Inhibition of Lung Tumorigenesis by Metformin Is Associated with Decreased Plasma IGF-I and Diminished Receptor Tyrosine Kinase Signaling

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Abstract

Metformin is the most commonly prescribed drug for type II diabetes and is associated with decreased cancer risk. Previously, we showed that metformin prevented tobacco carcinogen (NNK)-induced lung tumorigenesis in a non-diabetic mouse model, which was associated with decreased IGF-I/insulin receptor signaling but not activation of AMPK in lung tissues, as well as decreased circulating levels of IGF-I and insulin. Here, we used liver IGF-I–deficient (LID) mice to determine the importance of IGF-I in NNK-induced lung tumorigenesis and chemoprevention by metformin. LID mice had decreased lung tumor multiplicity and burden compared with wild-type (WT) mice. Metformin further decreased lung tumorigenesis in LID mice without affecting IGF-I levels, suggesting that metformin can act through IGF-I-independent mechanisms. In lung tissues, metformin decreased phosphorylation of multiple receptor tyrosine kinases (RTK) as well as levels of GTP-bound Ras independently of AMPK. Metformin also diminished plasma levels of several cognate ligands for these RTKs. Tissue distribution studies using [14C]-metformin showed that uptake of metformin was high in liver but four-fold lower in lungs, suggesting that the suppression of RTK activation by metformin occurs predominantly via systemic, indirect effects. Systemic inhibition of circulating growth factors and local RTK signaling are new AMPK-independent mechanisms of action of metformin that could underlie its ability to prevent tobacco carcinogen–induced lung tumorigenesis. Cancer Prev Res; 6(8); 801–10. ©2013 AACR.

Introduction

Lung cancer is the leading cause of cancer-related death worldwide, and no effective chemopreventive agents currently exist (1). Because a majority of lung cancers are associated with tobacco use (85%–90%), the development of chemopreventive agents is a priority for current or former smokers at high risk for this disease. The most common molecular driver in smoking-related lung cancer is K-ras, which is mutated in 20% to 30% of lung adenocarcinomas. Currently, no therapies against KRAS exist (2).

To address the need for targeted chemopreventive agents, strategies to inhibit ancillary pathways that cooperate with KRAS to decrease lung tumor formation are being developed. An example of such a strategy includes modulation of the insulin-like growth factor receptor (IGF-IR) pathway, which plays a critical role in cell metabolism, growth, and development (3, 4). While elevated levels of circulating IGF-I are associated with increased risk of breast, prostate, and colorectal cancers (5–7), it is unclear whether such an association exists in lung cancer, possibly due to a lower incidence of obesity in smokers at high risk to develop the disease (8). Preclinical studies show that overexpression of IGF-I in alveolar type II cells in lung tissues increases spontaneous tumor formation and synergizes with tobacco carcinogen (TC) exposure to accelerate lung tumorigenesis (9). Treatment with a specific IGF-IR inhibitor significantly decreased IGF-I/TC–induced lung tumor progression in this model (9). Although lung cancer clinical trials with drugs that inhibit IGF-IR such as figitumumab, an anti-IGF-IR antibody, have been disappointing, high levels of circulating IGF-I were retrospectively identified as a possible predictive biomarker of clinical benefit (10). These studies suggest that IGF-I plays a role in lung carcinogenesis and that genetic and pharmacologic manipulation of IGF-I in murine models of lung cancer might better define its role.

Metformin (1,1-dimethylbiguanide) is the most commonly prescribed anti-diabetic drug in the world. In diabetics, metformin activates AMP-activated protein kinase (AMPK) in the liver, which inhibits hepatic gluconeogenesis with subsequent decreases in insulin and IGF-I (11, 12).
Population-based studies show that metformin use is associated with decreased cancer risk, suggesting a potential role as an anti-cancer agent (13, 14). The mechanism of metformin action in cancer remains unclear, and recent evidence suggests that metformin exerts antineoplastic effects through pathways independent of AMPK, including inhibition of mTOR (15, 16). The fact that metformin must be actively transported into cells by transporters such as the organic cation transporter-1 (OCT-1) that are primarily expressed in the liver raises questions as to whether metformin has direct effects in target tissues (17, 18). Therefore, distinguishing between direct cellular actions and indirect systemic effects is critical for determining how metformin prevents cancer.

Our laboratory has shown that metformin prevents tobacco carcinogen (NNK)-induced lung tumorigenesis (19) in a model that is characterized by mutation in KRAS and increased activation of the mTOR pathway (20–22). Oral metformin reduced lung tumor burden by 40% to 50%, whereas intraperitoneal (i.p.) metformin decreased tumor burden by 72% (19). Despite the fact that AMPK was not activated in the lungs of metformin-treated mice, significant inhibition of IGF-IR/IR and downstream mTOR signaling was observed (19). Metformin also decreased circulating levels of insulin and IGF-1 by about 35% and 21%, respectively (19). To explain these data, we hypothesized that either modest but prolonged suppression of IGF-1/insulin signaling by metformin is sufficient to inhibit lung tumorigenesis or that inhibition of additional signaling pathways is involved. In support of the second hypothesis, metformin use has been associated with decrease in several growth factors and hormones in patients with diabetes or polycystic ovarian syndrome (23, 24).

Here, we investigate the role of IGF-1 in the ability of metformin to prevent lung tumorigenesis. Liver IGF-1-deficient (LID) mice, which have a 75% reduction in circulating IGF-1 levels (25), exhibited a marked decrease in NNK-induced lung tumorigenesis compared with wild-type (WT) mice. Metformin further prevented tumorigenesis in LID mice, which was associated with inhibition of several RTK signaling networks in lung tissues independently of local AMPK activation. Biodistribution studies showed that lung tissues had low metformin uptake relative to liver, supporting the concept of indirect mechanisms of chemoprevention by metformin in target tissues. These studies not only identified IGF-1 as a target for lung cancer chemoprevention but also describe a novel, systemic mode of metformin action that may underlie its chemopreventive effect in a variety of tissues.

Materials and Methods

Materials

LID mice were generated by Dr. Derek LeRoith (Mount Sinai Hospital) as previously described (25) and kindly provided to us by Dr. Stephen Hursting (UT-Austin). NNK was purchased from Toronto Research Chemicals. Primary antibodies for immunoblotting analysis were purchased from Cell Signaling Technologies. Metformin (1,1-dimethylbiguanide hydrochloride) was obtained from Sigma Chemicals. The Mouse Phospho-RTK Array kit and Growth Factor ELISAs were purchased from R&D Systems. The Ras Activation Assay Kit was purchased from Millipore. Metformin [biguanide-14C] was obtained from Moravek Biochemicals and Radiochemicals. The Enzylight ATP and Enzylight Lactate Assay Kits were purchased from BioAssay Systems.

Administration of NNK and metformin to A/J mice

All mice were housed according to the guidelines of the Animal Care and Use Committee under an approved animal protocol. LID mice were backcrossed 6 times into the A/J background to make them susceptible to NNK and genotyped using PCR for the presence of the Cre transgene and the LoxP sites flanking the fourth exon of the IGF-I gene, as described elsewhere (26). For the tumorigenesis studies, 8-week-old mice were given 3 weekly injections of 100 mg/kg NNK as previously described (19). One week following the last dose of NNK, mice were randomized into a control group or a group that received 5 mg/mL metformin dissolved in drinking water (n = 8 mice per group). For short-term biomarker studies, 8-week-old mice were treated once daily for 3 days with 200 μL saline or 250 mg/kg metformin. One hour following the third injection, mice were anesthetized using isofluorane and blood was collected by cardiac puncture using BD vacutainer vials containing EDTA. Plasma was obtained by centrifugation. Lung and liver tissues were harvested and snap-frozen in liquid nitrogen. Tissues were crushed on dry ice and lysed in radioimmunoprecipitation (RIPA) buffer containing protease inhibitors (Complete; Roche Applied Science) and phosphatase inhibitor cocktails I and II (Sigma).

RTK arrays

RTK arrays were conducted on lung lysates according to the manufacturer’s instructions. Briefly, 250 μg of protein was incubated with the array membrane containing antibodies for 39 different murine RTKs. Next, the arrays were incubated with anti-phospho-tyrosine-HRP detection antibody and then exposed to chemiluminescent reagents. Using ImageJ software, densitometry was conducted on duplicate spots of each antibody and expressed as a ratio over positive control spots in the upper right-hand corner of each array. Phosphorylation of each RTK was compared between vehicle and metformin-treated samples (n = 8 per group).

Western blot analysis

Immunoblotting of tissue or cell lysates was done as described previously. Briefly, protein concentrations were determined using the BCA Protein Assay Kit (Pierce Bioscience), and equal amounts of total protein were resolved on 10% SDS-PAGE gels. Proteins were transferred to nitrocellulose membranes, blocked in PBS containing 5% nonfat dry milk and 0.1% Tween-20, and then incubated overnight at 4°C with the appropriate primary antibody. For p-AMPK, p-IGF-IR/IR, and p-Met, antibodies
were used at 1:500 dilutions. All other antibodies were diluted 1:1,000. Bands were detected using horseradish peroxidase–labeled secondary antibodies (Cell Signaling Technologies) and enhanced chemiluminescence kit (GE Healthcare).

**Cell culture**

IO33 cell lines were generated from A/J mouse lung adenocarcinomas induced by NNK and kindly provided by Dr. Steven Belinsky in 2005 (27). Kras mutation was verified by sequencing in 2007, and cells used in experiments were within 8 passages of Kras mutation verification. AMPK<sup>−/−</sup> mouse embryonic fibroblasts (MEF) were obtained from Dr. Keith Laderoute and were described previously (28). The genotype of these MEFs was determined by PCR and immunoblotting (28) and confirmed in our laboratory upon receipt. Cells lines were incubated at 37°C in a 5.0% CO<sub>2</sub> atmosphere and maintained in RPMI media supplemented with 5% (v/v) FBS. Metformin was dissolved directly into media, and cells were treated at the given concentrations for 24 hours. Cells were harvested in cold lysis buffer (50 mmol/L Tris, 300 mmol/L NaCl, 0.1% NP40) containing protease inhibitors (Complete; Roche Applied Science) and phosphatase inhibitor cocktails I and II (Sigma).

**14C-Metformin biodistribution studies**

Eight-week-old A/J mice were injected intraperitoneally with 200 μL of metformin (250 mg/kg containing 14C-metformin at 100 μCi/kg body weight) prepared in 0.9% saline. One hour after injection, mice were sacrificed by cervical dislocation and tissues were harvested and weighed. Tissues were solubilized for 4 hours at 50°C in Soluene-350 (PerkinElmer) and then added to 10 mL of Ultima Gold (PerkinElmer) scintillation fluid. Radioactivity was measured using a liquid scintillation counter, and CPM was converted to μCi/kg of wet tissue. The amount of metformin uptake in tissues was expressed relative to liver uptake for each mouse. For gavage administration, 200 μL of metformin (5 mg/mL containing 14C-metformin at 100 μCi/kg body weight) was administered and mice were sacrificed 1 hour later. For ad libitum oral administration, mice were given 5 mg/mL metformin containing 14C-metformin dissolved in drinking water for 5 days before sacrifice. Six mice per group were used for each administration route.

**Growth factor ELISAs**

Levels of various growth factors (EGF, FGF, HGF, VEGF) were analyzed from plasma using the appropriate QuantiKine ELISA Kits (R&D Systems) according to the manufacturer’s protocol.

**ATP and lactate assays**

IO33 cells treated with varying concentrations of metformin for 24 hours, or mouse liver and lungs treated with metformin (250 mg/kg i.p. qdx3), were harvested and subjected to the Enzylight ATP or Lactate Assay Kits (Bio-Assay Systems), according to the manufacturer’s protocol.

**Statistics**

Data are presented as mean ± SD. Statistical significance was determined between groups using an unpaired 2-tailed Student t test. *P* < 0.05 was considered significant.

**Results**

**Mice with reduced IGF-I levels exhibit decreased susceptibility to lung tumorigenesis, which is potentiated by metformin treatment**

To specifically determine the role of circulating IGF-I in NNK-induced lung tumorigenesis, we used LID mice that were backcrossed 7 generations into the A/J strain, thereby inducing susceptibility to NNK. After treatment with NNK, lung tumor multiplicity, size, and burden were significantly decreased in LID mice compared with WT mice (67%, 40%, and 74% decrease, respectively; Fig. 1A–C). In WT mice, oral metformin decreased lung tumor multiplicity and burden to a similar extent as our previous study (64% and 77% decrease, respectively). LID mice treated with metformin had further inhibition of lung tumorigenesis. Tumor multiplicity and burden were decreased significantly in LID mice in the metformin group compared with the control group (76% and 85%, respectively). These data indicate that basal levels of IGF-I determine response to NNK and that metformin further potentiates the protective effect of IGF-I loss.

Because LID mice have lower but not absent levels of circulating IGF-I, it was possible that the additive effect of metformin could be due to ablation of the remaining circulating IGF-I. Therefore, we measured plasma IGF-I levels in the 4 groups at the end of the tumorigenesis study. LID mice had IGF-I levels 75% lower than WT mice (Fig. 1D), consistent with previous studies. In WT mice, metformin decreased levels of IGF-I by 28%. In LID mice, metformin had no effect on the remaining circulating IGF-I, disproving the hypothesis that metformin works through further decreasing IGF-I levels in LID mice.

Because metformin decreases insulin levels in diabetics, insulin levels were also measured, even though this is not a diabetic model. LID mice had 3-fold higher levels of insulin compared with WT mice (Fig. 1E), and all treatment groups were normoglycemic (Fig. 1F), which has been previously described. Although there was a trend toward a small decrease in insulin levels in WT mice with metformin, it did not reach statistical significance. Metformin decreased insulin levels by 36% in LID mice but did not return insulin to basal levels observed in WT mice. Taken together, metformin modestly decreases IGF-I but not insulin in WT mice. In LID mice, it has no effect on IGF-I but modestly decreases insulin levels. These studies show that circulating IGF-I promotes lung tumorigenesis and that metformin potentiates the preventive effect of IGF-I loss, suggesting that other signaling pathways are involved.

**Metformin inhibits phosphorylation of multiple RTKs in lung tissues and decreases circulating levels of their cognate ligands**

To investigate other potential targets of metformin, we assessed the activation status of 39 RTKs in lung tissues from...
mice given 3 daily injections of metformin (representative RTK array blots in Fig. 2A). 18 of the 39 RTKs exhibited greater than a 40% reduction in phosphorylation with metformin ($P < 0.05$; Fig. 2B). Many of these RTKs have been linked to lung tumorigenesis or have been identified as molecular targets in lung cancer, including EGFRs (29), FGFRs (30, 31), c-Met (32), and VEGFRs (33). To validate the changes in RTK signaling, immunoblotting for specific RTKs was conducted on the basis of antibody availability. We confirmed significant decreases in phosphorylation of IGF-IR/IR, EGFR, VEGFR2, cMET, and FGFR without changes in total levels of these RTKs (Fig. 2C and Supplementary Fig. S1). The change in phosphorylation of certain RTKs from the array in Fig. 2A, such as Axl and TrkC, could not be confirmed by immunoblotting (Supplementary Fig. S2). Therefore, these receptors were not pursued further. As reported previously, no activation of AMPK was observed in lung tissues. To assess whether RTK inhibition by metformin could be attributed to decreases in their respective circulating ligands, quantitative ELISA assays for EGF, HGF, FGF, and VEGF were conducted on plasma from the same mice treated with metformin (Fig. 2D). Metformin modestly, but significantly, decreased circulating plasma levels of EGF, HGF, and FGF by 32%, 24%, and 31%, respectively. The same circulating growth factors were also decreased by 13 weeks of oral metformin administration in the NNK-treated mice (Supplementary Fig. S3). No differences in VEGF levels were observed (data not shown). Together, these data suggest that metformin inhibits multiple RTKs in lung tissues by decreasing levels of their circulating ligands.

To confirm modulation of RTK activation, we analyzed RTK status after oral administration of metformin under conditions where lung tumorigenesis was inhibited (Fig. 2E). The same RTKs that were inhibited by short-term injection of metformin were also inhibited by 13 weeks of oral administration. However, the response of RTKs in lung tissues to oral metformin appeared to depend on administration of NNK. For example, oral administration of metformin for 13 weeks without NNK did not yield observable decreases in lung RTK phosphorylation (Supplementary Fig. S4). Because RTKs require Ras for signal propagation and NNK induces mutations in KRAS with subsequent mTOR activation, we analyzed the Ras/MEK/ERK and Akt/mTOR pathways in lungs from these mice. Oral metformin suppressed the formation of active, GTP-bound Ras, phosphorylation of MEK and ERK, and phosphorylation of Akt and S6 (a substrate of mTOR; Fig. 2E), indicating broad inhibition of RTK-stimulated signaling networks by metformin. Broad inhibition of local RTK signaling could create an unfavorable environment for the development and progression of NNK-induced lung tumors.

**Metformin decreases RTK activation in the absence of AMPK in vitro**

AMPK is the best-studied molecular target of metformin; however, no changes in AMPK activation were observed in metformin-treated lungs. To investigate the dependence of RTK inhibition on AMPK, we analyzed RTK phosphorylation and downstream signaling in vitro using AMPK-deficient MEs. Metformin inhibited phosphorylation of the 5 RTKs that were decreased by metformin in vivo (IGF-IR/IR, EGFR, VEGFR2, cMET, and FGFR). The Ras/Mek/Erk and Akt/mTOR pathways were also inhibited in a dose-dependent manner (Fig. 3). These studies confirm that RTK inhibition by metformin is independent of AMPK.

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**Figure 1.** Reduced susceptibility to NNK-induced lung tumorigenesis in LID mice is potentiated by metformin (Met) treatment. Tumor multiplicity (A), tumor volume (B), and tumor burden (C) were assessed in WT or LID mice treated with or without 13 weeks of 5 mg/mL oral metformin after NNK exposure ($n = 8$ mice per group). Each point represents one mouse and lines represent mean values ± SD, * $P < 0.01$. Plasma IGF-I (D), plasma insulin (E), and blood glucose (F) were measured in mice at the end of the tumorigenesis study ($n = 4$ mice per group).
Metformin exhibits tissue-specific distribution

Although the in vitro studies confirm inhibition of RTK signaling by metformin, these experiments required millimolar concentrations of metformin that can rarely, if ever, be achieved in patients, as steady-state concentrations of metformin in patients with diabetes are 0.5 to 2 \( \mu \)g/mL (\textbf{~}4–15 \( \mu \)mol/L; ref. 34). Therefore, we hypothesized that systemic effects of metformin are primarily responsible for decreased RTK signaling and decreased lung tumorigenesis rather than direct effects of metformin in lung tissues.

**Figure 2.** Metformin inhibits activation of multiple lung RTKs and decreases levels of their circulating ligands. A, A/J mice were treated with metformin (250 mg/kg i.p. daily for three days). One hour after the last injection, lungs were harvested and snap-frozen. Lung lysates were analyzed using mouse phospho-RTK arrays (R&D Systems). B, densitometry was conducted for these arrays using ImageJ software to compare vehicle and metformin-treated samples. RTKs listed are those that exhibited at least a 40% decrease in signal and statistical significance (\( P < 0.05, n = 8 \)). C, to confirm the RTK array results, Western blotting was conducted on parallel samples. D, plasma from these mice was also collected and growth factor levels were measured using the appropriate ELISA kit. E, A/J mice were exposed to NNK (100 mg/kg i.p. weekly for three weeks) to induce lung tumorigenesis and then treated with 5 mg/mL metformin in drinking water for 13 weeks. Immunoblotting of lung lysates was conducted for RTKs and downstream components of the Ras/Mek/Erk and Akt/mTOR pathways.

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Figure 3. Metformin inhibits activation of RTKs and downstream targets independently of AMPK. AMPK\( \text{KO}\) MEFs were treated for 24 hours with the indicated doses of metformin. Immunoblots are representative of 3 independent experiments.

Metformin inhibits activation of RTKs and downstream targets independently of AMPK. AMPK\( \text{KO}\) MEFs were treated for 24 hours with the indicated doses of metformin. Immunoblots are representative of 3 independent experiments.
directly measure metformin uptake, we conducted a biodistribution study in mice using \(^{14}\)C-labelled metformin. Three different routes of administration were tested: i.p. (Fig. 4A), gavage (Fig. 4B), and oral \textit{ad libitum} (Fig. 4C). For the i.p. and gavage studies, tissues were harvested 1 hour after administration, the time at which \(C_{\text{max}}\) occurs in patients. With i.p. or gavage administration, metformin levels were about 4.5 times higher in liver than in lungs, and the overall distribution patterns were similar. Only kidney and colon had higher metformin levels than liver with i.p. injection, which could be due to the proximity of injections to these organs that could result in artificially high local concentrations. In mice that were allowed to drink oral metformin \textit{ad libitum}, absolute levels of metformin were extremely low compared with i.p. or gavage administration (Supplementary Fig. S5A). Uptake in tissues was more uniform in the \textit{ad libitum} oral group compared with i.p. and gavage, suggesting that metformin equilibrates across tissues after continuous low-dose exposure (Supplementary Fig. S5B). The higher uptake of metformin in livers compared with lung tissues is consistent with higher levels of expression of metformin transporters and the ability of metformin to activate AMPK in liver tissues.

**Metformin does not alter energy metabolism in lungs**

Metformin administration in mice has been shown to reduce the energy state in the liver, resulting in a 3-fold increase in AMP/ATP ratio compared with control mice (35). It also hampers the mitochondrial complex I in hepatocytes, which inhibits oxidative phosphorylation and induces glycolysis (36). Therefore, we tested whether metformin induces similar metabolic effects in lungs by measuring ATP and lactate levels. No changes in ATP levels were observed in metformin-treated mouse liver or lungs in our study (Fig. 5A). Although these data are inconsistent with previous reports showing decreased hepatic ATP levels after metformin treatment (35), this could be due to administration route or mouse strain. For example, Foretz and colleagues used C57BL/6J mice treated orally for 5 days, whereas our study used A/J mice treated i.p. for 3 days. Metformin significantly increased lactate levels in liver, however, lactate was unchanged in metformin-treated lungs (Fig. 5B). These metabolites were also measured in metformin-treated IO33 cells \textit{in vitro}, a cell line derived from a murine lung adenocarcinoma caused by NNK. In IO33 cells, millimolar concentrations of metformin decreased ATP levels and dose dependently increased lactate levels (Fig. 5C). Immunoblotting confirmed dose-dependent...
AMPK activation as well as RTK inhibition (Fig. 5D). Together, these results suggest that the ability of metformin to inhibit mitochondrial ATP production and induce glycolysis is not a relevant mechanism in lung tissues in vivo, consistent with the observation that AMPK is not activated in lung tissues after metformin treatment.

Discussion

The mechanism of action of metformin in cancer remains a controversial issue, given the abundant but conflicting data across tissues and cell lines. Initially, it was shown that the primary mode of metformin action was disruption of mitochondrial complex I, leading to a decrease in ATP production and activation of the energy sensor AMPK (36, 37). In this setting, metformin imposes a bioenergetic crisis that forces cells to adapt by shutting down catabolic processes and switching from oxidative phosphorylation to glycolysis (38). Indeed, metformin-induced activation of AMPK affects many metabolic processes in liver, muscle, and fat leading to reduced glucose production and increased insulin sensitivity (11, 12, 39). However, these mechanisms may be more relevant for its anti-diabetic properties. In the setting of cancer, it was initially proposed that AMPK activation by metformin leads to inhibition of mTORC1 in a TSC1/2-dependent manner (40). However, metformin can suppress mTORC1 independently of AMPK activation (15, 16, 19).

Our current studies indicate that NNK-induced lung tumorigenesis is dependent upon the IGF-I/insulin signaling pathway. By using LID mice that have decreased circulating IGF-I levels, we showed that loss of IGF-I alone is sufficient to markedly inhibit lung tumorigenesis. LID mice are protected from a variety of cancer types (41–43), but this is the first study showing decreased lung tumor susceptibility in this model. Although large phase III trials with drugs targeting IGF-IR such as figitumumab have not shown clinical benefit in advanced-stage lung cancer, our study suggests that the IGF-I pathway plays an important, early role in carcinogenesis, implying that IGF-I signaling may be a better target for cancer prevention. Administration of metformin to LID mice suppressed lung tumorigenesis even further, suggesting that even if IGF-I were an important target of metformin, it does not explain all of its antitumor effects. LID mice exhibit high insulin levels as a compensatory mechanism for reduced IGF-I, which maintains normoglycemia. Although it is possible that lowering insulin levels in LID mice by metformin might contribute to its antitumor effects, we believe this is unlikely for several reasons. First, insulin levels were still 2-fold above baseline after metformin treatment. It is unlikely that this reduction explains the 90% reduction in lung tumor burden in LID mice treated with metformin. If insulin were an important promoter of lung tumorigenesis, we might expect the compensatory hyperinsulinemia observed in LID mice to counteract the loss of IGF-I and tumorigenesis to be similar between LID and WT mice. This was not the case, as loss of IGF-I alone (and hyperinsulinemia) markedly reduced lung tumorigenesis. Second, activation of IGF-IR/IR in lung tissues is much more responsive to exogenously administered IGF-I than insulin (19). Although a role for
insulin cannot be eliminated, it is unlikely that modulation of insulin by metformin significantly contributing to the decreased lung tumorigenesis in this model system.

The fact that metformin further suppressed lung tumorigenesis in LID mice without decreasing the levels of remaining IGF-I led us to hypothesize that metformin was affecting other growth factor pathways. An unbiased RTK phosphorylation assay showed that metformin suppresses the activation of multiple RTKs, most notably EGFR, cMET, VEGFR, and FGFR, all of which are implicated in lung tumorigenesis. Receptor tyrosine phosphorylation plays a critical role in oncogenesis and drug resistance, and aberrant activation of RTKs occurs frequently in cancer (44, 45). The Ras/Mek/Erk and Akt/mTOR pathways represent 2 intracellular points of convergence for RTK signaling, both of which are inhibited by metformin treatment.

Several reports have shown inhibitory effects of metformin on RTK regulation in breast cancer models, where metformin disrupted erbB2/IGF-1R complexes and inhibited erbB3 activity (46–48). Our study suggests that the effect of metformin on certain RTKs is due to decreased circulation of their respective ligands. The biologic origins of these growth factors vary, IGF-I is primarily synthesized in the liver, EGF is secreted primarily by the salivary glands (49), HGF is secreted by mesenchymal and hematopoietic cells (50), and FGFs are produced in most epithelial cells (51). Growth factors are also upregulated and secreted by cancer cells to locally promote growth in an autocrine fashion (52). On the basis of the high hepatic uptake of metformin, we hypothesize that metformin primarily inhibits liver-derived growth factor production that ultimately inhibits RTK signaling in end organs. The mechanism by which metformin decreases serum levels of growth factors is unexplained. Because trace levels of metformin were observed in the lungs, we cannot rule out other local mechanisms that may contribute to decreased RTK activation, such as induction of RTK phosphatases such as PTP1B and PTPN12 (53). The basis for broad RTK inhibition is under investigation.

Ras mutations are found in approximately 30% of all human tumors (54), with KRAS mutations being the most prevalent in pancreatic (55, 56), colorectal (57), and lung cancers (58). Targeting Ras has become an active area of pharmaceutical development, with efforts focusing on inhibiting Ras expression, inhibiting membrane localization, modulating Ras interaction with GEFs or GAPs, or inhibiting Ras effectors (59–61). Unfortunately, no approved agents currently exist. This report identifies metformin as a well-tolerated, inexpensive U.S. Food and Drug Administration (FDA)-approved drug that dampens Ras signaling through additive inhibition of upstream RTKs. Although NNK induces KRAS mutations in more than 90% of lung tumors, the total tumor volume induced by NNK occupies a small portion of lung volume. Therefore, the Ras activity data obtained in these studies with lung lysates likely reflects a small contribution of tumor tissue and is indicative of the ability of metformin to inhibit WT Ras. It is unknown whether metformin can inhibit the activity of mutant Kras. Nonetheless, the fact that metformin inhibits several RTKs and Ras at steady-state levels similar to those observed in patients with diabetes suggests that metformin might have activity in a variety of RAS- or RTK-driven cancers. We propose a novel systemic mechanism of action for metformin, whereby metformin creates a suboptimal environment for tumor growth in target tissues by limiting the availability of circulating growth factors that decreases activation of RTK signaling networks. Importantly, these studies show that the chemopreventive efficacy of metformin is not limited to diabetic models. Such mechanisms could be validated in clinical prevention trials, especially those that focus on current or former smokers at high risk for lung cancer.

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

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