

Mitogenic effects of cytokines on smooth muscle are critically dependent on protein kinase A and are unmasked by steroids and cyclooxygenase inhibitors

Anna M. Misior^a, Huandong Yan^a, Rodolfo M. Pascual, Deepak A. Deshpande, Reynold A. Panettieri, and Raymond B. Penn

Department of Internal Medicine and Center for Human Genomics, Wake Forest University Health Sciences, Winston-Salem, NC 27157 (A.M.M., H.Y.,R.M.P., D.A.D., R.B.P), and Department of Medicine, University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania; 19104 (R.A.P)

Running Title: PKA determines mitogenic effects of cytokines

Correspondence:

Raymond B. Penn

Wake Forest University Health Sciences Center, Center for Human Genomics

Medical Center Blvd, Winston-Salem NC 27157

336-713-7541 (tele)

336-713-7566 (fax)

rpenn@wfubmc.edu

Number of Text pages: 14

Number of tables: 0

Number of Figures: 8

Number of references: 24

Abstract words: 174

Introduction words: 360

Discussion words: 1291

Abbreviations: ASM, airway smooth muscle; cAMP, cyclic adenosine 3',5'-cyclic-phosphate; Bis I, bisindolylmaleimide I; COX-2, cyclooxygenase-2; EGF, epidermal growth factor, FLU, fluticasone; GFP, green fluorescent protein; GPCR, G protein-coupled receptor; IL-1 β , interleukin-1-beta; mPGES1, microsomal prostaglandin E synthase-1; PGE, prostaglandin E; PI3K, phosphoinositide-3 kinase; PKA, cAMP-dependent protein kinase; TNF- α , tumor necrosis factor-alpha, VASP, vasodilator-stimulated phosphoprotein.

Abstract

Excessive smooth muscle growth occurs within the context of inflammation associated with certain vascular and airway diseases. The inflammatory cytokines IL-1 β and TNF- α have previously been shown to inhibit mitogen-stimulated smooth muscle growth, through a mechanism presumed dependent on the induction of cyclooxygenase-2, prostaglandins, and activation of the cAMP-dependent protein kinase (PKA). Using both molecular and pharmacologic strategies, we demonstrate that the mitogenic effects of IL-1 β and TNF- α on cultured human airway smooth muscle (ASM) cells are tightly regulated by PKA activity. Suppression of induced PKA activity by either corticosteroids or cyclooxygenase inhibitors converts the cytokines from inhibitors to enhancers of mitogen-stimulated ASM growth, and biologic variability in the capacity to activate PKA influences the modulatory effect of cytokines. Pro-mitogenic effects of IL-1 β are associated with delayed increases in p42/p44 and PI3K activities, suggesting a role for induced autocrine factors. These findings suggest a mechanism by which mainstream therapies such as corticosteroids or cyclooxygenase inhibitors could fail to address or exacerbate the pathogenic smooth muscle growth that occurs in obstructive airway and cardiovascular diseases.

Airway smooth muscle (ASM) hyperplasia is a major feature of the airway remodeling associated with chronic asthma. Increased ASM mass contributes to both increased fixed airway obstruction, and by altering airway geometry exacerbates the reduction in airway lumen size caused by constricting agents (Deshpande and Penn, 2006). Despite the growing appreciation of ASM hyperplasia and its role in asthma pathogenesis and severity, surprisingly little is known regarding what causes it and how it should be addressed therapeutically.

Recent studies utilizing primary cultures of ASM cells have identified various agents capable of promoting ASM proliferation, and have provided insight into mitogenic signaling events. Numerous growth factors as well as certain G protein-coupled receptor (GPCR) agonists stimulate ASM cell proliferation (Billington and Penn, 2003). Importantly, levels of these agents have been shown to be elevated in the airways of asthmatic subjects (reviewed in (Billington and Penn, 2003; Hirst et al., 2004)) suggesting a mechanism by which airway inflammation associated with asthma can promote increased ASM *in vivo*. However, airway inflammation is also characterized by increased production of numerous cytokines, including interleukin-1beta (IL-1 β) and tumor necrosis factor–alpha (TNF- α). Although IL-1 β and TNF- α by themselves tend to be weak mitogens for ASM, they have been shown to significantly inhibit proliferation stimulated by several mitogenic agents (Belvisi et al., 1998; Billington and Penn, 2003; Hirst et al., 2004; Pascual et al., 2001). It is widely assumed, but has never been directly demonstrated, that the anti-mitogenic effect of IL-1 β and TNF- α is mediated via cAMP-dependent protein kinase (PKA) activity, caused by the induction of autocrine PGE₂ synthesis, which stimulates G_s-coupled EP receptors coupled to cAMP generation and PKA activation (Belvisi et al., 1998; Billington and Penn, 2003; Guo et al., 2005; Hirst et al., 2004; Pascual et al., 2001).

Herein we demonstrate that not only are the anti-mitogenic effects of IL-1 β and TNF- α mediated by PKA, but PKA plays a critical role in suppressing what is otherwise a powerful mitogenic effect of these cytokines on ASM cells. Accordingly, agents capable of suppressing cytokine-induced PKA activation, such as corticosteroids or cyclooxygenase (COX) inhibitors, have the potential to enable inflammatory environments highly conducive to smooth muscle growth.

Materials and Methods

Generation of human ASM cultures. Human ASM cultures were generated from tracheae from unidentified donors as described in Penn et al. (Penn et al., 2001) and examined in the 4th to 7th passage.

Generation of retroviral-infected human ASM cultures was performed as per (Guo et al., 2005). Retrovirus for expression of GFP-, PKI-GFP-, and RevAB-GFP- expressing lines was produced by transfecting GP2-293 cells with pLNCX2-CRE-Luc, pLNCX2-GFP, pLNCX2-PKI-GFP, or pLNCX2-RevAB-GFP, each with pVSV-G Vector which encodes the pantropic (VSV-G) envelope protein. Supernatants were harvested 48 h after transfection and used to infect human ASM cultures. Infected cells typically exhibited >70% GFP expression within 48 h (direct visualization by fluorescent microscopy) and selection to homogeneity with 250 µg/ml G418 was rapid (7 days). In direct comparison of GFP-expressing cells with naïve ASM cells from which the GFP (and PKI-GFP and RevAB-GFP) cultures were derived, results were similar (see below), demonstrating that retroviral infection per se did not affect outcomes.

Immunoblot analyses of time-dependent effects on phospho-Thr202/Tyr204p42/p44, phospho-S473Akt, vasodilator-stimulated phosphoprotein (VASP), COX-2, and beta-actin were performed as in Billington et al. (Billington et al., 2005) and Guo et al. (Guo et al., 2005) employing the referenced primary antibodies and infrared-conjugated secondary antibodies with detection by the Li-COR Odyssey Imaging system.

[³H] thymidine incorporation in human ASM cultures was assessed as per (Billington et al., 2005). Briefly, cells were grown in 24 well plates to near confluence then serum starved in 0.1% bovine serum albumin for 24 h. Cells were pretreated with vehicle, 10 nM fluticasone propionate (FLU),

or 1 μM PGE₂ for 30 min then stimulated with vehicle, 10 nM EGF, 20 U/ml IL-1 β , 10 ng/ml TNF- α , or EGF+ either 10 ng/ml TNF- α , 0.2-20 U/ml IL-1 β , or combined 2 U/ml IL-1 β + 1 ng/ml TNF- α . After 16 h of stimulation, cells were labeled with 3.0 μCi [methyl-³H] thymidine (1 $\mu\text{Ci}/\text{ml}$) and incubated for an additional 24 h. Cells were then washed with phosphate-buffered saline, lysed with 20% trichloroacetic acid, aspirated onto filter paper and counted in scintillation vials.

Cell proliferation assays were performed as described previously (Krymskaya et al., 2000) by growing ASM cells in 6 well plates (triplicate wells per condition) to near confluence, growth-arresting and stimulating as described above for analyses of thymidine incorporation. After 48 h stimulation, cells were harvested and viable cells counted with an automated cell counter (ViCell, BeckmanCoulter).

Statistical Analysis. Data are presented as mean \pm SE values, from n experiments in which each experiment was performed using a different culture derived from a unique donor. Individual data points from a single experiment were calculated as the mean value from 3 or 6 replicate observations for [³H] thymidine incorporation assays, or from 3 replicates for cell proliferation assays. For immunoblot analyses, band intensities representing signals from secondary antibodies blots conjugated with infrared fluorophores were visualized and directly quantified using the Odyssey Infrared Imaging System (Li-Cor, Lincoln, NE). These values were normalized to values determined for beta-actin and compared among stimuli and experimental groups. Statistically significant differences among groups were assessed by either analysis of variance (ANOVA) with Fisher's PLSD post-hoc analysis (Statview 4.5, Abacus Concepts, Berkeley, CA) or by t-test for paired samples, with p values < 0.05 sufficient to reject the null hypothesis.

Results

Previous studies have demonstrated that IL-1 β (and more variably, TNF- α) treatment of naïve human ASM cultures reduces growth factor- and serum- stimulated increases in DNA synthesis and cell number (Belvisi et al., 1998; Pascual et al., 2001; Vlahos et al., 2003). To directly examine the role of PKA in this anti-mitogenic effect, we generated human ASM cultures stably expressing GFP chimeras of 2 different inhibitors of PKA (PKI and RevAB), as well as GFP-expressing control cultures, with each set of cultures derived from the same (naïve) donor cells (Guo et al., 2005). Effective inhibition of PKA activation in PKI-GFP and RevAB-expressing cells was previously demonstrated in (Guo et al., 2005) by significant inhibition of both PGE₂- and IL-1 β -stimulated phosphorylation of the intracellular PKA substrate VASP.

In GFP-expressing ASM cells IL-1 β (20 U/ml) alone did not significantly affect [³H] thymidine incorporation, but significantly inhibited EGF-stimulated increases (Fig. 1A). In cells expressing PKI-GFP or RevAB-GFP, IL-1 β alone was a more effective mitogenic stimuli, but most strikingly, no longer inhibited but greatly increased the mitogenic effect of EGF. Similar effects on ASM cell number were observed (Fig. 1B).

If the principal source of cytokine-stimulated PKA activity responsible for the suppressive effect on EGF-stimulated growth is COX-2-derived PGE₂, we hypothesized that agents capable of inhibiting the induction of COX-2 protein or activity, or inhibiting other enzymes important in cytokine-induced PGE₂ production (Pascual et al., 2006), would have similar effects. This proved to be the case, as pretreatment of naïve ASM cells with indomethacin (an inhibitor of COX activity), SB203580 or bisindolylmaleimide I (Bis I) (inhibitors of p38 and PKC, respectively, previously shown to inhibit induction of COX-2 and mPGES1 by IL-1 β in ASM cells (Pascual et al., 2006) also increased IL- β -stimulated growth and converted IL-1 β from an inhibitor to an

enhancer of EGF-stimulated growth (Fig 2A). Pretreatment with the corticosteroid FLU, known to be a strong suppressor of cytokine-induced prostanoid synthesis (Pascual et al., 2006; Vlahos and Stewart, 1999) also caused IL-1 β to enhance EGF-stimulated growth. The magnitude of effects of indomethacin, SB203580, Bis I, or FLU corresponded to the efficacy of each inhibitor in inhibiting EGF+IL-1 β -induced PKA activation, which was determined by characterizing the reversal of the shift of the PKA substrate VASP from the 50 kDa species to the 46 kDa species (Figures 2C, D). Indomethacin, SB203580, and FLU proved to be strong inhibitors of induced PKA activity whereas Bis I was effective but less so, consistent with the lesser ability of Bis I to augment EGF+IL-1 β -stimulated thymidine incorporation. Unlike the other inhibitory strategies, FLU inhibited the weak mitogenic effect of IL-1 β alone (Fig. 2B). Pretreatment of cells with dexamethasone had similar effects to those of FLU (not shown).

To investigate whether the effects of FLU and direct PKA inhibition share a similar mechanistic basis, we compared effects of FLU with those of PKI-GFP expression and examined the combined effects of both FLU pretreatment and PKI-GFP expression. EGF+IL-1 β -stimulated growth was similar in GFP- and PKI-GFP expressing cells pretreated with FLU (Fig. 3). However, FLU pretreatment of PKI-GFP cells caused a significant reduction of EGF+IL-1 β -stimulated growth. These results suggest that suppression of induced PKA activity is the principal and shared mechanism mediating the effects of FLU and PKI-GFP, yet FLU is able to suppress a contributory mechanism promoted by PKA inhibition.

In a subset of experiments in which the effects of PKA inhibition on the regulatory effects of IL-1 β and TNF- α were compared, PKI-GFP expression and FLU pretreatment was shown to similarly increase EGF-stimulated [3 H] thymidine incorporation in cells co-stimulated with TNF- α or IL-1 β (Fig. 4). However, in GFP-expressing cells, TNF- α did not significantly inhibit

EGF-stimulated [³H] thymidine incorporation. When EGF-stimulated cells were co-stimulated with combined IL-1 β and TNF- α , both at low concentrations (2 U/ml and 1 ng/ml, respectively), the effect was comparable to that induced by 20 U/ml IL-1 β alone.

To further explore the relationship between PKA activity and the mitogenic effects of IL-1 β , the dose-dependent effect of IL-1 β on EGF-stimulated ASM growth and associated mitogenic signaling events was examined. In both naïve and GFP-expressing cells, 20 U/ml of IL-1 β inhibited EGF-stimulated growth, 2 U/ml of IL-1 β caused either no change or a slight increase in EGF-stimulated growth, and 0.2 U/ml of IL-1 β significantly enhanced EGF-stimulated growth (Fig. 5A). The increasing pro-mitogenic effect with progressively lower concentrations of IL-1 β was associated with a diminishing induction of both COX-2 protein and PKA activity, the latter paralleled by progressively lower levels of phosphorylated (50 kDa) VASP (Fig. 5B). In PKI-GFP-expressing cultures, in which induction of VASP phosphorylation was nearly abolished, each of the concentrations of IL-1 β was highly efficacious in augmenting EGF-stimulated growth, with only minimal differences in effect observed.

We have previously demonstrated important roles for p42/p44, PI3K, and p70S6K activities in the regulation of ASM growth (Billington et al., 2005; Kong et al., 2006; Krymskaya et al., 2000; Orsini et al., 1999). In naïve and GFP-expressing cells, the large COX-2 induction and PKA activation stimulated by 18 h treatment with EGF+20 U/ml IL-1 β were associated with either a slight inhibition or no change in p42/p44 and Akt phosphorylation (Akt phosphorylation serves as a readout for PI3K activation (Billington et al., 2005; Kong et al., 2006)) (Fig. 5B). However, lower concentrations of IL-1 β promoted an increase in Akt, and to a slightly lesser extent, p42/p44 phosphorylation. Phospho-p706K levels were low and could not be reliably

quantified at time points exceeding 6 h (not shown). In PKI-GFP-expressing cells, all concentrations of IL-1 β enhanced EGF-stimulated p42/p44 and Akt phosphorylation.

Analysis of the time-dependent regulation of p42/p44 and Akt phosphorylation revealed that at early time points up to 9 h, 20 U/ml IL-1 β increased EGF-stimulated Akt phosphorylation, and caused either no change or a slight increase in p42/p44 phosphorylation (Fig. 6). These patterns were similar in PKI-GFP-expressing cells. FLU treatment had a slight inhibitory effect on Akt phosphorylation in both GFP- and PKI-GFP-expressing, yet the relative effect of IL-1 β was retained. Conversely, FLU tended to augment p42/p44 phosphorylation stimulated by EGF and EGF+IL-1 β in both cell lines. By 18 h, and coinciding with higher levels of COX-2 induction and PKA activity, IL-1 β no longer augmented EGF-stimulated phospho- p42/p44 and Akt levels in GFP-expressing cells, in some lines having a slight inhibitory effect. However, at 18 h IL-1 β retained its ability to promote higher levels of Akt and p42/p44 phosphorylation in cells treated with FLU or expressing PKI. These time- and line- dependent regulatory effects on Akt and p42/p44 phosphorylation were inversely related to the level of PKA activity indicated by the shift in VASP mobility.

Consistent with a role of PKA in suppressing the otherwise mitogenic effect of IL-1 β on EGF-stimulated growth, co-stimulation of cultures with 1 μ M PGE₂ was able to inhibit the large increase in EGF+IL-1 β -stimulated [³H] thymidine incorporation conferred by FLU in naïve and GFP-expressing cells, but not in PKI-GFP expressing cells (Fig. 7A-C). Interestingly, exogenous PGE₂ significantly increased [³H] thymidine incorporation in PKI-GFP cells stimulated by EGF. This result suggests that under conditions of PKA inhibition, EP1 or EP3 receptor-dependent mitogenic signaling can emerge to cooperate with that stimulated by EGF (Billington et al., 2005; Kong et al., 2006).

Further analysis of the dose-dependent effect of PGE₂ on FLU-treated EGF+IL-1 β -stimulated cells demonstrates the high potency of PGE₂ in inhibiting thymidine incorporation under these conditions (Fig. 7D).

Lastly, an interesting observation afforded by the use of cultures generated from numerous donors was the degree of biologic variability exhibited in the regulatory effect of IL-1 β on EGF-stimulated growth. Analysis of data derived from 13 different (naïve) ASM cultures revealed considerable variability in the inhibitory effect of IL-1 β on EGF-stimulated [³H] thymidine incorporation (Fig. 8A). Indeed, in 2 of 13 cultures, 20 U/ml IL-1 β caused an increase in EGF-stimulated [³H] thymidine incorporation. To explore whether this variability could be attributed to variation in the induction of COX-2 or PKA activation, lysates for those cultures examined for COX-2 protein and VASP phosphorylation induced after 18 h stimulation were run on a single gel and an immunoblot was generated. Variability in both COX-2 and VASP phosphorylation was observed, and correlation analysis demonstrates a relationship between the outcomes and the inhibitory effect of IL-1 β on EGF-stimulated growth (represented as the ratio of thymidine incorporation stimulated by EGF+IL-1 β :EGF) (Fig. 8B-D).

Discussion

Results from the present study demonstrate the critical role of PKA in determining the modulatory effect of the cytokines IL-1 β and TNF- α on ASM growth, and thereby reveal a mechanism by which clinically relevant agents could promote smooth muscle growth *in vivo* and exacerbate disease.

Several studies have reported inhibitory effects of IL-1 β or TNF- α on ASM growth stimulated by either growth factors, GPCR agonists, or serum (Belvisi et al., 1998; Pascual et al., 2001; Vlahos et al., 2003). The magnitude of the inhibitory effects varies among studies and may be attributed to differences in species of ASM and culture conditions, and as suggested by the present study, variability among the cultures themselves. Combined treatment with IL-1 β and TNF- α , arguably the condition more relevant to the inflamed airway, has an even greater inhibitory effect than either agent alone (Belvisi et al., 1998; Pascual et al., 2001).

IL-1 β and (to a lesser extent) TNF- α can induce COX-2 protein and PGE₂ generation in ASM cells, and co-treatment with serum or EGF greatly increases this induction (Pascual et al., 2001; Pascual et al., 2006). For this reason, and given the observation that exogenous PGE₂ inhibits ASM growth, COX-2-dependent PGE₂ production has been assumed to mediate inhibition of ASM growth by these cytokines. Because PGE₂ can stimulate cAMP production in ASM cells, it is in turn widely assumed that PKA promotes the anti-mitogenic signaling generated by chronic IL-1 β and TNF- α treatment. However, although a role for COX-2 in the anti-mitogenic effects of cytokines has sufficient empirical basis, no evidence directly implicating PKA exists. The failure to implicate PKA stems from difficulties in both characterizing and directly inhibiting PKA activity in primary cells. Although pharmacologic agents known to inhibit PKA activity *in vitro* are frequently used as a means to directly inhibit

PKA activity in intact cells, we have recently demonstrated that many of the most commonly used pharmacologic PKA inhibitors are not only ineffective in ASM cultures, but also promote problematic non-specific effects (Guo et al., 2005; Penn et al., 1999).

Conversely, heterologous expression of PKI, which functions as a substrate mimetic, or RevAB, a mutant PKA regulatory subunit incapable of binding cAMP (Correll et al., 1989), successfully inhibits the activation of PKA by multiple stimuli in ASM (Guo et al., 2005). In PKI-GFP- or RevAB-GFP- expressing ASM cells, IL-1 β and TNF- α acquired the ability to stimulate ASM growth by themselves, and were converted from inhibitors to enhancers of EGF-stimulated growth. The role of PKA in dictating the mitogenic effect of cytokines is further suggested by the association of inhibition of COX-2 and PGE₂ induction, via multiple strategies, with a similar reversal of the growth inhibition by IL-1 β .

The ability of corticosteroids or COX inhibition to convert cytokines from inhibitors to enhancers of mitogen-stimulated growth has previously been reported for both airway (Vlahos and Stewart, 1999; Vlahos et al., 2003) and vascular (Libby et al., 1988a) smooth muscle, although the mechanistic basis of these effects were not determined. Vlahos and Stewart (Vlahos and Stewart, 1999) reported that pretreatment of human ASM with either indomethacin or dexamethasone caused combined IL-1 α and TNF- α treatment to augment (which otherwise inhibited) [³H] thymidine incorporation stimulated by basic fibroblast growth factor. Libby et al. (Libby et al., 1988b) reported that indomethacin pretreatment of human vascular smooth muscle cells causes IL-1 α to augment (rather than inhibit) [³H] thymidine incorporation stimulated by fetal calf serum. Although in both studies these pro-mitogenic effects of cyclooxygenase inhibition/steroid treatment were associated with inhibition of prostaglandin induction, neither study examined the specific role of PKA in this reversal.

In the current study, the role of PKA inhibition in the ability of steroids and COX inhibition to render IL-1 β a powerful enhancer of EGF-stimulated ASM growth is strongly suggested by the inability of FLU pretreatment to further enhance [³H] thymidine incorporation stimulated by EGF+IL-1 β in PKI-GFP expressing cells. Although it is likely that steroids affect numerous factors that regulate ASM growth that are distinct from those affected by PKA inhibition, the largely redundant effect of FLU treatment and PKA inhibition on IL-1 β modulation of EGF-stimulated ASM growth strongly suggests that PKA inhibition by FLU, a consequence of suppression of prostanoid induction, contributes significantly to the pro-mitogenic effect observed.

By virtue of the ability to screen multiple cultures of ASM, each derived from a different donor, we discovered considerable variability in the modulatory effect of IL-1 β . In fact, in two cultures 20 U/ml IL-1 β significantly increased EGF-stimulated growth. This variability in regulating growth was associated with similar variability in intracellular PKA activity. Multiple pro- and anti- mitogenic signals are probably involved in the regulation of growth by combined growth factor and cytokine stimulation. Pro-mitogenic signaling in ASM includes the p42/p44, PI3K, and p70S6K pathways (reviewed in (Deshpande and Penn, 2006; Hirst et al., 2004)). However, these pathways are also important in inducing enzymes (cPLA2, COX-2, and mPGES1) responsible for PGE₂ synthesis and anti-mitogenic PKA activation ((Pascual et al., 2001; Pascual et al., 2006), and Pascual and Penn unpublished observations). Differences in the capacity of IL-1 β and TNF- α to induce PKA activity could stem from variability in the expression or activity of numerous proteins linking IL-1 β and TNF- α with PKA activation- IL-1 β or TNF- α receptors, signaling molecules proximal and downstream of IL-1 β /TNF- α receptors (interleukin-1 receptor-associated kinase, TNF Receptor-Associated Factor, TNF factor

receptor-associated death domain, NF- κ B-inducing kinase, etc.), cytosolic regulators of cPLA₂, COX-2, and mPGES1 (MAPKs, PI3K isoforms, p70S6K, and NF- κ B), enzymes mediating PGE₂ synthesis (cPLA₂, COX-2, and mPGES1), EP2/4 receptors, the heterotrimeric G protein Gs and the downstream effector adenylyl cyclase, and finally regulatory and catalytic subunits of PKA, as well as additional molecules that regulate PKA enzymatic activity (multiple kinases) and localization (A-kinase anchoring proteins). It is conceivable that asthmatics in which cytokines promote minimal PGE₂ generation/PKA activation are at greater risk of inflammation-induced increases in ASM mass, do not outgrow their disease, and develop chronic asthma with a fixed obstruction component. Should our results in cultured cells be relevant to the *in vivo* condition, corticosteroid therapy could further compound this problem, by effectively inhibiting induction of prostaglandins and PKA activity, and further enabling pro-mitogenic signaling by cytokines. Although it is true that inhaled steroids are effective in reducing inflammatory cell accumulation and cytokine levels in the lung, they are frequently administered during ongoing inflammation, when cytokine levels are already elevated. Studies to date have only examined the effects of prophylactic corticosteroid administration on features of airway remodeling, using mouse or rat models in which allergic inflammation was induced by short-term sensitization and challenge with ovalbumin (Vanacker et al., 2002a; Vanacker et al., 2002b; Miller et al., 2006). Thus additional studies examining more clinically-relevant conditions are required to clarify the regulatory effects of corticosteroids on ASM growth *in vivo*.

A similar regulatory role of PKA in vascular smooth muscle growth that occurs during inflammation-driven injury and repair of the vascular wall could also greatly influence various forms and consequences of vascular disease. Lipid deposition in the vessel wall and subsequent infiltration of the intima by inflammatory cells are known to contribute to initial plaque

formation. Inflammatory cells in the environment of the intima expose vascular smooth muscle cells to cytokines, growth factors and other vasoactive substances and leads to phenotypic modulation of the smooth muscle. The initial VSM migration, proliferation and accumulation at the site of lesion are fundamental processes leading to atherosclerotic plaque formation that contributes to myocardial infarction and stroke pathogenesis (Bornfeldt and Krebs, 1999; Ross and Glomset, 1973; Campbell and Campbell, 1994). Under these conditions, the clinical use of cyclooxygenase inhibitors could create an environment favoring exaggerated smooth muscle growth. Such growth could further destabilize the vascular wall, increasing the likelihood of further inflammation, plaque formation, and damage leading to various acute clinical events.

Reference List

Belvisi MG, Saunders M, Yacoub M and Mitchell J A (1998) Expression of Cyclo-Oxygenase-2 in Human Airway Smooth Muscle Is Associated With Profound Reductions in Cell Growth. *Br J Pharmacol* **125**:1102-8.

Billington CK, Kong K C, Bhattacharyya R, Wedegaertner P B, Panettieri R A, Chan T O and Penn R B (2005) Cooperative Regulation of P70S6 Kinase by Receptor Tyrosine Kinases and G Protein-Coupled Receptors Augments Airway Smooth Muscle Growth. *Biochemistry* **44**:14595-14605.

Billington CK and Penn R B (2003) Signaling and Regulation of G Protein-Coupled Receptors in Airway Smooth Muscle. *Respir Res* **4**:2.

Bornfeldt KE and Krebs E G (1999) Crosstalk Between Protein Kinase A and Growth Factor Receptor Signaling Pathways in Arterial Smooth Muscle. *Cell Signal* **11**:465-77.

Campbell JH and Campbell G R (1994) The Role of Smooth Muscle Cells in Atherosclerosis. *Curr Opin Lipidol* **5**:323-330.

Correll LA, Woodford T A, Corbin J D, Mellon P L and McKnight G S (1989) Functional Characterization of CAMP-Binding Mutations in Type I Protein Kinase. *J Biol Chem* **264**:16672-8.

Deshpande DA and Penn R B (2006) Targeting G Protein-Coupled Receptor Signaling in Asthma. *Cell Signal* **18**:2105-2120.

Guo M, Pascual R M, Wang S, Fontana M F, Valancius C A, Panettieri R A, Jr., Tilley S L and Penn R B (2005) Cytokines Regulate Beta-2-Adrenergic Receptor Responsiveness in Airway Smooth Muscle Via Multiple PKA- and EP2 Receptor-Dependent Mechanisms. *Biochemistry* **44**:13771-13782.

Hirst SJ, Martin J G, Bonacci J V, Chan V, Fixman E D, Hamid Q A, Herszberg B, Lavoie J P, McVicker C G, Moir L M, Nguyen T T, Peng Q, Ramos-Barbon D and Stewart A G (2004) Proliferative Aspects of Airway Smooth Muscle. *J Allergy Clin Immunol* **114**:2-17.

Kong KC, Billington C K, Gandhi U, Panettieri R A, Jr. and Penn R B (2006) Cooperative Mitogenic Signaling by G Protein-Coupled Receptors and Growth Factors Is Dependent on G(q/11). *FASEB J* **20**:1558-60.

Krymskaya VP, Orsini M J, Eszterhas A, Benovic J L, Panettieri R A and Penn R B (2000) Potentiation of Human Airway Smooth Muscle Proliferation by Receptor Tyrosine Kinase and G Protein-Coupled Receptor Activation. *Am J Respir Cell Mol Biol* **23**:546-554.

Libby P, Warner S J and Friedman G B (1988b) Interleukin 1: a Mitogen for Human Vascular Smooth Muscle Cells That Induces the Release of Growth-Inhibitory Prostanoids. *J Clin Invest* **81**:487-498.

Libby P, Warner S J and Friedman G B (1988a) Interleukin 1: a Mitogen for Human Vascular Smooth Muscle Cells That Induces the Release of Growth-Inhibitory Prostanoids. *J Clin Invest* **81**:487-498.

Miller M, Cho J Y, McElwain K, McElwain S, Shim J Y, Manni M, Baek J S and Broide D H (2006) Corticosteroids Prevent Myofibroblast Accumulation and Airway Remodeling in Mice. *Am J Physiol Lung Cell Mol Physiol* **290**:L162-L169.

Orsini MJ, Krymskaya V P, Eszterhas A J, Benovic J L, Panettieri R A and Penn R B (1999) MAPK Superfamily Activation in Human Airway Smooth Muscle: Prolonged P42/P44 Activation Required for Mitogenesis. *Am J Physiol (Lung Cell Mol Physiol)* **277**:479-488.

Pascual RM, Billington C K, Hall I P, Panettieri R A, Jr., Fish J E, Peters S P and Penn R B (2001) Mechanisms of Cytokine Effects on G Protein-Coupled Receptor-Mediated Signaling in Airway Smooth Muscle. *Am J Physiol Lung Cell Mol Physiol* **281**:1425-35.

Pascual RM, Carr E, Seeds M C, Guo M, Panettieri R A, Peters S P and Penn R B (2006) Multiple Regulatory Elements Influence Interleukin-1beta-Mediated Prostaglandin E2 Synthesis in Airway Smooth Muscle. *Am J Physiol (Lung Cell Mol Physiol)* **290**:501-8.

Penn RB, Parent J L, Pronin A N, Panettieri R A, Jr. and Benovic J L (1999) Pharmacological Inhibition of Protein Kinases in Intact Cells: Antagonism of Beta Adrenergic Receptor Ligand Binding by H-89 Reveals Limitations of Usefulness. *J Pharmacol Exp Ther* **288**:428-437.

Penn RB, Pascual R M, Kim Y-M, Mundell S J, Krymskaya V P, Panettieri Jr R A and Benovic J L (2001) Arrestin Specificity for G Protein-Coupled Receptors in Human Airway Smooth Muscle. *J Biol Chem* **276**:32648-32656.

Ross R and Glomset J A (1973) Atherosclerosis and the Arterial Smooth Muscle Cell: Proliferation of Smooth Muscle Is a Key Event in the Genesis of the Lesions of Atherosclerosis. *Science* **180**:1332-1339.

Vanacker NJ, Palmans E, Pauwels R A and Kips J C (2002a) Dose-Related Effect of Inhaled Fluticasone on Allergen-Induced Airway Changes in Rats. *Eur Respir J* **20**:873-879.

Vanacker NJ, Palmans E, Pauwels R A and Kips J C (2002b) Effect of Combining Salmeterol and Fluticasone on the Progression of Airway Remodeling. *Am J Respir Crit Care Med* **166**:1128-1134.

Vlahos R, Lee K S, Guida E, Fernandes D J, Wilson J W and Stewart A G (2003) Differential Inhibition of Thrombin- and EGF-Stimulated Human Cultured Airway Smooth Muscle Proliferation by Glucocorticoids. *Pulm Pharmacol Ther* **16**:171-80.

Vlahos R and Stewart A G (1999) Interleukin-1alpha and Tumour Necrosis Factor-Alpha Modulate Airway Smooth Muscle DNA Synthesis by Induction of Cyclo-Oxygenase-2: Inhibition by Dexamethasone and Fluticasone Propionate. *Br J Pharmacol* **126**:1315-24.

Footnotes

This study was funded by NIH HL58506 (R.B.P.) and an independent investigator grant from GlaxoSmithKline (R.B.P.).

^aA.M.M. and H.Y. contributed equally and may be cited in either order.

Figure Legends

Figure 1. PKA inhibition promotes mitogenic effects of IL-1 β . Effect of PKA inhibition via heterologous expression of PKA inhibitors PKI or RevAB on IL-1 β -, EGF-, and EGF+IL-1 β -stimulated (A) [3 H] thymidine incorporation and (B) cell proliferation. Bars represent mean \pm SE values. n=11 (A), n=4 (B). * p<0.05 IL-1 β PKI-GFP or RevAB-GFP vs IL-1 β GFP; # EGF+IL-1 β (all groups) vs EGF GFP; ** EGF+IL-1 β PKI-GFP or RevAB-GFP vs EGF+IL-1 β GFP.

Figure 2. Multiple inhibitors of IL-1 β -induced PGE $_2$ synthesis promote a mitogenic effect of IL-1 β in ASM cells. A. Effect of 30 min pretreatment with inhibitors of cyclooxygenase activity (1 μ M indomethacin), p38 (1 μ M SB203580), or cPKC isoforms (3 μ M Bis I) on EGF-, IL-1 β -, or EGF+IL-1 β -stimulated [3 H] thymidine incorporation in naïve human AS, cultures. B. Effect of 30 min pretreatment with 10 nM FLU on ASM [3 H] thymidine incorporation. Bars represent mean \pm SE values, n=4-6 (A), n=12 (B). * p<0.05 IL-1 β Indomethacin, SB203580, Bis I, or FLU vs IL-1 β GFP.; # EGF+IL-1 β (all groups) vs EGF GFP; ** EGF+IL-1 β Indomethacin, SB203580, Bis I, and FLU vs EGF+IL-1 β GFP. C. Representative immunoblot assessing shifts in VASP protein mobility, as a readout for PKA activation, promoted by 9 and 18 h treatment with the IL-1 β or EGF+IL-1 β , in cells pretreated with either vehicle, indomethacin, SB203580, Bis I, or FLU. D. The relative ratio of the 50 and 46 kDa VASP band intensities were normalized to the corresponding values for beta-actin. Data shown represent mean \pm SE values from 4 independent experiments.

Figure 3. Glucocorticoid pretreatment (FLU) promotes similar pro-mitogenic effects to those induced by PKA inhibition. Effect of FLU pretreatment (10 nM, 30 min) on [3 H]

thymidine incorporation in GFP- and PKI-GFP- expressing ASM cells stimulated with IL-1 β , EGF, or EGF+IL-1 β for 18 h. Bars represent mean \pm SE values. n= 12 * p<0.05 IL-1 β PKI-GFP vs IL-1 β GFP; # EGF+IL-1 β (GFP or PKI-GFP) and EGF+IL-1 β + FLU (GFP or PKI-GFP) vs EGF GFP; ** EGF+IL-1 β + FLU PKI-GFP vs. EGF+IL-1 β PKI-GFP.

Figure 4. PKA inhibition, FLU pretreatment regulate modulation of EGF-stimulated thymidine incorporation by TNF- α . GFP or GFP-PKI were pretreated with Veh or 10 nM FLU then stimulated with EGF (10 ng/ml) \pm IL-1 β (I; 20 U/ml), TNF- α (T; 10 ng/ml), or IL-1 β +TNF- α (I+T; (2 U/ml and 1 ng/ml, respectively)). Bars represent mean \pm SE values, n=4-5. p<0.05 * EGF+IL-1 β and EGF+IL-1 β +TNF- α (GFP or PKI-GFP) and EGF+IL-1 β + FLU, EGF+TNF- α +FLU, or EGF+IL-1 β +TNF- α +FLU (GFP or PKI-GFP) vs EGF (GFP or PKI-GFP).

Figure 5. Dose-dependent effect of IL-1 β on ASM growth is associated with the induction COX-2 expression and PKA activation and inhibition of PI3K and p42/p44 pathways. Effects of 0.2-20 U/ml IL-1 β on EGF-stimulated [3 H] thymidine incorporation (**A**) and induction of COX-2 expression, PKA activation (readout as VASP phosphorylation), and phosphorylation of Akt (readout for PI3K activity) and p42/p44 (**B**) in naïve, GFP-, and PKI-GFP- expressing cells. Bars represent mean \pm SE values from 3 independent experiments using 3 different cultures.

Figure 6. FLU pretreatment or expressing PKI-GFP expression determines IL-1 β effects on late-phase Akt and p42/p44 phosphorylation. A. GFP- and PKI-GFP- expressing ASM cells were pretreated with FLU (10 nM, 30 min) then stimulated with EGF, IL-1 β or EGF+IL-1 β for 3, 6, 9 or 18 h. Cell lysates were subjected to immunoblotting to evaluate pS473Akt,

pT202/Y204p42/p44, COX-2, VASP, and beta-actin expression. **B, C.** Band intensities for p-Akt and p-p42/p44 for the 9 and 18 h time points were quantified and normalized to corresponding values for beta-actin. Data shown represent mean+SE values from 4 independent experiments.

Figure 7. Exogenous PGE₂ reverses mitogenic effect of fluticasone treatment but not direct PKA inhibition on EGF+IL-1 β -stimulated ASM cells. Naïve (**A**), GFP- (**B**), or PKI-GFP- (**C**) expressing cells were pretreated with vehicle or 10 nM FLU \pm 1 μ M PGE₂ prior to stimulation with the indicated agents. Cells were subsequently harvested for analysis of [³H] thymidine incorporation as described in *Materials and Methods*. Bars represent mean \pm SE values, n=7. * p<0.05, indicated value vs Veh-pretreated EGF value; # indicated value vs EGF+IL-1 β FLU value; ** IL-1 β PGE₂ PKI-GFP vs IL-1 β Veh PKI-GFP. **D.** Cells were pretreated with vehicle or 10 nM FLU \pm PGE₂ ranging in concentration from 1 nM- 1 μ M, stimulated with EGF+IL-1 β , and analyzed for [³H] thymidine incorporation as above. n=4

Figure 8. Variability in effect of IL-1 β on EGF-stimulated growth in ASM cells is correlated to the induction of COX-2 expression and PKA activation. **A.** Regulatory effect of IL-1 β on EGF-induced [³H] thymidine incorporation in naïve ASM cells. Assay performed as described in *Methods*. n=13. **B.** ASM cells derived from 7 different donors were stimulated with EGF+IL-1 β for 18h. Cell lysates were subjected to immunoblotting to assess COX-2 expression and VASP shift/phosphorylation. **C and D.** Correlation analysis between the ability of IL-1 β to regulate EGF-stimulated ASM growth (expressed as ratio of [³H] thymidine incorporation stimulated by EGF+IL-1 β to EGF) and its ability to induce COX-2 expression (normalized to β -actin) (**C**) or PKA activation (expressed as ratio of 50kDa:46kDa VASP) (**D**). n=7.

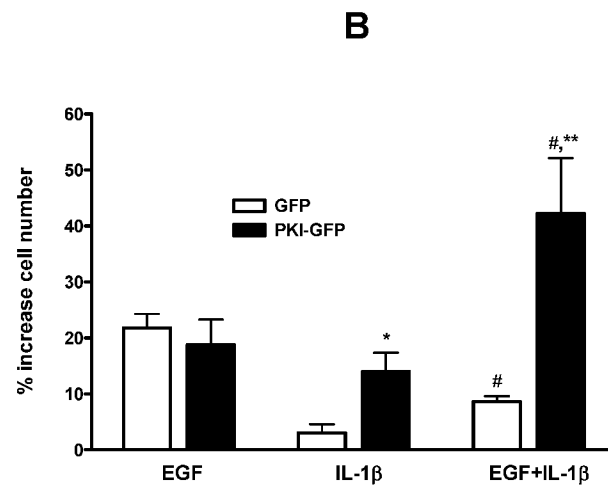
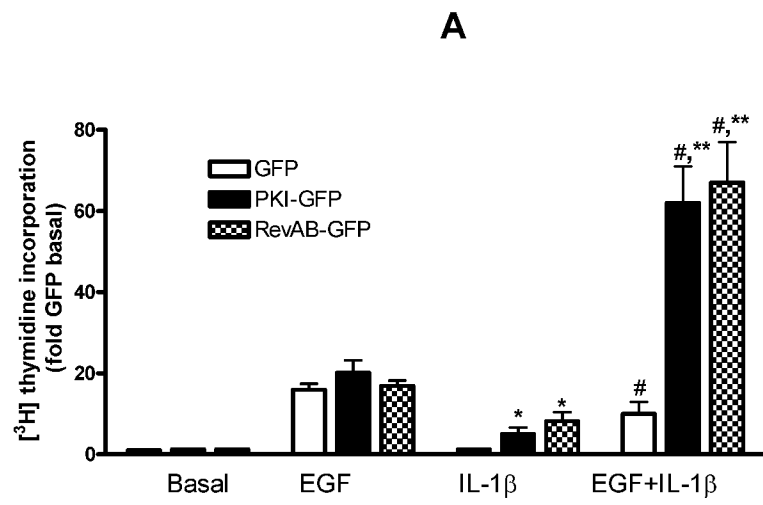
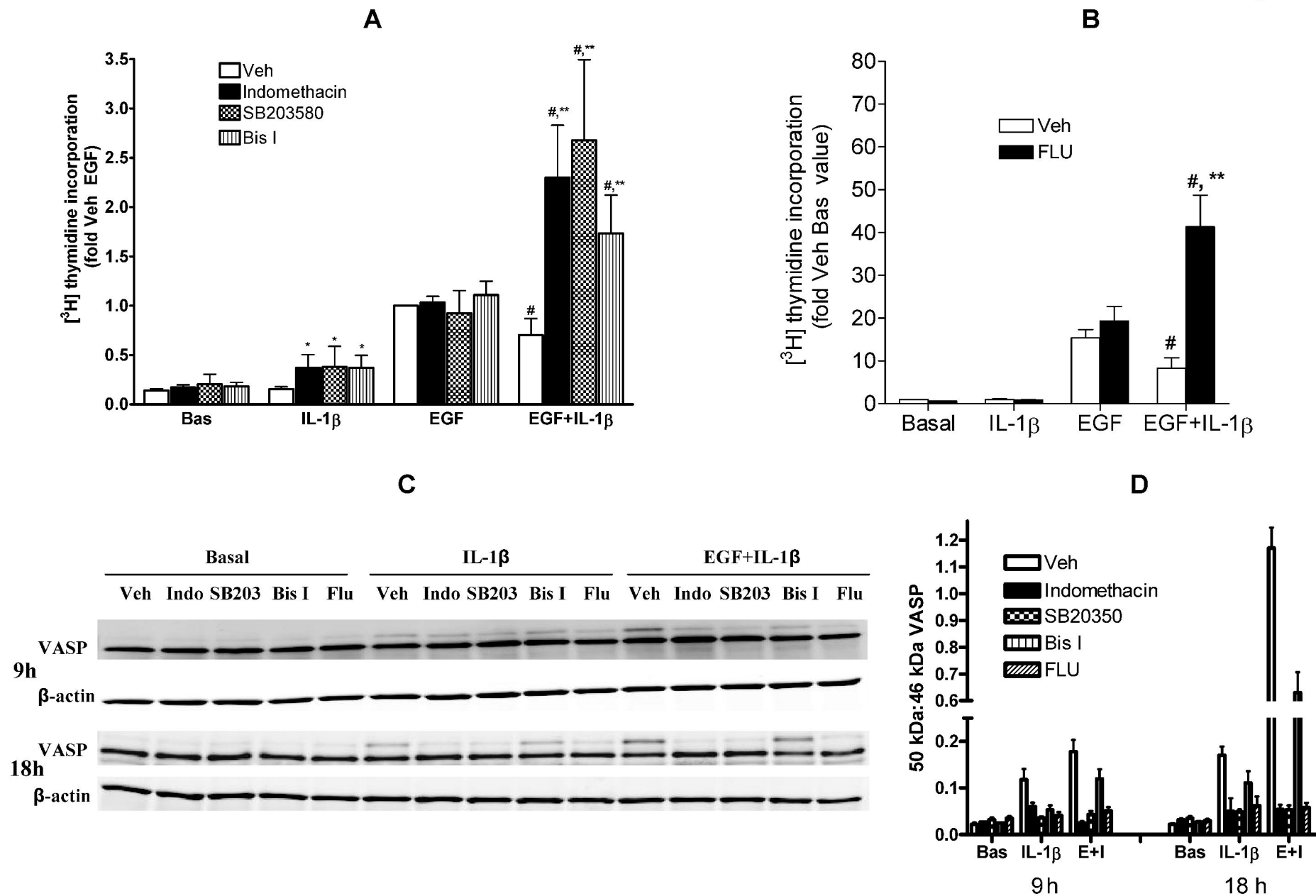


Figure 1



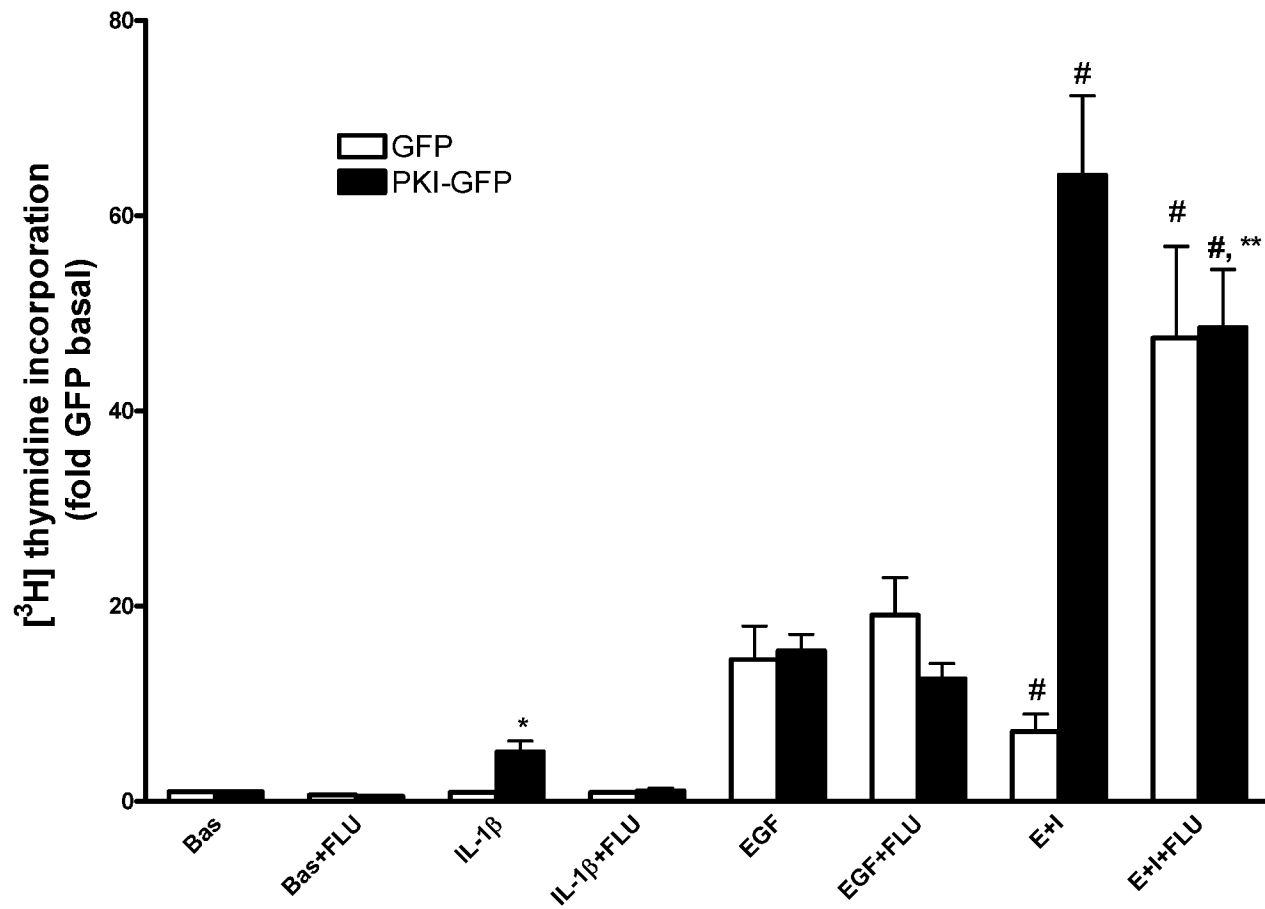


Figure 3

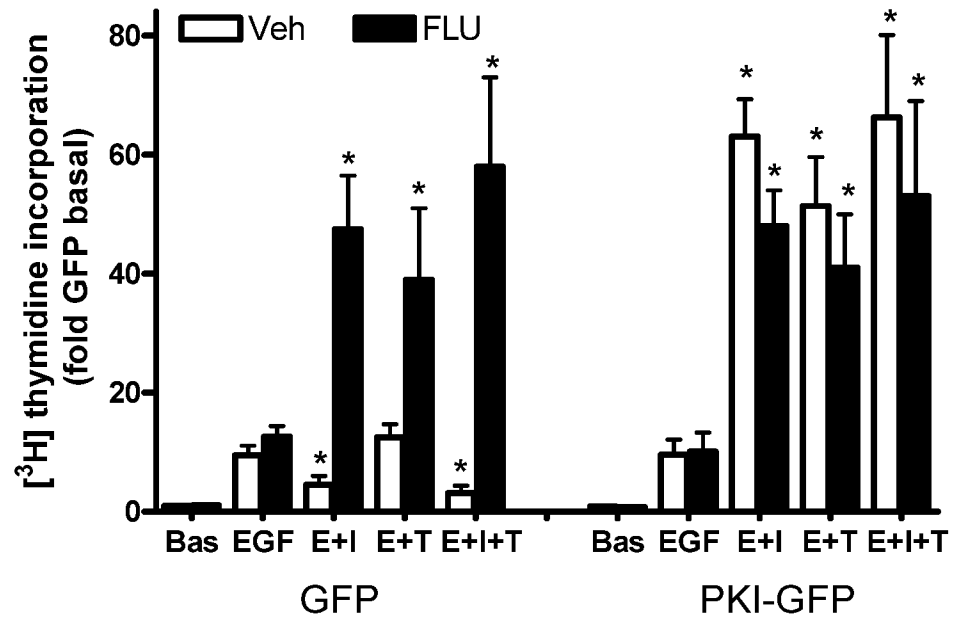


Figure 4

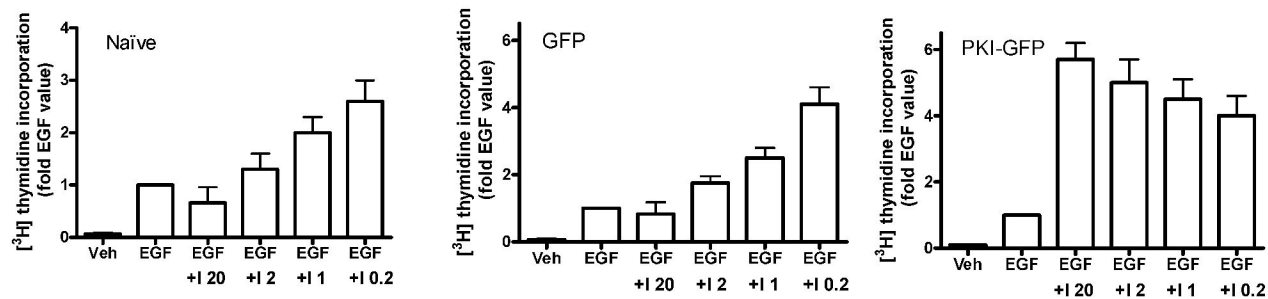
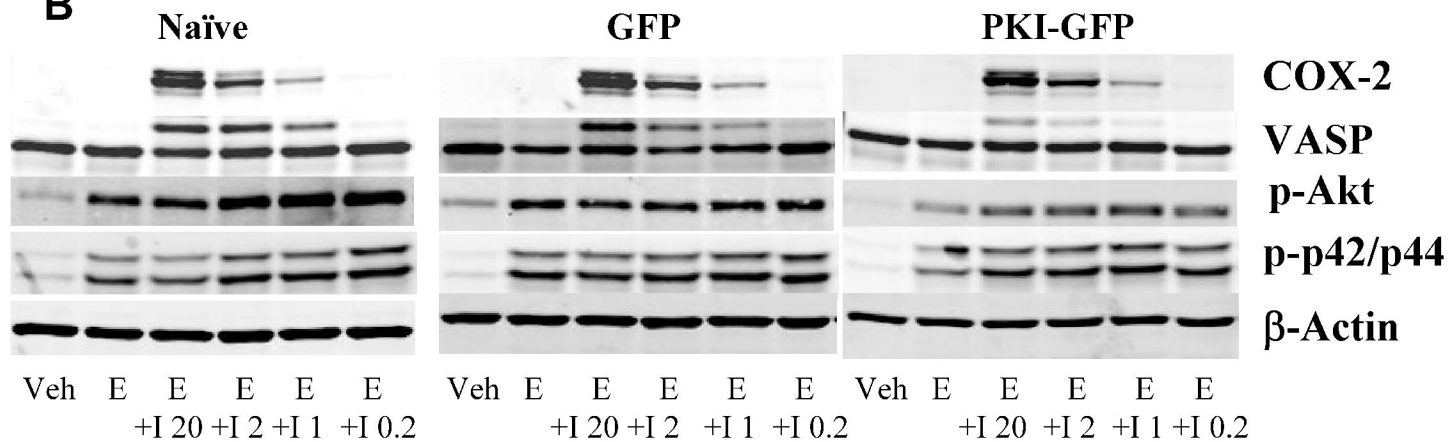
A**B**

Figure 5

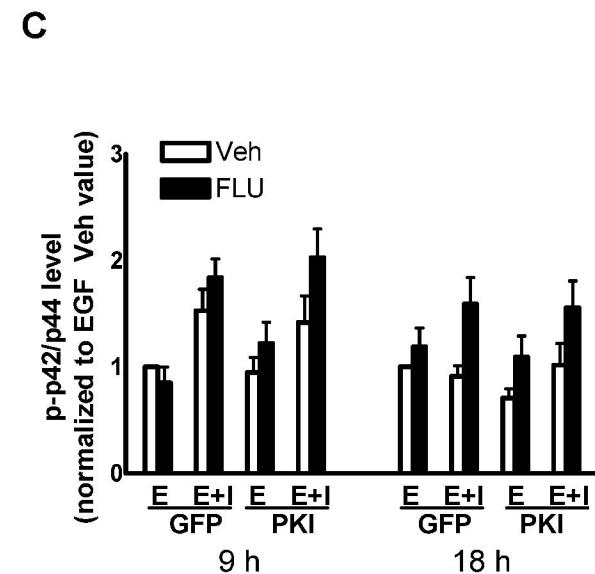
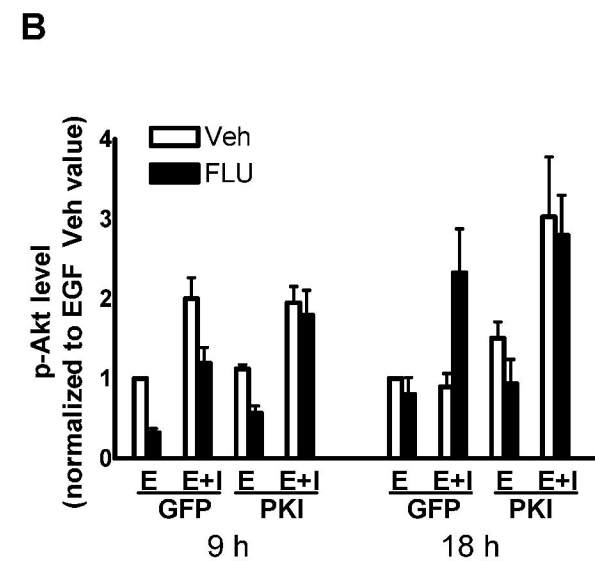
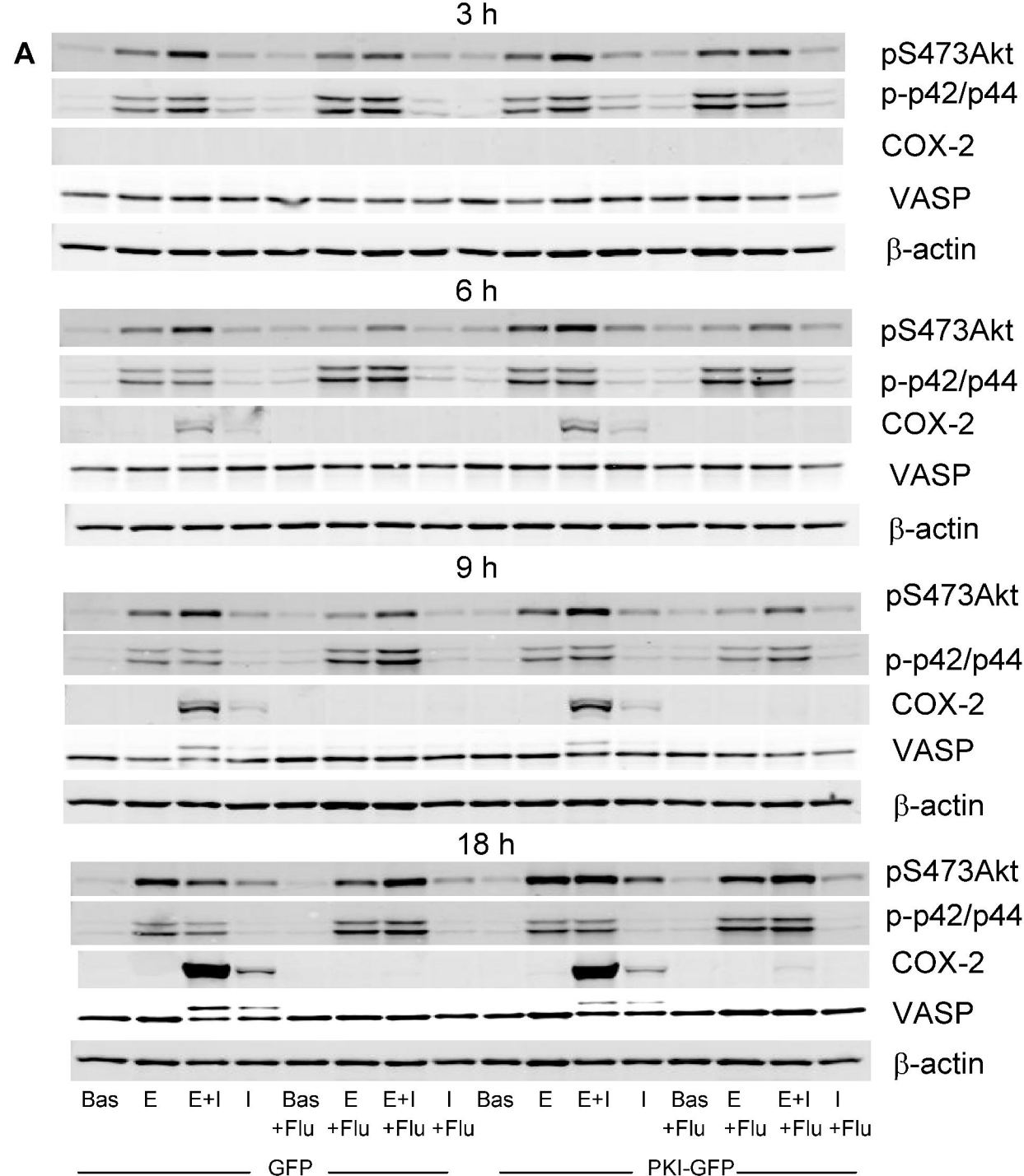


Figure 6

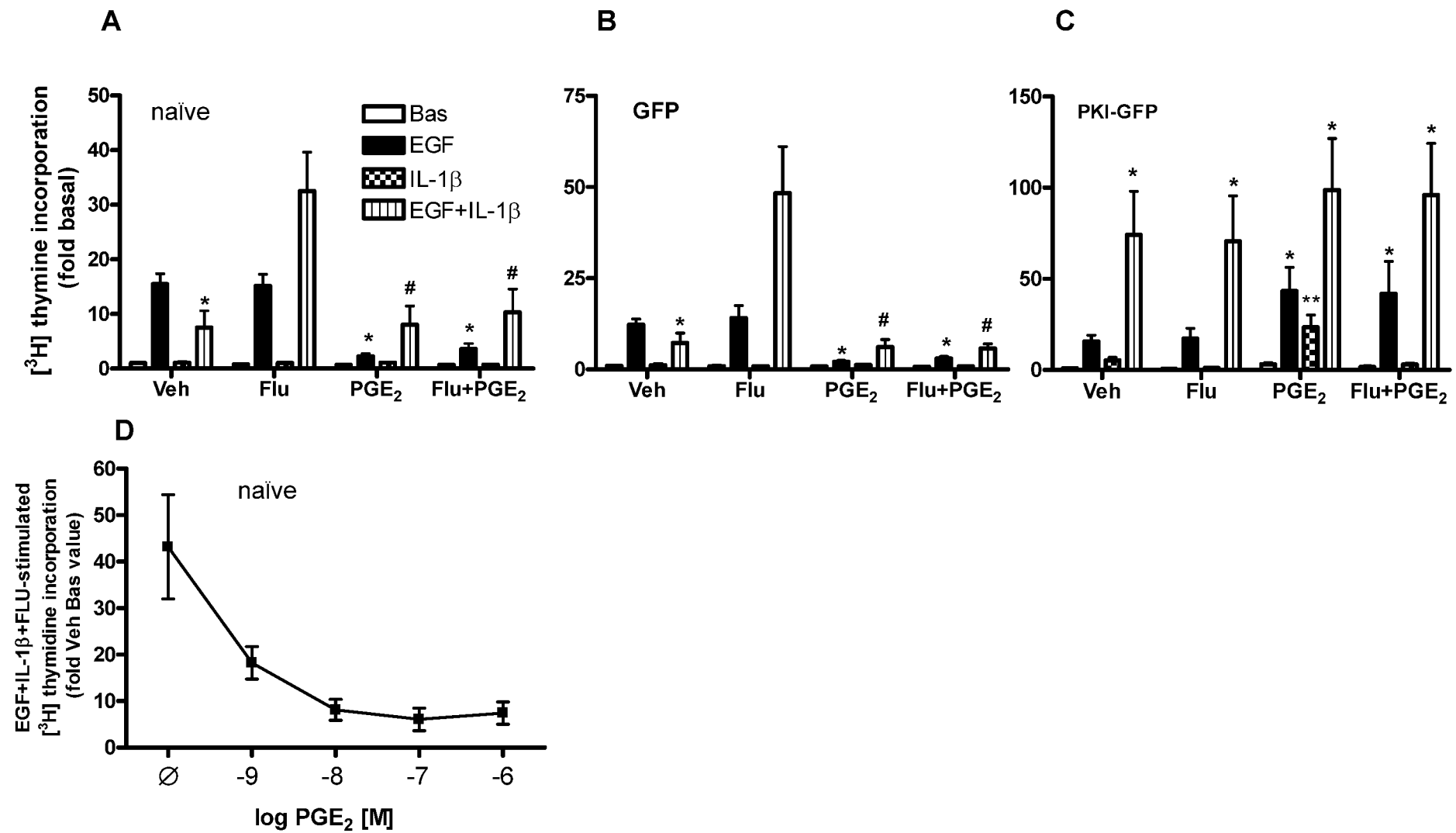


Figure 7

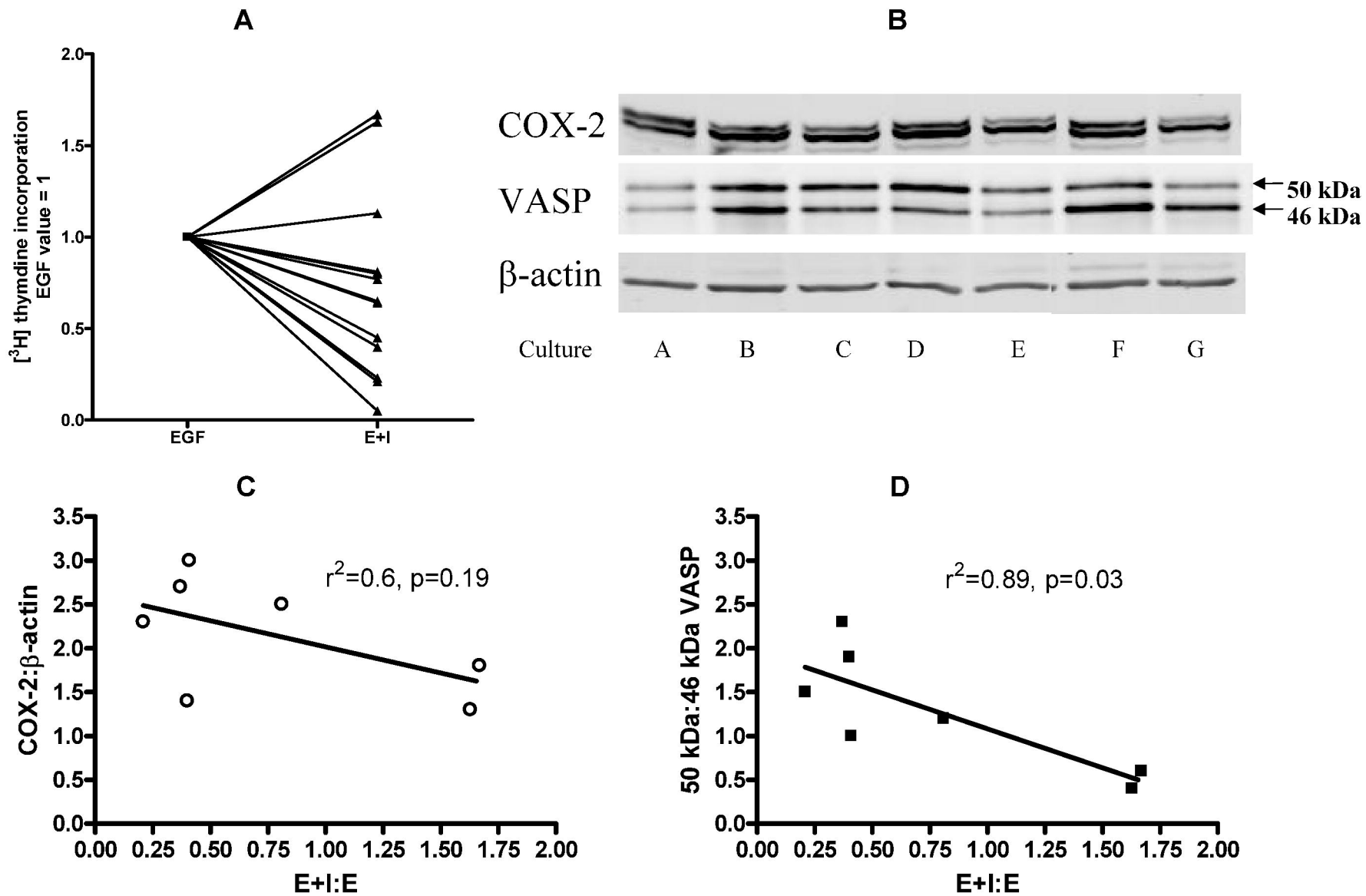


Figure 8