The Chemopreventive Agent Myoinositol Inhibits Akt and Extracellular Signal-Regulated Kinase in Bronchial Lesions from Heavy Smokers

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Abstract Myoinositol is an isomer of glucose that has chemopreventive activity in animal models of cancer. In a recent phase I clinical trial, myoinositol administration correlated with a statistically significant regression of preexisting bronchial dysplastic lesions in heavy smokers. To shed light on the potential mechanisms involved, activation of Akt and extracellular signal-regulated kinase (ERK), two kinases that control cellular proliferation and survival, was assessed in 206 paired bronchial biopsies from 21 patients who participated in this clinical trial. Before myoinositol treatment, strongly positive staining for activation of Akt was detected in 27% of hyperplastic/metaplastic lesions and 58% of dysplastic lesions ($P = 0.05$, $\chi^2$-test). There was also a trend toward increased activation of ERK (28% in regions of hyperplasia/metaplasia to 42% of dysplastic lesions). Following myoinositol treatment, significant decreases in Akt and ERK phosphorylation were observed in dysplastic ($P < 0.01$ and 0.05, respectively) but not hyperplastic/metaplastic lesions ($P > 0.05$). In vitro, myoinositol decreased endogenous and tobacco carcinogen–induced activation of Akt and ERK in immortalized human bronchial epithelial cells, which decreased cell proliferation and induced a $G_0$–$S$ cell cycle arrest. These results show that the phenotypic progression of premalignant bronchial lesions from smokers correlates with increased activation of Akt and ERK and that these kinases are targets of myoinositol. Moreover, they suggest that myoinositol might cause regression of bronchial dysplastic lesions through inhibition of active Akt and ERK.

Lung cancer is the leading cause of cancer mortality in the United States (1) and tobacco smoking is the greatest risk factor (2). Because current treatments for advanced disease are only palliative, prevention becomes an important strategy to mitigate the death and suffering due to lung cancer, particularly in high-risk populations of current and former smokers. The phosphatidylinositol 3-kinase (PI3K)/Akt/mammalian target of rapamycin pathway is an important signal transduction pathway that controls processes integral in the development of cancer, including protein translation, growth, metabolism, and survival. The clinical importance of Akt activation in lung cancer has been shown by showing it is detected in human bronchial dysplastic lesions and early-stage non–small cell lung cancer (NSCLC) specimens and confers a poor prognosis (3, 4). Akt is activated following activation of class I PI3K. The products of PI3K bind to the pleckstrin homology domain of Akt and induce its translocation to the plasma membrane, where it is phosphorylated on T308 by PDK-1 and on S473 by the rictor/mammalian target of rapamycin TORC2 complex as well as possibly by other proteins. Phosphorylation of both T308 and S473 is required for full kinase activity. Our previous studies have shown that evaluation of both sites of phosphorylation improves the prognostic value of Akt activation and that T308 alone was valuable and sufficient to indicate a poor prognosis for patients with stage I disease or with tumors ≤ 5 cm (4).

Tobacco components, such as nicotine or the tobacco-specific carcinogen 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK), activate the PI3K/Akt pathway in normal human bronchial and alveolar epithelial and NSCLC cells, which increases Akt-dependent proliferation and survival (5, 6). Nicotine or NNK can also lead to phosphorylation and activation of extracellular signal-regulated kinase (ERK) 1/2, a widely conserved member of the mitogen-activated protein kinase family (7–9). Activation of ERK1/2 is associated with advanced NSCLC tumors (10) and can lead to phosphorylation of a variety of nuclear substrates that are associated with proliferation and can result in malignant transformation both in vitro and in vivo (11, 12). These studies suggest that activation of Akt and ERK by tobacco carcinogens might contribute to the development of
lung cancer in smokers and that activated Akt and/or ERK could have value as targets for lung cancer prevention.

Although inhibitors of the PI3K/Akt pathway or mitogen-activated protein/ERK kinase (MEK)/ERK pathway are being developed as cancer therapeutics, toxicity profiles are likely to make them less attractive for chemoprevention than agents such as myoinositol that are present in the human diet. Myoinositol is equivalent to the head group of phosphatidylinositol, the basic substrate for PI3K, and its structure is similar to D-3-deoxy-3-fluoro-PtdIns, a known PI3K inhibitor. It has been reported that blocking both PI3K and ERK is involved in inositol-mediated anticancer activity (13–15). Moreover, inositol hexaphosphate (IP6) can directly target PI3K in an in vitro assay (15, 16). Myoinositol inhibits tobacco carcinogen–induced lung tumorigenesis in A/J mice and is one of the few agents that can suppress tumorigenesis when administered either before or after the carcinogen (17). This compound and its phosphorylated derivatives have little toxicity in animal models (18). A recent phase I clinical trial showed that myoinositol was well tolerated and possibly effective in causing regression of preexisting bronchial dysplastic lesions in heavy smokers (19). However, the molecular mechanisms responsible for this effect are still unclear. Because of the promising results obtained in this trial, we hypothesized that myoinositol may have targeted Akt and/or ERK in the bronchial epithelium of the heavy smokers in this trial, which may have contributed to the observed regression of bronchial dysplastic lesions.

Materials and Methods

Tissue specimens

Two hundred and six paired bronchial biopsies acquired before or after myoinositol treatment were obtained from 21 smokers with smoking histories of ≥30 pack-years who enrolled in a phase I clinical trial conducted by the British Columbia Cancer Agency and the University of British Columbia, Canada (19). The details of the study population, treatment response, and toxicity in the myoinositol phase I trial were reported elsewhere (19). Briefly, current and former smokers between 40 and 74 y of age, with a ≥30 pack-year smoking history, and one or more sites of bronchial dysplasia, were enrolled in the study. The details of the study population, treatment response, and toxicity in the myoinositol phase I trial were reported elsewhere (19). The baseline characteristics of the study population, treatment response, and toxicity in the myoinositol phase I trial were reported elsewhere (19).

Expression of active Akt and ERK in bronchial tissues

Two hundred and six bronchial biopsies from 21 smokers that participated in the myoinositol phase I clinical trial were composed of 103 paired, pre- and post-myoinositol samples that included 5 normal specimens, 67 specimens displaying hyperplasia/metaplasia, and 31 dysplastic specimens (19). Baseline levels of P-Akt and P-ERK were assessed in the pretreatment samples by immunohistochemistry. Staining was barely evident in normal specimens (Fig. 1A, top). In dysplastic specimens, P-Akt displayed nuclear and cytoplasmic expression patterns (Fig. 1A, bottom left), and P-ERK showed mainly nuclear localization and less cytoplasmic expression (Fig. 1A, bottom right). Active Akt was detected in 90% of the dysplastic specimens, with 58% staining strongly positive and 32% staining moderately positive (Fig. 1B). Active Akt was also observed in 71% of the hyperplastic/metaplastic specimens, including 27% that were strongly positive and 44% that were moderately positive. The increased frequency of strong P-Akt expression from hyperplasia/metaplasia to dysplasia was statistically significant (P = 0.05, χ² test). All normal bronchial epithelial specimens displayed either weakly positive or negative expression for P-Akt and P-ERK (data not shown). The expression of active Akt and ERK was coordinate in that 52% of hyperplastic/
metaplastic lesions and 68% of the dysplastic lesions showed positive staining for both P-Akt and P-ERK (Fig. 1C).

Effect of myoinositol on activation of Akt and ERK in bronchial tissues

To assess if myoinositol administration could modulate levels of active Akt and ERK in the bronchial epithelium of heavy smokers, levels of P-Akt and P-ERK were assessed in both pretreatment and posttreatment bronchial biopsies by immunohistochemistry. Lesions were scored and P-Akt or P-ERK staining indices were compared in paired, pretreatment, and posttreatment samples in a site-specific manner. Following myoinositol treatment, there was a significant decrease in both P-Akt and P-ERK expression levels in dysplastic lesions ($P = 0.001$ and 0.01, respectively) but not in hyperplastic/metaplastic lesions ($P > 0.05$; Fig. 2). There were only five normal specimens available for immunohistochemistry. During the study, these normal sites progressed to hyperplastic/metaplastic lesions. Following myoinositol, two of five increased P-Akt and one of five increased P-ERK staining, but these changes were not statistically significant. When all pretreatment and posttreatment sites within a given individual were grouped together, only 1 of 21 subjects (5%) showed a decrease in both Akt and ERK phosphorylation. This patient

Fig. 1. Immunohistochemical analysis of bronchial biopsies from smokers (including 31 dysplastic and 67 hyperplastic/metaplastic sites). A, photomicrographs showing representative immunohistochemical staining for P-Akt (T308) and P-ERK (T202/Y204) in normal lung (top) and dysplastic lesions (bottom). B, percentage of lesions positive for P-Akt (T308) and P-ERK (T202/Y204). C, association between activated Akt and ERK in hyperplastic/metaplastic and dysplastic lesions.
(subject 8) had a 48% decrease in Akt phosphorylation and a 43% decrease in ERK phosphorylation. Comparing all pretreatment and posttreatment biopsies from all patients, levels of P-Akt and P-ERK were significantly decreased ($P = 0.01$ and 0.02, respectively) following myoinositol treatment (Fig. 2, bottom). Interestingly, there was no relationship between dose of myoinositol and inhibition of Akt or ERK. These data show that myoinositol decreased Akt and ERK phosphorylation to the greatest extent in dysplastic lesions.

**Myoinositol decreases P-Akt and P-ERK expression and inhibits proliferation in HBECs in vitro**

To further assess the relationship between myoinositol, activation of Akt and ERK, and cellular proliferation, a series of *in vitro* studies were done with HBEC and HBEC(R) and a human lung cancer cell line (H322). Myoinositol decreased endogenous levels of Akt and ERK phosphorylation in HBECs in a dose-dependent manner (Fig. 3A, top left). Maximal inhibition occurred at 1 mmol/L. Because the phase I trial of myoinositol was done in subjects with heavy smoking histories, we assessed whether myoinositol would inhibit activation of Akt or ERK after nicotine exposure. HBECs were pretreated with myoinositol and exposed to nicotine. Myoinositol decreased basal levels of P-Akt and P-ERK. Nicotine only modestly increased levels of P-Akt and P-ERK in HBECs. In the presence of myoinositol, levels of Akt and ERK phosphorylation induced by nicotine were less than that observed in the absence of myoinositol (Fig. 3A, top right). Inhibitors of Akt activation (LY294002) or ERK activation (U0126) were used to correlate inhibition of these signaling pathways with cellular proliferation (Fig. 3B). In HBEC, these inhibitors decreased phosphorylation of their intended targets and decreased proliferation by >60%. Myoinositol was less effective in decreasing Akt and ERK phosphorylation and only inhibited cellular proliferation by 24%. Inhibition of proliferation was associated with induction of a G1 cell cycle arrest (data not shown). Similar results were observed with HBEC(R), except that myoinositol did not inhibit Akt or ERK phosphorylation as well as LY294002 or U0126, respectively. In fully transformed H322 cells, LY294002 and U0126 effectively inhibited activation of Akt and ERK but inhibited proliferation by only 22% and 48%, respectively. Myoinositol did not inhibit Akt or ERK and did not inhibit proliferation. These studies establish a link between inhibition of Akt and

![Myoinositol Inhibits Akt and ERK in Bronchial Lesions](image1)

![Myoinositol Inhibits Akt and ERK in Bronchial Lesions](image2)
ERK and cellular proliferation in immortalized but not transformed cells and support the selective activity of myo-inositol toward premalignant lesions.

**Discussion**

In the present study, we were able to successfully do immunohistochemistry on small bronchial biopsies and show that increased Akt and ERK activation is characteristic of premalignant lesions in smokers. The progression of hyperplastic or metaplastic lesions to dysplastic lesions was associated with increased activation of Akt and possibly ERK. Myo-inositol, which had previously been shown to be effective in reducing the number of dysplastic lesions, reduced the levels of P-Akt and P-ERK in these lesions. These clinical data correlated with *in vitro* studies that showed that myo-inositol inhibited endogenous and nicotine-induced activation of Akt and ERK in immortalized HBECs and decreased cellular proliferation.

How could smoking be related to increased activation of Akt and ERK in bronchial lesions? Tobacco components can activate Akt and ERK through nicotinic acetylcholine receptors (5, 23). Exposure to tobacco smoke or tobacco carcinogens can also lead to lung tumorigenesis primarily by inducing K-Ras mutations (24, 25). Activating K-Ras mutations stimulate the PI3K/Akt and MEK/ERK pathways (26). Although the K-Ras status of these lesions is not clear, we found positive P-Akt (T308) expression in a high percentage (90%) of bronchial dysplastic lesions from heavy smokers. This is the first report of high P-Akt (T308) expression in premalignant lesions.
bronchial lesions as well as an increased frequency of strong P-Akt (T308) expression in the transition from hyperplastic/metaplastic lesions to dysplastic lesions (P = 0.05, χ2 test). Our data measuring phosphorylation of Akt at T308 correlate well with a report that showed that 88% of dysplastic lesions from smokers showed activation of Akt as assessed by S473 phosphorylation (3). Although technically more difficult to measure, phosphorylation of T308 may be more valuable as a single marker for Akt activation than S473. For example, cells that lack PDK-1 (the kinase that phosphorylates T308) that are stimulated with insulin have normal levels of S473 phosphorylation but no T308 phosphorylation and no kinase activity (27). Thus, evaluation of S473 phosphorylation alone may overestimate Akt activation. Our group previously observed that phosphorylation of T308 alone is associated with a worse prognosis for stage I NSCLC patients or tumors ≤5 cm (4). The current study shows that enhanced T308 phosphorylation is an early event in tobacco-related lung cancer development, and the feasibility of detecting T308 phosphorylation in small bronchial biopsies highlights the potential of T308 phosphorylation as a biomarker for lung cancer prevention studies.

In addition to Akt activation, ERK activation was observed in 71% of the dysplastic lesions. Activation of ERK by nicotine can inhibit apoptosis of lung cancer cells (28), and the fact that ERK activation was observed in premalignant lesions suggests that it may play a crucial role in lung cancer progression by inhibiting apoptosis of damaged premalignant cells that could ultimately undergo full transformation. Our data support the hypothesis that dual inhibition of Akt and ERK might have greater potential than targeting either kinase alone.

Are the concentrations of myoinositol used in vitro relevant to the levels of myoinositol achieved in humans? We observed that myoinositol inhibited Akt and ERK phosphorylation at relatively high concentrations (≥1 mmol/L). However, myoinositol is well tolerated in humans, and an average North American diet provides 1 g of mixed inositol daily (29). In the phase I clinical trial, subjects took doses of 12, 18, 24, or 30 g of myoinositol for 1 month, and subjects without grade ≥2 toxicity were allowed to dose escalate once for an additional month. Once the maximum tolerated dose was established, 10 new participants received the maximum tolerated dose of 18 g of oral myoinositol daily for 3 months. Despite these high doses of myoinositol administration, myoinositol levels were not measured in this phase I study, so a direct correlation between levels in the clinical trial and our in vitro studies cannot be made. However, pharmacokinetic analysis using lower doses of myoinositol has been done by Groenen et al. (30). In women, blood plasma levels of 100 μmol/L were achieved after a single oral dose of 100 mg/kg myoinositol (for a 150-lb subject, this equates to an oral dose of 6.8 g). Furthermore, it has been reported that in most mammalian cells or tissues, the content of myoinositol is 5- to 500-fold higher than the level in plasma due to an effective, active transport system for myoinositol (31). Because the phase I trial with heavy smokers used myoinositol at doses 2- to 3-fold higher than that used by Groenen et al. for 2 to 3 months (during which time accumulation may have occurred), it is plausible that the concentrations of myoinositol used in vitro are relevant to that achieved in humans.

Myoinositol was most effective in decreasing Akt and ERK phosphorylation in lesions at highest risk to undergo transformation. The fact that only one patient showed inhibition of both Akt and ERK phosphorylation suggests that myoinositol exerts independent effects on these pathways. Because myoinositol is the head group of phoshatidylinositol, it has been hypothesized that Akt inhibition may be through direct effects on PI3K, whereas ERK inhibition has been suggested to be through protein kinase Cα (32). In fact, myoinositol may work through multiple mechanisms to inhibit tumor progression. Dong et al. (33) reported that IP6 strongly inhibited epidermal growth factor–induced and 12-O-tetradecanoylphorbol-13-acetate–induced cell transformation, activator protein-1 and ERK activation, as well as PI3K activity. Myoinositol has been shown to reduce tumor incidence in animal models (19, 34, 35) but only modestly reduces cellular proliferation in vitro. This suggests that myoinositol has other effects that contribute to the inhibition of tumorigenesis in vivo. Myoinositol is reported to have antioxidant, anti-inflammatory, and immune-enhancing activities that may also contribute to its cancer-preventive properties (16). For example, cigarette smoke decreases NK cell activity and causes lung inflammation (28). IP6 and inositol augment NK cell activity in vitro. In vivo, these compounds normalized the carcinogen-induced depression of NK cell activity and lowered tumor incidence (19). Thus, in vitro analysis likely underestimates the activity of myoinositol as a chemopreventive agent. An additional advantage of myoinositol for lung cancer prevention is that it might be useful as an aid in smoking cessation due to its possible efficacy against depression (36).

In conclusion, Akt and ERK are activated in early premalignant lesions from smokers. Activation of these kinases was associated with phenotypic progression to dysplastic lesions, which was inhibited by myoinositol treatment. Akt and ERK are therefore potential targets for lung cancer prevention and could be used as biomarkers for future lung cancer prevention trials using myoinositol.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

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