Metformin Inhibits Skin Tumor Promotion in Overweight and Obese Mice

L. Allyson Checkley, Okkyung Rho, Joe M. Angel, Jiyoung Cho, Jorge Blando, Linda Beltran, Stephen D. Hursting, and John DiGiovanni

Abstract
In the present study, the ability of metformin to inhibit skin tumor promotion by 12-O-tetradecanoylphorbol-13-acetate (TPA) was analyzed in mice maintained on either an overweight control diet or an obesity-inducing diet. Rapamycin was included for comparison, and a combination of metformin and rapamycin was also evaluated. Metformin (given in the drinking water) and rapamycin (given topically) inhibited development of both papillomas and squamous cell carcinomas in overweight and obese mice in a dose-dependent manner. A low-dose combination of these two compounds displayed an additive inhibitory effect on tumor development. Metformin treatment also reduced the size of papillomas. Interestingly, all treatments seemed to be at least as effective for inhibiting tumor formation in obese mice, and both metformin and rapamycin were more effective at reducing tumor size in obese mice compared with overweight control mice. The effect of metformin on skin tumor development was associated with a significant reduction in TPA-induced epidermal hyperproliferation. Furthermore, treatment with metformin led to activation of epidermal AMP-activated protein kinase (AMPK) and attenuated signaling through mTOR complex (mTORC)-1 and p70S6K. Combinations of metformin and rapamycin were more effective at blocking epidermal mTORC1 signaling induced by TPA consistent with the greater inhibitory effect on skin tumor promotion. Collectively, the current data demonstrate that metformin given in the drinking water effectively inhibited skin tumor promotion in both overweight and obese mice and that the mechanism involves activation of epidermal AMPK and attenuated signaling downstream of mTORC1.

Introduction
Metformin, a drug widely used for the treatment of type II diabetes, is effective through its ability to inhibit gluconeogenesis via activation of the LKB1/AMP-activated protein kinase (AMPK) pathway in the liver (1). Population-based studies have provided evidence that patients with type II diabetes treated with metformin have reduced cancer incidence as well as reduced mortality (2, 3). In vitro and in vivo studies have provided evidence in support of this association (4–7). Metformin, in part through its ability to activate AMPK, impacts multiple signaling pathways involved in regulating intracellular energy levels, especially signaling through mTOR complex (mTORC1; ref. 8). AMPK is a central metabolic sensor involved in the regulation of cellular energy homeostasis and is activated in response to cellular stressors that increase the AMP/ATP ratio including hypoxia, low glucose, or oxidative stress (9). In addition to inhibiting mTORC1, activation of AMPK has been shown to activate autophagy pathways in multiple cell types (10, 11). Activation of AMPK also leads to inhibition of lipid biosynthesis in multiple tissues via inhibition of acetyl CoA carboxylase (ACC1 and ACC2), fatty acid synthase, SREBP-1, as well as through activation of mitochondrial biosynthesis regulator PGC-1α (12–16). Thus, the consequences of AMPK activation make activators such as metformin attractive agents for both the prevention and treatment of a variety of cancers.

Recent evidence strongly supports an important role for Akt/mTORC1 signaling in tumor development in the mouse skin model of epithelial carcinogenesis (17). Epidermal Akt activation is sustained throughout two-stage skin carcinogenesis in mice (18), and treatment with diverse skin tumor promoters resulted in alteration (phosphorylation) of epidermal Akt downstream effectors including GSK3-β, BAD, and mTORC1 (19). Transgenic mice over-expressing insulin—like growth factor I (IGF-I) in the epidermis have increased susceptibility to two-stage skin carcinogenesis and spontaneous tumor formation as well as increased signaling through the PI3K/Akt/mTOR pathway (20, 21). Dysregulated expression of Akt in epidermis of...
transgenic mice led to alterations in mTORC1 downstream signaling and significantly heightened susceptibility to tumor promotion and two-stage skin carcinogenesis (22). Recently, we demonstrated that inhibition of mTORC1 using rapamycin dramatically inhibited skin tumor promotion by 12-O-tetradecanoylphorbol-13-acetate (TPA) primarily through blocking epidermal hyperproliferation and mTORC1 downstream signaling through p70S6K (23).

In the current study, the ability of metformin to inhibit skin tumor promotion by TPA in both overweight (modified AIN76A control diet with 10 Kcal% fat) and obese mice (60 Kcal% fat diet) was evaluated. Rapamycin and a low-dose combination of metformin and rapamycin were included in these experiments. There are very few studies in the literature to date that have evaluated host metabolic status as a variable to study the anticancer effects of metformin. Previously published data from our laboratory as well as others, have demonstrated that mice receiving a 60-Kcal% fat diet have body mass index values and demonstrate a metabolic profile similar to that seen in obese humans (24–27). Metformin significantly inhibited skin tumor promotion by TPA in both diet groups. Inhibition of tumor development by metformin was dose dependent and correlated with activation of epidermal AMPK and attenuation of TPA-induced activation of mTORC1 signaling in epidermal keratinocytes. Interestingly, a low-dose combination of metformin and rapamycin was significantly more effective at blocking skin tumor promotion and tumor development than either agent alone. Collectively, the data suggest that metformin is an effective inhibitor of skin tumor promotion by TPA and that its mechanism displays similarities to that of calorie restriction and rapamycin in the mouse skin carcinogenesis model system.

Materials and Methods

Animals and diets

FVB/N female mice (7–8 weeks of age, National Cancer Institute, Frederick, MD) were fed ad libitum and group housed for all experiments. Mice were weighed at study onset and then every 2 weeks for the duration of the experiments in accordance with institutional guidelines. For short-term studies, mice received a regular chow diet containing 10 Kcal% fat. For the tumor experiments, pelleted diets of varying caloric density [10 Kcal% fat (D12450B) and 60 Kcal% fat (D12492); Research Diets Inc.] were administered.

Two-stage skin carcinogenesis

Mice were placed on a 10 Kcal% fat diet and initiated with 25 nmol of 7,12-dimethylbenz[a]anthracene (DMBA; Sigma-Aldrich) or acetone. Two weeks after initiation, mice were randomized and received one of the two experimental diets. Six weeks later, mice were treated topically with various doses of rapamycin (2, 5, or 20 nmol) in 0.2 mL acetone (vehicle) or with metformin administered in the drinking water (50 or 250 mg/kg body weight/day; n = 15–20/group at the beginning of the study), which was replaced twice weekly and adjusted for changes in body weight every 2 weeks. At this time, mice also received twice weekly topical treatments with 6.8 nmol of TPA (LC Laboratories) for the duration of the experiments. Rapamycin (administered biweekly) was applied 30 minutes before TPA in all experiments. Tumor multiplicity (average number of papillomas per mouse) and tumor incidence (percentage of mice with papillomas) were recorded each week until multiplicity plateaued (week 25). Papillomas were measured at week 23 of tumor promotion by digital calipers, and tumor surface area was calculated. The incidence of squamous cell carcinomas (SCC) and average SCCs per mouse were determined weekly from initial detection until week 49. All SCCs were verified histologically as previously described (28–31).

Serum analysis

Blood was collected by cardiac puncture following CO₂ asphyxiation (n = 4–7/group), held at room temperature for 2 hours, spun at 7,500 rpm for 7 minutes (twice), and the serum (supernatant) was flash frozen in liquid nitrogen and stored at −80°C until analysis (10 μl sample/analysis). Serum levels of insulin and leptin were measured with a Milliplex MAP Mouse Serum Adipokine panel multiplex Luminex Assay (Millipore), adiponectin levels were measured with a Milliplex MAP Mouse Serum singleplex Luminex Assay, and IGF-I levels were determined with the Quantikine ELISA Mouse/Rat IGF-I Immunoassay (R&D Systems).

Epidermal hyperproliferation

The dorsal skin of mice was shaved and treated twice weekly for 2 weeks topically with either acetone (vehicle), 6.8 nmol of TPA, or metformin (50, 250, and 350 mg/kg body weight) administered in the drinking water (n = 3/group). Bromodeoxyuridine (BrdUrd) was injected (intraperitoneally, 100 μg/g body weight) in 0.9% NaCl 30 minutes before sacrifice. Mice were sacrificed 48 hours after the last treatment. Dorsal skin samples were fixed in 10% neutral-buffered formalin, stored in 70% ethanol, embedded in paraffin, and then sectioned for staining with H&E and anti-BrdUrd. Epidermal thickness and labeling index were determined as described previously (23).

Preparation of epidermal lysates and Western blot analysis

Mouse dorsal skin was shaved and treated twice weekly for 2 weeks with either acetone (0.2 mL) or TPA (6.8 nmol), or rapamycin, metformin or combinations of the two compounds (n = 5/group). Rapamycin (2 nmol) was applied topically 30 minutes before TPA. Metformin was administered in the drinking water at the start of the 2-week treatment period at doses of 50 or 250 mg/kg body weight per day. Mice were sacrificed 6 hours after the final treatment (acetone, TPA), epidermis was scraped, and protein lysates were prepared as previously described (23). Western blot analyses were performed as previously described.
Antibodies were obtained from Cell Signaling Technology, Inc.

Statistical analysis
An assumption of a normal distribution for comparison of tumor multiplicity, serum levels, BrdUrd labeling index, and epidermal thickness between each treatment group could not be made, and therefore a nonparametric statistical method (the one-tailed Mann–Whitney U test) was used for tests of statistical significance between treatment groups. To compare tumor incidence between treatment groups, the one-tailed Fisher exact test was used. To compare time to first tumor between groups, a one-tailed log-rank (Mantel–Cox) test was used, assigning a time point of 25 weeks to any mouse that did not develop a papilloma over the course of the study. Dose–response trend analyses were conducted using the Kruskal–Wallis test. To compare the percent decrease in papillomas per mouse and percent decrease in tumor size, the one-tailed Mann–Whitney U test was used. All comparisons were planned and the P values were not corrected for multiple comparisons. GraphPad Prism 5 software (GraphPad Software) was used for all statistical tests, and significance was set at P ≤ 0.05.

Results
Effect of metformin and rapamycin on skin tumor promotion and progression in overweight mice
A two-stage skin carcinogenesis experiment was conducted using mice maintained on the 10 Kcal% fat diet fed ad libitum (overweight control diet; refs. 25, 33). Eight weeks following initiation with DMBA, mice began receiving twice weekly treatments with TPA. Certain groups began receiving metformin in the drinking water (50 or 250 mg/kg body weight/day) or were treated topically with 5 or 20 nmol of rapamycin 30 minutes before treatment with TPA similar to our recent study (23). Metformin significantly inhibited skin tumor promotion by TPA in a dose-dependent manner (Fig. 1A). There was 36% and 72% inhibition of papilloma development in the 50 mg/kg and 250 mg/kg body weight dose groups, respectively. Although the reduction in papilloma response with the 50 mg/kg body weight per day dose of metformin was not statistically significant, the reduction with the 250 mg/kg body weight per day dose was highly significant (P < 0.01, Mann–Whitney U test). Furthermore, additional statistical analyses of these data revealed a significant dose-dependent trend for reduction in papillomas per mouse with metformin (P < 0.05; Kruskal–Wallis test). There were no significant differences in papilloma incidence observed at either dose of metformin in this experiment (Fig. 1B). Rapamycin inhibited skin tumor promotion by TPA as expected. The group receiving 5 nmol of rapamycin before TPA had a significant reduction (88%) in papilloma development at week 25 as compared with the TPA control group (P < 0.001; Mann–Whitney U test). The group receiving 20 nmol rapamycin before TPA had a 97% reduction in papilloma development (P < 0.001; Mann–Whitney U test). Similar to metformin, there was a significant dose-dependent trend for inhibition of papillomas...
with rapamycin ($P < 0.001$; Kruskal–Wallis test). As shown in Fig. 1B, the incidence of papillomas in the 5 and 20 nmol rapamycin treatment groups was significantly reduced (to 36% and 15%, respectively), at 25 weeks of promotion ($P < 0.01$ and $P < 0.001$, respectively, Fisher’s exact test). Metformin at either dose did not significantly affect tumor latency (Fig. 1B). In contrast, both doses of rapamycin significantly increased tumor latency ($P < 0.001$, Mantel–Cox test). Finally, there were no significant differences in body weight gain over the course of this experiment with any of the treatment regimens (data not shown).

All treatments in this experiment were conducted for an additional 24 weeks to evaluate the effects of metformin and rapamycin on formation of SCCs. As shown in Fig. 1C and D, both doses of metformin and rapamycin significantly decreased the number and incidence of SCCs in a dose-dependent manner consistent with the inhibition of papilloma development.

**Effect of metformin, rapamycin, and their combination on skin tumor promotion in obese mice**

A second two-stage skin carcinogenesis experiment was conducted to compare the effect of metformin in overweight versus obese mice. Mice were maintained on the modified AIN76A diet and initiated with DMBA. Two weeks following initiation, mice were randomized to receive either the obesity inducing diet (60 Kcal% fat) or the overweight control diet (10 Kcal% fat) for the duration of the study. Tumor promotion with TPA began after an additional 6 weeks on each experimental diet. Metformin was given in the drinking water at doses of either 50 or 250 mg/kg body weight per day in the obese diet groups and 50 mg/kg body weight per day in the overweight control diet groups. An additional group of mice received a low dose of topical rapamycin (2 nmol) administered before each TPA treatment and another group received a combination of rapamycin (2 nmol) and metformin (50 mg/kg). As shown in Fig. 2A, metformin treatment (50 mg/kg dose) inhibited papilloma development by 34%, whereas rapamycin treatment (2 nmol dose) inhibited papilloma development by only 19%. Neither of these reductions in tumor response was statistically significant. However, there was a 52% inhibition of papilloma development in the metformin + rapamycin treatment group compared with the TPA control group that was statistically significant ($P < 0.05$, Mann–Whitney $U$ test). The combination treatment group also exhibited a statistically significant reduction in papilloma incidence ($P < 0.05$; Fisher’s exact test; Fig. 2B). In this experiment, the groups treated with metformin and metformin + rapamycin also had significantly increased tumor latency compared with the DMBA-TPA only control group ($P < 0.05$ and $P < 0.01$, respectively, Mantel–Cox test).

Notably, both the individual treatments as well as the combination treatment produced statistically significant reductions in papilloma numbers in mice on the obesity-inducing diet (see Fig. 2C for specific $P$ values). Metformin at 50 mg/kg produced a 44% inhibition in papilloma development in the obese diet group compared with 34% in the overweight group (Fig. 2C and A, respectively). In addition, there was a 42% inhibition of papilloma development in the obese diet group with rapamycin (Fig. 2C) compared with 19% inhibition in the overweight mice (Fig. 2A). The combination of metformin + rapamycin inhibited papilloma formation in the obese diet group by 62% compared with 52% inhibition in the overweight group. No significant decreases in final tumor incidence were observed in any of the obese diet treatment groups (Fig. 2D). However, significant increases in tumor latency were observed in all treatment groups on the diet-induced obesity (DIO) diet compared with the DMBA-TPA only control group ($P < 0.01$ for all treatment groups; Mantel–Cox test).

During week 23 of the study shown in Fig. 2, a representative subset of papillomas ($n = 18–24$) from each treatment per diet group was measured to determine average surface area. All treatments led to a reduced tumor size regardless of diet (Fig. 2E and F). Except for the rapamycin only treatment group in overweight control mice, all other decreases in tumor size were statistically significant (Mann–Whitney $U$ test, $P$ values shown in Fig. 2). Interestingly, the effect of the individual compounds on tumor size seemed to be more pronounced in the obese mice. In this regard, the decrease in tumor size in obese mice was significantly greater than the decrease in tumor size in mice on the overweight control diet for the metformin and rapamycin treatment groups ($P<0.05$ for both groups; Mann–Whitney $U$ test) but not for the metformin + rapamycin group. Notably, the combination treatment dramatically reduced the size of tumors in both diet groups to similar levels, and this effect seemed to be additive in both cases.

**Influence of dietary manipulation and treatments on body weight and circulating levels of insulin, IGF-I, leptin, and adiponectin**

Figure 3A and B show the body weight gain for the various treatment groups maintained on the overweight control and DIO diets, respectively, over the course of the first 30 weeks of this study. Promotion and treatment began after the first 6 weeks represented on these figures. After 30 weeks on diet, the mean body weight (including all treatment groups) of the DIO diet group was 45.2 ± 0.86 g. These differences were statistically significant ($P < 0.05$; Mann–Whitney $U$ test). In contrast, there were no differences in mean body weight in any of the treatment groups maintained on a given diet.

Obese mice receiving TPA only had an approximately 8-fold increase in fasting serum insulin levels, an approximately 2.4-fold increase in serum IGF-I levels, and an approximately 25-fold increase in serum leptin levels relative to the overweight control mice receiving the same treatment (Fig. 3C; $P < 0.05$, Mann–Whitney $U$ test). Levels of serum adiponectin were not statistically significant in these two diet groups. Metformin at the 50 mg/kg dose significantly reduced serum insulin levels in the obese mice.
(5,427.67 \pm 1,131.5 \text{ vs. } 1,914.7 \pm 338.8 \text{ pg/mL, respectively; } P < 0.05, \text{ Mann–Whitney } U \text{ test; Fig. 3C). Similar decreases in serum insulin were observed at the 250 mg/kg dose in obese mice (5,427.67 \pm 1,131.5 \text{ vs. } 2,435.5 \pm 977.2 \text{ pg/mL, respectively; } P < 0.05, \text{ Mann–Whitney } U \text{ test). In contrast, metformin (50 mg/kg) had no effect on insulin levels in the overweight control mice. Serum adiponectin levels were not altered by any treatments in the overweight control mice. In mice on the obese diet, serum adiponectin levels were slightly elevated in the 50 mg/kg metformin treatment group (P < 0.05) but not in any of the other treated groups. Finally, leptin and IGF-I levels were not significantly altered by metformin in mice on either dietary regimen, and topical rapamycin (2 nmol per mouse) had no effect on any serum parameter analyzed in mice in either diet group.

Effect of metformin on TPA-induced epidermal hyperproliferation and hyperplasia

Figure 4A displays representative H&E and BrdUrd-stained skin sections from groups of mice treated with acetone, TPA, and 250 mg/kg metformin + TPA as described in Materials and Methods. Metformin treatment produced statistically significant decreases in both epidermal thickness and BrdUrd labeling index at all three doses used. Quantitative evaluation (Fig. 4B) revealed that metformin...
significantly reduced each of these parameters compared with the TPA control group (P < 0.05, Mann–Whitney U test) in a dose-dependent manner.

**Effect of metformin on epidermal AMPK and TPA-induced mTORC1 signaling**

As reported previously (19, 23), topical treatment with TPA resulted in activation of epidermal mTORC1 as seen through increases in p-p70S6KThr389, p-S6rSer235/236, and p-4EBP1Thr37/46, as well as degradation of the mTORC1 downstream target and translational repressor, PDCD4 (Fig. 5A). In treatment groups receiving metformin, there was a dose-dependent reduction in TPA-induced phosphorylation of p70S6KThr389 as well as S6rSer235/236 (Fig. 5A). In addition, PDCD4 was partially protected from TPA-mediated degradation with a greater effect seen at the higher dose of metformin (250 mg/kg). Metformin had no apparent effect on mTORC1-mediated phosphorylation of 4EBP1 following TPA treatment at the 50 mg/kg dose but did produce a small, statistically significant decrease at the 250 mg/kg dose. Metformin (250 mg/kg) given alone had no apparent effects on mTORC1 signaling. Analyses of AMPK activation (Fig. 5B) as measured by phosphorylation at Thr172 revealed that metformin alone increased activation of epidermal AMPK compared with the acetone control group. Both doses of metformin increased activation of AMPK compared with the TPA and acetone control groups (Fig. 5B). Figure 5C displays the quantification and statistical analyses of three independent experiments, whereas the Western blot analyses shown in Fig. 5A and B are from a single representative experiment. As a further confirmation that metformin activated epidermal AMPK,
the phosphorylation of ULK1 was also analyzed. As shown in Supplemental Fig. S1, phosphorylation of ULK1 at Ser555 was increased approximately 2-fold in epidermis of mice treated with 250 mg/kg metformin compared with the acetone control group. In contrast, TPA treatment reduced phosphorylation at this site compared with the acetone control group. Metformin at 250 mg/kg partially reversed the effect of TPA on ULK1 phosphorylation.

Effect of combination treatments with metformin and rapamycin on TPA-induced mTORC1 signaling in the epidermis

As shown in Fig. 6A, topical application of TPA again led to the activation of p70S6K, a downstream effector of mTORC1, and degradation of translation repressor, PDCD4, as measured in epidermal protein lysates prepared 6 hours after the last TPA treatment. Both metformin (50 mg/kg) and rapamycin (2 nmol) given alone inhibited these alterations. The combination of metformin + rapamycin produced a greater inhibition of the alterations in mTORC1 signaling seen following TPA treatment consistent with the greater inhibition of skin tumor promotion observed with this combination. Figure 6B displays the quantitation along with statistical analyses of combined data from three independent experiments, whereas the Western blot analysis shown in Fig. 6A is from a single representative experiment. These data further confirm that metformin given in the drinking water at a dose of 50 mg/kg inhibited mTORC1 signaling as seen in the experiment presented in Fig. 5 and that the combination of metformin + low-dose rapamycin produced a greater inhibitory effect on mTORC1 signaling.

Discussion

In the current study, metformin given in the drinking water at doses of 50 and 250 mg/kg body weight per day effectively inhibited skin tumor promotion by TPA in mice on an overweight control diet. Metformin effectively inhibited formation of both premalignant papillomas as well as SCCs. In addition, treatment with metformin reduced the size of papillomas. Mechanistic studies also revealed that metformin decreased TPA-induced epidermal hyperplasia and hyperproliferation, activated epidermal AMPK, and reduced TPA-induced mTORC1 signaling. Furthermore, a low-dose combination of metformin + rapamycin was more effective than either agent alone at the same doses. We also examined the effects of metformin, rapamycin, and the low-dose combination of metformin + rapamycin in mice maintained on an obesity-inducing diet for comparison. Metformin again effectively inhibited skin tumor promotion as did rapamycin and the combination of metformin + rapamycin. Metformin and rapamycin also reduced the size of papillomas, and this effect was greater...
in obese mice compared with that observed in overweight control mice. Overall, the data from this study demonstrate that metformin given in the drinking water is an effective inhibitor of skin tumor promotion in both overweight and obese mice.

The antitumorigenic properties of metformin have been recently explored in several in vitro and in vivo experimental systems. Studies in cancer cell lines using high concentrations have provided evidence that metformin can inhibit cell growth (6, 7). In HER-2/neu transgenic mice, metformin administered in the drinking water (100 mg/kg body weight/day) reduced the size and incidence of mammary adenocarcinomas as well as prolonged lifespan (4). In addition, metformin administered in a basal powdered diet form (250 mg/kg body weight/day) in APCmin/− mice reduced polyp growth as well as activated AMPK and reduced signaling through mTORC1 in tumor tissue (5). Recently, it was reported that metformin inhibited benzo[a]pyrene (B[a]P) as well as UVB-induced skin carcinogenesis. In this regard, metformin administered in the drinking water to female and male SHR (outbred Swiss) mice alone and in combination with melatonin significantly reduced the number and size of skin tumors induced by B[a]P (34, 35). In addition, metformin administered topically as well as systemically, suppressed the growth of existing UVB-induced skin tumors and prevented the growth of new tumors (36).

Figure 5. Effect of metformin on epidermal mTORC1 and AMPK in the absence or presence of TPA treatment. Pooled protein lysates were prepared from epidermal scrapings of FVB/N mice (n = 5/group) undergoing a multiple treatment regimen of either acetone (vehicle), metformin alone (250 mg/kg), 6.8 nmol TPA alone, or metformin + TPA (50 or 250 mg/kg body weight/day). A, representative Western blot analyses of p-p70S6K, p-56 ribosomal, PDCD4, and p-4EBP1. B, representative Western blot analyses of epidermal p-AMPK C, quantification of Western blot analyses from three independent experiments. Expression levels were normalized to β-actin and averaged. *, significantly different from the TPA-treated group (P < 0.05, Mann–Whitney U test). **, significantly different values between the indicated treatment groups (P < 0.05, Mann–Whitney U test).
to inhibit growth of A431 SCC cells in a tumor xenograft model (37). Collectively, these data and our current data demonstrate the cancer-preventive effects of metformin in a variety of animal model systems. Furthermore, the current data show that metformin primarily affects the tumor promotion stage of skin carcinogenesis in the two-stage chemical carcinogenesis model.

The anticancer activity of metformin has been attributed to both direct and indirect effects (38, 39). The primary direct mechanism of action occurs through inhibition of mitochondrial complex I and subsequent induction of cellular energy stress resulting in activation of AMPK (9). Activation of the LKB1/AMPK pathway modulates a host of downstream effectors that control cellular growth and metabolism to help regulate cellular energy balance during stress (40). Metformin has been shown to induce a growth-suppressive effect in a variety of transformed cells via inhibition of mTORC1 and reduced protein synthesis (6, 7, 41). We have shown that targeting mTORC1 effectively inhibits skin tumor promotion by TPA (ref. 23; Figs. 1 and 2, this study). Inhibition of skin tumor development in response to metformin treatment correlated with activation of epidermal AMPK and a decrease in TPA-induced mTORC1 signaling assessed by decreased levels of p-p70S6KThr389 and p-S6rSer235/236 protein. In addition, the translational repressor PDCD4, a downstream target of p70S6K, was partially protected from TPA-mediated degradation. Collectively, these data suggest that activation of epidermal AMPK and subsequent reduction of mTORC1 signaling contributed to the inhibition of skin tumor promotion by TPA. Because metformin treatment also modulated phosphorylation of ULK1 in epidermis, it is possible that activation of autophagy signaling pathways may have also contributed to the effects of metformin on skin tumor promotion, however, further work will be required to determine this possibility.

Epidemiologic data have provided evidence that patients with type II diabetes treated with metformin have reduced cancer incidence as well as reduced mortality compared with patients receiving other types of treatments for this
Metformin Inhibits Skin Tumor Promotion

1. Obese mice, which may have contributed to the overall effect of metformin was on circulating levels of insulin in the most consistent systemic change observed at both doses affected serum adiponectin levels in obese mice. Therefore, a slight but statistically significant increase in obese mice treatment-related changes in overweight control mice and a diet regimen. Analysis of adiponectin levels revealed no alteration circulating levels of IGF-I or leptin in mice on either formin at the doses used in the tumor experiments did not affect circulating levels of insulin but no change in the overweight control mice in response to metformin treatment (Fig. 3C). Metformin at the doses used in the tumor experiments did not alter circulating levels of IGF-I or leptin in mice on either diet regimen. Analysis of adiponectin levels revealed no treatment-related changes in overweight control mice and a slight but statistically significant increase in obese mice treated with 50 mg/kg metformin. No other treatment affected serum adiponectin levels in obese mice. Therefore, the most consistent systemic change observed at both doses of metformin was on circulating levels of insulin in the obese mice, which may have contributed to the overall action of metformin on tumor size in this diet group. However, the fact that rapamycin treatment was also more effective at reducing tumor size in obese mice argues against this hypothesis. Thus, additional studies are required to determine whether reduction in serum insulin levels contributed to the greater inhibition of tumor growth by metformin in obese mice.

Overall, the current data support the hypothesis that elevation of mTORC1 and subsequent activation of downstream signaling pathways are highly important events during skin tumor promotion. We show for the first time that oral administration of metformin given in the drinking water effectively inhibits skin tumor promotion in a chemically induced model of multistage skin carcinogenesis. This effect of metformin was evident in both overweight control mice as well as obese mice. Furthermore, we have shown that combinations of metformin + rapamycin are more effective at inhibiting skin tumor promotion than either compound alone. Metformin seems to be an ideal candidate for further evaluation of its chemopreventive effectiveness against multiple cancers, including skin cancer.

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

Authors’ Contributions
Conception and design: L.A. Checkley, S. Hursting, J. DiGiovanni
Development of methodology: L.A. Checkley, J. DiGiovanni
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): J.A. Checkley, I. Cho, J. Blando, S. Hursting, J. DiGiovanni
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): L.A. Checkley, O. Rho, J.M. Angel, J. Blando, J. DiGiovanni
Writing, review, and/or revision of the manuscript: L.A. Checkley, O. Rho, J.M. Angel, J. Cho, L. Beltran, S. Hursting, J. DiGiovanni
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): L.A. Checkley, J. DiGiovanni
Study supervision: L.A. Checkley, J. DiGiovanni

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