Integrated Systems and Technologies

AMPKα Modulation in Cancer Progression: Multilayer Integrative Analysis of the Whole Transcriptome in Asian Gastric Cancer

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Abstract

Gastric cancer is the most common cancer in Asia and most developing countries. Despite the use of multimodality therapeutics, it remains the second leading cause of cancer death in the world. To identify the molecular underpinnings of gastric cancer in the Asian population, we applied an RNA-sequencing approach to gastric tumor and noncancerous specimens, generating 680 million informative short reads to quantitatively characterize the entire transcriptome of gastric cancer (including mRNAs and miRNAs). A multilayer analysis was then developed to identify multiple types of transcriptional aberrations associated with different stages of gastric cancer, including differentially expressed mRNAs, recurrent somatic mutations, and key differentially expressed miRNAs. Through this approach, we identified the central metabolic regulator AMP-activated protein kinase (AMPK)α as a potential functional target in Asian gastric cancer. Furthermore, we experimentally showed the translational relevance of this gene as a potential therapeutic target for early-stage gastric cancer in Asian patients. Together, our findings not only provide a valuable information resource for identifying and elucidating the molecular mechanisms of Asian gastric cancer, but also represent a general integrative framework to develop more effective therapeutic targets. Cancer Res; 1–10. ©2012 AACR.

Introduction

Gastric cancer is the fourth most common cancer and the second leading cause of cancer-related deaths in the world (1). The incidence of cancer affecting the distal stomach has significantly declined over the past 40 years, but the incidence of proximal gastric and gastroesophageal junction adenocarcinoma in the United States and Europe has increased at a rate substantially exceeding that of prostate cancer, brain cancer, or melanoma (2). Moreover, the 5-year relative survival rate of patients with gastric cancer has not improved significantly in recent decades, remaining at approximately 20% to 30%.

The high mortality rate of gastric cancer is due largely to late-stage diagnosis of the cancer and a lack of effective medical treatment options. Treatment often consists of drug combinations that have provided survival advantages for patients with other cancer types (3, 4). Thus, there is clearly a need for new therapies specifically targeting gastric cancer. A comprehensive molecular profile of gastric cancer would provide important information about the disease pathways and targets that could facilitate the development of new therapeutic agents and strategies (5, 6).

So far, most transcriptional profiling studies in gastric cancer have used hybridization microarrays. For example, aberrant miRNA expression signatures in gastric tumor samples from Japanese and Italian patients have been reported using miRNA expression microarrays (7, 8), and mRNA expression signatures from Chinese patients have been recently reported using exon microarrays (9). RNA sequencing (RNA-seq) technology is rapidly supplanting hybridization-based approaches. This approach not only enables investigators to quantify gene expression levels but to simultaneously assess alternative splicing and gene fusion events and to detect nucleotide variations in transcribed regions (10, 11). Thus, multidimensional data sets from a single platform can generate a rich profile of cancer progression and development. In particular, whole-transcriptome RNA-seq provides a detailed and precise view of the entire spectrum of expressed transcripts for both mRNA and noncoding RNA.
In this study, we generated comprehensive mRNA and miRNA profiles for Asian gastric tumors. First, we conducted transcriptome-wide, unbiased analyses of the RNA-seq data to identify different types of transcriptional aberrations (mRNA, miRNA, and somatic mutation candidates) to leverage the existing knowledge of the pathogenesis. Second, integrating the results of our multilayer analyses, we identified a potential role in cancer progression for PRKAA2, which encodes AMP-activated protein kinase (AMPK)α2, a subunit of the AMPK serine/threonine protein kinase complex involved in the regulation of cellular and organismal metabolism. We experimentally validated the expression changes of PRKAA2 between early- and late-stage gastric cancers. Third, through functional studies in gastric cancer cell lines, we showed the translational relevance of PRKAA2 as a potential therapeutic target. Our work provides a valuable information basis for elucidating the molecular mechanisms of gastric cancer progression and also represents a general framework for the more effective development of disease-focused therapeutic targets.

Materials and Methods

Sample collection and characterization

This is a retrospective study conducted in archival fresh frozen human tissue specimens obtained from the National Research Resource Bank Program of the Korea Science and Engineering Foundation in the Ministry of Science and Technology. Patients consented to the use of the tissue specimens for research purpose, and the Institutional Review Boards of the College of Medicine, Yonsei University (Seoul, Korea), and the University of Texas MD Anderson Cancer Center (Houston, TX) approved the use of the specimens. Histologic classification and tumor stage were reviewed by a pathologist at the Gene Bank at Yonsei University Severance Hospital. Among 82 initially enrolled gastric cancer cases, 24 tumors and 6 noncancerous gastric tissues that met the criteria (sufficient amount and quality of RNA) were included in this study. Clinical and histopathologic characteristics obtained from the patients are summarized in Supplementary Table S1.

RNA-seq library preparation and SOLiD sequencing

The Miravana Kit (Ambion/Applied Biosystems) was used to isolate total RNA according to the vendor’s protocol. The whole-transcriptome sequencing (WT-seq) and small RNA-seq libraries were prepared by the small RNA expression kit (SREK, PN 4397682) of Applied Biosystems Inc. (ABI), based on SOLiD whole-transcriptome and small RNA standard protocols provided by ABI. The individual prepared “barcode” libraries were quantified and pooled equally together for multiplexing. The sequencing runs were carried out on SOLiD v 3.0 for both WT-seq and small RNA-seq. WT-seq samples were sequenced in 1/4 slide per sample using 50-nucleotide (nt) single tags; and small RNA-seq samples were sequenced in 1/10 slide per sample using 35-nt single tags. Detailed information is provided in the Supplementary Materials and Methods. The RNA-seq data were deposited in the National Centre for Biotechnology Information Gene Expression Omnibus database (accession number GSE36968).

Computational analyses of RNA-seq data

WT-seq short reads were mapped to the human reference genome (hg19) and exon junctions (defined as RefSeq gene annotation) using the ABI Bioscope (version 1.21) WT-seq analysis pipeline with default parameters. The reads mapped to the sequences that were not of biologic interest, such as rRNAs, tRNAs, and repetitive elements, were first filtered. Then mapped reads with mapping quality 10 or more were defined as uniquely mapped reads and used in the downstream analysis. The SOLiD System Small RNA Analysis Pipeline Tool (corona RNA2MAP version 0.50) was used to analyze small RNA-seq reads; after filtering, the reads were mapped to mature miRNAs in miRBase (version 13.0; ref. 12) and the human reference genome, respectively. To identify gastric cancer–related differentially expressed genes, the “reads per kilobase of exon per million mapped sequence reads” (RPKM; ref. 13) values of the human RefSeq genes were calculated using the RNA-seq flow in the Partek Genomics Suite (version 6.5 beta, Partek Inc.) and then log transformed. Single-factor ANOVA was used to detect differentially expressed genes among 18,890 protein-coding genes: \( P < 9.5 \times 10^{-4} \) [false discovery rate (FDR) < 0.05] was used as the cutoff value in the 5-group comparison (normal, tumor stage I, II, III, or IV); and \( P < 7 \times 10^{-4} \) was used in the 4-stage comparison (tumor stage I, II, III, or IV). A similar analysis was conducted on 2,569 long noncoding RNAs. Cross-platform gene expression comparison was conducted with a recent microarray study in gastric cancer (14). A gene ontology analysis was conducted using GoMiner (15) and a disease association analysis was conducted with Ingenuity Pathway Analysis software (version 7.0). Recurrent somatic mutations were identified on the basis of a recent exome-sequencing study on Asian patients with gastric cancer (16). miRNA expression was quantified as reads per million (RPM) of reads mapped to known miRNAs, and key differentially expressed miRNAs were defined on the basis of their differential expression and expression anticorrelation with their potential target genes. Detailed information is provided in the Supplementary Materials and Methods.

Experiments on biologic function

Cell culture. Human NCI-N87 and AGS gastric cancer cells were obtained from the American Type Culture Collection (ATCC; http://www.atcc.org/). The study was conducted within 6 months of resuscitation, and they were cultured in RPMI-1640 (CellGro) and 10% fetal calf serum (FCS; Hyclone) at 37°C in 5% CO₂. ATCC uses short tandem repeat (STR) profiling. For a hypoxia assay, culture flasks were incubated for various times at 37°C in humidified air, 5% (normoxia), or 1% O₂, 5% CO₂, and 94% N₂ (hypoxia) using an in vivo Hypoxia Workstation 500 with Ruskin hypoxic gas mixer (Biotrace International). Cells (2.5 \( \times 10^5 \)) were seeded and incubated under normoxic conditions to 70% confluence and then incubated under hypoxic conditions for 18 hours in the presence or absence of metformin at 10 mmol/L concentration. The NCI-N87-HRE cells were established according to the manufacturer’s protocol, Cignal HIF Reporter (luc; SA Biosciences, QIAGEN Co.).
luciferase activity was measured by the Dual Luciferase Reporter Assay System (Promega) according to the manufacturer’s protocol.

**Western blotting.** Cells were grown under hypoxic conditions in the presence or absence of 10 mmol/L metformin. The cells were washed twice in a PBS solution and Western blotting was conducted, as previously described (17).

**Real-time reverse transcriptase PCR.** Total RNA was isolated from cell lysates by the PARIS Kit (Ambion/Applied Biosystems) according to the manufacturer’s protocol. Next, TaqMan quantitative reverse transcriptase (RT)-PCR was carried out on the ABI 7300 system by the TaqMan one-step RT-PCR Master Mix kit and predesigned primer/probe pairs for PRKAA1, PRKAA2, PRKAB1, PRKG1, STK11, HNF4α, and β2-microglobulin (Applied Biosystems). Normalization procedures and analyses were carried out with β2-microglobulin using the 2(−ΔΔCt) method as the internal reference (18) and using Applied Biosystems GeneAmp 5700 SDS software. All measurements were carried out in triplicate.

**Short interfering RNA transfection.** Short interfering RNA (siRNA) SMARTpool sequences were obtained from Dharmacon/Thermo Fisher Scientific. The cells were transfected with 25 nmol/L siRNA-PRKAA2, siRNA-PRKAB1, siRNA-PRKAG1, siRNA-PRKAG2, or a siRNA nontargeting control with Dharma-FECT 1 lipid transfection reagent. The transfection medium was removed after 24 hours and replaced with fresh medium, and the cells were grown in 5% CO2 at 37°C for an additional 48 to 72 hours. RT-PCR and/or Western blot analyses were conducted to confirm target knockdown by siRNA. The transfected cells were treated with metformin and cultured under hypoxic conditions for an additional 18 hours.

**Statistical analysis.** For the experiments on individual genes in this section, statistical significance (P < 0.05) was determined using the Student t test to compare data points with control data.

## Results

### Overview of the gastric cancer RNA-seq data

Using Life Technologies SOLiD sequencing platform, we conducted transcriptome-wide profiling of gastric cancer samples from 30 anonymous, unrelated Asians of both sexes. Included were 6 noncancerous gastric tissue samples and 24 gastric tumor samples that represented stages I through IV of tumor development (Clinical characteristics of patients are shown in Supplementary Table S1). Applying 2 protocols that complementarily cover RNA fragments of different sizes from each sample resulted in 2 parallel large-scale data sets that allowed us to simultaneously measure mRNA and miRNA expression.

From the WT-seq protocol we generated a WT-seq data set of 2.1 billion 50-nt short reads from the 30 samples (mean of 70.8 million; Supplementary Table S1). Using the ABI Bioscope WT-seq analysis pipeline, 62.3% of the short reads, on average, were mappable: 28.4% were mapped to sequences of no biologic interest for this study (e.g., rRNAs and tRNAs), so we removed them from further analysis. On average, 26.0% (18.4 million per sample) of the short reads were uniquely mapped to the human reference genome (hg19) or exon junctions. B, Small RNA-seq data set of 894 million 35-nt short reads, mean of 36.4 million reads from the 25 samples. Using the SOLiD System Small RNA Analysis Pipeline Tool, 52.4% of the short reads were mappable: 33.6% mapped to sequences of no biologic interest were removed from further analysis. On average 13.9% (5.1 million (M) per sample) were mapped to known miRNAs in the miRBase database (version 13.0).

### Identification of gastric cancer–related differentially expressed genes

With millions of short reads mapped to the human genome/transcriptome, we quantified the expression levels of known
genes in each sample using the conventional parameter, RPKM (13). Among 18,890 annotated RefSeq coding genes, 15,421 genes, on average, per sample had detectable expression (RPKM > 0.05, about one mapped read for a gene with 1kb exons; Supplementary Table S1). To evaluate the reproducibility of our RNA-seq approach on expression quantification, for a subset of samples with available microarray data from a previous study (14), we compared the gene expression data from the 2 platforms (microarray and RNA-seq) and found sample-by-sample correlations, $R_k = 0.73 \pm 0.04$ (Spearman rank correlation, Supplementary Fig. S1A) that are similar to those reported in the literature (11, 13). The clustering pattern from an unsupervised analysis largely reflected the disease/staging status of the samples under survey (Supplementary Fig. S2). Moreover, a principal component analysis of the global gene expression profiles showed that gastric cancer samples differed from gastric intestinal stromal tumor samples, thereby confirming the pathologic classification of our tumor samples (Supplementary Fig. S3).

To identify gastric cancer–related differentially expressed genes, we conducted a single-factor ANOVA on the RPKM (log-scale transformed) data of 18,890 protein-coding genes across 5 groups (tissue type = normal or stage I, II, III, or IV as the independent variable). At FDR < 0.05 (ref. 19; $P < 9.5 \times 10^{-4}$), we identified 356 differentially expressed genes (Supplementary Table S2). As an independent validation, we conducted the same analysis on a published microarray data set (14) consisting of 83 Asian gastric samples taken from normal tissue and 4 tumor stages. In that analysis, 78% of the differentially expressed genes identified by our RNA-seq analysis showed significant expression changes in the same direction (tumor vs. normal) based on the microarray data; whereas only 17% would be expected if a same-size gene set were randomly chosen ($P < 1 \times 10^{-4}$, Supplementary Fig. S1B). In addition, we conducted a similar analysis on 2,569 long noncoding RNA genes and identified 7 differentially expressed genes (Supplementary Table S2).

To identify biologic characteristics of the differentially expressed genes, we conducted a gene ontology analysis using GoMiner (15). We found that the 356-gene data set showed high enrichment of genes involved in the biologic processes of digestion and phosphagen metabolism and the molecular functions of transmembrane transport and ATPase activity (Table 1). Using the Ingenuity Pathway Analysis software, we identified 101 of the 356 genes (28.4%) as associated with cancer (the Fisher exact test, $P = 2.8 \times 10^{-4}$), and 46 of them (12.9%) as related to gastrointestinal disease (the Fisher exact test, $P = 1.1 \times 10^{-4}$). Figure 2A categorizes these 356 genes by biologic and molecular functions (Supplementary Table S2). Because highly expressed genes tend to be identified in RNA-seq–based differential analysis (20), we used 12,213 genes with the same expression distribution as that of the 356 differentially expressed genes, rather than the whole gene set, as a reference set in the above analyses (see Supplementary Methods and Materials). As shown in Fig. 2B, these differentially expressed genes provided substantial power for classifying normal versus tumor tissue, as well as for distinguishing different clinical stages of the gastric tumors (although the distinction between stages III and IV became a little fuzzy). In comparison with the expression levels in the normal tissue, genes related to gastrointestinal functions were downregulated in 4 tumor stages (Fig. 2B). For example, loss of expression of gastrokines GKN1 and GKN2 occurs frequently in gastric adenocarcinoma, which is associated with shorter overall survival in the intestinal subtype of distal gastric cancer (21). Our results showed a dramatic tumor-related loss of expression level in both GKN1/2 and trefoil factor family peptides 1/2 (TFF1/2), supporting their potential use as predictive biomarkers (9).

In addition, we conducted a similar analysis on the 24 tumor samples using single-factor ANOVA (tissue type = stage I, II, III, or IV). In general, the expression variation among tumor samples was much less than that between normal and tumor samples. At $P < 7 \times 10^{-4}$, we identified 28 genes with significant stage-specific expression change. On the basis of these genes,

### Table 1. Gene ontology analysis of gastric cancer–related differentially expressed genes

<table>
<thead>
<tr>
<th>GO term</th>
<th>Description</th>
<th>Enrichment fold</th>
<th>Log10 ($P$)</th>
<th>FDR</th>
</tr>
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<td>0.059</td>
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<td>-3.80</td>
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<td><strong>Molecular function</strong></td>
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<td>ATPase activity</td>
<td>6.45</td>
<td>-3.57</td>
<td>0.059</td>
</tr>
</tbody>
</table>

NOTE: Biologic characteristics of the 356 differentially expressed genes identified using GoMiner. To adjust the bias toward highly expressed genes in detecting differential expression analysis, we used as the reference set 12,213 genes with the same expression distribution as that of the 356 differentially expressed genes.

Abbreviation: GO, Gene ontology.
the tumor samples clearly clustered according to their stage, with the largest distinction between stages I, II versus III, IV (Supplementary Fig. S4).

**Identification of recurrent somatic mutation candidates in gastric cancer**

To take full use of our RNA-seq data, we also made efforts to identify somatic mutation candidates in gastric cancer. Because we did not sequence the normal DNA from the same patients, we had a very limited power to infer somatic mutations based on our RNA-seq data alone. Instead, we took advantage of a recent exome-sequencing study on Asian patients with gastric cancer (16) and obtained a list of 2,651 somatic mutations with a potential functional effect (nonsynonymous/nonsense mutations and those at splicing sites). Among these reported somatic mutation positions, we detected the exact mutant alleles at 14 mutation positions in our WT-seq data, suggesting that they are recurrent somatic mutations (Supplementary Table S3). TP53 is the only gene with multiple recurrent mutation candidates (four mutations), consistent with its known high mutation frequency in gastric cancer (22). In addition, we detected 92 potential recurrent coding somatic mutations based on the COSMIC database (ref. 23; although

Asian patients with gastric cancer (16) and obtained a list of 2,651 somatic mutations with a potential functional effect (nonsynonymous/nonsense mutations and those at splicing sites). Among these reported somatic mutation positions, we detected the exact mutant alleles at 14 mutation positions in our WT-seq data, suggesting that they are recurrent somatic mutations (Supplementary Table S3). TP53 is the only gene with multiple recurrent mutation candidates (four mutations), consistent with its known high mutation frequency in gastric cancer (22). In addition, we detected 92 potential recurrent coding somatic mutations based on the COSMIC database (ref. 23; although
these recurrent mutations may not be specific to gastric cancer, Supplementary Table S4).

**Identification of key differentially expressed miRNAs related to gastric cancer**

In parallel with the analysis of gene expression using the WT-seq data set, we used the small RNA-seq data set to quantify the expression levels of known miRNAs in each sample using RPM, a measure analogous to RPKM for coding genes. Among 698 annotated, nonredundant mature miRNAs in the miRBase (version 13.0), on average, approximately 60% of the miRNAs had mapped reads. The observation that a large proportion of annotated miRNAs (40%) have zero or very low expression levels may be partially due to the inflation of the current miRBase annotation, as suggested by recent studies (24, 25). Therefore, we focused on 402 miRNAs with reliable expression (max RPM > 4 in 25 samples) in the subsequent analysis (see Supplementary Methods and Materials).

To identify the miRNAs that play a key role in gastric tumor development, we reasoned that (i) the key miRNAs themselves should show significant expression variations across different sample groups; and (ii) they should have detectable repression effects on the expression of their target genes (26). Therefore, we conducted a 2-step analysis. First, we conducted single-factor ANOVA (tissue type as the independent variable) on the RPM data (log-scale transformed) across 5 groups (normal tissue and four tumor stages). At $P < 0.01$ (FDR < 0.15), 26 miRNA genes showed significant differential expression: 9 upregulated and 17 downregulated (Fig. 3A and Supplementary Table S5). One of the upregulated miRNAs, miR-21 is the most commonly upregulated miRNA in both solid and hematologic tumors (8). Seven of the 26 differentially expressed miRNAs (Supplementary Table S5) were also identified by a recent microarray study on the miRNA biomarkers for the progression/prognosis of gastric cancer using samples from Japanese patients (7).

Second, for each of the 26 miRNAs, we used the Spearman rank correlation ($R_s$) to quantify its expression correlations with protein-coding genes across 25 samples with both the available coding gene and the miRNA expression data. We then tested whether the $R_s$ values of its potential target genes were significantly lower than those of other genes using the Wilcoxon rank sum test, resulting in 6 miRNAs showing significant anticorrelation with their potential targets (the Wilcoxon rank sum test $P < 0.01$, see Supplementary Methods and Materials). We defined these 6 miRNAs as key differentially expressed miRNAs of Asian gastric cancer (Fig. 3B).

**Integrative analysis suggests a potential role of PRKAA2, an AMPK activator in early-stage gastric cancer**

To identify candidate genes with the highest potential functional impact in gastric tumorigenesis, we surveyed all 3 types of transcriptional aberrations: (i) differentially expressed genes; (ii) genes related to recurrent somatic mutation candidates; and (iii) potential target genes of key differentially expressed miRNAs. Through a simple scoring analysis, PRKAA2 (AMPKα2) was the only gene identified by all the 3 criteria, suggesting that it is a potential key modulator in gastric cancer progression (Supplementary Fig. S3). PRKAA2 is the catalytic subunit of AMPK, which is a heterotrimer consisting of a catalytic α-subunit and regulatory noncatalytic β- and γ-subunits, each with 2 or 3 isoforms (27). AMPK is an energy-sensing enzyme and plays a central role in the regulation of energy homeostasis (28).

The most compelling evidence is that PRKAA2 is among the most highly differentially expressed genes identified in both 5-group and 4-stage expression analyses (5-group ANOVA, $P = 4.65 \times 10^{-5}$; 4-stage ANOVA, $P = 4.7 \times 10^{-3}$; only 22 genes were identified by both analyses). PRKAA2 showed a differential loss of mRNA level in tumor stage I/II relative to normal or tumor stage III/IV (Supplementary Fig. S6). Using qRT-PCR on an independent set of Asian gastric cancer samples (including normal, stage I through IV cases), we validated our findings by comparing the expression patterns of PRKAA2 along with the other 3 subunits of AMPK, PRKA1, PRKAB1, and PRKAG1, for which we had not observed changes in the RNA-seq experiment (Fig. 4).

Moreover, through our mRNA:miRNA integrative analysis (Fig. 4), PRKAA2 mRNA expression is inversely correlated with miR-19a expression (Pearson correlation test, $P < 0.02$), one of
We treated 2 gastric cancer cell lines (NCI-N87 and AGS) with metformin, an AMPK activator (35). We found increased mRNA expression of LKB1 (liver kinase B1, STK11), which is known to mediate AMPK activity upon metformin treatment (36). As expected, we observed a concentration-dependent increase in PRKAA2 mRNA levels, reflecting the activation of AMPK signaling (Fig. 5A). Importantly, we observed decreased expression of HNF4α (Fig. 5A for NCI-N87 data; similar results were observed for AGS, data not shown). Meanwhile, we observed clear inhibition of the expression and transactivating activity of HIF-1α by metformin (Fig. 5B, Western blotting). Furthermore, PRKAA2 knockdown with siRNA inhibited the decrease of HNF4α with metformin treatment at both the mRNA and protein levels (Fig. 5C, D, and E). We also observed increases of HNF4α expression for siRNA-PRKAA1, siRNA-PRKAB1, siRNA-PRKAG1, and siRNA-PRKAG2 (the siRNAs targeting the miRNAs of other subunits of AMPK), regardless of metformin treatment (Fig. 5C, D, and E). Consistently, in our RNA-seq data, the expression levels of HNF4α and HIF-1α in stage I and II were significantly higher than those in stage III, IV, and normal samples (t test, HNF4α, P < 0.04 and HIF-1α, P < 0.02). Taken together, our results showed the functional relevance of PRKAA2 loss for the AMPK signaling pathway, with downstream consequences that increase both HNF4α and HIF-1α. These data suggest that in early-stage gastric cancer, the loss of PRKAA2 may sustain tumor growth through the activation of HIF-1α (Fig. 6).

Discussion

Compared with previous RNA-seq studies, our whole-transcriptome RNA-seq approach has several merits. First, we used 2 protocols that complementarily cover RNA fragments of different sizes in the samples. Thus, we were able to quantify the expression of mRNA, long noncoding RNA and miRNA simultaneously, greatly facilitating the downstream integrative analysis. Second, we sequenced ribosome-depleted RNA samples rather than polyA-enriched RNA samples, generating a less biased view of the population of transcribed molecules (37, 38). As a result of this approach, the percentages of informative reads are relatively low because a considerable proportion of the sequenced short reads came from rRNAs or tRNAs. Nevertheless, because of the large number of total reads per sample, there were still sufficient numbers for our downstream analyses (18.4 million per sample for expression quantification of coding genes and 5.1 million per sample for expression quantification of miRNAs). Third, our protocols generated strand-specific short reads, which allows for more accurate quantification of gene expression as antisense transcription is widespread in humans (39).

Many challenges exist for the interpretation of transcriptome profiling data, both within and across individual studies. In the present study, we first conducted a multidimensional analysis to depict different types of transcriptional aberrations related to gastric cancer. Besides gene expression signatures, we took advantage of recently available somatic mutation data in gastric cancer and used our RNA-seq data to detect potential recurrent somatic

Figure 4. qRT-PCR validation of gene expression of AMPK subunits in an independent set of Asian gastric samples. AMPK is characterized by a heterotrimeric structure, catalytic α1,2-subunit and regulator β1,2,3-subunits. Measurement of qRT-PCR expression level of PRKAA1, PRKAA2, PRKAB1, and PRKAG1 between normal tissue and tumors, stages I, II, III, and IV, in an independent set of Asian gastric samples (n = 5 per group). Means of the measurements are shown with black lines.

the 6 key differentially expressed miRNAs we identified. PRKAA2 is a strong candidate target gene for miR-19a as its 3′-UTR contains an extremely conserved target site (29).

AMPK activities are closely related to the balances between ATP and AMP, and we found that ATPases were significantly enriched in the differentially expressed genes (P = 4.7 × 10−4 in Table 1). In addition, PRKAA2 directly regulates TP53 (30, 31), the gene with multiple recurrent somatic mutation candidates detected in our study (although no recurrent mutations were found in PRKAA2). These observations further support the hypothesis that loss of PRKAA2 expression might carry important functional consequences for AMPK activity in the early stages of gastric cancer.

Experimental evaluation of PRKAA2 as a potential functional modulator of energy homeostasis in gastric cancer

The AMPK enzyme occupies a unique position in the signaling pathways that monitor energy consumption and balance between glycolysis and lipid metabolism (32). AMPK directly inhibits hepatocyte nuclear factor 4α (HNF4α), which activates fatty acid and lipid metabolism. In addition, AMPK inhibits the mTOR pathway, a major cancer growth promoting signaling that regulates hypoxia-inducible factor-1α (HIF-1α; refs. 33, 34). Therefore, to explore the functional significance of PRKAA2 expression loss, we used both HNF4α and HIF-1α as downstream readouts for AMPK activity.
mutations in transcribed regions, thereby obtaining additional information from RNA-seq data. Through integrating these analyses, we were able to pinpoint individual key genes for further functional investigation. Our study shows the importance of multilayer data integration, which may more effectively identify candidate genes than conventional single-dimensional analysis.

While our study provides valuable insights into gastric cancer progression, there are some limitations. First, our RNA-seq data were single-tag reads generated from fragment analysis.
libraries and the read length is relatively short; therefore, we had limited power to study aberrant splicing and gene fusion events. A key extension to our study will be to conduct transcriptome profiling using paired-end and longer reads. This would provide a more comprehensive view of the transcriptional aberrations. Second, a lack of normal tissue samples from the same patients who provided tumor samples limited our ability to detect differentially expressed genes as well as to identify de novo somatic mutations (e.g., distinguishing somatic mutations from polymorphisms and RNA editing changes). Third, our study is based on only Asian patients, so future studies on gastric cancer in other patient populations are needed.

Through a multidimensional and integrative analysis of RNA-seq data of Asian patients, we identified a potentially critical role of AMPKα in the early stages of gastric cancer. The reason for different expression levels between stage I/II versus III/IV is unclear, and we speculate that late-stage tumor development may require higher energy-sensing enzymes. Through our metformin-based functional experiments, we further showed the translational relevance of PRKAA2, which encodes a central component of the energy-sensing AMPK enzyme. Because the expression level of PRKAA2 significantly affects key signaling nodes regulating tumor metabolism and angiogenesis, and shows activation by metformin, a drug widely used to treat type II diabetes, PRKAA2 may represent a promising therapeutic target for early gastric cancer. Our functional evidence supporting an important role of PRKAA2 in gastric cancer is still preliminary, and further functional studies are essential to elucidate how PRKAA2 modulation contributes to gastric cancer progression and to evaluate whether this gene is an effective therapeutic target.

Disclosure of Potential Conflicts of Interest

G. Powis has ownership interest (including patents) in OncoTheroy. No potential conflicts of interest were disclosed by the other authors.

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