Abstract

The prognosis for patients with unresectable advanced or recurrent gastric cancer remains poor. The identification of additional oncogenes with influences similar to those of epidermal growth factor receptor gene mutations, upon which the growth of cancer cells is dependent, is needed. In this study, we evaluated sensitivity to MEK inhibitors (GSK1120212 and PD0325901) in several gastric cancer cell lines in vitro and found three poorly differentiated gastric cancer cell lines that were hypersensitive to the inhibitors. The sequence analyses in these three cell lines revealed that one cell line had a novel MEK1 mutation, while the other two had previously reported KRAS and MEK1 mutations, respectively; the gene statuses of the other resistant cell lines were all wild-type. Experiments using MEK1 expression vectors demonstrated that the MEK1 mutations induced the phosphorylation of ERK1/2 and had a transforming potential, enhancing the tumorigenicity. The MEK1 inhibitor dramatically reduced the phosphorylation of ERK1/2 and induced apoptosis in the cell lines with MEK1 mutations. In vivo, tumor growth was also dramatically decreased by an inhibitor. One of the 46 gastric cancer clinical samples that were examined had a MEK1 mutation; this tumor had a poorly differentiated histology. Considering the addiction of cancer cells to active MEK1 mutations for proliferation, gastric cancer with such oncogenic MEK1 mutations might be suitable for targeted therapy with MEK inhibitors.

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Materials and Methods

Cell cultures and reagents
The HEK293 cell line (human embryonic kidney cell line) and the NIH-3T3 cell line (mouse fibroblast cell line) were maintained in DMEM medium (Nissui Pharmaceutical) supplemented with 10% FBS (GIBCO BRL) in a humidified atmosphere of 5% CO₂ at 37°C. All the gastric cancer cell lines used in this study were maintained in RPMI-1640 medium (Sigma-Aldrich), except for IM95 (DMEM; Nissui Pharmaceutical), supplemented with 10% FBS in a humidified atmosphere of 5% CO₂ at 37°C. The IM95 and OCUM-1 cell lines were obtained from the Japanese Collection of Research Bioresources, while the other cell lines were provided by the National Cancer Center Research Institute (Tokyo, Japan) in 2006. The OCUM-1, Okajima, SNU-16, and HEK293 cell lines were analyzed using a short tandem repeat (STR) method in July 2014, and the OCUM-1, SNU-16, and HEK293 cell lines were authenticated. The database did not include the STR pattern of the Okajima cell line, but the pattern did not match any of the other cell lines. GSK1120212 and PD0325901 (MEK inhibitors) were purchased from Selleck Chemicals and Wako, respectively (Fig. 1A).

Growth inhibition assay in vitro
The growth-inhibitory effects of GSK1120212 and PD0325901 were examined using the MTT assay (Sigma-Aldrich), as described previously (18). The experiment was performed in triplicate.

Antibody
Rabbit antibodies specific for MEK1/2, ERK1/2, phospho-ERK1/2, caspase-3, cleaved caspase-3, PARP, cleaved PARP, and β-actin were obtained from Cell Signaling Technology.

Western blot analysis
A Western blot analysis was performed as described previously (18). Briefly, subconfluent cells were washed with cold phosphate-buffered saline (PBS) and harvested with Lysis A buffer containing 1% Triton X-100, 20 mmol/L Tris–HCl (pH 7.0), 5 mmol/L EDTA, 50 mmol/L sodium chloride, 10 mmol/L sodium pyrophosphate, 50 mmol/L sodium fluoride, 1 mmol/L sodium orthovanadate, and a protease inhibitor mix, Complete (Roche Diagnostics). Whole-cell lysates were separated using SDS-PAGE and were blotted onto a polyvinylidene fluoride membrane. After blocking with 3% bovine serum albumin in a TBS buffer (pH 8.0) with 0.1% Tween-20, the membrane was probed with the primary antibody. After rinsing twice with TBS buffer, the membrane was incubated with a horseradish peroxidase-conjugated secondary antibody and washed, followed by visualization using an enhanced chemiluminescence.
MEK1
from Addgene. The Plasmid construction and transfectants Cloning kits (Invitrogen). and the PCR products were subcloned using TOPO TA confirm the results, the PCR amplification was repeated, nator v3.1 Sequencing Kit (Applied Biosystems). To were then directly sequenced using the BigDye Termi-
mations (exons 2–11). The PCR reactions were performed (Promega). Hygromycin selection (100 μg/mL) was
or NIH-3T3 cells using FuGENE6 transfection reagent Table S1). Vectors were transfected into HEK293 cells
essment Basal Kit (TaKaRa) and primers (Supplementary
mutations (exons 2, 4, 11, 12, and 15), and MEK1 muta-
genes
Genomic DNA samples from gastric cancer cell lines were screened for KRAS mutations (exon 2), BRAF mutations (exons 2, 4, 11, 12, and 15), and MEK1 muta-
Plasmid construction and transfectants
PcDNA-MEK1 with myc-tag vector was obtained from Addgene. The MEK1 exon point mutation Q56P or G72S was amplified using the PrimeSTAR Mutagenesis Basal Kit (TaKaRa) and primers (Supplementary Table S1). The PCR products were then directly sequenced using the BigDye Terminator v3.1 Sequencing Kit (Applied Biosystems). To confirm the results, the PCR amplification was repeated, and the PCR products were subcloned using TOPO TA Cloning kits (Invitrogen).
Focus formation assay
The transfectant NIH-3T3 cell lines were then cultured for 2 to 3 weeks in DMEM medium supplemented with 5% FBS. The focus formations were counted and photographed using a light microscope. The experiment was performed in triplicate.
Annexin V binding apoptosis analysis
The Annexin V binding apoptosis analyses were performed as described previously (19). Briefly, the cells were exposed to GS1120212 (1 nmol/L) for 48 hours, and the binding of Annexin V and propidium iodide (PI) to the cells was then measured using the FITC Annexin V Apoptosis Detection Kit I (BD Biosciences), according to the manufacturer’s instructions. The cells were stained with FITC Annexin V and PI at room temperature for 15 minutes and were analyzed using a flow cytometer and CellQuest software (BD Biosciences). The experiment was performed in triplicate.
Xenograph studies
Nude mice (6-week-old females; CLEA Japan) and NOD/SCID mice (6-week-old females; CLEA Japan) were used for the in vivo studies and were cared for in accordance with the recommendations for the Handling of Laboratory Animals for Biomedical Research compiled by the Committee on Safety and Ethical Handling Regulations for Laboratory Animals Experiments, Kinki University (Osaka, Japan). The ethical procedures followed met the requirements of the United Kingdom Coordinating Committee on Cancer Research guidelines. To evaluate tumorigenicity, a suspension of 1 × 10^6 NIH-3T3 transfectant cells (in 100 μL of PBS) was subcutaneously inoculated into the right flank of each nude mouse (n = 5), and tumor formation was examined after 2 weeks based on a previous report (17). To evaluate the effects of GS1120212, a suspension of 1 × 10^7 cells (in 50 μL of PBS) with 50 μL of Matrigel (Okajima cell line) or 5 × 10^6 cells (in 50 μL of PBS) with 50 μL of Matrigel (SNU-16 cell line) was subcutaneously inoculated into the right flank of each NOD/SCID mouse (n = 5); treatment was then initiated when the tumors in each group achieved an average volume of approximately 150 mm^3. In the treatment groups, GS1120212 (0.5 or 1.0 mg/kg) was administered by oral gavage daily for 7 days based on the results of a previous study (20); the control animals received 0.5% methylcellulose as a vehicle. The tumor volume was calculated as the length × width^2 × 0.5. The tumor formation and volume were assessed every 2 to 3 days. This method has been previously described (21).
Patients
Patients with advanced gastric cancer who underwent surgical resection at Kinki University Hospital (Osaka, Japan) between April 2009 and March 2012 were enrolled. This study was retrospectively performed and was approved by the Institutional Review Board of the Kinki University Faculty of Medicine (Osaka, Japan).
Isolation of genomic DNA
Genomic DNA samples were extracted from surgical specimens preserved as formalin-fixed paraffin-embedded (FFPE) tissue using the QIAamp DNA Micro Kit (Qiagen), according to the manufacturer’s instructions as described previously (10). Macrodissection of the FFPE specimens was performed to select a cancer region, which was marked by a pathologist after deparaffinization. The DNA concentration was determined using NanoDrop2000 (Thermo Fisher Scientific).
Statistical analysis
Continuous variables were analyzed using the Student t test, and the results were expressed as the average and standard deviation (SD). The statistical analyses were two-tailed and were performed using Microsoft Excel (Microsoft). A P value of less than 0.05 was considered statistically significant.

Results

OCUM-1, Okajima, and HSC-44 cell lines were hypersensitive to MEK inhibitors, and these cell lines had MEK1 mutations or a KRAS mutation

To examine the sensitivities of several gastric cancer cell lines to MEK inhibitors, we used the MTT assay (Fig. 1B). The 50% inhibitory concentrations (IC50) of the two MEK inhibitors (GSK1120212 and PD0325901) are summarized in Table 1. The OCUM-1, Okajima, and HSC-44 cell lines were hypersensitive to both MEK inhibitors; all three of these cell lines exhibited a poorly differentiated histology.

Next, to search for KRAS, BRAF, and MEK1 mutations, which were associated with sensitivity to MEK inhibitors, we sequenced these genes using direct sequencing. The MEK1 Q56P and S72G mutations were found in the OCUM-1 and Okajima cell lines, respectively, and a KRAS G12V mutation was also found in the HSC-44 cell line (Fig. 2A). In contrast, all cell lines that were not sensitive to MEK inhibitors did not have any mutations. The MEK1 Q56P mutation in the OCUM-1 cell line and the KRAS G12V mutation in the HSC-44 cell line have been previously reported (17), whereas the MEK1 S72G mutation in the Okajima cell line is a novel mutation. This novel mutation was confirmed using the TOPO TA Cloning Kit (Fig. 2B).

MEK1 Q56P and S72G mutations increased the phosphorylation level of ERK1/2, had transformational abilities, and enhanced tumorigenicity

To address the role of the MEK1 mutations, MEK1-overexpressed HEK293 and NIH-3T3 cell lines were created using each MEK1 expression vector (wild-type, Q56P, or S72G). ERK1/2 was phosphorylated in the HEK293-MEK1 Q56P, HEK293-MEK1 S72G, 3T3-MEK1-Q56P, and 3T3-MEK1-S72G cell lines, compared with the controls (Fig. 3A and B). We then investigated the transformational abilities and tumorigenicities of the MEK1 mutations using a focus formation assay and a tumorigenicity assay with the NIH-3T3 cell lines and nude mice; the results showed that the MEK1 Q56P and S72G mutations had transformational abilities and enhanced the tumorigenicity, compared with the controls. Foci or tumors were not formed in the controls (mock and wild-type; Fig. 3C and D). These findings suggest that both the MEK1 Q56P mutation and the novel MEK1 S72G mutation have transformational abilities and enhance tumorigenicity by activating the MAPK pathway.

Reduction in the phosphorylation level of ERK1/2 and induction of apoptosis in response to GSK1120212 in the OCUM-1 and Okajima cell lines

Next, we examined the phosphorylation levels of ERK1/2 after GSK1120212 exposure (0, 1, 3, 10, and 30 nmol/L) in each gastric cancer cell line. Three hours of exposure to GSK1120212 induced a significant decrease in the phosphorylation levels of ERK1/2 in the hypersensitive cell lines (OCUM-1 and Okajima), compared with the level in a nonsensitive cell line (SNU-16; Fig. 4A). We then analyzed the Annexin V binding apoptosis of the cell lines after exposure to GSK1120212 using a flow cytometer. The number of apoptotic cells in the OCUM-1 and Okajima cell lines, but not the SNU-16 cell line, increased greatly after

<table>
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<tr>
<th>Table 1. IC50 of MEK inhibitors</th>
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<tr>
<td><strong>OCUM-1</strong></td>
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<td>GSK (nmol/L)</td>
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Abbreviations: GSK, GSK1120212; PD, PD0325901.
GSK1120212 exposure (1 nmol/L; Fig. 4B). Western blot analyses for apoptosis-related molecules revealed that 48 hours of exposure to the reagent also greatly increased the levels of cleaved PARP and cleaved caspase-3 in the OCUM-1 and Okajima cell lines, compared with the SNU-16 cell line (Fig. 4C).

**In vivo efficacy of GSK1120212 in the Okajima cell line**

To perform a xenograft study, we used the Okajima (MEK1 Q72S) and the SNU-16 cell line (MEK1 wild-type). To evaluate the effects of GSK1120212, a suspension of 1 × 10^7 cells (in 50 μL PBS) with 50 μL of Matrigel (Okajima cell line) or 5 × 10^6 cells (in 50 μL PBS) with 50 μL of Matrigel (SNU-16 cell line) was subcutaneously inoculated into the right flank of each NOD/SCID mouse (n = 5). In the treatment groups, GSK1120212 (0.5 or 1.0 mg/kg) was administered by oral gavage daily for 7 days; the control animals received 0.5% methylcellulose as a vehicle. The tumors from the Okajima cell line were dramatically reduced by treatment with GSK1120212 [vehicle: 179.86 ± 44.88 mm^3 vs. GSK1120212 (0.5 mg/kg): 89.4 ± 22.84 mm^3; ∧, P = 0.0039 or vs. GSK1120212 (1.0 mg/kg): 27.04 ± 26.7 mm^3; ∧, P = 0.0018; GSK1120212 (0.5 mg/kg) vs. GSK1120212 (1.0 mg/kg): 27.04 ± 26.7 mm^3; ∧, P = 0.0041; Fig. 5A and B]. The phosphorylation of ERK1/2 in the tumors was inhibited by GSK1120212 (Fig. 5B). In contrast, the tumors from the SNU-16 cell line were not reduced by the drug [vehicle: 335.62 ± 131.36 mm^3 vs. GSK1120212 (0.5 mg/kg): 346.5 ± 182.31 mm^3; P = 0.92, or vs. GSK1120212 (1.0 mg/kg): 307.68 ± 106.03; P = 0.72; GSK1120212 (0.5 mg/kg) vs. GSK1120212 (1.0 mg/kg): P = 0.69; Fig. 5A].

**Clinicopathologic features of patients with MEK1-mutated gastric cancer**

A total of 46 patients with advanced gastric cancer participated in this study. We evaluated the patient characteristics according to their MEK1 gene status. The isolated genomic DNA samples were directly sequenced. The clinical features of all the patients are summarized in Supplementary Table S2. One of the patients had gastric cancer with a MEK1 Q56P mutation; this patient was a 64-year-old male whose gastric cancer had been diagnosed as...
a poorly differentiated scirrhous adenocarcinoma stage IV located in corpus.

Discussion

The Cancer Genome Atlas (TCGA) dataset for gastric cancer has shown that the gastric cancer populations with nonsynonymous \( \text{K\textsc{ras}}, \text{B\textsc{raf}}, \) or \( \text{MEK1} \) mutations were relatively small (28 of 289, 24 of 289, and 7 of 289, respectively), and \( \text{MEK1} \) Q56P or S72G mutations have not been identified in the TCGA dataset. In this study, we identified \( \text{MEK1} \) mutations in poorly differentiated gastric cancer cell lines that were hypersensitive to MEK inhibitors and showed that these mutations have transformational abilities and that the growth of the cancer cells is dependent on these mutations. Specifically, the \( \text{MEK1} \) S72Q mutation in the Okajima cell line is a novel activating mutation, whereas the \( \text{MEK1} \) Q56P mutation in the OCUM-1 cell line has been previously reported by Choi and colleagues (17). In addition, a \( \text{MEK1} \) Q56P mutation was identified in a clinical sample of a poorly differentiated gastric cancer; to the best of our knowledge, this is the first study in which a clinical sample of a \( \text{MEK1} \) Q56P-mutated gastric cancer has been identified.
GSK1120212 is an inhibitor of MEK1/2 that exhibits a high potency, selectivity, and long-circulating half-life (22). The results of a phase III study have demonstrated that GSK1120212 is associated with a significant improvement in progression-free survival and overall survival, compared with chemotherapy, in patients with V600E or V600K BRAF-mutated advanced melanoma (23). Several studies have shown that KRAS and/or BRAF mutations are associated with the sensitivity to MEK inhibitors in melanoma, thyroid cancer, colon cancer, and ovarian cancer (23–27). However, very limited information is available about the somatic MEK1 mutations in human malignancies. Similar to our present study, Choi and colleagues (17) have reported that the MEK1 Q56P mutation identified in the OCUM-1 cell line has a transformational ability, and somatic mutations in the MEK1 gene have been reported in several other cancers including lung cancer, ovarian cancer, colon cancer, and melanoma (28–32). Our present study demonstrated that both the MEK1 G56P and the novel MEK1 S72G mutation in poorly differentiated gastric cancer cell lines that were hypersensitive to MEK inhibitors have transformational abilities and that the growth of the cancer cells was dependent on these mutations. In both in vitro and in vivo studies, the gastric cancer cell lines with MEK1 mutations dramatically responded to the MEK inhibitor. Therefore, MEK inhibitors can be effective for patients with MEK1 mutations in a manner similar to the effect of EGFR-tyrosine kinase inhibitors in patients with EGFR mutations and the effect of ALK inhibitors in patients with ALK rearrangements (33–36). Then, not only KRAS and BRAF mutations, but also MEK1 mutations should be recognized as predictive biomarkers for the efficacy of MEK inhibitors.

In general, patients with a poorly differentiated gastric cancer histology have a poor prognosis and their treatment is challenging (37). FGFR2 or MET amplification seems to be predominant in poorly differentiated gastric cancer (10–12). Similarly, in this study, the two gastric cancer cell lines with MEK1 mutations had a poorly differentiated histology, and the one gastric cancer clinical
sample with a MEK1 mutation was a poorly differentiated adenocarcinoma. Choi and colleagues (17) previously reported that 1 of 86 gastric cancer samples had a MEK1 mutation and that the sample was a poorly differentiated adenocarcinoma (well-differentiated, 0 of 40 and poorly differentiated, 1 of 46). Despite the relatively small number of samples, these results suggest that gastric cancer with MEK1 mutations might be likely to have a poorly differentiated adenocarcinoma histology, similar to that resulting from FGFR2 or MET amplification, and treatment with a MEK inhibitor might be a promising option for such patients with gastric cancer. To confirm these findings, larger studies are needed.

In conclusion, we have identified MEK1 mutations in poorly differentiated gastric cancer cell lines and a poorly differentiated gastric cancer clinical sample and have shown that the mutations have transformational abilities and that the growth of the cancer cells is dependent on these mutations. In particular, the MEK1 S72Q mutation in the Okajima cell line is a novel activating mutation. Our results warrant strong consideration in the development of MEK inhibitors for the treatment of gastric cancer with MEK1 mutations.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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