffer (50 mM Tris-HCl pH 7.4, 1% NP-40, 0.25% sodium deoxycholate, 0.1% SDS, 150 mM NaCl, 1 mM EDTA, 1 × protease inhibitor tablet). Equal amounts of protein were determined by the bicinchoninic acid (BCA) assay (Pierce, Rockford, IL). Proteins were separated by SDS/PAGE and transferred to polyvinylidene difluoride membranes (Amersham Pharmacia Biotech). Membranes were
blocked with 5% nonfat dry milk for 1 h at room temperature and incubated with appropriate primary antibodies overnight at 4°C. After washing with PBS containing 0.1% Tween 20, the membrane was incubated with a horseradish peroxidase–conjugated secondary antibody at 1:5,000 dilution and the signal detected with a chemiluminescence reagent (Amersham Biosciences Corp).

**In vitro pull-down assay**

Recombinant human AKTs (200 ng) were incubated with 3CAI-Sepharose 4B (or Sepharose 4B only as a control) beads (50 μl, 50% slurry) in reaction buffer (50 mM Tris pH 7.5, 5 mM EDTA, 150 mM NaCl, 1 mM DTT, 0.01% NP40, 2 μg/mL bovine serum albumin). After incubation with gentle rocking overnight at 4°C, the beads were washed 5 times with buffer (50 mM Tris pH 7.5, 5 mM EDTA, 150 mM NaCl, 1 mM DTT, 0.01% NP40) and binding was visualized by Western blotting.

**Cell proliferation assay**

Cells were seeded (1 × 10³ cells per well) in 96-well plates and incubated for 24 h and then treated with different doses of each compound. After incubation for 48 h, 20 μl of
CellTiter96 Aqueous One Solution (Promega) were added and then cells were incubated for 1 h at 37°C in a 5% CO₂ incubator. Absorbance was measured at 492 nm.

**Apoptosis assay**

Colon cancer cells were plated into 60-mm culture dishes (1 × 10⁵ cells/dish) and incubated for 1 day in medium containing 10% FBS. The culture medium was then replaced with a 1% serum medium and cultured for 4 days with 3CAI, I3C or a commercial AKT inhibitor. The cells were collected by trypsinization and washed with phosphate buffered saline (PBS). The cells were resuspended in 200 μl of binding buffer. Annexin V staining was accomplished following the product instructions (Clontech, Palo Alto, CA). The cells were observed under a fluorescence microscope using a dual filter set for FITC and propidium iodide and then analyzed by flow cytometry.

**In vitro kinase assay**

The kinase assay was performed in accordance with instructions provided by Upstate Biotechnology (Billerica, MA). Briefly, the reaction was carried out in the presence of 10 μCi of [γ-³²P]ATP with each compound in 40 μl of reaction buffer containing 20 mM
HEPES (pH 7.4), 10 mM MgCl₂, 10 mM MnCl₂, and 1 mM dithiothreitol. After incubation at room temperature for 30 min, the reaction was stopped by adding 10 μl protein loading buffer and the mixture was separated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE). The relative amounts of incorporated radioactivity were assessed by autoradiography.

**Hematoxylin-eosin staining and immunohistochemistry**

Tumor tissues from mice were embedded in a paraffin block and subjected to hematoxylin and eosin (H&E) staining and immunohistochemistry. Tumor tissues were de-paraffinized and hydrated then permeabilized with 0.5% Triton X-100/1 × PBS for 10 min, hybridized with Ki-67 (1:500) as the primary antibody and horse-radish peroxidase (HRP)-conjugated goat anti-rabbit or mouse IgG antibody was used as secondary antibody. After developing with 3, 3′-diaminobenzidine, the sections were counterstained with H&E. All sections were observed by microscope and the Image-Pro Plus software (v. 4) program (Media Cybernetics).

**Xenograft mouse model**
Athymic mice [Cr:NIH(S), NIH Swiss nude, 6–9 wk old] were obtained from Charles River and were maintained under “specific pathogen-free” conditions based on the guidelines established by the University of Minnesota Institutional Animal Care and Use Committee. Mice were divided into five groups: 1) untreated vehicle group (n = 15); 2) 20 mg 3CAI/kg of body weight (n = 15), 3) 30 mg 3CAI/kg body weight (n = 15); 4) 100 mg I3C/kg of body weight (n = 15); 5) no cells and 30 mg 3CAI/kg of body weight (n = 15). HCT116 cells (3×10⁶ cells/100 μl) were suspended in serum free McCoy’s 5A medium and inoculated subcutaneously into the right flank of each mouse. 3CAI, I3C or vehicle was administered orally 5 times per week for 21 days. Tumor volume was calculated from measurements of 2 diameters of the individual tumor base using the following formula: tumor volume (mm³) = (length × width × height × 0.52). Mice were monitored until tumors reached 1 cm³ total volume, at which time mice were euthanized and tumors were extracted.

**Statistical analysis**

All quantitative results are expressed as mean values ± S.D. Statistically significant differences were obtained using the Student’s t test or by one-way ANOVA. A value of p < 0.05 was considered to be statistically significant.
Results

An I3C derivative, 3CAI, suppresses colon cancer cell growth. We screened for I3C derivatives that could effectively inhibit proliferation and anchorage-independent cell growth. To compare the effects of I3C (Fig. 1A) and its derivatives (Fig. 1B) on cancer cell growth, HCT116 colon cancer cells were treated with various concentrations of I3C or derivatives for 48 h. Proliferation was assessed by MTS assay and results indicated that growth was significantly decreased by I3C derivatives (#1, #2 or #3), but I3C or derivative #4 had little effect (Fig. 1C). Additionally, we compared the effect of the 5 compounds on anchorage-independent cell growth. HCT116 colon cancer cells were seeded with I3C or its derivatives in 0.3% agar and incubated for 3 weeks. Data showed that only the high dose of I3C (200 μM) or I3C derivatives (#1, #2 or #3), but not derivative #4, strongly suppressed anchorage-independent cell growth (Fig. 1D). Interestingly, I3C derivatives #2 or #3 had inhibitory effects on growth similar to derivative #1. Therefore, these findings suggested that methoxy and fluoro modification of 3CAI was not important for inhibiting proliferation or anchorage-independent cell growth. Based on these results, 3CAI appears
to be the most effective anti-colon cancer compound of the 4 derivatives tested and was used in further studies.

3CAI is a potent inhibitor of AKT kinase activity. To identify the direct molecular target of 3CAI, we screened 85 kinases against 3CAI in a high-throughput substrate-competitive assay (http://www.kinomescan.com/). Results identified 3CAI as a potential inhibitor of AKT (Supplemental Table 1). Based on these screening data, we tested the effect of 3CAI on the kinase activities of AKT1, MEK1, JNK1, ERK1 and TOPK using in vitro kinase assays. The results showed that 3CAI (1 μM) suppressed only AKT1 kinase activity and the other kinases tested were not affected by 3CAI (Fig. 2A). We also studied the affect of 3CAI on kinases upstream of AKT. PI3K activity was potently inhibited by LY294002, a well-known inhibitor of PI3K, and 3CAI inhibited PI3K by 60% at the highest concentration (10 μM; Fig. 2B). These data suggest that 3CAI is a much more potent AKT1 inhibitor than PI3K (60% inhibition at 1 vs 10 μM, respectively). Additionally, we compared the effect of I3C, 3CAI and the AKT inhibitor VIII on AKT1 and 2 activities. 3CAI, but not I3C, substantially suppressed AKT1 activity (Fig. 2C) as well as AKT2
activity (Fig. 2D) in a dose dependent manner. These data showed that 3CAI is a potent and specific AKT1 and AKT2 inhibitor.

**3CAI directly binds with AKT1 or AKT2 in an ATP non-competitive manner.**

We next performed a molecular docking study with 3CAI and AKT1 and AKT2 in order to determine its binding orientation. The docking score of 3CAI with AKT1 was -2.03 Kcal/mol, which was a little less favorable than the docking score of 3CAI with AKT2 (-2.25 Kcal/mol). 3CAI forms a hydrogen bond with Glu17 in the AKT1 PH domain, whereas 3CAI forms three hydrogen bonds with Lys14, Leu52 and Arg86 in the AKT2 PH domain (Fig. 3A). The structures of AKT1 or AKT2 were aligned and superimposed to compare the docked conformation of 3CAI. 3CAI adopts a pose parallel to Ins(1,3,4,5)P4 in AKT1, whereas 3CAI adopts a pose perpendicular with Ins(1,3,4,5)P4 in AKT2 (Fig. 3B).

To confirm the results of the computer docking model, we performed *in vitro* pull-down assays using 3CAI or I3C-conjugated Sepharose 4B beads. These results showed that 3CAI directly bound to recombinant AKT1 (Fig. 4A) and AKT2 (Fig. 4B) in an ATP non-competitive manner. I3C showed no binding. Similar results were obtained using an HCT116 colon cancer cell lysate (Fig. 4C and 4D). These results suggest that 3CAI binds to
an AKT allosteric site and not the ATP pocket.

**3CAI inhibits down-stream targets of AKT and induces apoptosis.** We investigated the effect of 3CAI on down-stream targets of AKT, including the phosphorylation of mTOR and GSK3β. Results indicated that the AKT-mediated phosphorylation site of mTOR (Ser2448) and GSK3β (Ser9) were substantially decreased by 3CAI in a time-dependent manner (Fig. 5A). However, phosphorylation of AKT (Thr308) was not changed. Furthermore, pro-apoptotic marker proteins p53 and p21 were also upregulated by 3CAI after 12 or 24 h of treatment. Additionally, the anti-apoptotic marker protein Bcl2 and AKT-mediated phosphorylation of ASK1 (Ser83) were significantly decreased (Fig. 4B). These findings suggested that pro- or anti-apoptotic marker proteins are regulated by 3CAI in colon cancer cells. Next, to determine whether apoptosis was induced by 3CAI, we compared the effect on cell death of this compound, I3C and an AKT inhibitor. HCT116 and HT29 colon cancer cells were seeded on 6 cm dishes in 1% FBS/McCoy’s 5A (HCT116) with 3CAI, I3C or the AKT inhibitor and then incubated for 4 days. Results showed that the number of apoptotic cells was significantly increased by 3CAI in HCT116 and HT29 colon cancer cells compared with untreated control cells (Fig. 5C).
3CAI inhibits growth of colon cancer cells in a xenograft model.

To examine the antitumor activity of 3CAI in vivo, HCT116 cancer cells were injected into the right flank of individual athymic nude mice. Mice were orally administered 3CAI at 20 or 30 mg/kg, I3C at 100 mg/kg, or vehicle 5 times a week for 21 days. Treatment of mice with 30 mg/kg of 3CAI significantly suppressed HCT116 tumor growth by 50% relative to the vehicle-treated group (Fig. 6A; p < 0.05). Remarkably, mice seemed to tolerate treatment with these doses of 3CAI without overt signs of toxicity or significant loss of body weight compared with vehicle-treated group (Fig. 6B). The effects of 3CAI on a tumor proliferation marker were evaluated by immunohistochemistry and H&E staining of HCT116 tumor tissues after the 21 days of treatments. The expression of Ki67 was markedly decreased by treatment with 3CAI (Fig. 6C). Next, we examined the effect of 3CAI on down-stream targets of AKT such as phosphorylation of mTOR and GSK3β by Western blot using the in vivo tumor tissues. Expression of these AKT-target proteins was strongly suppressed by 30mg/kg of 3CAI in tumor tissues (Fig. 6D). These data suggested that HCT116 colon tumor development was suppressed by 3CAI through inhibition of AKT signaling pathway.
Discussion

The natural phytochemical, I3C, has been reported to exert potent anti-proliferative activities in cell-based studies and has been implicated as a potential therapy for human cancers. However, only high concentrations of I3C can induce anti-cancer activity and appear to involve a non-specific broad range of targets. Therefore, interest in developing more potent synthetic I3C-based compounds has grown. However, only a few I3C analogues have been reported and exert only a low enhancement of potency in biological activity (23, 24). In contrast, 1-benzyl-I3C was reported as the most potent synthetic derivative of I3C with an approximate 1000-fold increased potency against breast cancer. The investigators suggested that 1-benzyl-I3C inhibited CDK2 enzymatic activity and CDK6 activity through the downregulation of CDK6 transcription and protein expression (25). However, direct targets of 1-benzyl-I3C or its specificity were not determined. We have identified a potent derivative of I3C, 3CAI, from a high throughput screening of 85 kinases (Supplemental Table 1). We found that 3CAI inhibited only AKT kinase activity (Fig 2A, B), suggesting that 3CAI is a specific AKT inhibitor.

Additionally, we determined the binding orientation between 3CAI and AKT using
a computer docking model. About 20 crystal structures of AKT2 and 10 of AKT1 are
available. The molecular alignment of the protein sequences using EMBOSS (26) showed
that they possess about 85% and 92% identity. 3CAI was docked to the allosteric site of
AKT1 and AKT2. The preference for AKT2 over AKT1 is much more difficult to explain
because the crystal structure of the AKT2 PH domain has not yet been solved. The
sequences of AKT1 and 2 are highly conserved, and the sequence identity between the PH
domains is about 80%. Thus a reliable homology model of the AKT2 PH domain can be
built based on the known structure of the AKT1 PH domain. The structure of the AKT2 PH
domain used in this study was modeled with the template structure of 1UNQ. The reason as
to why 3CAI prefers the allosteric site of AKT1 and AKT2 over the ATP site is puzzling.
The observed preference might not lie in a classical explanation where specific ligand-
protein noncovalent interactions do or do not exist, but potentially the explanation lies in
the realm of statistics. 3CAI was computationally predicted to possess multiple binding
orientations within the ATP binding site of both AKT1 and AKT2 (data not shown).
However, 3CAI preferred to dock only to the PH-domain in AKT1 and AKT2 (Fig. 3A and
3B). Therefore, we needed to analyze a docking simulation between 3CAI and the AKT1
and 2 proteins as well as examine binding with a deletion mutant of AKT1 and 2.
Previous studies showed that HER-2 mediated AKT activation to induce translocation of MDM2 from the cytoplasm to the nucleus. MDM2 directly binds to p53 and induces ubiquitination (27, 28). In other reports, an effect of AKT on MDM2 subcellular localization from the cytoplasm to the nucleus was not detected, but AKT was shown to facilitate the function of MDM2 to promote p53 ubiquitination by phosphorylation of Ser186 (29). In our study, the protein level of p53 was substantially increased by 3CAI in a time-dependent manner, as was the abundance of p21, a target of p53 (Fig. 5B). We examined whether inhibition of AKT kinase activity by 3CAI could induce stability of p53 by suppressing phosphorylation of MDM2 (Ser166). We confirmed the phosphorylation of MDM2 and p53 protein level using an immunofluorescence assay and Western blot analysis of cytoplasmic and nuclear protein fractions. However, we did not observe any significant translocation of MDM2 (data not shown). Importantly, 3CAI suppressed colon cancer cell growth and induced apoptosis more potently than I3C or a commercially available AKT inhibitor (Fig. 5). Results of a xenograft mouse model showed that oral administration of 3CAI at 30 mg/kg B.W. for 21 days significantly inhibited colon cancer cell growth and was not toxic (Fig. 6A, 6B).

In conclusion, we found that the I3C derivative, 3CAI, is a potent and specific
AKT inhibitor and suppressed cell growth and induced apoptosis both in vitro and in vivo. These findings should be useful for developing drugs targeting AKT and 3CAI seems to be a promising lead compound.

Conflict of Interest

The authors state no conflict of interest.

Acknowledgements

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inhibits diethylnitrosamine-initiated hepatocarcinogenesis in the infant mouse model.


**Figure legends**

**Figure 1. Anti-cancer activity of I3C derivatives.** (A) Structure of indole-3-carbinol (I3C) and (B) 4 derivatives. (C) 3CAI derivatives inhibit proliferation of colon cancer cells. Cells were treated with I3C or derivatives (#1, #2, #3 or #4) for 48 h and harvested. Proliferation was analyzed using the MTS assay. The asterisk indicates a significant decrease in proliferation compared to untreated control. (D) I3C and derivatives inhibit anchorage independent cell growth. Cells were incubated in 0.3% agar for 3 weeks with I3C or derivatives (#1, #2, #3 or #4). Colonies were counted using a microscope and the Image-
Pro PLUS (v.6) computer software program. Data are represented as means ± S.D. of values from triplicates and similar results were obtained from two independent experiments. The asterisk (*) indicates a significant (p < 0.05) decrease in colony formation induced by I3C or its derivatives (#1, #2 or #3) compared to untreated control.

**Figure 2. Effect of (3-chloroacetyl)indol (3CAI) on AKT activity.** (A) 3CAI suppresses AKT1 kinase activity *in vitro*. The effect of 3CAI on AKT1, MEK1, JNK1, ERK1 or TOPK activity was assessed by an *in vitro* kinase assay using AKT1 (active, 100 ng), histone H2B (AKT substrate, 500 ng), MEK1 (active, 400 ng), inactive ERK2 (MEK1 substrate, 500 ng), JNK1 (active, 50 ng), c-Jun (JNK1 substrate, 500 ng), ERK1 (active, 400 ng), inactive RSK2 (ERK1 substrate, 500 ng), TOPK (active, 500 ng) or histone H2AX (TOPK substrate, 500 ng) with [γ-32P]ATP. (B) 3CAI inhibits PI3K kinase activity at the highest concentration *in vitro*. The inhibitory effect of 3CAI or LY294002 as a PI3K inhibitor on PI3K activity was assessed by an *in vitro* kinase assay. The conversion of PIP4 to PIP3 was determined by autoradiography. (C) 3CAI substantially inhibits AKT1 or (D) AKT2 kinase activity in a dose-dependent manner. The inhibitory effect of 3CAI, I3C or an AKT inhibitor VIII on AKT1 or AKT2 activity was assessed by an *in vitro* kinase assay. The 32P-
labeled substrate was visualized by autoradiography. Band density was measured using the image J program. All data are represented as means ± S.D. of values from three independent experiments. The asterisk (*) indicates a significant (p < 0.05) decrease caused by 3CAI, LY294002 or AKT inhibitor VIII compared to untreated control.

**Figure 3. Computer modeling of 3CAI and AKT1/2.** (A) Binding modes of 3CAI with PH domains of AKT1 and 2. (A-a) binding mode of 3CAI with the AKT1 PH domain. (A-b) binding mode of 3CAI with the AKT2 PH domain. In the full images of AKT1/2 and 3CAI (A-c, A-d), 3CAI is represented as spheres and the carbon atoms are colored white. In the images of the binding site, 3CAI is represented as sticks. The carbon atoms are colored yellow and the carbon atoms of the residues are colored white. In all pictures, the oxygen atoms are colored red; the nitrogen atoms are colored blue; the chlorine atoms are colored green. (B) Docked conformation of 3CAI compared with Ins(1,3,4,5)P4 from 1UNQ. Left: docked conformation of 3CAI with the AKT1 PH domain. Right: docked conformation of 3CAI with the AKT2 PH domain. The binding sites are represented as surfaces and the ligands are represented as sticks. The carbon atoms of 3CAI are colored yellow and the carbon atoms of Ins(1,3,4,5)P4 are colored cyan. THIS FIGURE NEEDS LABELS ON IT
**Figure 4. 3CAI directly binds to AKT1 or 2 in an ATP non-competitive manner.** (A) 3CAI directly binds to AKT1 or (B) AKT2 in an ATP non-competitive manner.

Recombinant AKT1 (200 ng) was incubated with 3CAI- or I3C-conjugated Sepharose 4B beads, or with Sepharose 4B beads alone. The pulled down proteins were analyzed by Western blotting. (C) 3CAI directly binds to endogenous AKT1 and (D) AKT2. An HCT116 colon cancer cell lysate (500 μg) was incubated with 3CAI- or I3C-conjugated Sepharose 4B beads, or with Sepharose 4B beads alone, and then the pulled down proteins were analyzed by Western blotting. Similar results were obtained from two independent experiments.

**Figure 5. Effect of 3CAI on the AKT signaling pathway.** (A) 3CAI inhibits AKT-target proteins in HCT116 colon cancer cells. Cells were treated with 3CAI, I3C, or an AKT inhibitor, and then harvested at various times (0.5, 1 and 3 h). (B) 3CAI regulates pro- or anti-apoptotic proteins in HCT116 colon cancer cells. Cells were treated with 3CAI or I3C, and then harvested at various times (6, 12 and 24 h). The cells were immunoblotted with antibodies to detect GSK3β, p-GSK3β (Ser9), mTOR, p-mTOR (Ser2448), AKT, p-AKT
(Thr308), p53, p21, Bcl2, Bad, ASK1(Ser83) and β-actin. β-Actin was used to verify equivalent loading of protein. Band density and ratio (phosphorylation/total protein) was measured using the Image J software program. Similar results were obtained from two independent experiments. (C) 3CAI induces apoptosis in colon cancer cells. HCT116 or HCT29 colon cancer cells were seeded with 3CAI, I3C or AKT inhibitor in 1% FBS and medium and then incubated for 4 days. Cells were stained with annexin V and propidium iodide (PI) and apoptosis was determined by Fluorescence Activated Cell Sorting (FACS). The asterisk (*) indicates a significant difference (p < 0.05) between untreated controls and treated cells.

**Figure 6. Effect of 3CAI on colon cancer growth in a xenograft mouse model.** (A)

3CAI significantly suppresses colon tumor growth. Mice were monitored until tumors reached 1 cm³ total volume, at which time mice were euthanized and tumors were extracted. Tumor volume was calculated from measurements of 2 diameters of the individual tumor based on the following formula: tumor volume (mm³) = (length × width × height × 0.52).

Data are shown as means ± S.E. of values obtained from weekly measurements. The asterisk (*) indicates a significant difference between tumors from untreated and treated
mice as determined (p < 0.05). (B) 3CAI has no effect on mouse weight. Body weights from treated or untreated groups of mice were obtained once a week over 5 weeks. (C) Hematocytin & eosin (H&E) staining and immunohistochemistry analysis of tumor tissues. Treated or untreated groups of mice were euthanized and tumors extracted. Colon tumor tissue slides were prepared with paraffin sections after fixation with formalin and then stained with H&E or anti-Ki67. Expression of Ki67 was visualized by light microscope (X200). (D) 3CAI inhibits AKT-target protein expression in HCT116 colon tumor tissues. The tumor tissues from groups treated with vehicle, 30 mg 3CAI/kg or 100 mg I3C/kg B.W. were immunoblotted with antibodies to detect GSK3β, p-GSK3β (Ser9), mTOR, p-mTOR (Ser2448), AKT, p-AKT (Thr308) and β-actin. β-Actin was used to verify equivalent loading of protein.
Fig. 1 A+B+C+D by DJKim

A

Indole-3-carbinol

B

(3-Chloroacetyl)indole; I3C derivative #1

5-methoxy-(3-Chloroacetyl) indole; I3C derivative #2

5-Fluoro-(3-Chloroacetyl) indole; I3C derivative #3

2-(4-(2-hydroxyethyl)piperazin-1-yl)-1-(5-methoxy-1H-indol-3-yl)ethanone; I3C derivative #4

C

Cell proliferation

D

Number of colonies (600 cells)
(3-Chloroacetyl)-indole, a novel allosteric AKT inhibitor suppresses colon cancer growth in vitro and in vivo

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