accelerated or blast phase. In addition, patients receiving less than 600 mg/day of imatinib were eligible for participation if *BCR-ABL* mutations were found present by sequencing any one of the following amino acids: L248, G250, Q252, Y253, E255, T315, F317, H396, M237, M244, D325, S348, M351, E355, A380, L387, M388, F486, and F359.

Imatinib intolerance for CML patients was defined as the discontinuation of imatinib therapy due to any of the following: grade 3 or 4 adverse events that persisted in spite of optimal supportive care measures, or grade 2 adverse events related to imatinib therapy in spite of optimal supportive care measures that persisted for at least 1 month or that recurred more than 3 times whether the dose was reduced or discontinued. In addition, the protocol definition of imatinib intolerance included the lack of a MCyR with imatinib.

Nilotinib (400 mg) was administered twice daily (BID; every 12 h) with water, while fasting 2 h before and 2 h after dosing. Dose reductions to 400 mg daily and subsequently 200 mg daily were permitted for the management of toxicity. If administration of a dose was delayed for more than 21 days for the management of toxicity (or more than 42 days for grade 3 or 4 hematologic toxicity), the patient was discontinued from the study. Treatment with nilotinib was continued until the patient experienced disease progression, developed unacceptable toxicity that precluded any further treatment, withdrew consent, and/or if the patient no longer benefited from the treatment (at the investigator's discretion).

2.2 Statistical analysis

The intent-to-treat (ITT) population and the safety population were included in the efficacy (including analyses for biomarker) and the safety analyses, respectively. The ITT population included all patients who received at lease one dose of nilotinib 400 mg BID. The safety population included all the patients in the ITT population who had at least one safety assessment. Pharmacokinetic analyses were performed for the pharmacokinetic population that included all patients who had available pharmacokinetic sample data. All analyses presented in this paper are based on the data obtained with the cut-off date of 3 October 2007 in all patients who received nilotinib 400 mg BID in any component of the study, including the Phase I, II, and its extension portions.

The rates on overall best hematologic response were summarized by disease phases and type (CML-CP, -AP, -BC, relapsed/refractory Ph+ ALL, and Ph+ ALL with MRD). The rates on overall best cytogenetic response were summarized for all CML patients. For CML-CP group only, 95% confidence intervals (95% CIs) using Clopper–

Pearson limits were determined. Other efficacy analyses included the time-to-first response and duration of response using either the descriptive statistics or the Kaplan–Meier method.

2.3 Efficacy parameters

Hematologic and cytogenetic response criteria have been described in detail previously [10–14]. Criteria for cytogenetic responses are as follows: complete (0% Ph+ cells), partial (1–35% Ph+ cells), minor (36–65% Ph+ cells), and minimal (66–95% Ph+ cells). A MCyR includes both complete and partial cytogenetic responses. Cytogenetic responses were based on the percentage of Ph+ cells among 20 or more cells in metaphase in each bone marrow sample. Results obtained from fluorescent in situ hybridization (FISH) were also used to determine cytogenetic response only if fewer than 20 cells in metaphase were examined or bone marrow sample was not adequate on a particular assessment date due to other reasons. Only evaluable patients in the ITT population were included in the analysis for overall best hematologic and cytogenetic response rates. Patients with Ph+ CML who had a CHR at baseline were not included in the efficacy analysis for best hematologic response rates. Similarly, Ph+ CML patients who had CCyR at baseline were excluded from the analysis for best cytogenetic response. Evaluable patients who discontinued the study with no valid efficacy assessment were not included in the analysis for best responses.

2.4 Biomarkers

Peripheral blood samples were obtained prior to the first dose of nilotinib and every 3 months during nilotinib therapy. The BCR-ABL kinase domain (amino acid 230–490) was amplified from total blood RNA and mutations identified by direct sequencing that allowed for detection of more than 20% minor alleles. BCR-ABL transcript levels in blood were also monitored by a real-time quantitative RT-PCR (qRT-PCR) assay. The BCR-ABL mutational and qRT-PCR analyses were performed by Institute of Medical and Veterinary Science, Adelaide, Australia.

Patients were grouped based on their baseline mutational status: no mutation, any mutation, or multiple mutations. The number and percentage of patients who achieved a HR and CyR and major molecular response (MMR) were calculated for each mutation category in order to investigate the correlation between clinical responses and baseline BCR-ABL mutation status. A MMR was defined as BCR-ABL/control gene ratio of ≤0.1% based on international scale, equivalent to ≥3 log reduction in BCR-ABL transcripts from the standardized baseline as determined in the international randomized study of

interferon and STI571 (IRIS) study. The number and percentage of patients who had at least one MMR post-baseline were calculated by disease phase. Patients who had a MMR at baseline were excluded from the analysis.

2.5 Safety parameters

Safety assessments included evaluation of adverse events, hematologic and biochemical testing, urinalysis, cardiac enzyme assessment, blood coagulation test, WHO PS scores, vital signs, physical examinations, 12-lead ECG, echocardiography, and chest X-rays. All adverse events were recorded with grades based on the Common Terminology Criteria for Adverse Events (CTCAE, version 3.0) of the National Cancer Institute, and monitored for at least 28 days after the last dose of nilotinib in patients who discontinued the study. Laboratory measurements were evaluated based mainly on the calculated CTC grades at baseline and post-baseline.

2.6 Pharmacokinetic parameters

The pharmacokinetic parameters were calculated by the standard non-compartmental method using WinNonlin Professional Edition 5.0 (Pharsight Corporation). Serum concentrations of nilotinib below the limit of quantitation (2.5 ng/mL) were treated as zero for the calculation of pharmacokinetic parameters. The following parameters were obtained: maximum serum concentration of nilotinib (C_{max}), time to reach C_{max} (T_{max}), area under the serum nilotinib concentration time curve from time 0 to 12 h post-dosing (AUC_{0-12}), and minimum serum concentration of nilotinib (C_{min}), defined as the concentration immediately before nilotinib administration.

2.7 Study conduct

The study was conducted in accordance with the Declaration of Helsinki. Patients gave written informed consent, according to institutional guidelines. The study was approved by the institutional review board at each study center.

3 Results

3.1 Patient demographics

Results are presented for 34 patients with at least 12 months of follow-up or those who prematurely discontinued study treatment. These include 31 patients enrolled in the Phase II component of the study (14 CML-CP, 7 CML-AP, 3 CML-BC, 7 Ph+ ALL) and 3 patients enrolled in the Phase I component of the study who received nilotinib 400 mg BID (2 CML-CP, 1 CML-BC). Disposition of patients is shown in Table 1. Of the 34 patients, 25 were enrolled in the extension study (16 CML-CP, 3 CML-AP, 3 CML-BC, 3 Ph+ ALL). At the time of data cut-off, 17 (50%) patients remained in the study. The most frequent reason for treatment discontinuation was disease progression.

The median duration of exposure (293 days; range 13–615) closely approximates the median duration of treatment (291 days; range 13–615) indicating minimal duration of treatment interruption. Nilotinib was well tolerated as indicated by the administration of median dose intensity (756 mg/day; range 285–799) which was close to the planned dose (400 mg BID = 800 mg/day) for the study.

Demographic and other baseline characteristics of patients are shown in Table 2. The median age of all

Table 1 Disposition of patients (ITT population)

	n (%)				
	CML-CP N = 16	CML-AP N = 7	CML-BC N = 4	Ph+ ALL N = 7	Total N = 34
Patients who enrolled in the extension study	16 (100)	3 (43)	3 (75)	3 (43)	25 (74)
Patients with treatment ongoing at cut-off date	15 (94)	1 (14)	0 (0)	1 (14)	17 (50)
Discontinued treatment at cut-off date	1 (6)	5 (71)[a]	4 (100)	6 (86)	16 (47)[a]
Reason for discontinuation					
Adverse event(s)	0 (0)	1 (14)	1 (25)	1 (14)	3 (9)
alloHSCT performed	1 (6)	2 (29)	1 (25)	0 (0)	4 (12)
Disease progression	0 (0)	2 (29)	2 (50)	5 (71)	9 (27)

The ITT population included all patients in the Phase I and Phase II studies who were administered a 400 mg BID dose at least once

alloHSCT allogeneic hematopoietic stem cell transplantation

[a] Does not include one patient who completed three cycles of the initial therapy but did not move to the extension study

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Table 2 Demographic and other baseline characteristics (ITT population)

	CML-CP $N = 16$	CML-AP $N = 7$	CML-BC $N = 4$	Ph+ ALL $N = 7$	Total $N = 34$
Age (years)					
Median	57	61	53	62	62
Range (min–max)	30–83	30–74	29–70	23–80	23–83
Sex, n (%)					
Male	9 (56)	5 (71)	2 (50)	6 (86)	22 (65)
Female	7 (44)	2 (29)	2 (50)	1 (14)	12 (35)
Weight (kg)					
Median	61	65	63	56	61
Range (min–max)	45–89	49–83	36–69	46–60	36–89
WHO performance status, n (%)					
Grade 0	16 (100)	4 (57)	2 (50)	4 (57)	26 (76)
Grade 1	0 (0)	2 (29)	2 (50)	3 (43)	7 (21)
Grade 2	0 (0)	1 (14)	0 (0)	0 (0)	1 (3)
Grade >2	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Time since first diagnosis (months)					
<6 months	2 (13)	0 (0)	0 (0)	1 (14)	3 (9)
≥6 months to <1 year	2 (13)	0 (0)	0 (0)	1 (14)	3 (9)
≥1 year to <2 years	3 (19)	2 (29)	1 (25)	4 (57)	10 (29)
≥2 years to <5 years	3 (19)	0 (0)	1 (25)	0 (0)	4 (12)
≥5 years	6 (38)	5 (71)	2 (50.0)	1 (14)	14 (41)
Number of patients, n (%)					
Imatinib resistant	4 (25)	4 (57)	4 (100)	7 (100)	19 (56)
Imatinib intolerant	12 (75)	3 (43)	0 (0)	0 (0)	15 (44)
Highest imatinib dose					
Mean ± SD	519 ± 210	686 ± 157	700 ± 115	600 ± 0	591 ± 178
Median	500	800	700	600	600
Range (min–max)	200–800	400–800	600–800	600–600	200–800

patients was 62 years (range 23–83 years), and approximately 65% of all patients were male. The median weight of all patients was 61 kg (range 36–89 kg). Imatinib-intolerant patients constituted 75% (12/16) of CML-CP, though all CML-BC and Ph+ ALL patients were imatinib resistant. One of 4 imatinib-resistant CML-CP patients was primary resistant.

3.2 Pharmacokinetic analysis

Table 3 shows pharmacokinetic parameters determined following the administration of nilotinib 400 mg BID. Absorption of nilotinib was relatively rapid with median T_{max} of 3 h with large inter-individual variability. Steady state was achieved by day 6 after repeated dosing since C_{min} had been almost constant after day 6. The accumulation ratio calculated by ratio of AUC_{0-12} on days 15 to 1 was 2.64 ± 1.07 (mean ± SD). The serum concentrations of nilotinib did not differ among the phases of CML and Ph+ ALL group on the first day of treatment. On day 15,

nilotinib exposure in the CML-BC group and Ph+ ALL group appeared to be slightly higher than in other groups, but this difference is most likely due to the small patient number and relatively large inter-individual variability. Steady-state nilotinib concentrations observed on day 15 in this study were similar to those observed previously in non-Japanese patients [16].

3.3 Efficacy

3.3.1 Hematologic response

Table 4 details the HR rates. Six of the 16 patients with CML-CP patients without a CHR at baseline were included in the efficacy analysis for HR. All 6 patients achieved a CHR (100%; 95% CI: 54.1–100.0%). In the CML-AP patients, a HR was achieved in 5/7 (71%) patients, including 1 CHR, 3 marrow responses with no evidence of leukemia (NEL), and 1 return to CP. In the CML-BC patients, a HR was achieved in 2/4 (50%) patients,

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Table 3 Pharmacokinetic parameters following administration of 400 mg BID of nilotinib (ITT population)

	N	T_{max} (h) [median (range)]	Mean $\pm$ SD		
			C_{max} (ng/mL)	AUC$_{0-12}$ (ng h/mL)	C_{min} (ng/mL)
Day 1					
Total	33	3.0 (2.0–23.0)	1070 $\pm$ 458	7850 $\pm$ 2790	NA
CML-CP	15	3.0 (2.0–7.0)	942 $\pm$ 276	7110 $\pm$ 1800	NA
CML-AP	7	3.0 (2.9–23.0)	1120 $\pm$ 614	7550 $\pm$ 3150	NA
CML-BC	4	5.5 (3.0–7.0)	1150 $\pm$ 458	8880 $\pm$ 2700	NA
Ph+ ALL	7	3.0 (2.2–7.0)	1220 $\pm$ 618	9150 $\pm$ 4010	NA
Day 15					
Total	28	3.0 (1.8–8.0)	2320 $\pm$ 1070	19000 $\pm$ 9090[a]	1170 $\pm$ 588
CML-CP	13	3.0 (1.9–8.0)	2010 $\pm$ 652	17200 $\pm$ 6030[b]	1051 $\pm$ 410
CML-AP	6	3.0 (1.8–3.0)	1760 $\pm$ 884	15000 $\pm$ 6770	885 $\pm$ 349
CML-BC	3	2.1 (1.9–5.0)	3210 $\pm$ 1340	30300 $\pm$ 15200	1890 $\pm$ 893
Ph+ ALL	6	3.0 (1.9–8.0)	3140 $\pm$ 1310	21200 $\pm$ 10400[c]	1350 $\pm$ 732

NA not applicable

[a] $N = 26$

[b] $N = 12$

[c] $N = 5$

including 1 CHR and 1 return to CP. The rate of HR confirmed at 2 consecutive visits at least 4 weeks apart was achieved in 2/7 (29%) CML-AP patients, 2/4 (50%) CML-BC patients. A CR was achieved in 1/5 (20%) relapsed/refractory Ph+ ALL and both 2 Ph+ ALL patients with MRD.

The median time to CHR was 1 month (range 1–2 months) for CML-CP patients. Time to HR was 1 month for all of the CML-AP, BC and Ph+ ALL patients but 2 months in one CML-BC patient. The duration of CHR was not determined because all CML-CP patients were still responding to treatment at the data cut-off date. The range of duration of CHR in 6 CML-CP patients who achieved CHR up to the data cut-off date was 11.6–13.6 months. All ten patients with CHR at baseline were maintaining response at the time of data cut-off. In 3 of the 5 patients with CML-AP who achieved a HR, the response continued until either the time they discontinued study treatment or the data cut-off date. The duration of the other 2 CML-AP patients was 1 and 2 months each. Of the 2 patients with CML-BC who achieved a HR, one was still in HR at data cut-off and one had a duration of HR of 2 months. For patients with relapsed/refractory Ph+ ALL, 1 who achieved a HR continued to show a response for 3.9 months. One of the two Ph+ ALL patients with MRD was still in HR at data cut-off and the other lasted for 2 months.

3.3.2 Cytogenetic response

A MCyR was achieved in 15 of the 16 CML-CP patients (94%; 95% CI: 70–100.0%), and a CCyR in 11 (69%) of

these patients (Table 5). A CCyR was achieved in 1 (14%) of the 7 CML-AP patients. In the other 6 patients, 3 achieved a minimal CyR, 1 no CyR, and 2 patients were considered not assessable for response due to dry-tap bone marrow. As for the patients with CML-BC, 2 of the 4 patients (50%) achieved a CCyR.

Time to MCyR or CCyR was evaluated in CML-CP patients. The median time to MCyR was 3 months (range 1–6.6 months) and the time to CCyR was also 3.2 months (range 2–11.9 months). The MCyR continued, in all patients achieving MCyR, until the data cut-off date or discontinuation from study treatment, so the median duration of MCyR has not been reached at the time of data cut-off.

3.3.3 Molecular response

A MMR was achieved in 9 (56%) of 16 CML-CP patients. The median time to MMR was 6.3 months (range 3–18.3 months). These 9 patients are still in MMR at data cut-off. A MMR was achieved in 1 (14%) of the 7 CML-AP patients, 2 (50%) of the 4 CML-BC patients. None achieved MMR in relapsed/refractory Ph+ ALL. One of 2 Ph+ ALL with MRD achieved MMR and the other one was considered as not evaluable due to MMR at baseline.

3.3.4 Response by BCR-ABL mutation status

BCR-ABL mutations at baseline were detected in 4 (25%) of 16 CML-CP patients, in 6 (86%) of 7 CML-AP patients, in 2 (50%) of 4 CML-BC patients, and in 4 (57%) of 7 Ph+ ALL patients. A total of 14 different BCR-ABL mutations

Table 4 Best hematologic response (ITT population)

Disease	Evaluation criteria	n (%)
CML-CP (N = 16)	Not evaluable	10 (63)
	Evaluable	6 (38)
	Complete hematologic response	6 (100)
	Stable disease	0
	Progression of disease	0
	Not assessable	0.
CML-AP (N = 7)	Hematologic response	5 (71)
	Complete hematologic response	1 (14)
	Marrow response with no evidence of leukemia	3 (43)
	Return to chronic phase	1 (14)
	Stable disease	1 (14)
	Progression of disease	0
	Not assessable	1 (14)
CML-BC (N = 4)	Hematologic response	2 (50)
	Complete hematologic response	1 (25)
	Marrow response with no evidence of leukemia	0
	Return to chronic phase	1 (25)
	Stable disease	2 (50)
	Progression of disease	0
	Not assessable	0
Relapsed/refractory Ph+ ALL (N = 5)	Hematologic response	1 (20)
	Complete response	1 (20)
	Partial response	0
	Hematologic improvement	0
	Stable disease	1 (20)
	Progression of disease	3 (60)
	Not assessable	0
Ph+ ALL with minimal residual disease (N = 2)	Complete response	2 (100)
	Stable disease	0
	Progression of disease	0
	Not assessable	0

Table 5 Cytogenetic response (Ph+ CML, ITT population)

n (%)	CML-CP N = 16	CML-AP N = 7	CML-BC N = 4
Evaluable	16 (100)	7 (100)	4 (100)
Major CyR	15 (94)	1 (14)	2 (50)
Complete	11 (69)	1 (14)	2 (50)
Partial	4 (25)	0	0
Minor CyR	0	0	1 (25)
Minimal CyR	1 (6)	3 (43)	0
None	0	1 (14)	0
Not assessable	0	2 (29)	1 (25)

involving 12 amino acids were detected. There were no patients with a T315I mutation, which is known to cause imatinib and nilotinib resistance. HR and CyR could be observed in patients with any of the disease stages who were administered nilotinib, regardless of BCR-ABL mutation status and regardless of their specific mutation (Table 6).

3.3.5 Safety

Non-hematologic adverse events that were suspected to be related to nilotinib are summarized in Table 7. These were mostly mild to moderate in severity. The most commonly reported events were rash (50%), headache (32%), nausea (32%), vomiting (29%) and pyrexia (24%); however, grade 3 or higher events were uncommon.

The numbers of patients with newly occurring or worsening grade 3 or 4 laboratory abnormalities are summarized in Table 8. Grade 3 or 4 abnormalities in neutropenia and thrombocytopenia occurred in 50 and 28% of patients, respectively. These hematologic abnormalities were generally manageable with dose interruptions and reductions, and support with hematopoietic growth factors or transfusions occasionally. Only one patient discontinued from study treatment due to thrombocytopenia.

The majority of biochemistry abnormalities were mild to moderate in severity, resolved spontaneously with continued dosing of nilotinib. Grade 3 or 4 elevations in AST and ALT occurred in 6 and 12% of patients, respectively. Grade 3 or 4 total bilirubin occurred in 3%. Grade 3 or 4 elevations of lipase occurred in 15% of patients. Pancreatitis was reported in 1 patient; however, it was transient and resolved with dose interruption and reduction. No patients discontinued therapy due to serum biochemistry abnormalities. Gastrointestinal and central nervous system hemorrhage of grade 3 or 4 was not reported.

One death was occurred in the study, or within 28 days of discontinuing study. The patient discontinued study treatment because of back pain on study day 14 and died as a result of cardiac failure due to cardiac tamponade and pericardial effusion on day 16. Grade 3 or 4 peripheral edema, pericardial effusion, or pleural effusion was not reported in other patients. Because of a preclinical signal indicating that nilotinib could potentially prolong the QT interval, frequent ECG was performed during the study. One patient experienced a prolongation in the QTcF interval exceeding 500 ms. This event resolved spontaneously with dose reduction of nilotinib. No episodes of torsades de pointes were observed. No tendency was observed for the incidence of adverse events to increase or

Table 6 Hematologic response and cytogenetic response by BCR-ABL mutation at baseline (ITT population)

Disease type	Mutation	Hematologic response		Major cytogenetic response		Major molecular response	
		N^a	n (%)	N^b	n (%)	N^c	n (%)
CML-CP ($N = 16$)	No mutation	4	4 (100)	12	12 (100)	12	6 (50)
	Any mutation	2	2 (100)	4	3 (75)	4	3 (75)
	D276G	1	1 (100)	1	1 (100)	1	1 (100)
	M244V	1	1 (100)	1	0 (0)	1	0 (0)
	F359I	–	–	1	1 (100)	1	1 (100)
	F311I	–	–	1	1 (100)	1	1 (100)
CML-AP ($N = 7$)	No mutation	1	1 (100)	1	0 (0)	1	0 (0)
	Any mutation	6	4 (67)	6	1 (17)	6	1 (17)
	M351T	1	1 (100)	1	0 (0)	1	0 (0)
	Y253H	2	1 (50)	2	0 (0)	2	0 (0)
	F359I/L387 M	1	1 (100)	1	1 (100)	1	1 (100)
	F311I/M244V	1	1 (100)	1	0 (0)	1	0 (0)
	E279K	–	–	–	–	1	0 (0)
CML-BC ($N = 4$)	No mutation	2	1 (50)	2	1 (50)	2	1 (50)
	Any mutation	2	1 (50)	2	1 (50)	2	1 (50)
	F317L	1	1 (100)	1	1 (100)	1	1 (100)
	F359V	1	0 (0)	1	0 (0)	1	0 (0)
Ph+ ALL ($N = 7$)	No mutation	3	2 (67)	–	–	3	1 (33)
	Any mutation	4	1 (25)	–	–	3	0 (0)
	E255K, V/G250E	1	0 (0)	–	–	1	0 (0)
	E459K	1	0 (0)	–	–	1	0 (0)
	E255V	1	0 (0)	–	–	1	0 (0)
	F359V	1	1 (100)	–	–	–	–

[a] Number of patients deemed to be evaluable for hematologic response when an analysis of BCR-ABL mutations was performed post-baseline

[b] Number of patients deemed to be evaluable for cytogenetic response when an analysis of BCR-ABL mutations was performed post-baseline

[c] Number of evaluable patients to be included in the mutation category, i.e., patients who had mutation data and who did not have MMR at baseline

for their onset to be delayed as treatment with the study drug continued.

4 Discussion

Imatinib, the first BCR-ABL TKI approved for the treatment of Ph+ CML and Ph+ ALL, has demonstrated clinical efficacy. However, resistance develops in some patients and treatment options for patients who are resistant to, or intolerant of, imatinib have been very limited. Nilotinib is a more potent and more selective inhibitor of the BCR-ABL protein tyrosine kinase.

The results of this study show the high level of clinical activity of nilotinib in Japanese patients with CML and Ph+ ALL as the overseas Phase II registration study. The rates of CHR and MCyR were relatively higher than that of overseas data. However, due to the limited data in Japanese patients, it is difficult to draw a meaningful conclusion. Overall, imatinib resistance or intolerance, and baseline BCR-ABL mutation status, did not appear to have an impact on response to nilotinib.

The most frequent drug-related adverse events were rash, headache, nausea, vomiting, and pyrexia; however, grade 3 or 4 events were uncommon. Grade 3 or 4 peripheral edema or pleural effusion was not reported. Though neutropenia and thrombocytopenia occurred in 50 and 28% of patients, respectively, these were generally manageable with dose interruptions and reductions, and support with hematopoietic growth factors or transfusions occasionally. Hemorrhage of grade 3 or 4 was not reported. The majority of serum biochemistry abnormalities were infrequent, and mild to moderate in severity, resolved spontaneously with continued dosing of nilotinib.

Although imatinib intolerance constituted 75% (12/16) in CML-CP patients, no patient experienced same serious side effects or side effects lead to discontinuation of

administration of nilotinib. Nilotinib and imatinib have some structural features in common, but the minimal occurrence of cross-intolerance between the 2 agents may represent significant therapeutic advantage. It is important to note that no imatinib-intolerant patient on this study had achieved a prior CyR on imatinib at any time.

Consistent with previous findings, the pharmacokinetic profile of nilotinib showed moderate inter-individual variability in this study with Japanese CML patients. The observed variation in nilotinib pharmacokinetics may be partly attributed to the inter-individual variability in CYP3A4, since CYP3A4 activity has been shown to vary among different individuals and nilotinib is mainly metabolized by CYP3A4. Pharmacokinetic parameters obtained in this study were similar with those in non-Japanese patients, indicating that there would be no ethnic difference in pharmacokinetic profile of nilotinib [16]. Thus, the mean steady-state plasma trough level of 1170 mg/mL (2.2 µM) represents a concentration sufficient to inhibit the in vitro proliferation of most cell lines expressing imatinib-resistant mutant forms of BCR-ABL (with the exception of the T315I mutation) [9].

In summary, nilotinib is highly active and safe, and provides an effective treatment for Japanese patients with Ph+ CML whose disease becomes resistant or intolerant to imatinib. Promising activity is also observed in relapsed/refractory Ph+ ALL patients.

Table 7 Non-hematologic adverse events suspected to be related to nilotinib (10% or more, SAF population)

	Total ($N = 34$)			
	All grades		Grade 3/4	
	n	%	n	%
Rash	17	50	1	3
Headache	11	32	2	6
Nausea	11	32	1	3
Vomiting	10	29	0	0
Pyrexia	8	24	0	0
Malaise	5	15	0	0
Hepatic function abnormal	5	15	0	0
Anorexia	5	15	0	0
Eczema	5	15	0	0
Constipation	4	12	0	0
Stomach discomfort	4	12	0	0
Chest pain	4	12	0	0
Back pain	4	12	1	3
Muscle spasms	4	12	0	0
Erythema	4	12	0	0
Pruritus	4	12	0	0

Table 8 Newly occurring or worsening grade 3/4 laboratory abnormalities (SAF population)

	n/N (%)				
	CML-CP $N = 16$	CML-AP $N = 7$	CML-BC $N = 4$	Ph+ ALL $N = 7$	Total $N = 34$
Hematology					
WBC	5/16 (31)	3/7 (43)	3/4 (75)	3/6 (50)	14/33 (42)
Neutrophils	6/16 38)	5/7 (71)	2/3 (67)	3/6 (50)	16/32 (50)
Lymphocyte	6/16 (38)	1/7 (14)	2/4 (50)	2/6 (33)	11/33 (33)
PLT	3/16 (19)	2/6 (33)	2/4 (50)	2/6 (33)	9/32 (28)
Hemoglobin	3/16 (19)	4/7 (57)	4/4 (100)	4/7 (57)	15/34 (44)
Biochemistry					
ALP	0/16 (0)	0/7 (0)	0/4 (0)	0/7 (0)	0/34 (0)
AST (GOT)	0/16 (0)	0/7 (0)	1/4 (25)	1/7 (14)	2/34 (6)
ALT (GPT)	2/16 (13)	0/7 (0)	1/4 (25)	1/7 (14)	4/34 (12)
Bilirubin (total)	1/16 (6)	0/7 (0)	0/4 (0)	0/7 (0)	1/34 (3)
Amylase	1/16 (6)	0/7 (0)	0/4 (0)	0/7 (0)	1/34 (3)
Lipase	4/16 (25)	1/7 (14)	0/4 (0)	0/7 (0)	5/34 (15)
Phosphate (hypo)	2/16 (13)	1/7 (14)	1/4 (25)	1/6 (17)	5/33 (15)
Glucose (hyper)	2/16 (13)	1/7 (14)	0/4 (0)	0/7 (0)	3/34 (9)
Glucose (hypo)	0/16 (0)	0/7 (0)	0/4 (0)	0/7 (0)	0/34 (0)

Patients are counted only for the worst grade observed post-baseline

n number of patients who had less than grade X at baseline, and worsened to grade X post-baseline; N total number of patients evaluable post-baseline who had less than grade X at baseline

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KW-2449, a novel multikinase inhibitor, suppresses the growth of leukemia cells with FLT3 mutations or T315I-mutated *BCR/ABL* translocation

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KW-2449, a multikinase inhibitor of FLT3, ABL, ABL-T315I, and Aurora kinase, is under investigation to treat leukemia patients. In this study, we examined its possible modes of action for antileukemic effects on FLT3-activated, FLT3 wild-type, or imatinib-resistant leukemia cells. KW-2449 showed the potent growth inhibitory effects on leukemia cells with FLT3 mutations by inhibition of the FLT3 kinase, resulting in the down-regulation of phosphorylated-FLT3/STAT5, G_1 arrest, and apoptosis. Oral administration of KW-2449 showed dose-dependent and significant tumor growth inhibition in FLT3-mutated xenograft model with minimum bone marrow suppression. In FLT3 wild-type human leukemia, it induced the reduction of phosphorylated histone H3, G_2/M arrest, and apoptosis. In imatinib-resistant leukemia, KW-2449 contributed to release of the resistance by the simultaneous down-regulation of BCR/ABL and Aurora kinases. Furthermore, the antiproliferative activity of KW-2449 was confirmed in primary samples from AML and imatinib-resistant patients. The inhibitory activity of KW-2449 is not affected by the presence of human plasma protein, such as α1-acid glycoprotein. These results indicate KW-2449 has potent growth inhibitory activity against various types of leukemia by several mechanisms of action. Our studies indicate KW-2449 has significant activity and warrants clinical study in leukemia patients with FLT3 mutations as well as imatinib-resistant mutations. (Blood. 2009;114:1607-1617)

Introduction

Overexpression and activating mutations of protein tyrosine kinases (PTK) are frequently observed in several kinds of hematologic malignancies.[1,2] Abnormally activated PTK-mediated signal transduction pathways are involved in their pathogenesis, such as autonomous proliferation, antiapoptosis, and differentiation block. The remarkable clinical success of the ABL kinase inhibitor, imatinib mesylate (IM), in the treatment of BCR/ABL-positive chronic myeloid leukemia (CML) and acute lymphoblastic leukemia (ALL) has proved the principle of molecularly targeted therapy.[3,4] Therapeutic intervention targeting PTKs is therefore highly expected to improve prognosis of patients with hematologic malignancy. FMS-like receptor tyrosine kinase (FLT3) is a class III receptor tyrosine kinase together with cKIT, FMS, and PDGFR.[5,6] FLT3 mutations were first reported as internal tandem duplication (FLT3/ITD) of the juxtamembrane domain-coding sequence; subsequently, a missense point mutation at the Asp835 residue and point mutations, deletions, and insertions in the codons surrounding Asp835 within a tyrosine kinase domain of FLT3 (FLT3/KDM) have been found.[7,8] FLT3 mutation is the most frequent genetic alteration in acute myeloid leukemia (AML) and involved in the signaling pathway of proliferation and survival in leukemia cells.[5,6] Several large-scale studies have confirmed that FLT3/ITD is strongly associated with leukocytosis and a poor prognosis.[9] In addition to FLT3 mutation, overexpression of FLT3 is an unfavor-

able prognostic factor for overall survival in AML, and it has been revealed that overexpressed FLT3 had the same sensitivity to the FLT3 inhibitor as FLT3/ITD.[10] Because high-dose chemotherapy and stem cell transplantation cannot conquer the adverse effects of FLT3 mutations, it is expected that the development of FLT3 kinase inhibitors will make more efficacious therapeutic strategy for leukemia therapy.[11,12] To date, several small-molecule tyrosine kinase inhibitors have been shown to have a potency to inhibit the FLT3 kinase, and several of them, such as CEP-701, PKC412, MLN-518, and SU11248, have been subjected to clinical trials.[13-16] However, the clinical efficacy of these FLT3 inhibitors for AML with FLT3 mutations is limited to the transient clearance of leukemia blast cells as a single agent; thus, the therapeutic strategy of some FLT3 inhibitors moves toward a combination with conventional chemotherapy.[17] This move is a logical step based on the in vitro evidence of the synergy with conventional cytotoxic agents,[18,19] although it should be considered that several problems regarding adverse effects and pharmacokinetics have been apparent from clinical trials of monotherapy.[20] Furthermore, because acute leukemia is a complex multigenetic disorder,[21-23] a simultaneous inhibition of multiple protein kinases is thought to be advantageous over the increasing potency against the selective kinases. Recent high-throughput resequencing of TK in AML samples revealed new somatic mutations of JAK1, DDR1, and NRTK1 in addition to

previously well-known FLT3, cKit, JAK2, and FGFR mutations.[24,25] These observations collectively indicate that FLT3 inhibitors in the next generation should have an adequately balanced potency against key oncogenic kinases, which are responsible for the disease progression and/or the resistance to standard therapeutics. Here we describe efficacy of a novel small-molecule protein kinase inhibitor, KW-2449, which has a potent and unique kinase inhibition profile against FLT3, ABL, T315I-mutant ABL (ABL-T315I) tyrosine kinases as well as Aurora kinase.

Methods

Kinase inhibition profile

The in vitro kinase assays were performed according to the KinaseProfiler Assay Protocols of Upstate Biotechnology.

Growth inhibition profile cell-cycle analysis

FLT3/ITD-, FLT3/D835Y-expressing, wt-FLT3/FL-coexpressing, and FLT3/ITD-green fluorescent protein (GFP)-expressing murine myeloid-progenitor 32D cells were previously reported.[26] Human leukemia cell line MOLM-13 was obtained from DSMZ (German Resource Center for Biological Material); MV4;11, RS4;11, K562, and HL60 from ATCC. Wt-BCR/ABL-positive human ALL cell line TCC-Y and its IM-resistant clones, TCC-Y/sr cells, which has the T315I-mutated BCR/ABL, were reported previously.[27] Cell viability was determined by the sodium 3'-[1-(phenylaminocarbonyl)-3, 4-tetrazolium]-bis (4-methoxy-6-nitro) benzene sulfonic acid hydrate assay after incubation with or without KW-2449 for 72 hours at 37°C. The number of viable cells was determined using the Cell Proliferation Kit II (Roche Diagnostics). For cell-cycle analysis, MOLM-13 and RS4;11 cells were treated with KW-2449. After 24, 48, and 72 hours of incubation at 37°C, DNA contents were analyzed as previously described.[28] Cell cycle distribution of K562, TCC-Y, and TCC/Ysr was analyzed 24 hours after treatment with KW-2449 or imatinib.

Effects of hAGP on growth inhibitory activity by FLT3 inhibitors

MOLM-13 cells were incubated with various concentrations of KW-2449, PKC-412, and CEP-701 in the presence of 0.1% of human α1-acid glycoprotein (hAGP; Sigma-Aldrich). Cell viability was determined by sodium 3'-[1-(phenylaminocarbonyl)-3, 4-tetrazolium]-bis (4-methoxy-6-nitro) benzene sulfonic acid hydrate assay after incubation for 72 hours at 37°C.

Western blot

MOLM-13 cells were treated with KW-2449 for 24 hours, and cell pellets were suspended with lysis buffer. FLT3 proteins were immunoprecipitated with anti-FLT3 antibody (S18; Santa Cruz Biotechnology). The precipitated samples were separated by sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE), and electroblotted onto Immobilon polyvinylidene difluoride membranes (Millipore). Immunoblotting was performed with antiphosphotyrosine antibody (4G10; Upstate Biotechnology). The membranes were incubated with the stripping buffer and then reprobed with anti-FLT3 antibody (C20; Santa Cruz Biotechnology). Signals were developed using an enhanced chemiluminescence system (GE Healthcare). To examine the phosphorylation level of STAT5, whole cell lysates were subjected to immunoblotting with antiphospho-STAT5 antibody (Kyowa Hakko Kogyo). The membranes were incubated with the stripping buffer and then reprobed with anti-STAT5 antibody (Santa Cruz Biotechnology).

RS4;11 cells were suspended in culture medium containing nocodazole with or without KW-2449. After a 30-minute incubation, cells were harvested and cell pellets were suspended in lysis buffer. Whole cell lysates were subjected to immunoblotting with antiphospho-HH3 (Ser10) antibody (Upstate Biotechnology). The membranes were incubated with the stripping buffer and then reprobed with anti-HH3 antibody (Cell Signaling).

Concentration of KW-2449 in plasma and tumors

Severe combined immunodeficiency (SCID) mice (Fox CHASE C.B-17/Icr-scidJcl, male, 5 weeks old) were purchased from CLEA Japan. Mice were treated with an intraperitoneal injection of antiasialo GM1 antibody (0.3 mg/mouse, Wako Pure Chemical Industries). The day after antiasialo GM1 antibody treatment, all mice were subcutaneously inoculated in the shaved area with 10⁷ of MOLM-13 cells. Ten days after inoculation, KW-2449 at 20 mg/kg was orally administered to mice twice. Blood and tumor samples were collected 4, 8, 12, and 24 hours after the second administration. The plasma and tumor samples were analyzed to measure KW-2449 concentration with liquid chromatography–mass spectrometry–mass spectrometry (LC/MS/MS).

In vivo antileukemia effects on xenograft transplantation

SCID mice were subcutaneously inoculated with MOLM-13 cells. Five days after inoculation, tumor volume was measured using the Antitumor test system II (Human Life). The 25 mice with tumors ranging from 90 to 130 mm³ were selected and randomized using the Antitumor test system II. From the day of randomization, vehicle (0.5 wt/vol% MC400) or KW-2449 (2.5, 5.0, 10, and 20 mg/kg) was orally administered to mice twice a day for 14 days. Tumor volume was measured twice a week during the treatment.

In vivo antileukemia effects on syngeneic transplantation

C3H/Hej mice were purchased from Charles River Japan. Fifteen C3H/Hej mice were intravenously inoculated with 2 × 10⁶ of FLT3/ITD-GFP-32D cells and then randomly divided into 3 groups of 5 mice each. On the seventh day after inoculation, peripheral blood (PB) was collected from the mice. From the 10th day after inoculation, mice were treated with KW-2449 at 40 mg/kg (orally) twice a day, cytosine arabinoside (AraC) at 150 mg/kg (intravenously) daily, or vehicle for 4 days. Six hours after the last administration, PB was collected. Total RNA was extracted from each PB sample using a QIAamp RNA Blood Mini Kit (QIAGEN). cDNA was synthesized from each RNA sample using a random primer and Moloney murine leukemia virus reverse transcriptase (Super-Script II; Invitrogen) according to the manufacturer's recommendations. The expression level of the human FLT3 transcript was quantitated using a real-time fluorescence detection method on an ABI Prism 7000 sequence detection system (Applied Biosystems) as previously reported.[10] After the collection of PB, spleens and bone marrow (BM) cells from femora were collected, and the total cell number from each femur was counted using a cell counter. To discriminate the FLT3/ITD-GFP-32D leukemia cells and normal BM cells, all collected cells were subjected to flow cytometry analysis after phycoerythrin-conjugated antihuman FLT3 monoclonal antibody (SF1.340; Immunotech) staining. In this flow cytometry analysis, GFP-positive cells were defined as residual leukemia in the femur. The weight of each collected spleen was measured.

Primary patient samples

BM samples from patients with AML or CML in blast crisis were subjected to Ficoll-Hypaque (Pharmacia LKB) density gradient centrifugation. All samples were morphologically confirmed to contain more than 90% leukemia cells after centrifugation on May-Grünwald Giemsa-stained cytospin slides, and then cryopreserved in liquid nitrogen before use. Informed consent was obtained from all patients in accordance with the Declaration of Helsinki to use their samples for the present study as well as banking and molecular analysis, and approval was obtained from the ethics committees of Nagoya University and Ogaki Municipal Hospital for this study. Mutations of the FLT3 gene were examined as previously reported.[8] Primary AML cells were incubated with RPMI1640 medium containing 10% fetal calf serum and 0.1 μM KW-2449 for 6 hours, and cell pellets were suspended with lysis buffer. Whole cell lysates were subjected to immunoblotting with antiphospho-FLT3 (Tyr591) (Cell Signaling Technology) and antiphospho-STAT5 antibodies. The membranes were incubated with the stripping buffer and then reprobed with anti-FLT3 (C20; Santa Cruz Biotechnology) and anti-STAT5 antibodies (Santa Cruz Biotechnology).

Colony formation analysis

Human AML cells (10^5 cells) were plated in MethoCult methylcellulose semisolid medium containing human stem cell factor, granulocyte-macrophage colony-stimulating factor (GM-CSF), and interleukin-3 (H4534; Stem Cell Technologies) with or without KW-2449 (0.1 μM) and then incubated at 37°C for 14 days. Colonies with more than 20 cells were scored using an inverted microscope.

Human cord blood (CB) was collected after full-term deliveries with informed consent obtained in accordance with the Declaration of Helsinki and approved by the Review Board of Tokai Cord Blood Bank. Mononuclear cells were collected by the Ficoll-Hypaque (Pharmacia LKB) density gradient centrifugation. CB mononuclear cells (5×10^4 cells) were plated in complete MethoCult methylcellulose medium (H4435; Stem Cell Technologies) with an increasing concentration of KW-2449. After 14 days in culture, erythroid burst-forming units (BFU-E), colony-forming unit–granulocyte macrophage (CFU-GM), and colony-forming unit–granulocyte, erythrocyte, monocyte/macrophage, megakaryocyte (CFU-GEMM) colonies were counted.

Inhibitory effects on BCR/ABL-positive leukemia cells

K562, TCC-Y, and TCC/Ysr cells were incubated with an increasing concentration of KW-2449 or imatinib for 72 hours, and cell pellets were suspended with lysis buffer. Whole cell lysates were subjected to immunoblotting with antiphospho-ABL (Tyr245; Cell Signaling Technology), antiphospho-STAT5, and anti-poly(ADP-ribose) polymerase (PARP; Cell Signaling Technology) antibodies.

Human CML in blast crisis (CML-BC) cells with T315I-mutation were intravenously inoculated into nonobese diabetic (NOD)/SCID mice (CLEA Japan). On the 28th day after the inoculation, engraftment of leukemia cells in each mouse was confirmed by the detection of human CD45-positive cells in PB. On the next day, PB was collected from the leukemia cell-engrafted mice, and then the mice were treated with KW-2449 at 20 mg/kg twice a day, IM at 150 mg/kg daily, or vehicle for 5 days. Twelve hours after the last administration, PB was collected from each mouse. Total RNA was extracted from each PB sample, and cDNA was synthesized from each RNA sample using a random primer and Moloney murine leukemia virus reverse transcriptase as described in "In vivo antileukemia effects on syngeneic transplantation." The expression level of the BCR/ABL transcript was quantitated using a real-time fluorescence detection method as previously reported.[29] The GAPDH served as a control for cDNA quality. Relative gene expression levels were calculated using standard curves and adjusted based on the expression level of the GAPDH gene.

After the collection of PB, femora were subjected to pathologic examination. Residual leukemia cells were evaluated by the immunohistochemical staining with antihuman CD45 antibody (Dako North America) as previously reported.[30] The animal experiments were approved by the institutional ethics committee for Laboratory Animal Research, Nagoya University School of Medicine and performed according to the guidelines of the institute.

Statistical analysis

Differences in continuous variables were analyzed with the Mann-Whitney U test for distribution among 2 groups or the Bonferroni test for distribution among more than 3 groups. Differences in therapeutic effects were analyzed with the repeated-measures analysis of variance method. These statistical analyses were performed with the StatView-J 5.0 software (Abacus Concepts).

Results

Development of KW-2449 and its kinase inhibition profile

Our aim was to generate an orally available and highly potent FLT3 inhibitor with low toxicity profile for leukemia patients. For this goal, we screened the chemical libraries of Kyowa Hakko Kirin (previously Kyowa Hakko Kogyo) using several leukemia cells, which have several activated mutations in FLT3 or BCR-ABL translocation. As a result, we identified several chemo-types with different kinase inhibition profiles, intensively studied the structures of the identified chemo-types to improve the potency and selectivity, and then finally generated KW-2449 (Figure 1A).

KW-2449 inhibited FLT3 and ABL kinases with half-maximal inhibitory concentration (IC_{50}) values of 0.0066 and 0.014 μM, respectively. In addition, it potently inhibited ABL-T315I, which is associated with IM resistance, with an IC_{50} value of 0.004 μM. On the other hand, KW-2449 had little effect on PDGFRβ, IGF-1R, EGFR, and various serine/threonine kinases even at a concentration of 1 μM. Among various serine/threonine kinases examined, KW-2449 inhibited Aurora A kinase with IC_{50} of 0.048 μM (Table 1) and Aurora B kinase with the equivalent potency (data not shown).

In vitro effects of KW-2449 on FLT3 mutated leukemia

In vitro kinase inhibition profile of KW-2449 indicated its extreme potency against FLT3 kinase. We first examined the effects of KW-2449 on several human leukemia cell lines with activated FLT3 and mutant FLT3-transfected cells. Because constitutive activation of FLT3 in leukemia cells is reportedly induced by mutation or coexpression of wild-type FLT3 (wt-FLT3) and FLT3 ligand (FL), we evaluated the growth inhibitory effect on mutant FLT3 (FLT3/ITD or FLT3/D835Y)–expressing and wt-FLT3– and FL-coexpressing (wt-FLT3/FL) murine myeloid-progenitor 32D cells. In addition, we evaluated the efficacy against FLT3/ITD-harboring human AML cell lines, MOLM-13 and MV4;11. Previously, we confirmed that FLT3 kinase is constitutively activated in these cell lines, and FI-700, a FLT3 selective inhibitor, can suppress the growth of mutated FLT3 transfected 32D cells as well as MOLM-13 and MV4;11 cells.[31] As expected, KW-2449 showed growth inhibitory activities against FLT3/ITD-, FLT3/D835Y-, and wt-FLT3/FL-expressing 32D cells, MOLM-13 and MV4;11 with half-maximal growth inhibitory concentration (GI_{50}) values of 0.024, 0.046, 0.014, 0.024, and 0.011 μM, respectively (Table 2). These results indicate that KW-2449 has the potent growth inhibitory activities against not only FLT3/ITD-expressing leukemia cells but also FLT3/KDM-activated and wild-type FLT3-overexpressing leukemia cells.

It has been reported that PKC-412 and CEP-701, whose chemical structure contains indolocarbazole, tightly bind to hAGP. Although these compounds have been in clinical investigation as FLT3 inhibitors, the significant reduction of their inhibitory activity caused by tight hAGP binding is in part associated with the limited clinical efficacy despite their long exposure in vivo, as well as the potency in vitro.[32,33] In these circumstances, we selected the compounds whose cellular efficacy was not attenuated by the presence of hAGP. Indeed, an addition of hAGP to culture media reduced the growth inhibitory effect of PKC-412 and CEP-701 more than 100- to 1000-fold, whereas the growth inhibitory activity of KW-2449 was not attenuated by hAGP (Figure 1E).

In accordance with growth inhibitory effect, KW-2449 suppressed the phosphorylations of FLT3 (P-FLT3) and its downstream molecule phospho-STAT5 (P-STAT5) in MOLM-13 cells in a dose-dependent manner (Figure 1B). Furthermore, KW-2449 increased the percentage of cells in the G_1 phase of the cell cycle and reciprocally reduced the percentage of cells in the S phase, resulting in the increase of apoptotic cell population (Figure 1C-D). These results indicated that the dephosphorylation of constitutively active FLT3 kinase by KW-2449 induced the G_1 arrest to leukemia
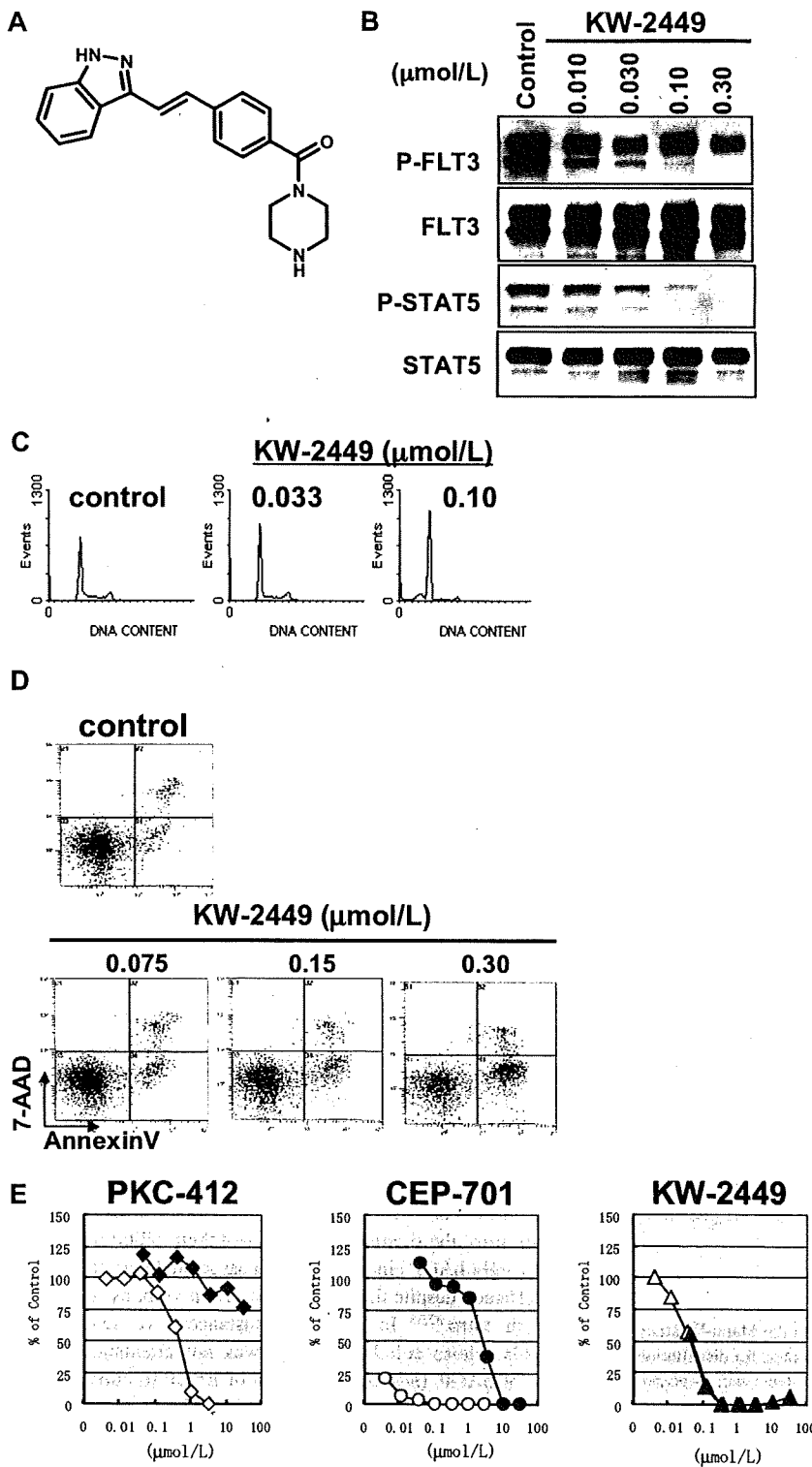
Figure 1. Effects of KW-2449 on human leukemia cells with FLT3 mutation. (A) Chemical structure of KW-2449. (B) MOLM-13 cells, which express FLT3/ITD, were treated with KW-2449 at the indicated concentrations for 24 hours. For analysis of FLT3 and its phosphorylated form (P-FLT3), the blots of immunoprecipitated FLT3 SDS-PAGE samples were analyzed by antiphosphotyrosine (P-Tyr) antibody and anti-FLT3 antibody. For detection of STAT5 and its phosphorylated form (P-STAT5), total cell lysate SDS-PAGE samples were analyzed by anti-P-STAT5 antibody and anti-STAT5 antibody as primary antibodies. Phosphorylation levels of FLT3 and STAT5 were decreased by KW-2449 in a dose-dependent manner. (C) MOLM-13 cells were treated with various concentrations of KW-2449 for 48 hours, and cell-cycle distribution was analyzed as described in "Growth inhibition profile and cell-cycle analysis." (D) MOLM-13 cells were treated with various concentrations of KW-2449 for 48 hours, and apoptosis induction was analyzed by 7-amino-actinomycin D/annexin V staining. (E) Inhibitory effects of hAGP on growth inhibitory activity against MOLM-13 cells were compared between KW-2449 and potent FLT3 inhibitors, PKC-412 and CEP-701, as described in "Effects of hAGP on growth inhibitory activity by FLT3 inhibitors." Growth inhibitory activity of KW-2449 was not affected by the presence of hAGP.

cells with FLT3 activation, resulting in apoptosis. Apparent increase of sub-G_1 apoptotic cells was also observed after KW-2449 exposure over 0.10 μM, at which concentration complete down-regulation of P-FLT3 was observed.

To confirm these effects on primary leukemia, we further analyzed the activities of KW-2449 using 10 human primary AML cells that consisted of 5 AML with wt-FLT3: 4 with FLT3/ITD and

1 with both FLT3/ITD and FLT3/KDM. In all AML cases with FLT3 mutation, KW-2449 (0.1 μM) reduced the phosphorylation levels both of FLT3 and STAT5 (Figure 2A). In accordance with the dephosphorylation level, the colony formations of AML cases with FLT3 mutation were inhibited by KW-2449 (Figure 2B). In contrast, the inhibitory effect of KW-2449 on the colony formations of all AML cases with wt-FLT3 was minimal at 0.1 μM

Table 1. Kinase inhibitory profile of KW-2449

Kinase	KW-2449
Tyrosine kinase	
FLT3	0.0066
FLT3/D835Y	0.001
KIT	0.30
PDFGRα	1.7
ABL	0.014
ABL-T315I	0.004
SRC	0.40
JAK2	0.15
FGFR1	0.036
Serine/threonine kinase	
Aurora A	0.048

In vitro kinase inhibition IC_{50} (μmol/L). IC_{50} values of KW-2449 were determined by in vitro kinase assays as described in "Kinase inhibition profile."

(Figure 2B). In 2 cases with wt-FLT3 (Wt-3 and Wt-5), constitutive phosphorylations of FLT3 were observed, although KW-2449 did not inhibit their colony formations. In the Wt-3 case, the weak inhibitory effect on P-FLT3 might reflect the minimum effect on the colony formation. However, in the Wt-5 case, KW-2449 significantly reduced the level of P-FLT3, whereas the colony formation was not inhibited. In this case, constitutive phosphorylation of STAT5 was also observed, although KW-2449 did not reduce its phosphorylation level, indicating that the STAT5 was phosphorylated by another kinase signal. These results therefore suggested that KW-2449 can dephosphorylate constitutively active wt-FLT3 kinase but not inhibit the proliferation of leukemia cells if they were not mainly addicted to FLT3 the kinase.

The inhibitory effect of KW-2449 on normal hematopoiesis was also evaluated using human hematopoietic progenitors. Mononuclear cells from 5 independent CB were plated in complete methylcellulose semisolid medium with an increasing concentration of KW-2449. Although KW-2449 inhibited the colony formation of CB mononuclear cells in a dose-dependent manner, the distribution of BFU-E, CFU-GM, and CFU-GEMM colonies was not affected by the KW-2449 treatment (Figure 2C-D). The Bonferroni test revealed that statistically significant differences in

Table 2. Growth inhibitory profile of KW-2449

| Cell lines	KW-2449	Imatinib
32D transfectant		
Mock (with IL-3)	> 10	—
FLT3/ITD	0.024	—
FLT3/D835Y	0.046	—
Wt-FLT3/FL	0.014	—
Human leukemia		
MOLM-13	0.024	> 10
MV4;11	0.011	—
RS4;11	0.23	20
HL-60	0.65	> 10
BCR/ABL+ leukemia		
K562	0.27	0.24
TCC-Y	0.49	0.18
TCC-Y/sr	0.42	24

Growth inhibition GI_{50} (μmol/L). GI_{50} values of KW-2449 and imatinib were determined by in vitro XTT assays. MOLM-13 and MV4;11 cells had FLT3/ITD. K562 and TCC-Y cells had wt-BCR/ABL, and TCC-Y/sr had the T315I mutation in the *BCR/ABL* gene.
— indicates not applicable.
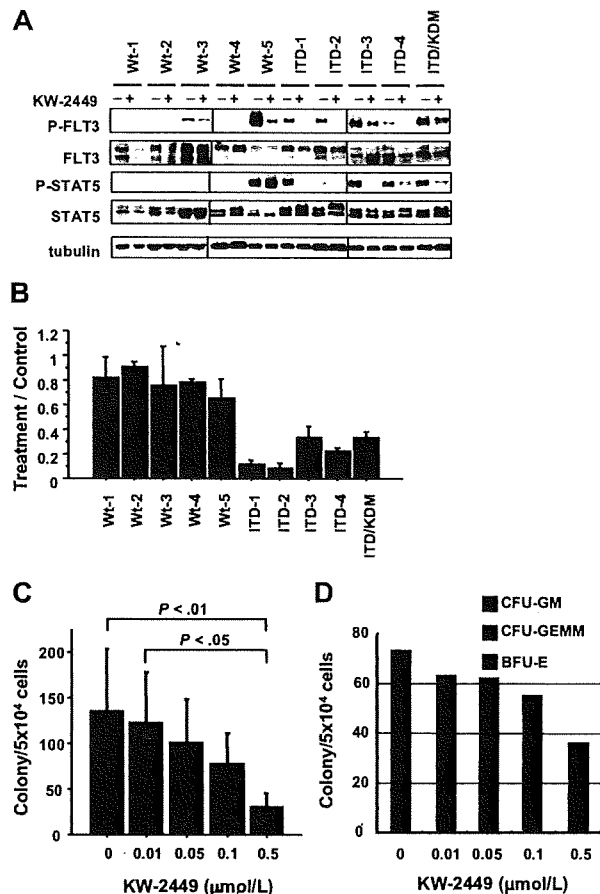
Figure 2. Inhibitory effects of KW-2449 on primary AML and colony-forming cells. (A) Ten AML samples consisting of 5 with wild-type FLT3 (Wt-1 to Wt-5), 3 with FLT3/ITD (ITD-1 to ITD-4), and one with both FLT3/ITD and FLT3/KDM (ITD/KDM), were analyzed. Primary AML cells were incubated with or without KW-2449 at 0.1 μM for 6 hours, and then phosphorylation status of FLT3 and STAT5 was analyzed. KW-2449 reduced phosphorylation levels of FLT3 and STAT5 in all AML samples with *FLT3* mutations. In the Wt-5 sample, KW-2449 reduced the phosphorylation level of FLT3 but not of STAT5. Vertical lines have been inserted to indicate a repositioned gel lane. (B) AML cells were suspended in methylcellulose semisolid medium containing human stem cell factor, GM-CSF, and interleukin-3 with or without KW-2449. Colonies were counted after 14 days. Mean treatment/control ratio ± SD from 3 experiments in each sample are shown. In accordance with the down-regulation levels of FLT3 and STAT5 phosphorylations, KW-2449 inhibited the colony formations in all AML samples with FLT3 mutations. In the Wt-5 sample, weak inhibition of the colony formation seems to reflect the sustained STAT5 activation induced by another activation mechanism. (C) Mononuclear cells from human CB were plated in the complete methylcellulose semisolid medium with an increasing concentration of KW-2449. After 14 days of culture, BFU-E, CFU-GM, and CFU-GEMM colonies were counted. Mean total colony numbers ± SD at the indicated concentrations of KW-2449 are shown (n = 5). Although KW-2449 inhibited a total number of colonies in a dose-dependent manner, the Bonferroni test revealed that the statistical significances were found between control and at the 0.5 μM ($P < .01$), and at the .01 μM and at the 0.5 μM ($P < .05$). (D) The representative result of the distribution of BFU-E, CFU-GM, and CFU-GEMM colonies from 1 CB sample is shown. Although KW-2449 inhibited the colony formation of CB mononuclear cells in a dose-dependent manner, the distribution of BFU-E, CFU-GM, and CFU-GEMM colonies was not affected by the KW-2449 treatment.

the total number of colonies were found between control and at the 0.5 μM ($P < .01$) concentration, and at the 0.01 μM and at the 0.5 μM ($P < .05$) concentration. The reduction of a total colony number was at most 59.6% plus or minus 20.2% of the control, at 0.1 μM of KW-2449. These results indicated that the suppressive effect of KW-2449 on the normal hematopiesis was modest, whereas that on leukemia with FLT3 mutations was significant (Figure 2B-C).
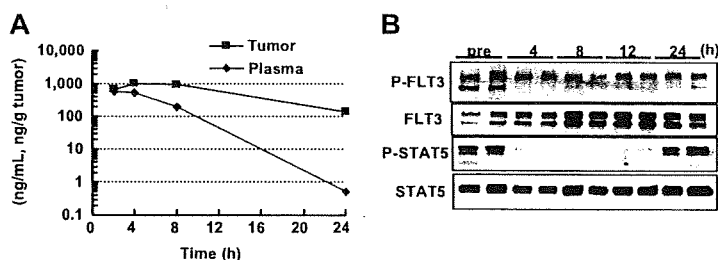
Figure 3. Pharmacokinetic and pharmacodynamic effects of KW-2449 in FLT3-activated leukemia. (A) MOLM-13 cells (10^7 cells/mouse) were subcutaneously inoculated into 2 SCID mice. Ten days after inoculation, KW-2449 at 20 mg/kg was orally administered twice every 12 hours. The concentrations of KW-2449 in plasma and tumor were sequentially analyzed by LC/MS/MS after the final administration of KW-2449. (B) The transition of FLT3 and STAT5 phosphorylation levels in tumor were analyzed by Western blotting. For analysis of FLT3 and its phosphorylated form (P-FLT3), the blots of immunoprecipitated FLT3 SDS-PAGE samples were analyzed by antiphospho-tyrosine (P-Tyr) antibody and anti-FLT3 antibody. For detection of STAT5 and its phosphorylated form (P-STAT5), total tumor lysate SDS-PAGE samples were analyzed by anti-P-STAT5 antibody and anti-STAT5 antibody as primary antibodies. Dephosphorylations of FLT3 and STAT5 in MOLM-13 were observed until 12 hours after the last administration. Results from 2 mice at each point are shown.

In vivo effects of KW-2449 on leukemia cells with FLT3 mutation

In vivo antileukemia activities of KW-2449 were evaluated using MOLM-13, FLT3-ITD AML, xenograft model. First, the concentrations of KW-2449 in both plasma and tumor after oral administration were sequentially examined in SCID mice bearing the subcutaneous MOLM-13 tumor. The tumor/plasma concentration ratio of KW-2449 tended to increase along with the time after administration and reached approximately 400, 24 hours after dosing (Figure 3A). The levels of P-FLT3 and P-STAT5 in the tumor were completely reduced from 4 to 12 hours after the administration of KW-2449 (Figure 3B). Although dephosphorylations of FLT3 and STAT5 were observed until 12 hours after administration, these returned to almost the basal level at 24 hours. These results suggested that the oral administration of KW-2449 at a twice daily schedule could be adequate for continuous inhibition of activated FLT3 in the mouse model.

In the MOLM-13 tumor xenograft model, oral administration of KW-2449 for 14 days showed a potent and significant antitumor effect in a dose-dependent manner (Figure 4A). KW-2449 treatment at 2.5 and 5.0 mg/kg twice a day showed growth inhibition of tumors with the ratio of tumor volume in the treated to control mice minimum values (T/C$_{min}$) of 0.57 and 0.29, respectively (Figure 4B). Furthermore, KW-2449 treatment at 10 mg/kg twice a day showed tumor regression with T/C$_{min}$ of 0.010 and treatment at 20 mg/kg twice a day completely eradicated tumors in all mice (Figure 4C).

We next compared the effects of KW-2449 on mutant FLT3-expressing cells with a conventional antileukemic agent, AraC, using the syngeneic transplantation mouse model. Human FLT3/ITD-ires-GFP-expressing 32D (FLT3/ITD-GFP-32D) cells were intravenously inoculated into syngeneic C3H/Hej mice, and then KW-2449, AraC, or vehicle was administered to the mice 11 days after inoculation for 4 days (Figure 5A). At the seventh day after inoculation, mean FLT3 transcript levels in PB were 24.4 plus or minus 6.7, 11.8 plus or minus 5.7, and 42.0 plus or minus 21.7 copies/μg RNA in vehicle-, KW-2449- and AraC-treated mice, respectively. In all vehicle-treated mice, FLT3 transcript level increased, and the mean FLT3 transcript level in PB on day 13 was 5869.6 plus or minus 1640.1 copies/μg RNA. In contrast, KW-2449 treatment repressed the expansion of FLT3/ITD-GFP-32D cells as the decrease of FLT3 transcript levels was observed in all mice, and the mean FLT3 transcript level in PB was 3.25 plus or minus 2.29 copies/μg RNA on day 13. The increase in FLT3 transcripts level in all AraC-treated mice was lower than that in vehicle-treated mice, although the effect of AraC treatment was limited as the mean FLT3 transcript level in PB was 882.7 plus or minus 305.5 copies/μg RNA on day 13. These results demonstrated that the repressive effects by KW-2449 on the expansion of FLT3/ITD-GFP-32D cells were significantly stronger than those by AraC ($P = .026$ by the repeated-measures analysis of variance; Figure 5B). Flow cytometry analysis revealed that KW-2449 significantly eradicated FLT3/ITD-GFP-32D cells from BM (the mean percentages of FLT3/ITD-GFP-32D cells in BM after
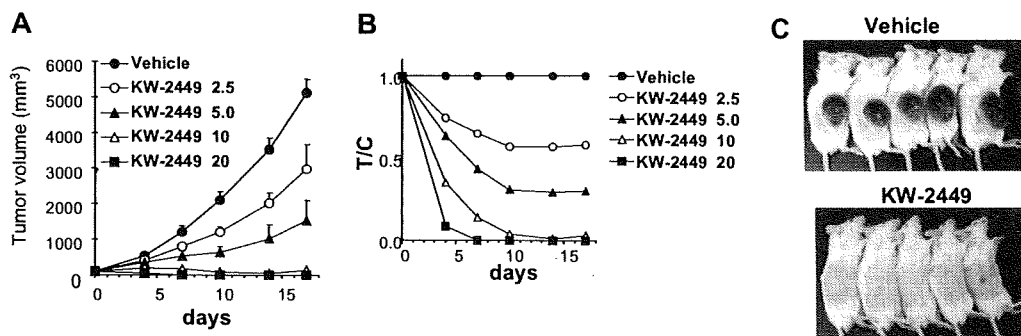
Figure 4. In vivo efficacy of xenotransplanted tumors with FLT3/ITD. (A-C) MOLM-13 cells (10^7 cells/mouse) were subcutaneously inoculated into SCID mice. Five days after inoculation, tumor volume was measured. The 25 mice with tumors ranging from 90 to 130 mm^3 were selected 5 days after inoculation and divided into 5 groups. Mice (n = 5 in each group) were orally administered with vehicle or KW-2449 (2.5, 5.0, 10, and 20 mg/kg) twice a day for 14 days. (A) Tumor volume was measured twice a week during the treatment. Mean tumor volume ± SD is shown. KW-2449 showed potent and significant antitumor effect in a dose-dependent manner. (B) Relative ratio of tumor volume (V) to initial tumor volume (V0) was represented (V/V0). Relative V/V0 ratio of a drug-treated group compared with a control group was represented as T/C. (C) KW-2449 treatment at 20 mg/kg twice a day showed complete regression and disappearance of tumors in all mice.
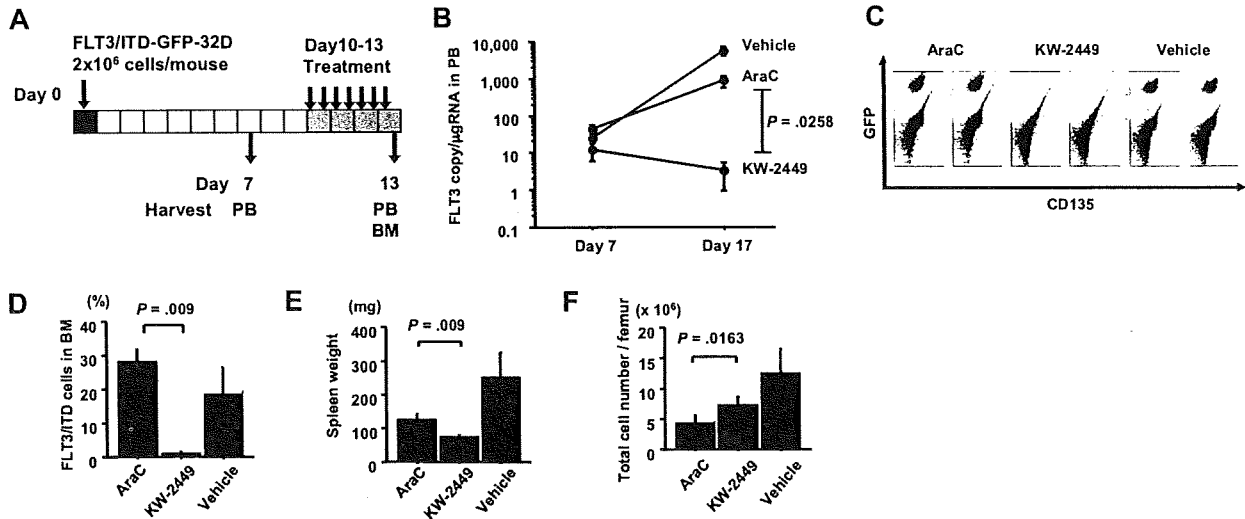
Figure 5. Inhibition effects on FLT3/ITD-GFP-32D cells in C3H/HeJ-mice syngeneic transplantation model. (A) C3H/HeJ mice were inoculated with 2×10^6 of FLT3/ITD-GFP-32D cells on day 0. From the 10th day after inoculation, mice were administrated with KW-2449 at 40 mg/kg (orally) twice a day, AraC at 150 mg/kg (intravenously) daily or vehicle for 4 days (n = 5 in each group). PB was collected from each mouse on day 7 and day 13. BM was collected on day 13. (B) Human FLT3 transcripts in PB were quantitated by a real-time fluorescence detection method. Mean transcript level ± SEM is shown. KW-2449 treatment significantly repressed the expansion of FLT3/ITD-GFP-32D cells compared with AraC treatment ($P = .026$ by the repeated-measures analysis of variance method). (C) The percentage of residual BM FLT3/ITD-GFP-32D cells in femur was compared among vehicle-, KW-2449-, and AraC-treated mice using flow cytometry. Representative results of flow cytometry are shown. (D) Mean percentages of residual FLT3/ITD-GFP-32D cells plus or minus SD in BM are shown. KW-2449 significantly eradicated FLT3/ITD-GFP-32D cells from BM compared with AraC treatment ($P = .009$ by the Mann-Whitney U test). (E) Mean spleen weight of each treated mouse ± SD is shown. The mean spleen weight of KW-2449-treated mice was significantly lighter than that of AraC-treated mice ($P = .009$ by the Mann-Whitney U test). (F) Mean total cell numbers in femur after the treatment ± SD are shown. The total number of nuclear cells in the BM of AraC-treated mice was significantly decreased compared with that of KW-2449-treated mice ($P = .016$ by the Mann-Whitney U test).

treatment were $30.0\% \pm 3.6\%$ and $0.75\% \pm 0.75\%$ in AraC- and KW-2449-treated mice, respectively; $P = .009$ by the Mann-Whitney U test; Figure 5C-D). Furthermore, the mean spleen weight of KW-2449-treated mice was significantly lighter than that of AraC-treated mice (71.4 ± 6.2 and 122.2 ± 20.4 mg, respectively; $P = .009$ by the Mann-Whitney U test; Figure 5E). Notably, the total number of nuclear cells in the BM of AraC-treated mice was significantly decreased compared with that of KW-2449-treated mice ([4.2 ± 1.3] $\times 10^6$ and [7.3 ± 1.3] $\times 10^6$ cells/femur, respectively; $P = .016$ by the Mann-Whitney U test; Figure 5F). In this model, we confirmed that KW-2449 could potently and selectively eradicate mutant FLT3-expressing leukemia cells both in PB and BM in contrast to the nonselective BM suppression of conventional cytotoxic agents such as AraC.

In vitro effects of KW-2449 on FLT3 wild-type leukemia

On the other hand, KW-2449 inhibited the growth of human ALL cell line RS4;11, which expresses unphosphorylated wt-FLT3, with the GI_{50} value of 0.23 µM (Table 2). Because KW-2449 shows potent Aurora A and Aurora B kinase inhibition, we evaluated whether the growth inhibitory effect on RS4;11 was induced by Aurora kinase inhibition. When the cell cycle was arrested in the M-phase by nocodazole, phosphorylated histone-H3 (P-HH3) was clearly observed in RS4;11, but it was decreased by the treatment with KW-2449 in a dose-dependent manner (Figure 6A). Cell cycle distribution analysis indicated that KW-2449 (0.60 µM) induced G_2/M arrest and apparent increase of sub-G_1 apoptotic cells after 24 hours and 48 hours of exposure, respectively (Figure 6B). Even at 0.30 µM, KW-2449 slightly decreased the population of S-phase cells from 49.0% to 40.6% after 72 hours (histogram data not shown). The increase of annexin V–positive (early apoptotic) cells was also observed at the GI_{50} value against RS4;11 cells (Figure 6C). These results suggested that KW-2449 has a growth inhibitory

potency against leukemia cells even without activated FLT3 through the inhibition of Aurora kinase, although its potency was 5- to10-fold lower than that against those with activated FLT3 kinase.

Effects of KW-2449 on wt and T315I-mutated BCR/ABL-expressing leukemia cells

IM resistance is a critical issue to be resolved in the treatment of patients with BCR/ABL-positive leukemia. Because KW-2449 showed potency against both ABL and ABL-T315I kinases in the in vitro kinase assays, we evaluated its growth inhibitory effects on wt (K562 and TCC-Y) and T315I-mutated (TCC-Y/sr) BCR/ABL-expressing human leukemia cell lines. IM inhibited the growth of K562 and TCC-Y cells with GI_{50} values of 0.24 and 0.18 µM, respectively, whereas its GI_{50} value against TCC-Y/sr was 24 µM, which was approximately 100-fold higher than against K562 and TCC-Y cells. However, KW-2449 equally inhibited the growth of wt and T315I-mutated BCR/ABL-expressing leukemia cells: GI_{50} values were 0.27, 0.49, and 0.42 µM in K562, TCC-Y, and TCC-Y/sr cells, respectively (Table 2). In K562 cells, IM decreased the phosphorylation levels of BCR/ABL and STAT5 (Figure 7A), increased the number of the G_1 phase-arrested cells at 0.5 µM, and induced apoptosis, which was also shown by an increase of cleaved PARP (Figure 7A,D). On the other hand, KW-2449 induced G_2/M phase-arrested cells at 0.50 µM and increased the sub-G_1 and polyploidy cells at 1.0 µM (Figure 7D). These inductions of G_2/M arrest and polyploidy in K562 cells are presumed to be caused both by the Aurora A and Aurora B inhibitory profile of KW-2449. In TCC-Y cells, the IM treatment at 0.5 and 1.0 µM decreased the phosphorylation levels of BCR/ABL and STAT5, whereas it did not increase the apoptotic or the G_1 phase-arrested cells. In contrast, KW-2449 decreased the phosphorylation levels of BCR/ABL and STAT5 from 0.25 µM and induced the G_2/M-arrested cells at
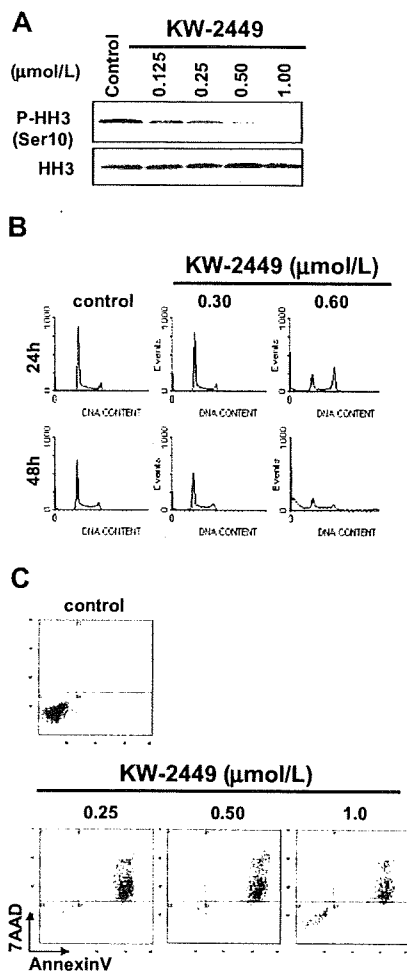
Figure 6. Effects of KW-2449 on human leukemia cells without FLT3 mutation. (A) RS4;11 cells, which express wild-type FLT3/ITD, were treated with KW-2449 at the indicated concentrations for 30 minutes. Total and phosphorylation levels of HH3 were analyzed by Western blotting. (B) RS4;11 cells were treated with various concentrations of KW-2449 for 48 hours, and cell-cycle distribution was analyzed. (C) RS4;11 cells were treated with various concentration of KW-2449 for 48 hours, and apoptosis induction was analyzed.

0.25 μM (data not shown), as well as apoptosis at 1.0 μM (Figure 7B,D). In TCC-Y/sr cells, IM did not affect the phosphorylation levels of BCR/ABL and STAT5 as well as apoptosis and the cell cycle, whereas KW-2449 decreased both phosphorylation levels from 0.25 and 0.5 μM, respectively. Furthermore, KW-2449 apparently induced apoptosis at 1.0 μM, which was shown by PARP cleavage and the sub-G_1 population (Figure 7C-D).

We next compared the effects of KW-2449 on human CML-BC cells harboring T315I mutation with IM, using the xenotransplantation mouse model. After confirming the engraftment of human CML-BC cells, NOD/SCID mice were administered with KW-2449, IM, or vehicle for 5 days. After the treatment, the BCR/ABL transcript levels in PB increased to 3.391 plus or minus 1.071 and 1.927 plus or minus 0.332 times as much as those before the treatment in the vehicle- and IM-treated mice, respectively. In contrast, KW-2449 significantly decreased BCR/ABL transcript levels as to 0.553 plus or minus 0.288 times as much as those before treatment compared with the vehicle- and IM-treated mice ($P = .001$ and $P = .003$ by the unpaired t test, respectively; Figure 7E). Furthermore, the immunohistochemical analysis showed that KW-2449 dramatically eradicated leukemia cells in BM (Figure

7F). In addition, KW-2449 treatment significantly prolonged the survival time of TCC-Y/sr-inoculated SCID mice (data not shown). These results collectively suggested that KW-2449 potently suppresses the growth both of wt- and T315I-mutated BCR/ABL-expressing leukemia cells by dual-inhibitory activities against BCR/ABL and Aurora kinases.

Discussion

Here we describe how KW-2449 potently and selectively inhibits the growth of leukemia cells harboring constitutively activated FLT3 kinase both in vitro and in vivo. As described previously, KW-2449 was selected from chemical libraries of Kyowa Hakko Kirin as a highly potent compound whose GI_{50} values against MOLM-13 and FLT3-D835Y-expressing 32D cells were less than 0.10 μM. In parallel, we evaluated the growth inhibitory activities against BCR/ABL-positive K562 cells and several hematologic malignant cell lines. As shown in this study, KW-2449 inhibited FLT3, ABL, and ABL-T315I kinases. In addition to these tyrosine kinases, which are involved in oncogenic addiction of several leukemia cells, KW-2449 has inhibitory effect on Aurora kinase, which is a key regulatory kinase in mitosis. Because KW-2449 potently inhibited the proliferation of various hematologic malignant cells, including wt-BCR/ABL- and T315I-mutated BCR/ABL-expressing cells, with GI_{50} values ranging from 0.014 to 0.65 μM, we evaluated which kinase was targeted in each malignant cell. To address this issue, we analyzed the phosphorylation status of possibly targeted kinases and the cell cycle distribution after KW-2449 treatment. In mutant FLT3-expressing leukemia cells, the reduction of P-FLT3 level was observed from less than 0.030 μM of KW-2449, which was consistent with its growth inhibitory and the G_1-arrest effects. In leukemia cells without FLT3 activation such as RS4;11, the sensitivity of KW-2449 was 5- to 10-fold lower than that in mutant FLT3-expressing leukemia cells. In these cells, KW-2449 induced the G_2/M arrest or polyploidy and apoptosis at approximately GI_{50} value (0.25 μM) via Aurora kinase inhibition, which was detected by the reduction of P-HH3. It has been reported that P-HH3 is the target molecule of Aurora B kinase, and the decrease of P-HH3 level was observed from 0.125 μM (Figure 6A), whereas G_2/M arrest, an indicator of Aurora kinase A inhibition, was clear at 0.60 μM of KW-2449. It suggested that both Aurora B and Aurora A kinase inhibition by KW-2449 contributes antileukemia effects in FLT3 wild-type. These results collectively suggested that KW-2449 potently suppressed the growth of leukemia cells immortalized by FLT3 activation via FLT3 inhibition alone at a lower concentration, whereas the growth suppression of FLT3-inactivated leukemia cells was induced by Aurora inhibition at a higher concentration. It has been reported that several kinase inhibitors, such as MK-0457 (VX-680), simultaneously suppress both FLT3 and Aurora kinases.[34] When we examined the effects of MK-0457 on mutant FLT3-expressing leukemia cells, it induced the G_2/M arrest at the GI_{50} values, indicating that its primary cellular target was Aurora kinase, but not FLT3 even in the constitutively FLT3-activated cells (data not shown). However, KW-2449 first inhibits FLT3 kinase with approximately 10-fold higher potency than Aurora kinase. Therefore, this characteristic mode of inhibitory action may be advantageous over the adverse events associated with the Aurora kinase inhibition.

The clinical efficacy of both PKC-412 and CEP-701 given as monotherapy was reportedly unimpressive despite their high

Figure 7. Inhibitory effects of KW-2449 on BCR/ABL-positive leukemia cells. We compared inhibitory effects on wt (K562 and TCC-Y) and T315I-mutated (TCC-Y/sr) BCR/ABL-expressing human leukemia cells between KW-2449 and imatinib (IM). (A) In K562 cells, KW-2449 and IM equally decreased the phosphorylation levels of BCR/ABL and STAT5 and increased cleaved PARP. (B) In TCC-Y cells, IM decreased the phosphorylation levels of BCR/ABL and STAT5, but did not increase cleaved PARP. In contrast, KW-2449 decreased the phosphorylation levels of BCR/ABL and STAT5 and increased cleaved PARP. (C) In TCC-Y/sr cells, IM did not affect the phosphorylation levels of BCR/ABL and STAT5, whereas KW-2449 decreased both phosphorylation levels and increased cleaved PARP. (D) DNA contents were also compared between KW-2449 and IM treatments. IM increased the number of the G$_1$-arrested cells only in K562 cells. However, KW-2449 induced the G$_2$/M-arrested cells in K562, TCC-Y, and TCC-Y/sr cells. (E) We compared the antileukemic efficacy in NOD/SCID mice xenotransplanted with human CML in blast crisis cells harboring the T315I mutation after IM treatment. The treatment effects on the leukemia cells in PB are shown by the after/before BCR/ABL transcript ratio. After the treatment, the BCR/ABL transcript levels in PB increased to 3.391 plus or minus 1.071 and 1.927 plus or minus 0.332 times as much as those before the treatment in the vehicle- and IM-treated mice, respectively. In contrast, KW-2449 significantly decreased BCR/ABL transcript levels as to 0.553 ± 0.288 times as much as those before the treatment compared with the vehicle- and IM-treated mice (P = .001 and P = .003 by the unpaired t test, respectively). (F) Residual leukemia cells in femora were evaluated by the immunohistochemical staining with human CD45. KW-2449 more potently eradicated leukemia cells in BM than IM.
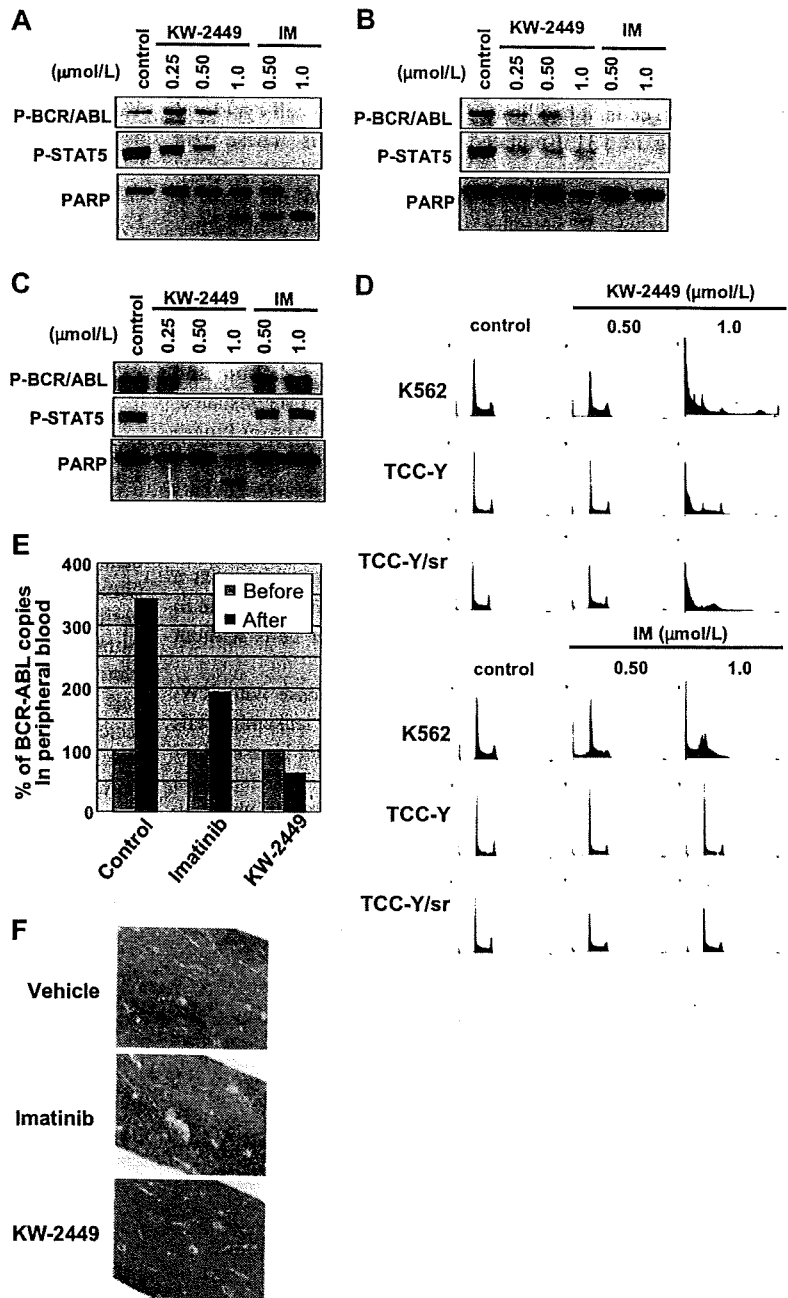
potency in the in vitro studies and extensive exposure in humans. This was partly explained by their structural problem (both compounds are well known as tight binders to hAGP in human plasma) because they contain indolocarbazole motif and result in the significant reduction of their biologic activities in human bodies. In contrast, the growth inhibitory activity of KW-2449 was not attenuated by hAGP, indicating the advantage to keep the biologically active concentration in human plasma.

It is well known that IM that targets the adenosine triphosphate-binding site of the kinase domain of BCR/ABL, inducing remissions in patients with chronic-phase CML. However, whereas responses in the chronic phase were durable, remissions observed in blast crisis patients were typically short-lived, with relapse occurring within 6 months despite continued therapy. Thus, IM resistance is becoming an increasingly recognized

problem for the treatment of patients with BCR/ABL-positive leukemia. Several IM-resistant mechanisms, such as acquired mutation in the *BCR/ABL* gene, overexpression of BCR/ABL, hAGP binding, and the emerging other kinase activations, have been reported.[35] To overcome the resistance, ABL kinase inhibitors in the second generation have been investigated, and some of them showed significant clinical response to IM-resistant or refractory patients, although the resistance of T315I-mutated BCR/ABL kinase remains to be resolved.[36] We therefore evaluated the efficacy of KW-2449 for leukemia cells with T315I-mutated BCR/ABL both in vitro and in vivo. KW-2449 at 0.25 μM showed the decrease of P-ABL and P-STAT5 in K562, TCC-Y, and TCC-Y/sr cells, whereas IM had little effect on these signaling molecules in T315I-mutated leukemia (Figure 7A). In addition to inhibitory activity of

KW-2449 to T315I-mutated BCR/ABL, Aurora kinase inhibition, which was indicated by cell-cycle distribution in TCC-Y/sr, could contribute to the release of IM resistance. On the other hand, whereas IM showed G_1 arrest and ABL inhibition in wt-BCR/ABL cells, it had limited activity both in cell cycle and cell signaling in T315I-mutated BCR/ABL cells. These data indicated that the inhibition of wt- and T315I-mutated BCR/ABL kinase by KW-2449 at lower concentrations showed limited effects on cell viability, whereas the additional inhibitory effects on Aurora kinase by KW-2449 at higher concentrations modulated the survival and proliferation of the IM-resistant leukemia cells. These multifunctional action mechanisms, as well as the order of potency against various kinases, which were involved in oncogenic addiction and drug-resistance, would contribute to overcome the IM resistance.

It has been reported that potent and selective Aurora kinase inhibitors show remarkable growth inhibition of a variety of cancer cells in vitro, although several severe adverse events such as hematopoietic toxicity have been observed in the early-phase clinical trials. However, our results suggest that the additive and/or simultaneous inhibition of Aurora kinase at a lower potency than mainly targeted kinases might contribute to increase the growth inhibitory effects on cancer cells without severe adverse effects.

In conclusion, targeted inhibition of FLT3 kinase with KW-2449 induced the potent growth inhibition of leukemia cells transformed by the constitutive activation of FLT3 kinase. KW-2449 also showed growth inhibitory effects against FLT3 leukemia by its Aurora kinase inhibition. In addition, simultaneous inhibition of T315I-mutated BCR/ABL and Aurora kinases by KW-2449 also induced the growth inhibition of IM-resistant leukemia cells. Currently, KW-2449 is being investigated in a phase 1/2 study in patients with relapsed or refractory AML (NCT00779480). The present results, nevertheless, provide an important insight into clinical investigations for the treatment of patients with BCR/ABL-positive leukemia acquiring the IM resistance, including the T315I-mutation.

Acknowledgments

Authorship

Contribution: Y. Shiotsu designed experiments; screened chemical libraries; performed cell-based assay, Western blot, and animal studies; analyzed data; generated figures; and wrote the manuscript; H.K. designed experiments; performed Western blot, colony assay, animal studies, and quantitative real-time RT-PCR; analyzed data; generated figures; and wrote the manuscript; Y.I. collected clinical samples and performed Western blot and FCM; R.T. performed animal studies, quantitative real-time RT-PCR, and pathologic analysis; M.S. performed FCM analysis and Western blot; H.U. screened chemical libraries; K.I. performed Western blot and animal studies; Y. Mori performed colony assay; K.O. collected clinical samples and performed animal studies and quantitative real-time RT-PCR; Y. Minami performed cell cycle analysis; A.A. performed animal studies; H.M. analyzed the LC/MS/MS; T.A. and S.A. provided input into experiment design; Y.K. provided input into chemical synthesis; Y. Sato established imatinib-resistant cell lines; and T.N. designed experiments and wrote the manuscript.

Conflict-of-interest disclosure: Y. Shiotsu, M.S., H.U., K.I., H.M., T.A., Y.K., and S.A. are employed by Kyowa Hakko Kirin Co Ltd. H.K. has a consultancy with Kyowa Hakko Kirin Co Ltd.

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ORIGINAL ARTICLE

Comprehensive analysis of cooperative gene mutations between class I and class II in *de novo* acute myeloid leukemia

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Abstract

Acute myeloid leukemia (AML) has been thought to be the consequence of two broad complementation classes of mutations: class I and class II. However, overlap-mutations between them or within the same class and the position of *TP53* mutation are not fully analyzed. We comprehensively analyzed the *FLT3*, *cKIT*, *N-RAS*, *C/EBPA*, *AML1*, *MLL*, *NPM1*, and *TP53* mutations in 144 newly diagnosed *de novo* AML. We found 103 of 165 identified mutations were overlapped with other mutations, and most overlap-mutations consisted of class I and class II mutations. Although overlap-mutations within the same class were found in seven patients, five of them additionally had the other class mutation. These results suggest that most overlap-mutations within the same class might be the consequence of acquiring an additional mutation after the completion both of class I and class II mutations. However, mutated genes overlapped with the same class were limited in *N-RAS*, *TP53*, *MLL*-PTD, and *NPM1*, suggesting the possibility that these irregular overlap-mutations might cooperatively participate in the development of AML. Notably, *TP53* mutation was overlapped with both class I and class II mutations, and associated with morphologic multilineage dysplasia and complex karyotype. The genotype consisting of complex karyotype and *TP53* mutation was an unfavorable prognostic factor in entire AML patients, indicating this genotype generates a disease entity in *de novo* AML. These results collectively suggest that *TP53* mutation might be a functionally distinguishable class of mutation.

Key words acute myeloid leukemia; overlap mutations; TP53; multilineage dysplasia; prognosis

Acute myeloid leukemia (AML) is a genetically and phenotypically heterogeneous disease (1). In 1999, the third edition of the World Health Organization (WHO) classification of the myeloid neoplasms classified AML into four major categories: AML with recurrent genetic abnormalities (AML-RGA), AML with multilineage dysplasia (AML-MLD), AML, therapy-related, and AML not otherwise categorized (2). The first category included AML with t(8;21)(q22;q22), (*AML1/ETO*), inv(16)(p13q22) or t(16;16)(p13;q22), (*CBFB/MYH11*), t(15;17)(q22;q12), (*PML/RARA*) and 11q23 (*MLL*) abnormalities, which create fusion genes associated with leukemogenesis. Each balanced translocation corresponded to characteristic cytogenetical and clinical