Lipid Catabolism via CPT1 as a Therapeutic Target for Prostate Cancer

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Abstract
Prostate cancer is the most commonly diagnosed malignancy among Western men and accounts for the second leading cause of cancer-related deaths. Prostate cancer tends to grow slowly and recent studies suggest that it relies on lipid fuel more than on aerobic glycolysis. However, the biochemical mechanisms governing the relationships between lipid synthesis, lipid utilization, and cancer growth remain unknown. To address the role of lipid metabolism in prostate cancer, we have used etomoxir and orlistat, clinically safe drugs that block lipid oxidation and lipid synthesis/lipolysis, respectively. Etomoxir is an irreversible inhibitor of the carnitine palmitoyltransferase (CPT1) enzyme that decreases β oxidation in the mitochondria. Combinatorial treatments using etomoxir and orlistat resulted in synergistic decreased viability in LNCaP, VCaP, and patient-derived benign and prostate cancer cells. These effects were associated with decreased androgen receptor expression, decreased mTOR signaling, and increased caspase-3 activation. Knockdown of CPT1A enzyme in LNCaP cells resulted in decreased palmitate oxidation but increased sensitivity to etomoxir, with inactivation of AKT kinase and activation of caspase-3. Systemic treatment with etomoxir in nude mice resulted in decreased xenograft growth over 21 days, underscoring the therapeutic potential of blocking lipid catabolism to decrease prostate cancer tumor growth.

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Introduction
Prostate cancer is the most commonly diagnosed malignancy and the second highest contributor to cancer deaths in men in the United States (1). Currently, the standard systemic treatment for advanced prostate cancer is based on androgen deprivation with initial positive responses, but prostate cancer tumors eventually become resistant and restore androgen receptor (AR) signaling (2). After prostate cancer becomes castration resistant, no curative treatments exist, making the identification of novel therapies imperative.

The mechanisms by which prostate cancer cells use lipids to their benefit are poorly understood. De novo fatty acid synthesis can occur in cancer cells from glucose, in a pathway largely controlled by the enzyme fatty acid synthase (FASN), and is associated with cell growth, survival, and drug resistance (3, 4). However, the biochemical mechanisms governing the relationships between lipid synthesis, lipid utilization, and cancer growth are still largely unknown.

Overexpression of key enzymes in lipid synthesis in prostate cancer is characteristic of both primary and advanced disease (5), suggesting that targeting lipid metabolism enzymes in prostate cancer may offer new avenues for therapeutic approaches. Recent research has focused on the development of small FASN inhibitors for prostate cancer therapeutics (6). The lipase and FASN inhibitor orlistat has been used in several preclinical studies to decrease tumor growth (7–9). However, much less attention is being focused on the oxidation of newly synthesized lipid in prostate cancer cells. The lipid utilization pathways in these cells are inferred from indirect evidence, but they are not well studied or understood (10, 11).

Several lines of evidence indicate that intracellular lipid turnover (not just lipid synthesis) is important in cancer cell survival: monoacylglycerol lipase, which catalyzes the release of fatty acids from intracellular lipid stores, promotes tumor growth and survival (12); blocking fat
oxidation results in significant death of leukemia cells exposed to proapoptotic agents (13); fatty acid oxidation is associated with increased resistance to radiation and chemotherapeutic agents (14); finally, fatty acid oxidation fuels the production of metabolites needed to synthesize lipids and to protect cells from oxidative stress (15). Altogether, lipid oxidation is an important component of cancer metabolism together with aerobic glycolysis and lipogenesis, but remains ill-defined in prostate cancer metabolism.

One way to study the role of lipid oxidation in a translatable manner is through the use of safe metabolic inhibitors that can be used both in the laboratory and the clinic. Etomoxir is a safe irreversible inhibitor of the long-chain fatty acid transporter and has been used in the treatment of heart failure (16). Etomoxir works by inhibiting carnitine palmitoyltransferase 1 (CPT1) and blocking the entry of long-chain fatty acids into mitochondria for oxidation, forcing cells to use the oxidation of glucose for energy (17). Only a few studies describe the effect of etomoxir on cancer survival (13, 18), but there are no studies of its effects on prostate cancer tumor metabolism.

In this report, we examined the effects of pharmacologically blocking lipid synthesis and oxidation in prostate cancer cell viability, AR content, molecular signaling, and tumor growth. Our results suggest that prostate cancer cells are dependent on lipid oxidation for their survival and this may represent a novel avenue to investigate new nontoxic therapeutic approaches to prostate cancer treatment.

Materials and Methods

Cell culture and drug treatment

Cell lines were obtained from the University of Colorado Cancer Center Tissue Culture Core (Aurora, CO; year 2011) and were authenticated by single tandem repeat analysis. Cells were used at low passage number and grown in RPMI or DMEM (for VCaP cells) containing 5% FBS supplemented with amino acids and insulin (Hyclone). CSS was used for androgen-deprived conditions. Human prostate-derived cells were isolated from deidentified surgical specimen at Wake Forest University (Winston-Salem, NC) using our previously described protocol (19). The histologic origin of the sample was determined by analysis of the tissue surrounding the plug used for culture. Etomoxir-HCl (Sigma) was dissolved as a 15 mmol/L stock solution; orlistat (Sigma) was dissolved as a 50 mmol/L stock in DMSO.

Cell viability and proliferation analysis

Cell proliferation was analyzed using the Beckman Coulter Vi-Cell Automated Cell Viability Analyzer. MTS proliferation assays were carried out using CellTiter 96 AQueous One solution from Promega according to manufacturer’s protocols.

qRT-PCR

Total RNA was isolated from cells (RNeasy, Qiagen), and cDNA was synthesized (high-capacity cDNA reverse transcription kit; Applied Biosystems) and quantified by qRT-PCR using SYBR green (Applied Biosystems) detection. Results were normalized to the housekeeping gene β-2-microglobulin for mRNA and expressed as arbitrary units of 2^{-ΔΔCt} relative to the control group. X-box binding protein-1 was amplified with Taq polymerase and products were resolved on 2% Tris-acetate-EDTA agarose gels and imaged on AlphaImager HP. Supplementary Table S1 contains the primer sequences used for the qPCR studies.

Immunoblot analyses

Protein extracts (20 μg) were separated on 7.5% or 4% to 20% SDS-PAGE gels and transferred to polyvinylidene difluoride (General Electric) as described (20). All antibodies were from Cell Signaling Technology (Supplementary Table S2). Band signals were visualized with ECL substrate (Pierce). Cell lysates were run on different blots to avoid stripping and rebinding except for phospho-antibody blots.

Glucose uptake

Basal glucose uptakes were determined as previously reported for human cells in vitro (20). Briefly, cells (10^6/well) in 6-well plates were incubated with 2-deoxyglucose (0.5 mmol/L; Sigma-Aldrich) and [1,2-^3H]2-deoxy-D-glucose (GE). Counts were converted to moles of glucose taken-up and normalized to the protein concentration of the lysates.

Lipid oxidation

Cells were plated in 12-well plates and grown to 70% confluence in their respective growth media conditions and with 150 μmol/L etomoxir at the indicated times. At the time of the assay, 1 mmol/L carnitine, 100 μmol/L BSA-conjugated fatty acids (Sigma) and C14-labeled fatty acids (1 μCi/mL; PerkinElmer), and fresh medium were added to the cells for 3 hours. Entrainment of the generated ^14CO2 was done by injecting perchloric acid as described (21). Radioactivity was measured by scintillation (Beckman) and normalized to protein.

CPT1A shRNA transductions

TRCN0000036279 (CPTsh1) and TRCN0000036281 (CPTsh2) CPT1A shRNAs and the nontargeting control SHC002 were purchased from Functional Genomics Core. Lentiviral transduction and selection were performed according to Sigma’s MISSION protocol but using lentiviral packing plasmids pCMV-R8.74psPAX2 and VSV-G/pMD2.G and transfection reagent TransIT-LT1 (Mirius).

Lipid fractionation and analysis by gas chromatography coupled to mass spectrometry

LNCaP cells were grown in 60-mm plates and treated with etomoxir or vehicle for 24 hours. Incubation was...
stopped by adding 1 volume of methanol. To an aliquot representing 25% of the total sample, a mixture of internal standards was added: 20 μL of a solution containing 0.5 nmol each of 12:0-ceramide, 12:0-sphingomyelin, glucosyl (β)-C12-ceramide and Lactosyl(β)-C12-ceramide (Cer/Sph Mixture I; Avanti Polar Lipids). After extracting lipids using Bligh & Dyer method (22), sphingolipids were analyzed by liquid chromatography/tandem mass spectrometry essentially as described (23). Data were analyzed using MultiQuant software from AB Sciex, and are presented as the ratios between the integrated area of the intensity peak of each analyte and the intensity peak of the corresponding internal standard.

Xenograft production in nude mice

Male athymic nude mice, 4- to 6-week-old were purchased from Harlan Laboratories. Tumor xenografts were generated by injecting human VCaP cells in the flank of nude male mice as described (24). Approximately 2 × 10⁶ cells were used for each injection. When tumors were palpable the mice were randomized into two groups: vehicle or etomoxir. Treatment was carried out with intraperitoneal injection of etomoxir (40 mg/kg) or vehicle (water) every other day for 3 weeks. All procedures were carried out under a protocol approved by the Institutional Animal Care and Use Committee of the University of Colorado. After treatment, xenografts were collected and processed for IHC studies using standard protocols at the UC Denver Pathology core.

Statistical analysis

ANOVA tests were used to compare between groups followed by posthoc Tukey tests when appropriate. Analysis of in vivo tumor growth was done with ANOVA followed by t tests with SPSS v20 software. All tests were two sided. P < 0.05 was considered significant. Data represent mean ± SD except for qPCR that is mean ± SEM. Synergism was analyzed using CalcuSyn 2.0 (Biosoft) as described (25).

Results

Lipid metabolic inhibitors reduce the viability of prostate cancer cell lines

Benign (BPH-1, epithelial and WPMY-1, stroma) and prostate cancer (VCaP, LNCaP, and PC3) cell lines were treated with etomoxir (75 μmol/L) for 48 hours and subjected to viability analysis using Trypan blue exclusion. Figure 1A shows that prostate cancer cells have decreased viability in response to etomoxir when compared with normal BPH-1 (epithelial) and WPMY-1 (stroma) prostate-derived cell lines. VCaP cells showed the highest sensitivity to etomoxir treatment, with a 60% reduction in viability (P < 0.01), followed by LNCaP (50% reduction, P < 0.01) and PC3 (40% reduction, P < 0.01).

Because LNCaP cells were sensitive to etomoxir and orlistat after treatment. Figure 2E shows increased lipid oxidation in prostate cancer cells compared with the benign BPH-1 cells (∼5-fold, P < 0.01). Orlistat incubation did not affect the viability and proliferation of LNCaP and VCaP cells exposed to both inhibitors. Treatments were done in FBS and androgen-deprived CSS conditions. Figure 1B and C show the effects of the drug combination on cell viability for LNCaP and VCaP cells, respectively, indicating a strong effect (P < 0.001) of both inhibitors compared with control.

Figure 1D and E show the proliferation of LNCaP cells treated with drugs in the presence of FBS or CSS media, respectively. A dose-dependent effect and a strong inhibition of proliferation were observed with the combination of drugs (P < 0.001 compared with either drug alone). The combinatory index (CI) for the drugs is indicated at the bottom of figures. A number less than 1 indicates synergism between both drugs, whereas 1 or greater reflects additive or antagonistic effects, respectively. These results indicate that lower doses were needed to obtain a synergistic effect on proliferation. CSS media increased the sensitivity of LNCaP cells to the drugs, especially etomoxir. Figure 1F and G shows the same paradigm for VCaP cells. Treatments in the presence of CSS media resulted in increased sensitivity to the combination of drugs compared with treatments with FBS-containing media. This was reflected in the strong synergistic CI scores.

We also examined the effect of etomoxir and orlistat on the proliferation of patient-derived primary human prostate epithelial cells. Purity of the epithelial cultures was assessed by E-cadherin and vimentin expression (Supplementary Fig. S1). Figure 1H and I shows the effect of inhibitors on benign and cancer primary cells, respectively. Increasing drug concentrations decreased proliferation (P < 0.001) for both cell types. However, the cancer cells were more sensitive to each drug than the benign cells at the lower drug concentrations, and more sensitive to the combination of drugs at the higher concentrations (P < 0.05). Strong synergism was observed in the cancer cell lines (CI = 0.5) compared with the benign cells (CI = 0.75), suggesting a higher sensitivity of the cancer cells to the inhibitors, especially etomoxir. Additional patient-derived primary prostate cell lines are shown in Supplementary Fig. S2.

Etomoxir and orlistat decrease AR isoform expression and modify lipid oxidation and glucose uptake

Because AR activity is associated with lipid metabolism, we examined the expression of AR mRNA as well as its downstream targets PSA and NKX3.1. Figure 2A and B shows a significant decrease of transcripts in the presence of inhibitors, regardless of the presence of androgens (P ≤ 0.05). Similar results were obtained for VCaP cells but to a lesser extent (Fig. 2C and D). Examination of the effect of inhibitors on lipid oxidation in prostate cancer and BPH-1 cells was done by trapping the CO₂ produced by the cells after treatment. Figure 2E shows increased lipid oxidation in prostate cancer cells compared with the benign BPH-1 cells (∼5-fold, P < 0.01). Orlistat incubation did not affect
oxidation rate significantly, except for VCaP cells. However, addition of etomoxir decreased the oxidation rate by 50% in LNCaP and VCaP cells (P < 0.05). These results demonstrate that prostate cancer cells are lipolytic, and suggest that their survival strongly depends on AR action and lipid utilization.

Because etomoxir is known to increase glucose uptake in heart cells (26), we also examined the effect of inhibitors on glucose uptake (Fig. 2F). Interestingly, the drug combination produced a significant increase in glucose uptake in all the cells but was greater in BPH-1 cells, suggesting that different metabolic pathways operate in benign and cancer cells.

**Lipid catabolism blockade results in decreased mTOR signaling and increased apoptosis**

To study the molecular mechanisms of etomoxir and orlistat on prostate cancer cells, we examined the phosphorylation status of the proapoptotic BAD protein, which has been shown to be associated with the metabolic status of the cell and is necessary to protect prostate cancer cells from apoptosis, likely mediated...
by AKT activation (27). Figure 3A and B shows blots of etomoxir and/or orlistat-treated LNCaP and VCaP lysates, respectively. Decreased BAD S112 phosphorylation was observed in both cell lines with etomoxir treatment at 6 hours.

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ER stress and apoptotic ceramides are increased after lipid metabolism blockade in LNCaP cells

Because mTOR inactivation is associated with survival signals like endoplasmic reticulum (ER) stress and autophagy, we examined the expression of canonical markers in LNCaP and VCaP lysates. Figure 4A shows activation of the ER stress transcription factor XBP-1 by splicing in response to etomoxir. Interestingly, addition of palmitate to the treatments resulted in less XBP-1 splicing, underscoring the role of lipogenesis/lipolysis cycle in cell homeostasis (Supplementary Fig. S3). ER stress-related
factors ATF4, CHOP, GADD34, and GRP78 were also increased after etomoxir treatment (Fig. 4B). The most dramatic changes were observed in the expression of CHOP (C/EBP homologous protein) and GADD34 (growth arrest and DNA damage 34) expression, both of which have been associated with the proapoptotic side of the ER stress response (29). No changes in the mRNA expression of ER stress-related factors were observed in VCaP cells (not shown).

Because ER stress also leads to a block in protein translation, we examined phospho-eIF2a in the same LNCaP samples that had XBP1 activation (Fig. 4C). A slight increase in p-eIF2a was observed with orlistat as shown before (30), but stronger signals were observed in the etomoxir-treated samples. The weaker p-eIF2a signal in the combination treatment was parallel to the increased expression of the GADD34 phosphatase regulator (Fig. 4B), potentially leading to suppression of the unfolded protein response and induction of apoptosis (31). Finally, because unresolved ER stress activates autophagy (32), we examined the conversion of LC3-II (17 KDa), which was evident in the etomoxir-treated samples (Fig. 4C). VCaP cells did not show increased phospho-eIF2a with etomoxir, but changes in autophagy were noticeable with orlistat (Fig. 4D).

Because ceramides containing 16- and 18-carbon fatty acids are also associated with decreased mTOR activity and autophagy (33), we examined the levels of different ceramide species present in etomoxir-treated LNCaP cells after 24 hours. Figure 4E shows a significant increase in ceramide species containing palmitic (16:0) and stearic (18:0) acyl chains. Interestingly, 16C and 18C containing-ceramides seem to be most important for intrinsic apoptosis induction (34).
Downregulation of CPT1A decreases fat oxidation and leads to apoptosis

To verify the role of CPT1A as the target of etomoxir action, we used two different shRNAs to knock down (KD) CPT1A expression in LNCaP cells. Control cells were transduced with a nontargeting shRNA construct. Clones were treated with vehicle (V, H2O/DMSO), orlistat (O, 20 μmol/L), orlistat/etomoxir (OE, 20 μmol/L/75 μmol/L) or etomoxir alone (E, 75 μmol/L) for 24 hours. Figure 5A shows the decrease in CPT1A expression in the KD clones compared with control cells (V lanes). An unexpected increase in CPT1A expression with etomoxir was observed in all clones, suggesting a compensatory feedback effect. A lack of S112 and S155 phosphorylation of BAD was observed in the combinatorial treatment, suggesting an activation of BAD proapoptotic activity (27, 28). Decreases in pAKT and mTOR action (via pS6K) were also observed, concomitant with cleaved caspase-3 signal, suggesting apoptosis induction. VCaP cells were not viable after CPT1A KD selection but they also showed a slight increase of CPT1A protein expression with etomoxir (Fig. 5B).

Analysis of cell viability and sensitivity of clones to etomoxir was also examined (Fig. 5C). CPT1A KD clones were sensitive to 50 μmol/L etomoxir (reduced by 60%, P < 0.001) while the control cells showed a 20% decrease in viability. This effect was dose dependent as the 75 and 100 μmol/L doses decreased viability in all the clones. Because the total AKT expression was strongly reduced in the CPT1A KD clones with the etomoxir treatments, this suggests a lack of compensatory survival pathway leading to decreased viability. Concomitant with decreased CPT1A expression, we also observed lower palmitate oxidation in the KD clones (Fig. 5D). Clone CPTsh1 showed a stronger decrease in fat oxidation (60% decrease, P < 0.01) followed by CPTsh2 (25% decrease, P = 0.01).

Systemic treatment with etomoxir decreases xenograft tumor growth in nude mice

Male nude mice were grafted with VCaP cancer cells subcutaneously, randomized to four groups (two vehicles and two treatment doses) when the tumors were palpable, and treated with etomoxir systemically for 21 days. VCaP cells were used instead of LNCaP because they grow well as xenografts in nude mice (35) and are also sensitive to etomoxir (Fig. 1A). To account for possible toxicity, we used two different doses of etomoxir. Figure 6A shows the

![Figure 5. Downregulation of CPT1A decreases fat oxidation and leads to apoptosis. A. Western blot analyses of CPT1A KD cells treated with vehicle (V), orlistat (O), orlistat + etomoxir (OE), or etomoxir alone (E) for 24 hours. B. CPT1A expression in VCaP cells treated with inhibitors. C. Trypan blue viability assay of shRNA clones treated with three doses of etomoxir for 2 days; *, P < 0.01 compared with control cells treated with control shRNA clone. D. Palmitate oxidation rate in KD clones compared with control, **, P < 0.01 compared with control shRNA clone.](http://mct.aacrjournals.org)
progressive growth of tumors using a 40 mg/kg dose every other day. Significant differences were observed in the last week of treatment (ANOVA P < 0.001, posthoc P < 0.05) suggesting that systemic inhibition of fat oxidation impairs growth of implanted tumors. Animals were healthy and their body weight remained stable over the 3 weeks of treatments (Fig. 6B). CPT1A content in the tumors was still strong after 21 days, albeit weaker in the etomoxir group (Fig. 6C). Phospho-S6 (marker of mTOR action) did not show any changes. The study using 20mg/kg did not produce significant results over 3 weeks (data not shown).

Discussion

The results of our study point to an important role of β-oxidation of fatty acids in prostate cancer. We have observed a significant decrease in viability when prostate cancer cells are grown in the presence of the CPT1 inhibitor etomoxir, but this effect was not replicated in non-tumor forming cells, suggesting a possible therapeutic window for prostate cancer. Furthermore, because lipogenesis from sugar carbons is a well-documented observation in prostate cancer (36), the combinatorial approach of inhibiting fat oxidation and fat synthesis simultaneously, with etomoxir and orlistat, respectively, generated synergistic results in prostate cancer cell growth assays. Unfortunately, the main problem with targeting FASN is the low solubility and bioavailability of currently approved drugs (like orlistat), mainly due to the hydrophobicity of the FASN active site (37), making it difficult to advance to clinical trials.

ARs are involved in the activation of lipid metabolism (38) as well as the growth of prostate cancer cells, even in castration-resistant or recurrent prostate cancer (39). Very little is known about how lipids regulate the AR and its variants in prostate cancer. Our results blocking lipid catabolism and significantly decreasing AR expression in both LNCaP and VCaP cells suggest that thwarting the ability of prostate cancer cells to utilize lipids, regardless of the PTEN status, may synergize with current androgen therapies for a more effective AR blockade. Expression of PSA and NKX3.1 was also decreased, suggesting a reduced AR-signaling axis. Furthermore, benign BPH-1 cells showed higher glucose uptake than prostate cancer cells when treated with both etomoxir and orlistat, suggesting that they were able to compensate for the lipid blockade. This lack of metabolic flexibility in prostate cancer cells may contribute to their decreased viability when challenged with metabolic stress, opening doors for combinatorial treatments to be explored clinically, like etomoxir and enzalutamide.

The role of BAD proteins in sensing mitochondrial metabolism is well described (43), linking glucose use with apoptosis. Our studies provide evidence that lipid use by prostate cancer cells is also connected to the apoptotic machinery because phospho-BAD S112 was decreased in both cell lines leading to caspase activation with the drug combination. The possibility that the...
observed decreased mTOR-S6K axis is responsible for this effect needs to be further validated.

Additional consequences of blocking lipid turnover in LNCaP cells are ER stress, autophagy, and ceramide production. It is unknown which phenomenon occurs first but it is possible that accumulated palmitate in the ER (that is not oxidized) leads to activation of the unfolded protein response and a survival autophagic response, an effect that has been previously reported in yeast (44) and more recently in leukemia cells (45), where phosphorylation of eIF2α by PERK leads to a survival autophagy response. Ceramide synthesis in prostate cancer is also another potential target for therapeutic intervention. We have observed significant increases in ceramide species in LNCaP cells treated with etomoxir, suggesting that the excess fatty acids (mainly C16:0 and C18:0) that could not get oxidized in the mitochondria due to CPT1 inhibition, were used to generate proapoptotic ceramides. Indeed, ceramidases are becoming therapeutic targets for advanced prostate cancer because these degrading enzymes are abundant and contribute to chemoresistance (34).

The most significant preclinical extension of our work is the result from the prostate cancer xenografts in mice. The effect of fat oxidation inhibition in leukemia cells is well documented (13, 46), but there are no reports of its effects on prostate cancer cells, which depend on fat metabolism for survival. Results from injections with etomoxir revealed a dose-dependent effect on tumor growth without affecting the body weight or health of the mice. These results emphasize the dependence of prostate cancer cells on fatty acid availability for oxidation and ATP production. Because the use of orlistat in our in vitro studies further decreased the viability of the prostate cancer cells, this suggests that de novo lipogenesis and/or lipase activity are likely the sources of fatty acids for β-oxidation in prostate cancer cells. The possibility of using 2-DG (non-usable glucose) and etomoxir in combination is a promising therapeutic avenue for prostate cancer that needs to be explored.

Several studies have indicated that fat availability to tumors (via high-fat diets or obesity) leads to prostate cancer growth (47, 48). However, lipid markers like FASN and insulin-like growth factor-I levels do not fully explain the association between obesity and poor prostate cancer outcome (48), indicating that the availability of lipids to tumors may be an important factor worth exploring in depth. This is relevant in the setting of androgen deprivation therapy, where the metabolic syndrome with altered blood lipid profile favors increased fatty acid availability to the growing prostate cancer tumors. In addition, our data suggest that lipid catabolism also modulates AR content, likely creating a feed-forward cycle that sustains prostate cancer growth. In conclusion, systemically targeting lipid use by tumors offers possibilities to reduce prostate cancer tumor burden.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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