Constitutive Activation of Signal Transducer and Activator of Transcription 5 Contributes to Tumor Growth, Epithelial-Mesenchymal Transition, and Resistance to Epidermal Growth Factor Receptor Targeting

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Abstract

Purpose: Signal transducer and activator of transcription 5 (STAT5) is activated in squamous cell carcinoma of the head and neck (SCCHN), where targeting of STAT5 inhibits tumor growth *in vitro* and *in vivo*. The role of STAT5 activation in carcinogenesis, tumor progression, and response to therapy remains incompletely understood. In this study, we investigated the effects of STAT5 activation on squamous epithelial carcinogenesis and response to therapy.

Experimental Design: The functional consequences of STAT5 activation in squamous epithelial carcinogenesis were examined using cells derived from normal (Het-1A) and transformed mucosal epithelial cells engineered to express constitutive-active mutants of STAT5.

Results: The growth rate of stable clones derived from both normal and transformed squamous epithelial cells expressing the constitutive-active STAT5 was increased. In SCCHN xenografts, tumor volumes were increased in constitutive-active STAT5 mutant cells compared with vector-transfected controls. Constitutive activation of STAT5 significantly increased cell migration and invasion through Matrigel, as well as the transforming efficiency of SCCHN cells *in vitro*, as assessed by soft agar assays. The constitutive-active STAT5 clones derived from SCCHN cells showed changes consistent with an epithelial-mesenchymal transition including decreased expression of E-cadherin and increased vimentin in comparison with control transfectants. In these cells, STAT5 activation was associated with resistance to cisplatin-mediated apoptosis and growth inhibition induced by the epidermal growth factor receptor tyrosine kinase inhibitor, erlotinib.

Conclusions: These results suggest that constitutive STAT5 signaling enhances tumor growth, invasion, and epithelial-to-mesenchymal transition in squamous epithelial carcinogenesis and may contribute to resistance to epidermal growth factor receptor tyrosine kinase inhibitor and chemotherapy.

Signal transducer and activator of transcription 5 (STAT5), a transcription factor that is activated by tyrosine phosphorylation, regulates gene expression when stimulated by a wide variety of growth factors, hormones, and cytokines (1). Activated STAT5 dimers bind to specific DNA response elements in the promoter region of target genes in the nucleus and regulate various cellular responses including growth, migration, survival, and cell motility. Two highly homologous forms of STAT5, STAT5a and STAT5b, are encoded by two closely linked genes on human chromosome 17q11.2. Cumulative evidence suggests that STAT5 isoforms may display distinct as well as redundant functions.

STAT5 activation has been implicated in oncogenesis. Studies in hematopoietic malignancies suggest that STAT5 may be necessary and sufficient for malignant transformation (2). Emerging evidence also supports an important role for STAT5 in solid tumors. STAT5 is constitutively activated in several solid tumors including prostate cancer (3, 4), breast cancer (5), nasopharyngeal carcinoma (6), and squamous cell carcinoma of the head and neck (SCCHN; ref. 7). However, the precise role of STAT5 in epithelial carcinogenesis remains incompletely understood.

The functional consequences of STAT5 activation seem to depend on the cellular context. In prostate cancer, constitutive activation of STAT5 correlated with high histologic grade and early disease recurrence (3, 4). In contrast, activated STAT5 correlated with increased patient survival in breast cancer and

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Note: P. Koppikar and V.W.Y. Lui contributed equally to this work.

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Translational Relevance

Activation of signal transducer and activator of transcription 5 (STAT5) has been reported in a variety of malignancies where blockade of STAT5 inhibits cancer growth in preclinical cancer models. Generation of dominant-active mutants of STAT5 led to the observation that STAT5 activation was sufficient to transform hematopoietic cells. In these studies, we show that expression of dominant-active STAT5 mutants increases the growth and invasion of SCCHN cells *in vitro* and *in vivo* but is not sufficient to transform normal mucosal epithelial cells. Further investigation showed that increased STAT5 activation conferred an epithelial-to-mesenchymal (EMT) phenotype as well as resistance to cisplatin chemotherapy and epidermal growth factor receptor (EGFR) inhibition. We previously reported that STAT5 is activated downstream of EGFR in squamous cell carcinoma of the head and neck (SCCHN). EGFR targeted therapy was Food and Drug Administration approved for SCCHN 2006. However, despite the ubiquitous expression of EGFR in SCCHN tumors, only a subset of patients will respond to EGFR targeting. The translational implications of the present study suggest that STAT5 activation may contribute to therapeutic resistance in SCCHN where strategies that specifically inhibit STAT5 may improve therapeutic responses.

nasopharyngeal cancer, indicating that STAT5 maybe a favorable prognostic factor in these malignancies (5, 6).

We previously reported constitutive activation of STAT5 downstream of epidermal growth factor receptor (EGFR) in SCCHN compared with normal oral epithelial cells from unaffected individuals, wherein STAT5 activation was higher in the SCCHN tumors compared with levels in the corresponding normal mucosa from the same SCCHN patients (7). Further investigation showed that specific targeting of STAT5 isoforms by antisense oligonucleotides resulted in abrogation of STAT5 expression and activation, inhibition of SCCHN growth *in vitro* and *in vivo*, as well as inhibition of expression of STAT5 target genes (7, 8). Thus, loss-of-function studies have implicated a role for STAT5 activation in SCCHN proliferation.

The present study was undertaken to test the hypothesis that constitutive activation of STAT5 contributes to SCCHN tumorigenesis and response to therapy. EGFR is emerging as a therapeutic target in several cancers including SCCHN. Despite promising results in preclinical models, the response rate to tyrosine kinase inhibitors or monoclonal antibodies as monotherapy is no greater than 10% to 13% in the setting of recurrent or metastatic disease (9–11). We studied the functional consequences of constitutive STAT5 activation in two representative SCCHN cell lines and in nontransformed immortalized squamous epithelial cells using stable expression of constitutive-active mutants of STAT5. Our results suggest that constitutive STAT5 signaling enhances tumor growth, invasion, and epithelial-to-mesenchymal transition (EMT) in squamous epithelial carcinogenesis, as well as contributes to the resistance of SCCHN cells to apoptosis and growth inhibition induced by cisplatin or the EGFR tyrosine kinase inhibitor erlotinib, respectively.

Materials and Methods

Reagents. Antibodies used include E-cadherin (BD Biosciences PharMingen), vimentin (Sigma-Aldrich), p-Tyr PY99 (Santa Cruz Biotechnology, Inc.), anti-STAT5a rabbit antiserum and anti-STAT5b rabbit antiserum (Santa Cruz Biotechnology), glyceraldehyde-3-phosphate dehydrogenase (Abcam, Inc.), and β-actin (Calbiochem). The enhanced chemiluminescence kit was from Santa Cruz Biotechnology. Geneticin (G418) was from Invitrogen. The EGFR-specific tyrosine kinase inhibitor erlotinib (Tarceva) was obtained from Genentech.

Plasmids. The vector control plasmid, pUSEamp(+), was purchased from Upstate Biotechnology. Plasmids carrying the activated mutants of STAT5a and STAT5b (pMX STAT5a 1*6 and pMX STAT5b 1*6 plasmids, respectively; kind gifts from Dr. Toshio Kitamura, University of Tokyo, Tokyo, Japan; ref. 12) were subcloned into the pUSEamp(+) backbone. Briefly, the STAT5 activated mutant genes were released from the pMX STAT5a 1*6 or pMX STAT5b 1*6 plasmids by restriction digestion with *Eco*RI and *Sal*I, which was then cloned into the *Eco*RI and *Xho*I sites of the pUSEamp (+) vector. The subcloned plasmids, which carried a cytomegalovirus promoter, were named as pUSTAT5a 1*6 and pUSTAT5b 1*6, respectively. The sequence of the plasmids was confirmed by automated sequencing (University of Pittsburgh, Pittsburgh, PA). The β-casein luciferase reporter gene construct, β-casein Luc, and the E-cadherin Luc construct were kind gifts from Dr. Richard Jove (H. Lee Moffitt Cancer Center & Research Institute, Orlando, FL) and Dr. J. Torchia at the University of Western Ontario (London, Ontario).

Cell culture and generation of stable clones. SCCHN cell lines PCI-15B and UM-22B are of human origin (14). A human esophageal cell line, Het-1A, was purchased from American Type Culture Collection. SCCHN cells were maintained in DMEM with 10% FCS (Mediatech). Het-1A cells were maintained in Airway epithelial cell culture medium with supplements (PromoCell) and 2% FCS (Invitrogen) with 1× penicillin/streptomycin (Life Technologies). Cell lines were cultured at 37°C with 5% CO_2 in humidified incubators. For stable clone generation, cells were transfected with pUSTAT5a 1*6 and pUSTAT5b 1*6 plasmids with Lipofectamine 2000 (Invitrogen). Two days after transfection, transfectants were maintained in G418 selection medium. Single colonies were isolated and maintained in G418 selection medium (0.8 mg/mL for PCI-15B clones, 2 mg/mL for UM-22B, and 0.4 mg/mL for Het-1A clones).

Luciferase assays. Stable clones were screened for increase in STAT5 transcriptional activity using β-casein luciferase reporter gene. Transient transfection of stable clones (3×10^5 cells) was done using 2 μg of β-casein luciferase plasmid in six-well plates. Five hours after transfection, the medium was replaced with complete medium. Twenty-four to 48 h posttransfection, cells were lysed in luciferase lysis buffer (0.05% Triton X-100, 2 mmol/L EDTA, and 0.1 mol/L Tris-HCl at pH 7.8) for 5 min on ice. Lysates were then centrifuged at 14,000 rpm for 5 min at 4°C. Supernatants were collected and assayed for luciferase activity with the luciferase assay kit from Promega. Luminescence was measured with a luminometer (Wallac, Inc.). Luciferase activity was expressed as relative light units per microgram of total protein. Fold changes in transcriptional activity with reference to the respective vector transfected control cells were calculated.

Western blotting. Cells were lysed with the western lysis buffer [1% NP40, 150 mmol/L NaCl, 1 mmol/L EDTA, 10 mmol/L sodium phosphate buffer (pH 7.2), 0.25 mmol/L DTT, 1 mmol/L phenylmethylsulfonyl fluoride, 10 g/mL leupeptin and 10 g/mL aprotinin] for 5 min at 4°C. The lysate was then centrifuged at 4°C, 12,000 rpm for 10 min. Supernatant was collected for protein quantitation. Protein quantitation was done with the Protein Assay Solution (Bio-Rad Laboratories) and bovine serum albumin of known concentration as the standard. Fifty micrograms of total protein were resolved on 8% SDS-PAGE gel and transferred onto the Trans-Blot nitrocellulose

membrane (Bio-Rad Laboratories) using the semidry transfer machine (Bio-Rad Laboratories). Membranes were probed for specific antibodies as previously described (7).

In vitro *growth*. Equal number of cells were plated in 12-well dishes and allowed to adhere overnight. Cell proliferation was followed every day up to 4 d. Cells were harvested by trypsinization and cell numbers, in triplicates, were determined by counting (with the trypan blue dye) with a hemocytometer.

Soft agar colony formation assay. Briefly, 0.2×10^5 cells were plated in triplicate in a 0.35% agarose layer (with low-melting agarose) on top of a 0.7% prechilled agarose layer in a 60-mm tissue culture dish. Both layers contained 1× complete medium. After plating, the tissue culture dishes were chilled at 4°C to solidify the agarose before they were incubated at 37°C (and 5% CO_2) for 2 to 4 wk. Colonies were then stained with *p*-iodonitrotetrazolium violet solution in 1× PBS (1 mg/mL; Sigma). The number of colonies in nine random fields was counted under a light microscope at ×40 magnification.

Matrigel invasion assay. Cellular invasion was quantified with BD Biocoat Matrigel Invasion Chambers with 8 μm pore size (BD Biosciences) according to the manufacturer's instructions. Briefly, the filter inserts and lower chambers were rehydrated with 250 and 500 μL of complete medium, respectively, and incubated at 37°C for 2 h. Cells (4×10^4) in complete media were then seeded onto the Matrigel-coated fibers and incubated for 24 h. Postincubation, the noninvading cells were removed from the upper surface of the filter insert with cotton-tipped swabs and then stained with Protocol Hema 3 Manual Staining System (Fisher Scientific). Invading cells were counted under ×200 magnification from four randomly selected fields per samples, and mean values from several independent assays done in duplicate were calculated.

Cell migration assay. At 90% to 95% confluence, the cells were quiesced in medium without serum for 36 to 48 h. A wound was induced with a sterile tip, after which the cells were treated with complete medium and incubated at 37°C for 24 h. Photographs were taken at 0 h (immediately after wound induction) and 24 h, and relative distance traveled by the cells at the acellular front was determined by computer-assisted image analysis.

Tumor xenograft studies. Four- to six-week-old female athymic nude mice (nu/nu; Harlan Sprague-Dawley; $n = 5$) were s.c. injected with 1×10^6 PCI-15B STAT5a 1*6 #2 cells on the right flank and 1×10^6 PCI-15B pUSEamp #1 cells on the left flank. Tumors were measured with calipers every 5 d after inoculation and tumor volumes were calculated with the following formula: volume = (length × width^2)/2. Animal care was in strict compliance with institutional guidelines established by the University of Pittsburgh, the Guide for the Care and Use of Laboratory Animals [National Academy of Sciences (1996)], and the Association for Assessment and Accreditation of Laboratory Animal Care International.

In vitro *apoptosis assay.* PCI-15B pUSEamp #1 and PCI-15B STAT5a 1*6 #2 cells (0.4×10^5) were plated in complete DMEM, with or without 10 μmol/L cisplatin, which was added after the cells were allowed to adhere overnight. Twenty-four hours after drug treatment, cells were detached by trypsinization, counted, and pelleted (1,000 rpm for 5 min). Cell pellets were washed once with PBS (pH 7.4) and resuspended in 100 μL of Annexin V binding buffer [10 mmol/L HEPES (pH 7.4), 140 mmol/L NaCl, 2.5 mmol/L $CaCl_2$]. Five microliters of Annexin V-Cy3 (BioVision Research Products) were added per tube and allowed to incubate at room temperature for 15 min in the dark. Then, the stained cell suspension was dropped on clean slides and covered with coverslips. The membrane of apoptotic cells stained a bright orange color when analyzed by fluorescence microscopy. The ratio (percentage) of apoptotic to total cells (apoptotic plus non apoptotic) was calculated for each high-power field. For each treatment, 5 to 10 high-power fields of view were quantitated on each section.

Erlotinib treatment of STAT5 dominant-active– and vector control–transfected cells. PCI-15B pUSEamp #1 and PCI-15B STAT5a 1*6 #2 cells (0.2×10^5) were plated in complete medium in 12-well plates. Twenty-four hours later, cells were treated with erlotinib (10 μmol/L). Cell counts were done 48 h after treatment using trypan blue vital dye exclusion. Percent inhibition of cell growth induced by erlotinib was calculated compared with DMSO-treated controls for both PCI-15B pUSEamp #1 and PCI-15B STAT5a 1*6 #2 cells. Each treatment was carried out in triplicate, and the experiment was repeated six times.

Statistics. The StatXact software with Cytel Studio (Cytel Software Corporation) was used for statistical analysis. Comparisons of *in vitro* cell proliferation, transforming efficiency, cellular migration and invasion, apoptosis, and erlotinib-mediated growth inhibition were done using the exact one-tailed (Wilcox-Mann-Whitney) test. *In vivo* tumor growth experiments compared the tumor volume in one flank to the paired tumor volume in the opposite flank with the one-tailed sign ranked test, under the a priori assumption that tumors derived from the STAT5 constitutive-active cells would be higher in volume when compared with those derived from the vector-transfected cells.

Results

Generation of SCCHN and immortalized squamous epithelial cells expressing dominant-active STAT5. We previously reported that STAT5 was activated in SCCHN downstream of EGFR and Src family kinases (7, 8, 13). To elucidate the role of STAT5 activation in head and neck carcinogenesis, we established stable clones expressing constitutive-active mutants of STAT5 in two representative SCCHN cell lines (PCI-15B and UM-22B) and an immortalized mucosal squamous epithelial cell line (Het-1A). The constitutive-active mutants were generated by PCR-driven random mutagenesis under a retroviral promoter leading to either of two mutations that result in constitutive tyrosine phosphorylation of STAT5 isoforms (both STAT5a and STAT5b) in the absence of growth factor stimulation (ref. 12; Fig. 1A). The mutant STAT5 plasmids were subcloned under a cytomegalovirus promoter to replace the retroviral promoter of the parent construct, and cells were transfected with vector alone (pUSEamp) or plasmids expressing constitutive-active mutants of STAT5. On long-term G418 selection, stable clones expressing the activated mutants were isolated and screened by β-casein luciferase reporter assays. Consistent with prior reports, stable expression of either STAT5a 1*6 or STAT5b 1*6 in these cell lines resulted in tyrosine phosphorylation of both STAT5a and STAT5b in coimmunoprecipitation assays (12, 14), thereby limiting our ability to examine the consequences of activation of the individual STAT5 isoforms (data not shown). Transcriptional activity in the STAT5 stably transfected clones was evaluated by luciferase assays (Fig. 1B-D). The PCI-15B stable clones STAT5a 1*6 #2 and STAT5b 1*6 #15 showed 10- and 4.1-fold increases in transcriptional activity compared with the pUSEamp #1 control clone, indicating that these clones expressed the constitutive active STAT5 mutants. Similarly, the UM-22B STAT5a 1*6 #4 clone showed a 12-fold increase in transcriptional activity compared with the vector control UM-22B pUSEamp #1. The Het-1A STAT5a 1*6 #6 clone showed a 9.5-fold increase in transcriptional activity when compared with the vector-transfected control Het-1A pUSEamp #3.

***Activation of STAT5 increases SCCHN and normal epithelial cell proliferation* in vitro *and SCCHN growth* in vivo.** To examine the biological consequence of STAT5 activation on cell growth in both SCCHN and nontransformed mucosal epithelial cells, the growth rates of SCCHN and Het-1A stably transfected with the STAT5a constitutive-active mutants were evaluated. As shown in Fig. 2, the growth rates of PCI-15B

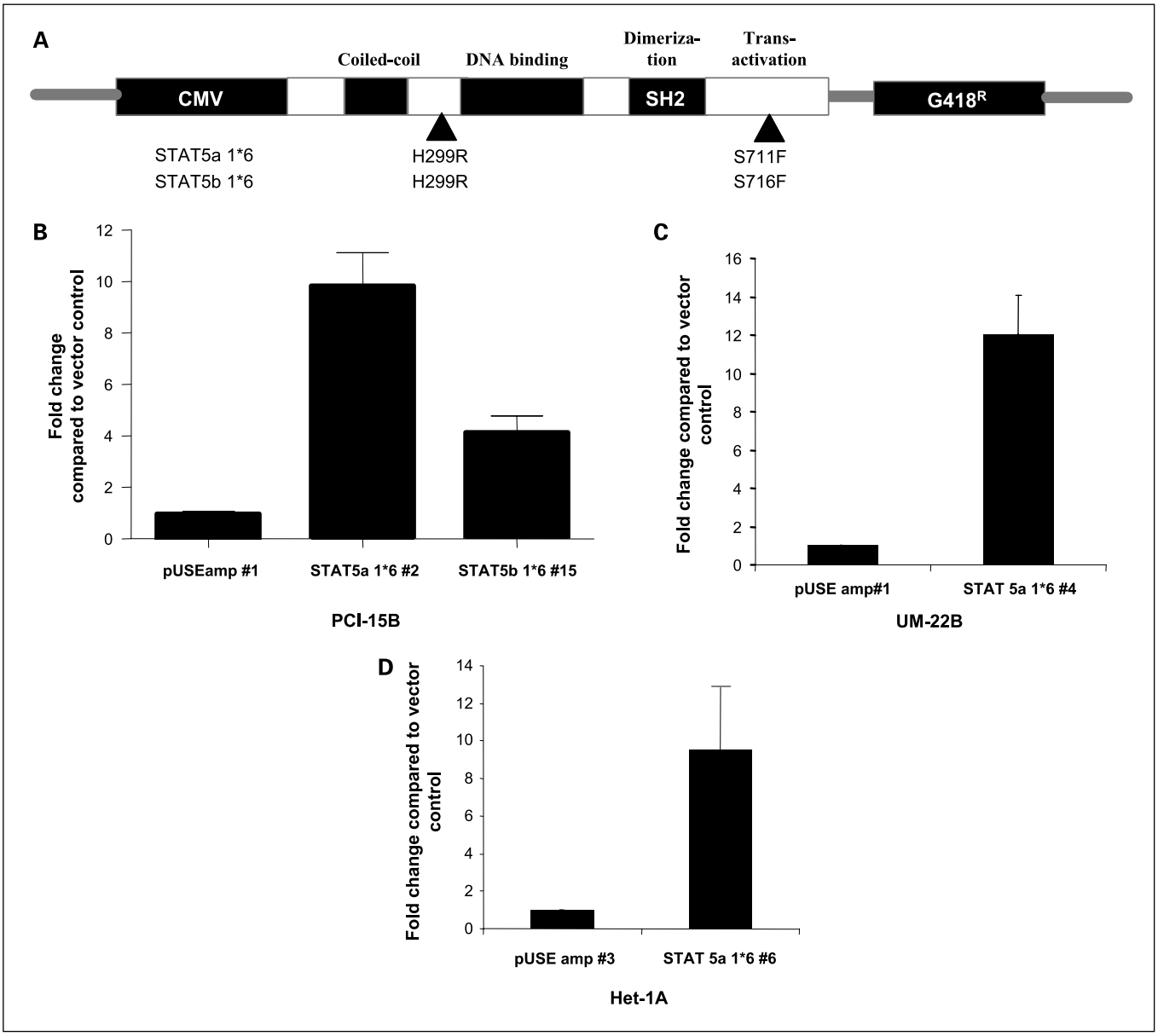

Fig. 1. Increased STAT5 promoter activity and target gene expression is detected in cells transfected with dominant-active STAT5 isoforms. Stable clones using dominant-active STAT5 isoforms were generated by transfection of pUSEamp (+) (vector control), pUSTAT5a 1*6 (activated STAT5a), and pUSTAT5b 1*6 (activated STAT5b) plasmids in SCCHN cells (*A*), PCI-15B cells (*B*), UM-22B cells (*C*), and Het-1A cells (*D*). On G418 selection, stable clones were isolated from the SCCHN cell lines and the immortalized mucosal epithelial cell line and screened for increase in STAT5 transcriptional activity using a β-casein luciferase reporter gene construct. Luciferase activity was expressed as relative light units per microgram of total protein (*RLU/g protein*). Fold change compared with the respective vector-transfected cells was calculated. Experiments were done thrice with similar results.

STAT5a 1*6 #2, PCI-15B STAT5b 1*6#15, and Het-1A STAT5a 1*6 #6 were higher than that of the respective vector-transfected control cells (Fig. 2A and B; $P = 0.004$).

Because STAT5 activation resulted in enhanced proliferation *in vitro*, we next examined if STAT5 activation would affect the growth of SCCHN tumors *in vivo*. A two-flank xenograft model was used to assess the growth of stably transfected SCCHN cells in nude mice. The growth rates of the SCCHN xenografts were followed for up to 25 days after inoculation. Tumors derived from PCI-15B STAT5a 1*6 #2 and PCI-15B STAT5b 1*6 #15 grew significantly faster ($P = 0.03125$) than those derived from the control clone (PCI-15B pUSEamp #1; Fig. 2C). However, inoculation of Het-1A STAT5a 1*6 #6 cells in nude mice did not lead to tumor formation (data not shown), suggesting that whereas STAT5 activation may contribute to SCCHN growth *in vivo*, STAT5 activation alone is not sufficient to transform normal squamous epithelial cells.

STAT5 activation results in increased transforming efficiency in SCCHN. STAT5 can potentiate the transforming activity of other oncogenes, such as v-Src (13), as well as function as a transforming oncogene in hematopoietic cells (2). To determine whether STAT5 activation can contribute to cancer initiation in SCCHN, we examined the effect of STAT5 activation on the transforming efficiency of SCCHN cells using a soft agar colony formation assay. As shown in Fig. 3, the PCI-15B STAT5a 1*6 #2 and PCI-15B STAT5b 1*6 #15 clones,

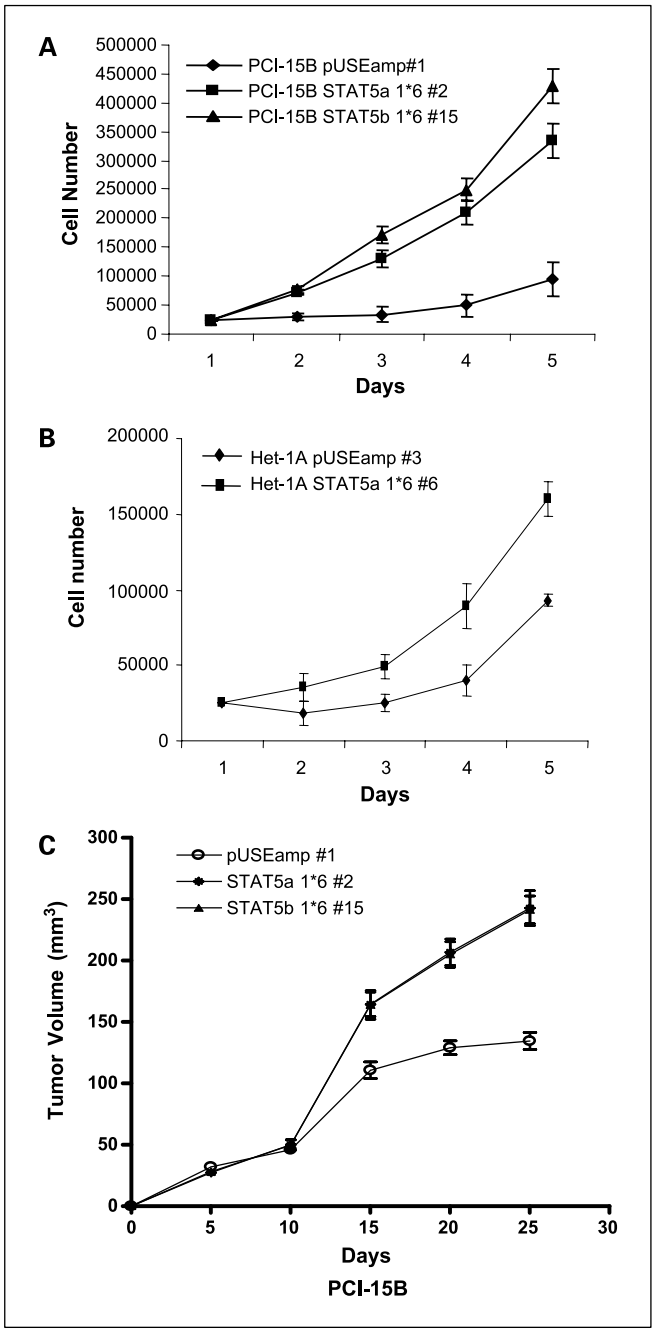

Fig. 2. Activation of STAT5 induces SCCHN and normal epithelial cell proliferation *in vitro*. Representative STAT5 constitutive-active stable clones in the cell lines PCI-15B (*A*) and Het-1A (*B*) were plated in triplicate at equal densities in complete growth medium. The growth rates of the STAT5 constitutive-active clones (PCI-15B STAT5a 1*6 #2 and Het-1A STAT5a 1*6 #6) were compared with the growth rates of their respective vector control – transfected cells (PCI-15B pUSE amp#1 and Het-1A pUSE amp#3); cell growth was determined by cell counting. Viable cells were counted using trypan blue exclusion dye. The numbers of vector-transfected control cells and STAT5 constitutive-active cells were compared at day 2 after plating. PCI-15B STAT5a grew 1.496-fold faster than the vector control PCI-15B pUSE amp #1 ($n = 5$ experiments, $P = 0.004$), whereas Het-1A STAT5a 1*6 #6 grew 1.56-fold faster than its vector control Het-1A pUSE amp #3 ($n = 3$ experiments, $P = 0.05$). *C,* activation of STAT5 induces SCCHN growth *in vivo*. One million PCI-15B STAT5a 1*6 #2 cells were inoculated on the right flank of the nude mice ($n = 5$), and 1 million PCI-15B pUSEamp #1 cells on the left flank ($n = 5$). Tumor volumes were measured every 5 d after inoculation for up to 25 d. At day 15, tumor derived from PCI-15B STAT5a1*6 #2 clone grew significantly faster than that from the control clone, PCI-15B pUSEamp #1 ($P = 0.03125$). At day 25, the tumor volume of PCI-15B STAT5a 1*6 #2 clone was 80.35% greater than that of the control PCI-15B pUSEamp #1 clone ($P = 0.03125$).

but not the Het-1A STAT5a 1*6 #6 clone (data not shown), showed a significant increase in the number of transforming colonies when compared with the respective vector-transfected control (PCI-15B STAT5a 1*6 #2: 51.78 2.56 colonies and PCI-15B STAT5b 1*6 #15: 48.00 2.38 colonies versus PCI-15B pUSEamp #1: 16.8 1.3 colonies; $n = 9$ fields; $P < 0.0001$).

STAT5 activation increases SCCHN migration and invasion. STAT5 has been implicated in cell migration and/or invasion in prostate cancer and kidney epithelial cells (4, 15). To determine if STAT5 activation was associated with normal and/or transformed mucosal epithelial cell migration, Het-1A pUSEamp #3, Het-1A STAT5a 1*6 #6, PCI-15B pUSE amp #1, and PCI-15B STAT5a 1*6 #2 cells were seeded onto 12-well plates and grown until 90% to 95% confluent, followed by serum starvation for 36 to 48 hours, after which a wound was induced and cell migration was measured at 24 hours after wound induction. Het-1A constitutive-active STAT5 cells (Het-1A STAT5a 1*6 #6) were only modestly more motile than the vector-transfected control cells (data not shown). However, in SCCHN cells, we observed a mean 8.5-fold increase in migration (equivalent to fold decrease in area of wound) compared with the vector-transfected control cells ($P = 0.05$; Fig. 4A). To determine the functional consequence of STAT5 activation on the invasive potential of SCCHN, we examined the invasion of SCCHN cells expressing constitutive-active STAT5 through Matrigel. Stable clones expressing the vector-transfected control (PCI-15B pUSEamp #1) showed no detectable invasion (0.00 cell per well ± 0.00 SE) whereas the PCI-15B STAT5a 1*6 #2 and STAT5b 1*6 #15 clones were invasive [13.70 cells per well ± 4.356 SE ($P < 0.001$) and 17.10 cells per well ± 4.557 SE ($P < 0.001$), respectively; Fig. 4B]. The vector-transfected control Het-1A clone was minimally invasive and its capacity to invade was not significantly increased by expression of constitutive-active STAT5 (data not shown). These results show that activation of STAT5 increases the migration and invasive potential of SCCHN cells but is not sufficient to induce migration and/or invasion of nontransformed squamous epithelial cells.

Activation of STAT5 abrogates E-cadherin and increases vimentin expression in SCCHN. Reduced expression of E-cadherin is associated with an increased risk of tumor invasion and metastasis in several cancers (16–18). Loss of E-cadherin and increase in vimentin expression are consistent with an EMT, a central process implicated in cancer invasion and metastasis (18). Because we observed an increase in cellular migration through Matrigel, we next examined if these alterations induced by STAT5 activation were consistent with EMT. E-cadherin expression in PCI-15B STAT5 – activated cells (PCI-15B STAT5a 1*6 #2 and PCI-15B STAT5b 1*6 #15) was lost and vimentin expression was elevated when compared with expression levels in the vector-transfected control cells (PCI-15B pUSEamp #1; Fig. 5A). Consistent with the induction of EMT markers, PCI-15B STAT5a 1*6 #2 cells showed distinct morphologic alterations when compared with vector-transfected control cells (PCI-15B pUSEamp #1; Fig. 5B). The latter showed a more pleomorphic and attached morphology compared with the SCCHN cells expressing activated STAT5, which showed a cell scattering phenotype that was less adherent. To further investigate the reduction of E-cadherin expression levels in STAT5 dominant-active clones, we performed luciferase assays in PCI-15B cells cotransfected transiently with either E-cadherin

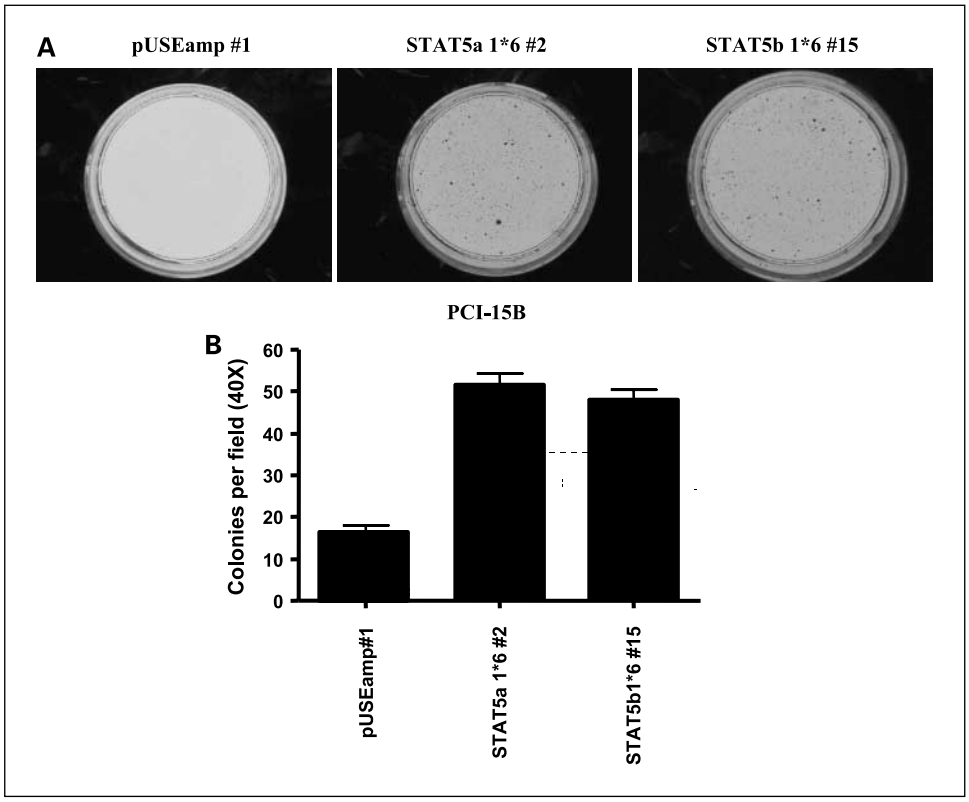

Fig. 3. STAT5 activation results in increased growth of SCCHN cells in soft agar. Stable clones of PCI-15B pUSEamp #1 and PCI-15B STAT5a 1*6 #2 were plated in triplicate at a density of 0.2×10^5 cells per plate in soft agar containing 1 × complete DMEM. Two to four weeks after plating, colonies were stained with *p*-iodonitrotetrazolium violet. *A,* representative stained colonies of PCI-15B pUSEamp #1, PCI-15B STAT5a 1*6 #2, and PCI-15B STAT5b 1*6 #15 are shown at ×4 magnification. *B,* the number of colonies in nine random fields was counted under a light microscope at ×40 magnification. Columns, mean; bars, SE. $P < 0.0001$.

Luc and pUSE amp(+) constructs or E-cadherin Luc and pUSTAT5a 1*6 constructs. Forty-eight hours after transfection, cells were lysed and luciferase assays were done. As shown in Fig. 5C, cotransfection of E-cadherin Luc and pUSTAT5a 1*6 caused reduction in transcriptional activity of E-cadherin Luc by >50% ($P = 0.002$). This suggests that dominant-active STAT5 causes transcriptional repression of E-cadherin. However, this transcriptional repression may not be the only mechanism for the complete loss of E-cadherin expression as seen in Fig. 5A, and other factors such as promoter methylation or mutation in the E-cadherin gene may be involved. Transcriptional repression of E-cadherin by STAT5b has been shown before (19).

Activation of STAT5 increases resistance to cisplatin-induced apoptosis and erlotinib-induced growth inhibition. STAT5 activation has been associated with resistance to apoptotic stimuli (20, 21), although in other models expression of constitutive-active STAT5 resulted in apoptosis of interleukin-3–independent BaF/3 cells on interleukin-3 treatment (22). We previously showed that chemotherapeutic agents including cisplastin induced SCCHN cell death through apoptosis.[4] To determine the effects of STAT5 activation on apoptosis in SCCHN cell lines, we measured the percentage of apoptotic cells on addition of cisplatin (10 μmol/L), a commonly used chemotherapeutic reagent in SCCHN. Cisplatin treatment of PCI-15B pUSEamp #1 cells resulted in significantly more apoptosis compared with the response in cells expressing constitutive-active STAT5 [36.825% (± 2.727% SE) in PCI-15B pUSEamp #1 versus 6.4125% (± 1.1575% SE) in PCI-15B STAT5a 1*6 #2; $P = 0.0143$; Fig. 6A]. Similar responses were obtained using viability 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assays wherein the cells expressing dominant-active STAT5 were more resistant to cisplatin than vector-transfected control cells(data not shown).

The EMT phenotype is associated with decreased *in vitro* sensitivity to the EGFR tyrosine kinase inhibitor erlotinib in lung cancer (23, 24). Because constitutive activation of STAT5 induced markers associated with EMT, we next examined if activated STAT5 led to resistance to erlotinib. The IC_{50} value of erlotinib in PCI-15B pUSEamp#1 cells was determined to be 10 μmol/L, which is consistent with most SCCHN cell lines examined (data not shown). PCI-15B cells express very high levels of EGFR wherein EGFR phosphorylation is inhibited by treatment with erlotinib (25). We detected significantly less growth inhibition induced by erlotinib treatment of the SCCHN cells expressing constitutive-active STAT5 (PCI-15B STAT5a 1*6 #2) compared with vector-transfected control cells (PCI-15B pUSE amp #1; $P = 0.0011$; Fig. 6B), suggesting that STAT5 activation may contribute to the modest clinical responses observed when SCCHN patients receive EGFR tyrosine kinase inhibitors.

Discussion

The role of STAT5 activation in cancer depends on the specific tumor type under investigation. We show here that STAT5 activation enhances the growth of normal and transformed squamous epithelial cells, increases the migration and invasion of squamous carcinoma cells, and induces phenotypic and molecular changes associated with EMT. Our results are consistent with the reported oncogenic functions of STAT5 in a variety of hematopoietic malignancies and support a role for

[4] Xi et al., Oncogene 2005; S.M. Thomas et al., Mol Pharm 2008.

STAT5 activation in solid tumors. The translational significance is shown by our finding that STAT5 activation is associated with resistance to cisplatin or erlotinib in SCCHN cells expressing dominant-active STAT5 isoforms.

STAT5 has been implicated as an oncogene, primarily in hematopoietic malignancies. The same constitutively activated STAT5a mutant that was used in the present study (S711F) was able to transform hematopoietic cell lines (2). In chronic myelogenous leukemia, STAT5 activation has been shown to mediate the transforming activity of Bcr-Abl (26). Activation of STAT5a in myeloma and lymphoma associated with the *TEL/JAK2* oncogenic gene fusion is independent of cell stimulus and has been shown to be essential for the tumorigenicity of the *TEL/JAK2* oncogene (27). Indeed, activation of STAT5 is both necessary and sufficient for transformation by *TEL/JAK2*

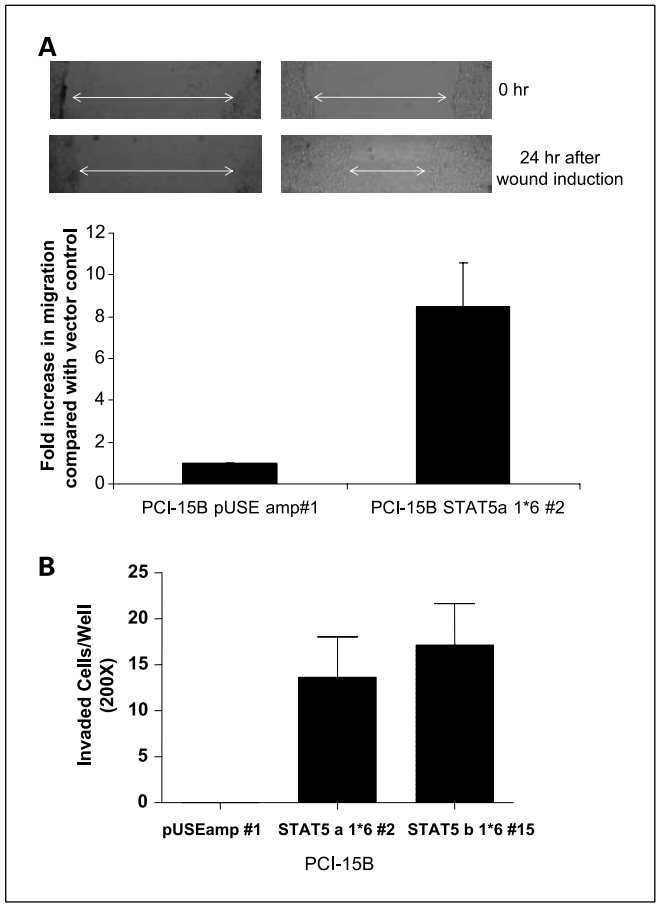

Fig. 4. STAT5 activation increases the migration and invasion of SCCHN, but not normal epithelial, cells. *A,* SCCHN cells (PCI-15B pUSEamp #1 and PCI-15B STAT5a 1*6 #2) were grown until 90% to 95% confluent in 12-well plates and then serum starved for 36 h. A wound was induced with a sterile tip and cell migration was monitored after 24 h. Photographs were taken immediately after wound induction and 24 h later (*top*), and the relative distance traveled by the cells at the acellular front was determined by computer-assisted image analysis (*arrow bars*). Cellular migration was determined by the decrease in total area of the wound after 24 h. The graph indicates fold increase in migration of PCI-15B STAT5a 1*6 #2 compared with the vector-transfected cells, PCI-15B pUSE amp #1, and represents cumulative data from three independent experiments ($P = 0.05$). *B,* PCI-15B stable clones were plated (4×10^4 cells) in complete medium onto Matrigel. Both the upper and lower chambers were filled with complete medium. Twenty-four hours postincubation, noninvading cells were removed from the upper surface of the filter insert and only invading cells were stained and counted (at ×200 magnification) from randomly selected fields ($n = 4$). Columns, mean for SCCHN cells from several independent experiments each done in duplicate; bars, SE ($P = 0.004$).

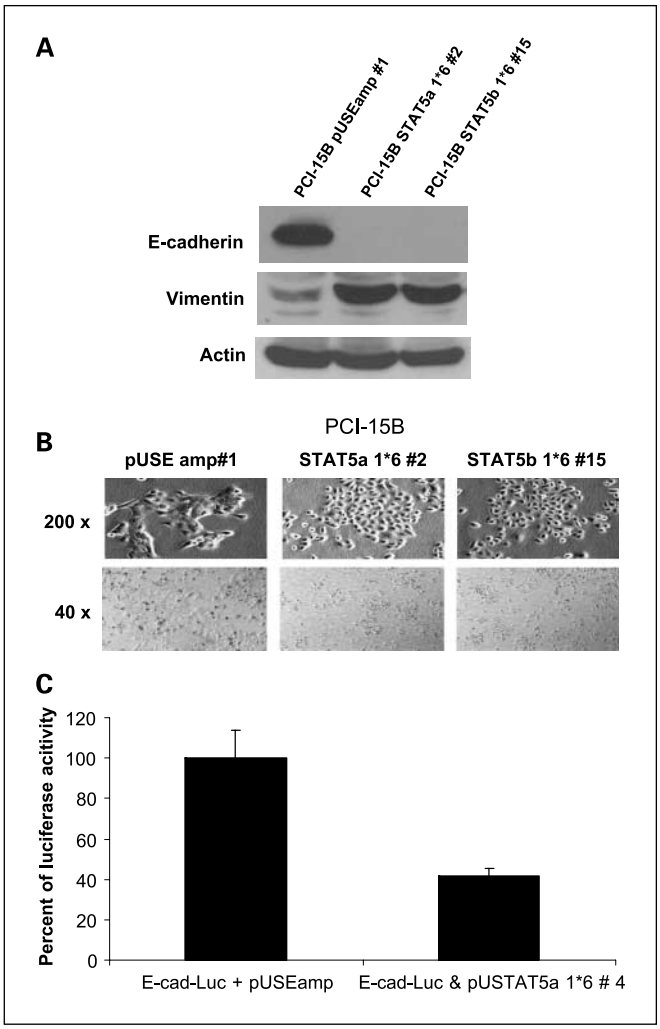

Fig. 5. Activation of STAT5 induces molecular and phenotypic changes consistent with EMT. *A,* activation of STAT5 abrogates E-cadherin expression and increases vimentin expression in SCCHN cells. PCI-15B pUSEamp #1 cells and cells from two representative STAT5 dominant-active clones, PCI-15B STAT5a 1*6 #2 and PCI-15B STAT5b 1*6 #15, were harvested for Western blot analysis. Expression of E-cadherin was totally abrogated in the STAT5 constitutive-active cells when compared with the PCI-15B pUSEamp #1 control. The loss of E-cadherin was accompanied by an increase in vimentin expression. Actin is shown as a loading control. *B,* activation of STAT5 results in cell scattering and reduced cell-cell adhesion in SCCHN cells. The stable clones, PCI-15B pUSEamp #1 and PCI-15B STAT5a 1*6 #2, were plated (3×10^5 cells each) in tissue culture dishes. Twenty-four hours after plating, cellular morphology was recorded with a digital camera under a microscope (at ×40 and ×200 magnifications). The experiment was done twice with similar results. *C,* PCI-15B cells (3×10^5) were plated in triplicate in six-well plates. Twenty-four hours after plating, cells were transiently cotransfected with either 1.5 μg of E-cadherin Luc and 1.5 μg of pUSE amp (+) or 1.5 μg of E-cadherin Luc and 1.5 μg of pSTAT5a DA plasmids. Luciferase assay was done 48 h after transfection. Luciferase activity was expressed as relative light units per microgram of total protein. Luciferase activity values from vector control – and E-cadherin-Luc – transfected cells were normalized to 100%, and the decrease in luciferase activity of pSTAT5a DA – and E-cadherin Luc – transfected cells was calculated ($P = 0.002$). *P* values were calculated from several independent experiments each done in triplicate.

(and STAT5 activation), leading to induction of the single downstream target gene oncostatin M (*OSM*) and induction of a lethal myeloproliferative disease. STAT5 activation has been linked to transformation mediated by other fusion genes including NPM/ALK and TEL/ABL (28, 29). The STAT5b/retinoic acid receptor α gene fusion has been detected in a small subset of acute promyelocytic-like leukemias (30).

Fewer studies have elucidated the role of STAT5 activation in solid tumors. In prostate cancers, STAT5 activation is a poor prognostic factor, where cumulative evidence implicates STAT5 in disease progression and recurrence (3, 4). In contrast, STAT5 activation is correlated with improved survival in breast and nasopharyngeal cancers (5, 6). We previously reported that STAT5 is activated in SCCHN, downstream of EGFR and/or Src family of kinases (7, 13). Using loss-of-function approaches, including antisense oligonucleotides and dominant-negative mutants targeting STAT5 isoforms, we found that inhibition of STAT5b, but not STAT5a, abrogated SCCHN growth (7, 8). In the present study, we used a gain-of-function approach to introduce constitutive-active mutants of STAT5 into SCCHN and normal mucosal squamous epithelial cells. Forced overexpression of activating mutations of STAT5 is a more direct way to study the functional consequences and contribution of STAT5 activation. These double mutations are known to result in gain of function of STAT5 as reflected by constitutive tyrosine phosphorylation and enhanced transcriptional activity of STAT5 (12). Whereas it is possible that activation of STAT5a may induce a phenotype that is inconsistent with our previous studies abrogating STAT5a (7), the persistent activation of STAT5b in the cells transfected with either dominant-active construct is the most likely explanation for the transforming potential of the STAT5a construct in the present study.

Constitutive activation of STAT5 resulted in increased cell proliferation of both normal and transformed squamous epithelial cells. STAT5, in concert with Raf, has been shown to induce proliferation in interleukin-3–dependent cell lines, abrogating the need for the addition of exogenous cytokines (12). Activated STAT5 also plays a role in cellular proliferation of a diverse phenotype of cells including primary endothelial cells (31), myeloid cells (32), as well as head and neck cancer cells (7).

Constitutively active mutants of STAT5 have been shown to be oncogenic *in vivo* and *in vitro* and are capable of restoring the defective functions of STAT5 null mice (2). In contrast to the profound effects of STAT5 activation on transformed squamous cells, activation of STAT5 in immortalized normal epithelial cells failed to enhance migration and invasion or induce transformation. These findings suggest that unlike hematopoietic cells where STAT5 activation alone can lead to malignant transformation (2), other events are required in mucosal epithelial cells.

In addition to enhancing cell and tumor growth, increased STAT5 activation also increased SCCHN invasion. The role of STAT5 in tumor invasion and/or metastasis is incompletely understood. Our previous finding that STAT5 mediates erythropoietin-induced invasion in SCCHN suggests that STAT5 activation may be involved in tumor invasion (33). Here, we show that cell migration and invasion are, at least in part, a consequence of STAT5 activation in SCCHN.

EMT is a crucial embryogenic and developmental process during which epithelial cells acquire mesenchymal, fibroblast-like properties and show reduced intercellular adhesion and increased motility. Accumulating evidence points to a critical role of EMT-like events during tumor progression and malignant transformation, endowing the incipient cancer cell with invasive and metastatic properties (34). We found that activation of STAT5 resulted in phenotypic and molecular changes consistent with induction of EMT in transformed squamous epithelial cells. Further, STAT5 activation seems, at least partially, to cause transcriptional repression of E-cadherin (Fig. 5C). Previous studies have shown that STAT5 may facilitate mesenchymal transition in kidney epithelial cells as well as enhance the aggressive behavior of hepatocellular carcinomas via induction of EMT (19, 35). However, in breast cancer cells,

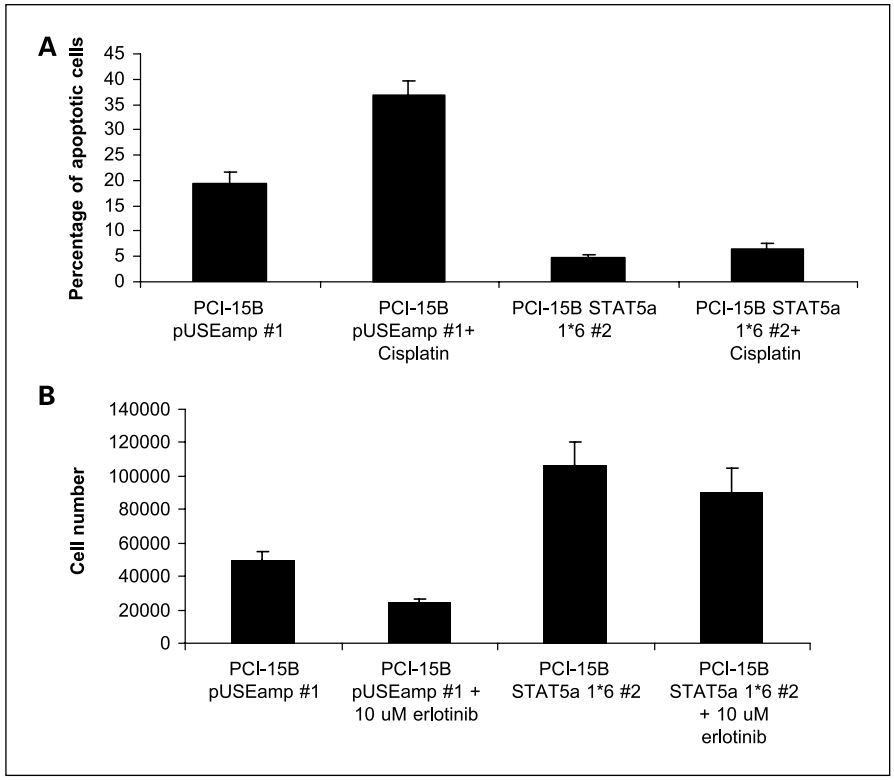

Fig. 6. Activation of STAT5 increases resistance to cisplatin-induced apoptosis and erlotinib-induced growth inhibition. *A,* PCI-15B pUSEamp #1 and PCI-15B STAT5a1*6 #2 cells (0.4×10^5) were plated in complete DMEM, with or without 10 μmol/L cisplatin. Twenty-four hours after drug treatment, cells were harvested for Annexin staining. Eight to ten fields were quantified per sample in each experiment. The graph represents cumulative data from four independent experiments showing decreased apoptosis in response to cisplatin in the cells expressing dominant-active STAT5 ($P = 0.0143$). *B,* PCI-15B pUSEamp #1 and PCI-15B STAT5a1*6 #2 cells (0.2×10^5 each) were plated in complete medium in 12-well plates. Twenty-four hours later, cells were treated with erlotinib (10 μmol/L). Cell counts were done 48 h after treatment using trypan blue vital dye exclusion. Percent inhibition of cell growth induced by erlotinib was calculated compared with DMSO-treated controls for both PCI-15B pUSE amp#1 and PCI-15B STAT5a1*6 #2. The graph represents cumulative data from six independent experiments ($P = 0.0011$).

dominant-negative STAT5 mutants resulted in the induction of invasion and EMT (36), implicating an invasion-suppressive role for STAT5 in breast cancer. Prolactin-induced STAT5 activation resulted in an invasion-suppressive phenotype, including an increase in E-cadherin expression and reduced invasion through Matrigel (36). The basis for the distinct roles of STAT5 in mediating invasion and EMT in different types of tumors is not entirely clear. Potential contributing factors include different cell types, tumor microenvironments, and regulation of upstream cytokines and growth factors.

Recently, EMT has been reported to serve as a determinant of sensitivity to EGFR inhibition by erlotinib in lung cancer (22, 23). Because constitutive STAT5 activation resulted in an EMT phenotype in SCCHN cells in our studies, we compared the sensitivity of constitutive-active STAT5 – expressing SCCHN cells and vector-transfected control cells to the growth-inhibiting effects of the EGFR tyrosine kinase inhibitor erlotinib. We found that constitutive-active STAT5 – expressing cells were less susceptible to growth suppression or apoptosis induced by erlotinib or cisplatin, respectively, in comparison with vector-transfected controls. These findings may have important implications for EGFR tyrosine kinase inhibitor therapy. Increased STAT5 activation and/or the transition to a mesenchymal type may provide a "molecular signature" to identify patients who are less likely to benefit from EGFR tyrosine kinase therapy.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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