Haplotype and Cell Proliferation Analyses of Candidate Lung Cancer Susceptibility Genes on Chromosome 15q24-25.1

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Abstract

Recent genome-wide association studies have linked the chromosome 15q24-25.1 locus to nicotine addiction and lung cancer susceptibility. To refine the 15q24-25.1 locus, we performed a haplotype-based association analysis of 194 familial lung cases and 219 cancer-free controls from the Genetic Epidemiology of Lung Cancer Consortium (GEiLC) collection, and used proliferation and apoptosis analyses to determine which gene(s) in the 15q24-25.1 locus mediates effects on lung cancer cell growth in vitro. We identified two distinct subregions, hapl (P = 3.20 × 10^-6) and hapN (P = 1.51 × 10^-6), which were significantly associated with familial lung cancer. hapl encompasses IREB2, LOC123688, and PSMA4, and hapN encompasses the three nicotinic acetylcholine receptor subunit genes CHRNA5, CHRNA3, and CHRNB4. Examination of the genes around hapl revealed that PSMA4 plays a role in promoting cancer cell proliferation. PSMA4 mRNA levels were increased in lung tumors compared with normal lung tissues. Down-regulation of PSMA4 expression decreased proteasome activity and induced apoptosis. Proteasome dysfunction leads to many diseases including cancer, and drugs that inhibit proteasome activity show promise as a form of cancer treatment. Genes around hapN were also investigated, but did not show any direct effect on lung cancer cell proliferation. We concluded that PSMA4 is a strong candidate mediator of lung cancer cell growth, and may directly affect lung cancer susceptibility through its modulation of cell proliferation and apoptosis. [Cancer Res 2009;69(19):7844–50]

Introduction

Lung cancer is the leading cause of cancer death in both men and women worldwide (1). Many factors contribute to the risk of lung cancer including tobacco smoke and genetic variations among populations. Tobacco smoke is well established as the major risk factor for lung cancer; however, only 10% to 15% of long-term smokers develop lung cancer in their lifetime, suggesting a genetic predisposition to the disease (2). Benzo[a]pyrene and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butane in tobacco smoke are two major carcinogens that cause DNA damage, oxidative stress, and inflammation, thus promoting the initiation and growth of lung tumors (3, 4). Nicotine in tobacco smoke is noncarcinogenic but highly addictive and acts through nicotinic acetylcholine receptors (nAChR). nAChRs are plasma membrane ion channels present in many tissues including the central and peripheral nervous systems and bronchial epithelial cells (5–8).

Both lung cancer and nicotine dependence studies have independently identified associations with the same variants of the 15q24-25.1 locus (9–12). Several highly significant single nucleotide polymorphisms (SNP) were identified in this locus, which spans a linkage disequilibrium block of ~240 kilobases and contains the genes IREB2, LOC123688, PSMA4, CHRNA5, CHRNA3, and CHRNB4. The CHRN genes encode for subunits of the nAChRs and were initially attractive candidates. Of the other genes in the locus, IREB2 encodes an iron regulatory protein 2 and plays a central role in maintaining cellular iron homeostasis (13), PSMA4 encodes a structural protein of the 20S proteasome core (14, 15), and LOC123688 is a hypothetical gene. It remains unclear whether the 15q24-25.1 locus has any direct or indirect effect on lung cancer susceptibility since many SNPs in this locus have high linkage disequilibrium. In the first scenario, a gene(s) in the 15q24-25.1 locus may regulate cell proliferation and/or apoptosis in the lung and thus predispose smokers to lung cancer. In the second scenario, polymorphisms in the locus may affect nicotine dependence and propensity to smoke, and thus increase the likelihood of developing lung cancer.

Based on our fine mapping analysis, we have systematically examined all of the six genes located in the 15q24-25.1 region for their role in regulating lung cancer cell growth in vitro. Via gene knockdown and apoptosis analyses, we showed that PSMA4 at the 15q24-25.1 locus has a role in modulating human lung cancer cell proliferation. We further showed that PSMA4 is required for proteasomal activities. Expression of PSMA4 was increased in lung tumors compared with matched normal lung tissues. Our results suggest that PSMA4 is a novel candidate gene that may contribute to lung cancer susceptibility.

Materials and Methods

Plasmids. Full-length cDNAs in cloning vectors encoding IREB2 (BC017880), LOC123688 (BC132753), PSMA4 (BC047667), CHRNA3 (BC012992), and CHRNA5 (BC012991) were obtained from Open Biosystems (Huntsville, AL). Plasmids encoding 3′UTR of IREB2 were purchased from Origene Technologies (Rockville, MD).
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(BCO01642), CHRNA5 (BC033639), and CHRNBA4 (BC096880) were purchased from Open Biosystems, amplified by PCR, and subcloned into the BamHI I and Xho I sites of p Lentiv6/V5-DOPO (pLV) vector (Invitrogen) to generate pLV-IREB2, pLV-LOC123688, pLV-PSMA4, pLV-CHRNA5, pLV-CHRNBA3, and pLV-CHRNBA4, respectively. PCR segments were confirmed by sequencing. Short hairpin RNAs in pLKO.1 lentiviral vectors for IREB2, LOC123688, PSMA4, and CHRNA5 knockdown were purchased from Open Biosystems.

Cell lines. Human non–small cell lung cancer (NSCLC) cell lines A549 and H1299 were maintained in RPMI1640 supplemented with 10% fetal bovine serum (FBS) and 2 mmol/L glutamine. 293T cells were maintained with 50 Ag/mL bovine pituitary extract and 5 ng/mL epidermal growth factor; Invitrogen). All cells were grown at 37°C in a humidified incubator with 5% CO2.

Transfection, viral packaging, and target cell infection. All transfections were performed using Lipofectamine 2000 (Invitrogen). To package lentiviral vectors, 293T cells were transfected with pLV or pLKO.1 vector along with pMDM Z6 and pΔR. Thirty-six hours after transfection, the supernatant was harvested and spun at 3,000 rpm for 10 min at 4°C, and then incubated with target cells in the presence of 8 μg/mL polybrene (Sigma) for 24 h. Three days after infection, A549 cells were selected under 9 μg/mL blasticidin (Invitrogen) for 2 wk (for pLV positive cells) or 1 μg/mL puromycin (Sigma) for 3 d (for pLKO.1-positive cells), H1299 cells were selected under 6 μg/mL blasticidin (for 2 wk or 1 μg/mL puromycin for 3 d), and HBECSKT cells were selected under 6 μg/mL blasticidin for 2 wk. Antibiotic-resistant cells were pooled and expanded for further analysis under selective conditions.

Cell proliferation assay. Cells were seeded in a 96-well plate at 1,000 cells per well (100 μL aliquots) and cultured for a period of up to 4 d for A549 and 6 d for H1299. Viable cells were counted daily by MTT assay (Promega). Twenty-five nanograms of the cDNA was used in a 25 μL total volume reaction mixture containing SYBR Green PCR Master Mix (Bio-Rad) and primers, and then quantitative PCR (qPCR) was performed using MyiQ Single Color Real-time PCR Detection System according to the manufacturer’s protocol (Bio-Rad). All primers were designed using Primer 3. The primers were as follows, for IREB2: (forward) 5'-TTTGGTGAAGCTCTGTCGTA-3', and (reverse) 5'-GGAGAAAGGGCATCTCAACA-3'; for LOC123688: (forward) 5'-GGAACAGCCTCTGCTGTG-3', and (reverse) 5'-GGCCCTACTTGGTGTGTTGA-3'; for PSMA4: (forward) 5'-GGAGCGAAATCTCTGTGGAGC-3', and (reverse) 5'-CCAGCCAATGTACGCAATG-3'; for CHRNA5: (forward) 5'-TGTTGCTCTGGTGAACACTC-3', (reverse) 5'-TCTTCTACATCCACAA-3'; for CHRNBA4: (forward) 5'-CGGGCTGTCATGCTTAA-3', and (reverse) 5'-CAAGAGTGGCCAGGGGTG-3', and (reverse) 5'-TCTTCTCGATCTGTCG-3'. All qPCR reactions were performed in triplicate.

Caspase-3/7 activity assay. Apoptosis was determined using Sendolys-teTM Homogeneous Rh110 Caspase-3/7 Assay kit (ANASPEC). Cells grown in 100-mm culture dishes were washed with PBS and collected by trypsinization. An aliquot containing 1 × 10^5 cells was precipitated and lysed in 150 μL 1× lysis buffer. Caspase-3/7 substrate solution (50 μL) was further added, and the reaction mixture was incubated at RT for 14 h. The end point fluorescence intensity was measured by a fluorescence microplate reader at Ex/Em of 496 nm/520 nm. All apoptosis assays were performed in triplicate.

Proteasome activity assay. The assay was performed as described (16) with modifications. Briefly, cells were washed with PBS and then collected with a rubber policeman in a lysis buffer containing 50 mmol/L Tris-HCl (pH 8.0), 5 mmol/L EDTA, 500 mmol/L NaCl, 0.5% NP40, 0.5 mmol/L DTT, and a protease inhibitor cocktail (Roche). The suspended cells were incubated on ice for 15 min with occasional vortexing. Lysates were spun at top speed in a microcentrifuge at 4°C for 20 min and supernatants were collected. An aliquot containing 100 μg of lysates was incubated with 20 mmol/L fluorogenic peptide substrates Suc-LIVY-AMC and Z-LEU-AMC (Calbiochem) in 100 μL for 90 min at 37°C. The end point fluorescence intensity was measured by a fluorescence microplate reader at Ex/Em of 380 nm/460 nm. All proteasome activity analyses were performed in triplicate.

Western blotting. Eighty to 90% confluent cells in each well of six-well plates were lysed in 250 μL of 1× LDS buffer (Invitrogen) containing proteinase and phosphatase inhibitor cocktails (Sigma), sonicated, and then boiled for 10 min. Twenty microfilters of each sample were resolved on SDS-PAGE and immunoblotting analyzed with the indicated antibodies.

Figure 1. Haplotype analysis of the 15q24-25.1 locus. A, association of haplotypes with familial lung cancer susceptibility in the GELCC collections. Blue lines, the results from omnibus/global haplotype analysis; red lines, the results from individual haplotype analysis. B, physical map of the 15q24-25.1 locus.
Proteins were visualized with horseradish peroxidase–conjugated second-
ary antibodies (Amersham Biosciences) and an enhanced chemilumines-
cent substrate kit (Pierce).

Haplotype analysis of 15q24-25.1 locus. Haplotype-based association
analysis was performed on the 15q24-25.1 locus using 194 familial lung
cases and 219 cancer-free controls from the GELCC collections (12). A total
of 251 SNPs spanning from 76,016,651 to 76,992,181 bases on the 15q24-25.1
locus were analyzed. To exhaustively exploit the haplotype information, we
then subjected alleles (contiguous sets of markers) from sliding windows of
all sizes to haplotype association tests. Haplotype analyses were
implemented in the statistical package PLINK. Both omnibus/global
association statistic and haplotype-specific statistic were computed. The
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haplotypes using \( \chi^2 \) with one degree of freedom (df). In total, H-1
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performed to assess the overall association. If the overall association is
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determine which haplotype at that location shows the strongest evidence
for an association with familial lung cancer susceptibility.

**Results**

Fine mapping of 15q24-25.1 locus. To refine the 15q24-25.1
locus, we performed haplotype-based association analysis using
194 familial lung cases and 219 cancer-free controls from the
GELCC collections (Fig. 1). To exhaustively exploit the haplotype
information, we analyzed haplotypes ranging from 3 to 15
contiguous SNPs in the 15q24-25.1 locus and identified two
distinct subregions that showed the most significant associations
with familial lung cancer. The subregion on the left side of the
15q24-25.1 locus (named HapL) encompasses eight SNPs
(rs16969899, rs13180, rs16969914, rs9788682, rs9788721, rs8034191, rs10519203,
and rs7163730). Hap N spans 76,698,236 to 76,755,323 bp, and consists of
rs8040868, rs8192475, rs3743072, rs17487223, rs950776, rs11072768, rs11637890,
rs11072773, rs1269519, rs12594550, rs12905641, and rs11857332.

**Table 1. Two haplotypes are associated with familial lung cancer**

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<th>Haplotypes</th>
<th>Frequency</th>
<th>P</th>
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<td></td>
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<td>Controls</td>
</tr>
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NOTE: HapL spans 76,569,281 to 76,601,736 bp, and consists of rs16969899, rs13180, rs16969914, rs9788682, rs9788721, rs8034191, rs10519203, and
rs7163730. Hap N spans 76,698,236 to 76,755,323 bp, and consists of rs8040868, rs8192475, rs3743072, rs17487223, rs950776, rs11072768, rs11637890,
rs11072773, rs1269519, rs12594550, rs12905641, and rs11857332.

Abbreviation: NA, not applicable.

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ary antibodies (Amersham Biosciences) and an enhanced chemilumines-
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haplotypes using \( \chi^2 \) with one degree of freedom (df). In total, H-1
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with H-1 df. At each location, the omnibus association analysis is first
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Fine mapping of 15q24-25.1 locus. To refine the 15q24-25.1
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(rs16969899, rs13180, rs16969914, rs9788682, rs9788721, rs8034191, rs10519203,
and rs7163730) and spans 32.4 kb. Omnidius/global
association analysis yielded a \( P \) value of 2.71 × 10⁻⁶ at HapL. Eight
haplotypes were detected with frequencies of >1% at HapL. Among
them, the haplotype ATAGCCGCA showed the strongest association
with familial lung cancer (\( P = 3.20 \times 10^{-6} \)). This haplotype is a risk
allele with a frequency of 38.12% in cases versus 20.54% in controls,
whereas three less common haplotypes, ATAGCCGCA, ACAATATG,
and ACAGTTA, reduce the risk of lung cancer (Table 1). The

subregion on the right side of the 15q24-25.1 locus (named hapN) encompasses 12 SNPs (rs8040868, rs8192475, rs3740372, rs17487223, rs950776, rs11072768, rs11637890, rs11072773, rs12900519, rs12594550, rs12905641, and rs11857532) and spans 57.1 kb. The haplotype CCCGAACGCTGGC had the strongest association with familial lung cancer at hapN ($P = 1.51 \times 10^{-6}$).

On the 15q24-25.1 locus, IREB2, LOC123688, and PSMA4 are within or around hapL, whereas the nAChR subunit genes CHRN5A, CHRNA3, and CHRNA4 are within or around hapN. It is likely that the two subregions may have distinct roles in lung cancer susceptibility. Gene(s) around hapL may regulate cell proliferation and/or apoptosis in the lung and thus predispose smokers to lung cancer (a direct effect), whereas gene(s) around hapN may affect nicotine dependence and propensity to smoke and thus increase the likelihood of developing lung cancer (an indirect effect).

nAChRs have previously been implicated in nicotine dependence and related phenotypes (9–12, 17–19). The present study uses gene overexpression and/or gene knockdown and apoptosis analyses to determine if any gene(s) around hapL mediates effects on lung cancer cell growth in vitro.

**IREB2, LOC123688, PSMA4, and lung cancer cell proliferation.** To determine whether genes around the hapL play a role in regulating human lung cancer cell proliferation, IREB2, LOC123688, and PSMA4 were first overexpressed in A549 and H1299 cells. For unknown reasons, we could only increase the PSMA4 transcript levels up to 1-fold in both cell lines and the IREB2 transcript levels up to 1-fold in A549 (Supplementary Fig. S1). Consequently, we opted to conduct gene knockdown experiments using short hairpin RNAs. Effective individual knockdown of IREB2, LOC123688, and PSMA4 in A549 and H1299 cells was examined by RT-qPCR (Fig. 2A, a). Next, we measured cell growth by MTT cell proliferation assay and found that LOC123688 knockdown had no effects on A549 and H1299 human lung cancer cell growth and apoptosis. A, effects of IREB2, LOC123688, and PSMA4 knockdown on A549 and H1299 human lung cancer cell growth and apoptosis. a. results of IREB2, LOC123688, and PSMA4 knockdown by RT-qPCR analyses. Columns, mean percentage of the target gene remaining; bars, SD of the mean in at least three individual experiments. b. growth curves of IREB2, LOC123688, and PSMA4 knockdown versus empty vector knockdown by MTT assay. c. results of caspase-3/7 activity assays with and without IREB2, LOC123688, and PSMA4 expression. Columns, mean relative fluorescence unit (RFU). A larger RFU value represents a higher caspase-3/7 activity and thus a stronger apoptotic response. PSMA4 knockdown in lung cancer cells inhibited cell growth and induced apoptosis. KD, knockdown. B, effects of PSMA4 overexpression on HBEC3KT nontumorigenic human bronchial epithelial cell growth. a. results of PSMA4 overexpression versus endogenous expression in HBEC3KT cells by RT-qPCR analysis. Columns, mean $-\Delta\Delta$Ct values (threshold cycle of $\beta$-actin minus threshold cycle for target gene). A larger $-\Delta\Delta$Ct value represents a higher abundance of the transcript. The numbers in the boxes are the fold increase after overexpression. ED, endogenous; OE, overexpression. b. growth curves of PSMA4 overexpression versus empty vector overexpression by MTT assay. All assays were performed in triplicate.

**Figure 2.** Effects of IREB2, LOC123688, and PSMA4 on A549 and H1299 human lung cancer cell growth and apoptosis. A, effects of IREB2, LOC123688, and PSMA4 knockdown on A549 and H1299 human lung cancer cell growth and apoptosis. a. results of IREB2, LOC123688, and PSMA4 knockdown by RT-qPCR analyses. Columns, mean percentage of the target gene remaining; bars, SD of the mean in at least three individual experiments. b. growth curves of IREB2, LOC123688, and PSMA4 knockdown versus empty vector knockdown by MTT assay. c. results of caspase-3/7 activity assays with and without IREB2, LOC123688, and PSMA4 expression. Columns, mean relative fluorescence unit (RFU). A larger RFU value represents a higher caspase-3/7 activity and thus a stronger apoptotic response. PSMA4 knockdown in lung cancer cells inhibited cell growth and induced apoptosis. KD, knockdown. B, effects of PSMA4 overexpression on HBEC3KT nontumorigenic human bronchial epithelial cell growth. a. results of PSMA4 overexpression versus endogenous expression in HBEC3KT cells by RT-qPCR analysis. Columns, mean $-\Delta\Delta$Ct values (threshold cycle of $\beta$-actin minus threshold cycle for target gene). A larger $-\Delta\Delta$Ct value represents a higher abundance of the transcript. The numbers in the boxes are the fold increase after overexpression. ED, endogenous; OE, overexpression. b. growth curves of PSMA4 overexpression versus empty vector overexpression by MTT assay. All assays were performed in triplicate.

**PSMA4 Promotes Lung Cancer Cell Proliferation**
effect on cell growth, whereas PSMA4 knockdown slowed down both A549 and H1299 cell proliferation compared with vector control cells (Fig. 2A, b). IREB2 knockdown in A549 cells slightly promoted cell growth, but had no effect on H1299 cell growth (Fig. 2A, b). We further tested to see if the growth inhibition was mediated through apoptosis and found that caspase-3/7 activity was only significantly increased in both A549 and H1299 cells when PSMA4 was knocked down (Fig. 2A, c). IREB2 and LOC123688 knockdown in A549 and H1299 cells did not affect apoptotic status in these cell lines (Fig. 2A, c). We also examined the effect of PSMA4 on nontumorigenic HBEC3KT, a human bronchial epithelial cell line. Overexpression of PSMA4 in HBEC3KT cells increased the transcript level of PSMA4 up to 9-fold (Fig. 2B, a), but not the rate of proliferation of HBEC3KT cells (Fig. 2B, b). Collectively, our data suggest that PSMA4 has a role in regulating human lung cancer cell proliferation and apoptosis.

**CHRNA5, CHRNA3, and lung cancer cell proliferation.** To determine the candidacy of genes around the hapN and to see if they play a direct role in modulating cancer cell proliferation, CHRNA5, CHRNA3, and CHRNA4 were overexpressed in A549 and H1299 cells. RT-qPCR analysis revealed that overexpression of CHRNA5 in H1299 cells and overexpression of CHRNA3 and CHRNA4 in A549 and H1299 cells were significant, whereas overexpression of CHRNA5 in A549 cells was less efficient (Fig. 3A). MTT cell proliferation assays showed that the overexpression of these genes did not have significant and consistent effects on the regulation of A549 and H1299 cell growth compared with vector control cells (Fig. 3B).

As the overexpression of CHRNA5 in A549 cells was not significant, we decided to use gene knockdown to explore the role of CHRNA5 on A549 cell growth. Successful CHRNA5 knockdown in A549 cells was examined by RT-qPCR (Fig. 3C). MTT cell proliferation analysis revealed that CHRNA5 knockdown did not alter A549 cell growth compared with vector control cells (Fig. 3D). Moreover, caspase-3/7 activity analyses showed similar enzyme activity between A549 vector control cells and A549 CHRNA5 knockdown cells, indicating that these cells had similar apoptotic statuses (Fig. 3E).

Taken together, our data show that altering the expression levels of CHRNA5, CHRNA3, and CHRNA4 do not affect A549 and H1299 cell proliferation, suggesting that these genes are not required to maintain cancer cell proliferation.

**PSMA4-dependent proteasome activity.** The 26S proteasome is a biological macromolecule consisting of a variety of structural and catalytic subunits. The 26S proteasome functions as multi-catalytic proteinases containing chymotrypsin-like (CT-like) and peptidylglutamyl peptide hydrolyzing-like (PGPH-like) proteolytic activities. Altering the stoichiometry of the PSMA4 structural subunit with other proteasomal subunits may affect proteasomal proteolytic activities. We followed proteasomal CT- and PGPH-like proteolytic activities and examined the effect of PSMA4 knockdown on proteasome activities in A549 PSMA4 knockout versus A549 vector control cells. Knocking down PSMA4 reduced proteasomal CT- and PGPH-like activities to 50% of that observed in vector control activities (Fig. 4A). This result showed that PSMA4 is required for maintaining normal proteasomal catalytic activities. A consequence of the decreased proteasome activity was an increase in the number of ubiquitinated proteins in A549 PSMA4 knockout cells compared with A549 control cells (Fig. 4B).

**Increased PSMA4 transcripts in human lung cancers.** Although in vitro overexpression of PSMA4 yielded almost no

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**Figure 3.** CHRNA5, CHRNA3, CHRNA4, and human lung cancer cell proliferation. A, results of CHRNA5, CHRNA3, and CHRNA4 overexpression versus endogenous expression in A549 and H1299 cells by RT-qPCR analysis. Columns, mean −ΔΔCt values. The numbers in the boxes are the fold increase after overexpression. B, effects of CHRNA5, CHRNA3, and CHRNA4 overexpression on A549 and H1299 cell growth by MTT proliferation assays. One thousand cells per well in 100 μL were seeded into 96-well plates for 12 h, and then viable cells were measured by MTT analysis (see text for details) on daily pace for up to 4 d for A549 and 6 d for H1299 cells. Columns, mean MTT values (A490). C, results of CHRNA5 knockdown by RT-qPCR analyses. Columns, mean percentage of the target gene remaining. D, growth curves of CHRNA5 knockdown versus empty vector knockdown by MTT assay. E, results of caspase-3/7 activity assays with and without CHRNA5 expression. Columns, mean RFU. KD, knockdown.
increase in transcription levels, gene knockdown analysis, in turn, confirmed that PSMA4 plays a role in modulating cell proliferation. To see if the expression of PSMA4 is altered in human NSCLC, the abundance of PSMA4 transcripts in 52 paired human normal lung and lung tumor samples was examined by RT-qPCR. Of the 52 paired samples, 21 (40.4%) had increased levels (>1.5-fold) of PSMA4 transcripts in the tumor, 1 (1.9%) had decreased levels (<0.5-fold), and 30 (57.7%) had no change (0.5- to 1.5-fold; Fig. 5). These 52 paired samples include acinar adenocarcinoma, bronchioloalveolar adenocarcinoma, adenocarcinoma NOS, papillary adenocarcinoma, adenosquamous carcinoma, epidermoid squamous cell carcinoma, keratinizing squamous cell carcinoma, and squamous cell carcinoma NOS. The percentage of paired samples with increased PSMA4 transcripts in the tumors varied from 30% to 60% among different histologic types of lung cancer, except for papillary adenocarcinoma that only had a 20% increase (Fig. 5). As shown in Fig. 5, cell type seems important in terms of PSMA4 overexpression. However, except for one tumor sample from the subtype adenosquamous carcinoma showing decreased expression of PSMA4, all other samples from the different subtypes showed either no changes or increased expression in PSMA4. Thus, although PSMA4 expression varied considerably among different lung cancer subtypes, in general, tumor samples from these different lung subtypes tend to show increased expression of PSMA4 compared with their pair-matched normal tissues. This result indicates that, in vivo, expression of PSMA4 is up-regulated in almost half of all lung cancers.

Discussion

Recent efforts to elucidate genetic factors in lung cancer susceptibility have identified the chromosome 15q24-25.1 locus (9–11). The 15q24-25.1 locus contains an iron metabolism protein gene IREB2, a 20S proteasome structural protein gene PSMA4, three nAChR subunit genes CHRNA5, CHRNA3, and CHRN8B, and a hypothetical gene LOC123688. An ongoing question is which among the six candidates accounts for an increased risk of lung cancer. In the current study, we have fine-mapped the 15q24-25.1 locus into two subregions: hapl for IREB2, LOC123688, and PSMA4; and hapN for CHRNA5, CHRNA3, and CHRN8B. Our in vitro investigation into the genes around hapl as modulators of tumor cell proliferation implicated PSMA4 as a strong candidate. This result is physiologically relevant for two reasons. First, there is endogenous expression of PSMA4 in the two human cancer cell lines used in this study, and second, expression of PSMA4 is up-regulated in lung cancer as well as in other cancer types.

At present, there is no evidence that SNP status of these genes is directly linked to the mitogenic activity of their protein products. Haplotype or SNP data neither reflect genetic changes (such as at the mRNA/protein expression level or protein function) of the candidate gene(s) in detail, nor tell whether these genetic changes could alter biological functions. Identifying causal genetic variants in the candidate gene(s) is very challenging and requires further extensive genetic and biological investigations. Any genetic change will eventually be exhibited at the mRNA/protein level or protein function to play biological function. Therefore, in vitro changing gene expression levels via overexpression/knockdowns and assaying for proliferation and apoptosis would be more efficient and informative. By these approaches, we have shown that PSMA4 affects lung cancer cell proliferation and apoptosis. This result suggests that PSMA4 is a candidate lung cancer susceptibility gene in the 15q24-25.1 locus, although the other five candidate genes in

Figure 4. PSMA4-dependent proteasome activity. A, effects of PSMA4 knockdown on 26S proteasome activity. Proteasomal CT- and PGPH-like activities were measured. Columns, mean proteasomal CT- or PGPH-like activities (RFU). B, the lysates used in Fig. 4A were resolved on SDS-PAGE and analyzed by immunoblotting with the indicated antibodies. KD, knockdown.

Figure 5. RT-qPCR analysis of PSMA4 transcript levels using total RNA samples from 52 paired tumor and normal tissues of the lung. Columns, mean values of fold change in PSMA4 expression in lung tumor versus normal lung tissues of the same patient. ADD, acinar adenocarcinoma; BAD, bronchioloalveolar adenocarcinoma; ADN, adenocarcinoma NOS; PAD, papillary adenocarcinoma; ASC, adenosquamous carcinoma; ESCC, epidermoid squamous cell carcinoma; KSCC, keratinizing squamous cell carcinoma; and SCCN, squamous cell carcinoma NOS. All RT-qPCRs were performed in triplicate. PSMA4 transcript level was increased in 40% of human NSCLCs.
this high linkage disequilibrium region cannot be completely excluded. Our in vitro analyses were limited to human lung cancer (lung cancer cell lines and lung cancer samples). However, the role of PSMA4 in leading tumorogenesis may not be limited to lung cancer. Similar to other oncogene/tumor suppressor genes, such as P53 and PTEN, elevated expression of PSMA4 is also found in other human cancer types.

The 26S proteasome contains one 20S proteasome core and two 19S regulatory caps. The 20S proteasome core is hollow and forms an enclosed cavity where proteins are degraded. The 20S proteasome core contains two types of subunits: α subunits are structural and serve as docking domains for proteasome assembly and regulators of proper function; β subunits are predominantly catalytic (14). PSMA4, a proteasome α type subunit 4, has been characterized as a structural subunit of the 20S proteasome core (14, 15). Our preliminary biological analysis revealed that PSMA4 governs proteasome activity. We showed in vitro that knockdown of PSMA4 expression decreases proteasome activity and results in the accumulation of ubiquitinated proteins. This proteasome is responsible for the degradation of proteins involved in the activation or repression of many cellular processes, including transcription, cell-cycle progression, and apoptosis. Therefore, proteasome dysfunction stresses cells. In our case, knockdown of PSMA4 expression in cancer cells induced apoptosis. Cancer cells show increased proliferation and decreased apoptosis in vivo via various mechanisms. Our findings that the down-regulation of PSMA4 expression induces apoptosis and that PSMA4 expression is increased in nearly half of the lung cancers studied suggest that up-regulation of proteasome activity may be a novel mechanism of tumorogenesis. Indeed, inhibition or down-regulation of proteasome activity by proteasome inhibitors has already been adopted as a form of cancer treatment (20). Therefore, our findings strongly suggest that PSMA4 plays a direct role in cancer cell proliferation.

We also systemically evaluated the nAChR subunit genes, particularly CHRNA5, to determine if any of them has a regulatory effect on lung cancer cell growth. Recent studies have linked rs1696968, a missense SNP (D398N) in CHRNA5, to smoking, nicotine addiction, and lung cancer (12, 21). We overexpressed CHRNA5-D398 in parallel with CHRNA5-N398 (rs1696968) in A549 and H1299 cells and did not observe any difference in growth (data not shown). Collectively, our current biological analysis of the nAChR subunit genes around hapN did not reveal any growth or apoptotic differences between normal lung and lung cancer cells. Our data strongly suggest that these nAChR subunit genes are not directly involved in lung cancer, but may instead affect nicotine dependence and propensity to smoke and thus indirectly increase the likelihood of developing lung cancer.

In summary, we have shown for the first time that PSMA4 at the 15q24-25.1 locus plays a direct role in regulating lung cancer cell growth. Further understanding of the molecular mechanisms of the candidate genes may result in the development of new strategies for prevention, early detection, diagnosis, and treatment of lung cancer and other human cancers.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

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