PRAME induced inhibition of retinoic acid receptor signaling-mediated differentiation – a possible target for ATRA response in AML without t(15;17)

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Running Title: PRAME in AML

Key words: acute myeloid leukemia (AML), leukemia associated antigen (LAA), preferentially expressed antigen in melanoma (PRAME), all-trans retinoic acid (ATRA), gene expression profiling (GEP)

Financial support: Supported by grants from the German José Carreras Leukemia Foundation to J.G. and L.B. (DJCLS A 10/01, R07/15v and R09/13) and the German Research Foundation (DFG GR2676/3-1 and BU 1339/3-1)

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Disclosure of potential conflicts of interests: The authors have no potential conflicts of interest to disclose.

Word count (excluding references): 4264

Total number of figures and tables: 5
Statement of translational relevance

In this study, we provide first evidence that PRAME (preferentially expressed antigen in melanoma), a ligand-dependent corepressor of retinoic acid receptor signaling, might be involved in blocking myeloid differentiation in acute myeloid leukemia (AML) without t(15;17). In this AML subgroup it has been shown that especially AML cases with NPM1 mutations benefit from a therapy with all-trans retinoic acid (ATRA), however the underlying mechanism remains elusive. As PRAME is also a known leukemia-associated antigen (LAA), which is therapeutically used to specifically induce anti-leukemic T-cells, our observation that PRAME expression also plays a role in cell proliferation and differentiation opens an additional therapeutic avenue for targeting high PRAME expression in AML. Thus, the addition of ATRA to the induction chemotherapy might contribute to an improved eradication of the disease. Furthermore, a maintenance therapy combining ATRA and an immunotherapy targeting PRAME might facilitate the elimination of minimal residual disease in PRAME-high AML cases.
Abstract

Purpose: In acute myeloid leukemia (AML) without retinoic acid receptor (RAR) rearrangement the effect of all-trans retinoic acid (ATRA) is still poorly understood despite an association of NPM1 mutation and ATRA response. Recently, PRAME (preferentially expressed antigen in melanoma) has been shown to be a dominant repressor of RAR-signaling.

Experimental design: Thus, we further investigated ATRA response mechanisms, especially the impact of PRAME expression on ATRA-responsiveness. We profiled gene expression in diagnostic samples derived from our AML HD98B trial, in which ATRA was administered in addition to intensive chemotherapy.

Results: Our data revealed a PRAME-expression associated gene pattern to be significantly enriched for genes involved in the retinoic acid metabolic process. In leukemia cell line models we could demonstrate that retinoic acid-regulated cell proliferation and differentiation are impacted by PRAME expression. In primary AML patients repressor activity of high PRAME levels might be overcome by the addition of ATRA as indicated by better outcome in two independent studies (P=0.029).

Conclusions: PRAME seems to impair differentiation and to increase proliferation likely via blocking RAR-signaling, which might be reversed by ATRA. PRAME therefore represents a promising target for both ATRA-treatment and possibly future immunotherapeutic approaches in AML.
INTRODUCTION

The translocation t(15;17) in acute promyelocytic leukemia (APL) was among the first recurrent aberrations detected by chromosome banding analysis in acute myeloid leukemia (AML). (1) APL also became the first human leukemia successfully treated by molecularly targeted therapy. Using all-trans retinoic acid (ATRA), which targets the rearranged retinoic acid receptor alpha (RARA) in the fusion gene PML-RARA, the repressive potential of PML-RARA on the transcription of wild-type RARA target genes could be successfully overcome. (2)

Today, molecular insights have also grown significantly in non-APL AML based on the advancement of novel technologies allowing comprehensive genomic, transcriptomic and epigenomic analyses. (3-5) This improved understanding of the molecular aberrations underlying the disease started to translate into daily routine and AML guidelines support genotype-specific treatment approaches. (6) For example, NPM1 mutations represent the most frequent genetic alteration found in 45-64% of cytogenetically normal AML (CN-AML). Recently, this entity has been included in the revised WHO classification as novel provisional molecularly defined AML entity. “Targeted” therapies investigated within clinical trials provided evidence that ATRA in combination with chemotherapy might be a powerful therapeutic approach in NPM1-mutated AML. (7) However, so far little is known about the functional role of ATRA in NPM1-mutated AML.

PRAME (preferentially expressed antigen in melanoma) is a dominant repressor of retinoic acid receptor (RAR) signaling. It binds to RAR in the presence of retinoic acid (RA), and thus prevents ligand-induced receptor activation and target genes transcription. (8) RA induces the transcription of a set of target genes by binding of its active receptor RAR. This results in differentiation and cell cycle arrest of responsive cells, and therefore loss of RA responsiveness might be beneficial to cancer cells. (9) PRAME is found to be overexpressed in many solid tumors as well as in hematologic malignancies like AML. (10) In accordance, down-regulating the expression of PRAME through the overexpression of SOX9 induced cell cycle arrest by increasing p21 transcription and restored sensitivity to RA in both human and mouse melanoma cell lines, thereby inhibiting tumorigenicity in melanoma. (11) This supports the hypothesis that PRAME might also be involved in regulation of cell proliferation and impaired differentiation of leukemia cells.

Moreover, PRAME is a leukemia-associated antigen (LAA) that has been shown to induce specific T cell responses in both solid tumors and leukemias. (10) Furthermore, expression of PRAME was shown to represent an indicator of a good prognosis in childhood AML, (12) although part of this effect might be secondary to its correlation with favorable cytogenetics.
such as a translocation t(8;21), which has been previously described.\(^\text{(13)}\) Recently, Santamaria and colleagues proposed a score based on \textit{ERG}, \textit{EVI1} and \textit{PRAME} gene expression that allows a better distinction between CN-AML patients, who are known to have significantly different outcomes, and thus the patient-risk stratification could be improved.\(^\text{(14)}\)

In contrast, in CML patients \textit{PRAME} expression was shown to be significantly higher in advanced stages.\(^\text{(15)}\) \textit{PRAME} over-expression in normal hematopoietic progenitors was reported to inhibit myeloid differentiation, and in accordance \textit{PRAME} down-regulation in primary CML progenitors could reverse blocked differentiation.\(^\text{(16)}\) Thus, \textit{PRAME} expression seems to play a dual role in leukemogenesis and leukemia management with higher expression being involved in more aggressive myeloid disease, but on the other hand providing an additional target for immunological defense mechanisms.

In this work, we now further highlight an important role of \textit{PRAME} in the regulation of cell proliferation and differentiation in AML cells. In addition, based on data from two independent clinical trials we provide evidence that \textit{PRAME} might be a predictive marker for ATRA response in non-APL AML patients treated with a combination of chemotherapy and ATRA.
MATERIAL AND METHODS

AML patient samples
Diagnostic peripheral blood and bone marrow samples from adult AML patients (n=80) were provided by the German-Austrian AML Study Group (AMLSG) with informed consent obtained from all patients entered within the AML HD98B trial.(7) Clinical information and response to ATRA are provided as Supplementary Table 1 (n=39 patients had been randomized into the ATRA treatment arm). Moreover, we investigated previously published data(17) from an independent cohort of patients (n=69) treated within a randomized phase III-study on ATRA in combination with induction and consolidation therapy (AMLSG 07-04; Clinicaltrials.gov identifier NCT00151242). Here, younger AML patients (≤60 years) were randomized up-front for open-label treatment with ATRA (n=28 patients were randomized into the ATRA treatment arm and compared with n=41 patients from the non-ATRA arm).

Leukemia samples were enriched for leukemic cells by Ficoll separation (Biochrom, Berlin, Germany) and stored for RNA-preparation at –80°C. For cellular assays, Ficoll-separated peripheral blood mononuclear cells (PBMCs) were tested freshly or following cryopreservation in AB serum (IKT, Ulm, Germany) containing 10% DMSO (Sigma Aldrich, Steinheim, Germany).

Gene expression profiling (GEP) analysis in primary leukemia samples
Gene expression profiling (GEP) was performed as previously described using cDNA microarrays.(18) The complete gene expression microarray dataset is available at Gene Expression Omnibus (GEO accession number: GSE16432). For supervised analysis cases were grouped based on PRAME expression and the highest and lowest quartiles compared by ClassComparison using BRB-Array Tools Version 3.6.1 (developed by Dr. Richard Simon and Amy Peng Lam, available at http://linus.nci.nih.gov/BRB-ArrayTools.html) and R Version 2.6.0 (available at www.r-project.org). Gene signatures were further evaluated using the Molecular Signatures Database (MSigDB, http://www.broadinstitute.org/gsea/msigdb),(19) and Database for Annotation, Visualization and Integrated Discovery (DAVID, http://david.abcc.ncifcrf.gov/).(20) For the correlation with survival data expression values have been dichotomized by the median expression of the respective gene across all AML samples, and Kaplan Meier curves were plotted using GraphPad Prism 4 (GraphPad Software Inc., La Jolla, USA).

For further evaluation of the impact of PRAME expression on ATRA responsiveness, we evaluated a previously published independent data set profiled on Affymetrix HG-U133 plus 2.0 microarrays (GEO accession number: GSE15434).(17)
Western blot analysis and quantitative RT-PCR

Western blot analysis was performed according to standard protocols as previously described using a polyclonal PRAME antibody (Abcam, Cambridge, UK) and a β-Actin antibody as loading control (Sigma-Aldrich, St. Louis, USA).(21) The mRNA expression of PRAME was measured by quantitative RT-PCR using light cycler SYBR Green I technology and previously published primers according to the manufacturer’s instructions.(22) The amount of mRNA of PRAME was normalized to the housekeeping gene TATA-box binding protein (TBP).

Culture of cell lines

The human cell lines K562, THP-1, KG-1, and Kasumi-1 were obtained from the German Collection of Microorganisms and Cell Cultures (DSMZ, Braunschweig, Germany). Cell lines were cultured under standard conditions in RPMI 1640 medium (Biochrom, Berlin, Germany) containing 10-20% FCS, 2 mM L-glutamine, 100 units/ml penicillin and 100 units/ml streptomycin.

Cell culturing using ATRA

ATRA was obtained as a powder (Tretinoin, Sigma-Aldrich, Munich, Germany), dissolved in dimethyl sulfoxide (DMSO) and stored at -20°C. For cell culture experiments the ATRA stock was further diluted in RPMI 1640 medium containing 10% FCS, 2 mM L-glutamine, 100 units/ml penicillin and 100 units/ml streptomycin to achieve final concentrations of $10^{-6}$ mol/l to $10^{-9}$ mol/l. The final concentration of DMSO in cell culture was 0.01% or less. All assays were performed in triplicate.

Conventional RT-PCR

mRNA was isolated from PBMC of healthy controls or tumor samples using the mRNA QuickPrep Micro purification kit (Amersham Pharmacia Biotech, Little Chalfont, England, UK). 2.0 µg of each mRNA sample was subjected to cDNA synthesis (Superscript II Gibco BRL, Frederick, Maryland). PCR for PRAME was performed as previously described using the indicated conditions and reagents.(22)

siRNA-mediated PRAME knock-down

Four different small interfering RNAs (siRNAs) specific for PRAME as well as a negative scrambled siRNA control (scrRNA) were obtained from Qiagen (Hilden, Germany) and tested towards their ability to decrease PRAME expression in the K562 cell line. Briefly, 2-3 x $10^6$ cells were pelleted, resuspended in 100 µl Cell Line Nucleofector Solution V (Lonza...
Cologne, Germany), and nucleofected with up to 200 nM siRNA using the program T-016. Following nucleofection cells were mixed with pre-warmed culture medium, transferred into 6 well plates, and incubated at 37°C at 5% CO₂ for 24 h. Then, siRNA or scrRNA transfected cells were treated with ATRA at final concentrations of 10⁻⁷ mol/l and 10⁻⁹ mol/l.

**Transfection of PRAME in PRAME-low cell lines**
PRAME plasmid (LICR, Brussels Branch, Belgium) was linearised, purified and transfected into the PRAME-low cell line KG-1 using electroporation technology (Lonza, Cologne, Germany). In brief, as described above 2-3 x 10⁶ cells were nucleofected with 2 µg plasmid DNA (program V-001 for KG-1), and 24 h post nucleofection different concentrations of ATRA were added and cells kept in culture for up to 6 days (medium was changed every 3 days with or without ATRA).

**BrdU-proliferation assay**
After transfecting the cell lines and adding ATRA at different concentrations, cells were labeled with bromodeoxyuridine (BrdU) for 2 h or 24 h according to the manufacturer’s instructions (BD Biosciences, Heidelberg, Germany). Thereafter the BrdU Flow Kit staining protocol was performed for intracellular staining to determine the proliferation ability of the transfected or non-transfected cells.

**Flow cytometry-based measurement of differentiation and apoptosis markers**
CD66b is a cell surface antigen expressed in mature myeloid cells and was used as a marker for lineage-specific cell differentiation. Following transfection with either PRAME plasmid or shRNAs directed against PRAME flow cytometry was performed to determine the fraction of CD66b positive cells. Samples were stained with 10 µl of CD66b antibody (BD, Heidelberg, Germany) without ATRA at 4°C for 20 min and analyzed by flow cytometry using a FACS Calibur analyzer. Each sample was run with the corresponding isotype control to define the gate of positive cells.

For the detection of apoptosis we used Annexin V and propidium iodide (PI) staining. Cells were stained with Annexin V and/or PI according to manufacturer’s protocol (BD, Heidelberg, Germany). Data analysis was performed using the Weasel software.

**Gene expression profiling (GEP) following siRNA-mediated PRAME knock-down and ATRA treatment in the K562 cell line model**
For the cell line models GEP was performed using Affymetrix microarray technology according to the manufacturer’s recommendations as previously reported (Human Genome U133plus2.0 Array, Affymetrix).(21) siRNA and scrRNA treated as well as ATRA treated
K562 cells were profiled in triplicate stemming from independent experiments. Fluorescence ratios were normalized by applying the RMA algorithm using the BRB Array Tools software package (see above). The complete microarray data is available at the Gene Expression Omnibus (GEO accession number: GSE43258).
RESULTS

**PRAME expression associated GEP in AML**

We previously observed, that non-APL AML cases, and especially those who are NPM1-mutated, might benefit from a combination of chemotherapy and ATRA.(7) Furthermore, a recent report demonstrated that retinoic acid-associated regulation of cell proliferation and differentiation were impacted by PRAME expression.(16) PRAME is a ligand-dependent corepressor of retinoic acid receptor α (RARα), RARβ, and RARγ signaling.(8) Based on these observations, we wanted to investigate the role of PRAME on ATRA response in non-APL cases. Thus, we aimed to define a PRAME-expression associated gene pattern in our primary AML cases as such a gene pattern might provide further insights into the association of PRAME expression with deregulated retinoic acid receptor signaling in AML.

In a first step we verified that PRAME mRNA expression correlated with PRAME protein levels in myeloid leukemia cells by Western blot analysis (Figure 1A) and that PRAME expression was well measured by our microarray by validating PRAME expression levels by quantitative RT-PCR (Figure 1B) in a random set of cases (n=29). Quantitative RT-PCR results for PRAME correlated well with our microarray findings (P<0.001; Figure 1B), and interestingly PRAME was not correlated with any of the molecular markers NPM1 mutation, CEBPA mutation or FLT3 internal tandem duplication (ITD; see Supplementary Table 1).

We next grouped our primary AML cases based on PRAME expression (n=80 cases with valid information on PRAME expression) and identified genes and gene sets characterizing the AML cohorts defined by either low or high PRAME expression. ClassComparison analysis revealed 1051 clones to be significantly differentially expressed between the PRAME expression subgroups at the nominal p=0.05 level of significance in univariate tests (760 clones were positively, and 291 negatively correlated; Figure 1C and Supplementary Table 2). Notably, this PRAME-associated signature was found enriched for gene set modules associated with gene expression changes in the leukemia cell line U937 following immune response and myeloid differentiation in K562 (e.g. MSigDB module 52, P<0.001; Supplementary Table 3, C4), and functional annotation using DAVID revealed an enrichment of annotation terms associated with retinoic acid receptor signaling. For example, there was a correlation with the annotation terms “response to vitamin A”, “response to retinoic acid”, and “retinoid binding”, “retinoid metabolic process”, “retinol binding”, and “retinoic acid metabolic process” (P<0.05; Figure 1D).

**PRAME expression in cell lines**

Next, we studied PRAME expression in leukemia cell lines in order to identify models for further functional analysis of the role of PRAME in retinoic acid signaling. Based on a
previous GEP study analyzing different myeloid leukemia derived cell lines (23) we could identify cell lines with either higher (HL-60, MONO-MAC-1, K562, UT-7, and THP-1) or lower PRAME expression levels (OCI-AML2, KG-1, NB4, ME1, MV4-11 and Kasumi-1; 35-fold mean PRAME expression difference between cell line groups; Figure 1E and Supplementary Table 4). Following validation of PRAME expression levels by qRT-PCR, we decided to use K562 and THP-1 as “PRAME-high” and KG-1 and Kasumi-1 as respective “PRAME-low” model to study the impact of ATRA.

**Response to ATRA in leukemia cell lines is dependent on PRAME expression level**

Higher doses of ATRA similar to the doses used for the clinical treatment of AML patients [note: the highest concentration of $10^{-6}$ mol/l used in the manuscript is still in the range of peak plasma levels seen in patients treated with ATRA.(24)] led to reduced cell numbers and cell proliferation of leukemic blasts *in vitro*. Notably, in PRAME-low AML cells (Kasumi-1) a reduction of the proliferation rate in half as measured by BrdU incorporation was observed already at low ATRA concentrations and could not be further decreased by increasing ATRA levels (Figure 2A). In contrast, in PRAME-high (THP-1) AML cells increasing ATRA concentrations were associated with continuously decreasing proliferation rates (Figure 2B). While the proliferation of PRAME-low cells could not be intensively inhibited with higher ATRA concentrations, with regard to the impact on cell numbers these cells were nevertheless quite sensitive to ATRA (Figure 2A). In contrast, PRAME-high cells showed a dose-dependent effect for both the reduction of cell numbers and the proliferation rate (Figure 2B).

ATRA treatment induced cellular differentiation reflected by the expression of the myeloid differentiation marker expressed on granulocytes CD66b,(25) for which the cell-surface expression was measured by FACS analysis, was depended on the expression of PRAME. The PRAME-low AML cell lines, KG-1 and Kasumi-1, reacted already with a high differentiation rate at a low ATRA concentration, and the expression of CD66b did not further increase using higher ATRA doses (Figure 2C). While the percentage of CD66b expressing cells was low in the PRAME-high leukemia cells, treatment with higher ATRA concentrations increased the percentage of CD66b expressing cells (Figure 2D). These results suggest that PRAME may block differentiation and increase proliferation via PRAME-mediated inhibition of RAR-signaling, which might be overcome with increasing doses of ATRA. In contrast, in PRAME-low cases, even low ATRA doses lead to a differentiation initiation, suggesting that the RAR signaling pathway is responsive and not blocked in these cells.

To further evaluate the ATRA induced decrease in cell numbers, we also investigated a potential role of apoptosis in the PRAME-high and -low cell lines. While no relevant
changes in the apoptosis rate were observed in PRAME-high cells treated with increasing ATRA concentrations (Supplementary Figure 1), the operating mode of ATRA in myeloid leukemia cells seems to be primarily the modulation of proliferation and differentiation.

**siRNA-mediated PRAME knock-down impacts ATRA response**

In order to further study the role of PRAME expression, we transfected the PRAME-high leukemia cell line K562 with four different short hairpin RNA molecules (siRNAs) targeted against PRAME. Using nucleofection we could achieve an average transfection rate of 45-50% (26) resulting in a ~50% reduction of PRAME expression for siRNA#8 following 24 and 72 h post-transfection (Figure 3A). Using this siRNA we then treated siRNA and scrRNA transfected K562 cells with ATRA at high a concentration of $10^{-7}$ mol/l. Following siRNA#8-mediated PRAME knock-down proliferation rate and differentiation potential of the leukemia cells were again analyzed by measuring cell counts and CD66b cell surface expression (see above). Cell differentiation as indicated by CD66b expression could only be mildly increased in PRAME-high K562 cells treated with scrRNA as determined 72 h past treatment start (Figure 3B). However, PRAME knock-down increased the ATRA-induced differentiation greater 4-fold (Figure 3B), thereby further suggesting a PRAME-induced block of RAR-signaling. In line, cell counts were also more effectively decreased by low-dose ATRA treatment in PRAME-high leukemia cells following siRNA-mediated PRAME knock-down as compared to scrRNA-transfected K562 controls (Figure 3C).

**PRAME overexpression in PRAME-low cells mitigates ATRA response**

In order to determine whether ATRA response could be mitigated in PRAME-low cells, we overexpressed PRAME in KG1 cells by transfecting a plasmid coding for PRAME. Despite a respectively low transfection efficiency (20-30%, data not shown) PRAME overexpression led to an over 2-fold increase of cells numbers (Supplementary Figure 2). We again investigated changes following ATRA treatment. Using increasing ATRA concentrations we observed a larger reduction of cell numbers in PRAME transfected than in mock treated cells, although due to low transfection rates results have to be cautiously interpreted. Therefore these data provide only a hint for a respective PRAME-mitigated ATRA response.

**siRNA-mediated PRAME knock-down associated gene expression changes**

In order to gain additional insights into the effects following PRAME knock-down in PRAME-high cells, we profiled gene expression in siRNA and scrRNA transfected K562 cells and performed a ClassComparison analysis for paired samples, which revealed 485 genes to be significantly differentially expressed ($p<0.05$, univariate t-test). As anticipated the top
candidate was \textit{PRAME}, which in line with the qRT-PCR data was found to be repressed ~2-fold by siRNA#8 (Figure 4A and Supplementary Table 5).

Interestingly, the \textit{PRAME} knock-down associated signature was similar to the primary leukemia-derived \textit{PRAME}-expression associated gene pattern as it showed an enrichment of gene sets associated with myeloid differentiation and CD34+ stem cells (e.g. module 15; Supplementary Table 6). In accordance, DAVID functional annotation clustering revealed e.g. “stem cell development” and “stem cell differentiation” among the significant gene ontology terms ($P$=0.0096 and $P$=0.017, respectively; Enrichment Score: 1.44; data not shown). Functional annotation also revealed e.g. the terms “negative regulation of retinoic acid receptor signaling pathway” and “regulation of retinoic acid receptor signaling pathway” ($P$=0.0058 and $P$=0.0097, respectively). Notably, \textit{PRAME} seems to be also involved in epigenetic mechanisms, as MSigDB analysis showed an overlap with HDAC3 and HDAC1 knock-down associated gene expression changes (Supplementary Table 6, C2), and in line the DAVID functional annotation showed significant results e.g. for “acetylation”, “chromatin remodeling”, and “bromodomains”, although results have to cautiously interpreted ($P$<0.05 for all terms, Enrichment Score > 1.54 in all cases; data not shown).

Next, we also evaluated the ATRA response at the gene expression level in K562 (ATRA response signature). While we observed significant expression changes for 427 genes, over 80% of genes were up-regulated following ATRA treatment ($P$<0.05, Figure 4B and Supplementary Table 7). Notably, we observed a prominent upregulation of a \textit{HOX} gene signature including e.g. \textit{HOXA1}, \textit{HOXA3}, \textit{HOXB3}, \textit{MEIS1}, and \textit{PBX1}. Similarly, in line with the location of miR-10a within the \textit{HOX} gene cluster, we observed a significant enrichment of miR-10a/miR-10b target genes ($P$<0.05, Supplementary Table 8). Thus, in \textit{PRAME}-high K562 cells ATRA-induced upregulation of \textit{HOX} genes, a gene pattern characteristic for \textit{NPM1} mutated AML,(17) might confer a favorable impact on the response to conventional chemotherapy similar to the favorable response to chemotherapy seen in \textit{NPM1} mutated AML.

\textbf{Impact of \textit{PRAME} expression on clinical outcome in patients treated with ATRA}

Finally, we went back to our primary AML cases treated with ATRA and investigated the impact of \textit{PRAME} expression on the treatment outcome. Although we only had limited samples with information on \textit{PRAME} expression, we nevertheless observed a trend for improved overall survival in ATRA treated \textit{PRAME}-high AML patients as compared to all other as well as ATRA treated \textit{PRAME}-low AML patients ($P$=0.11 and $P$=0.16, respectively; log rank test; Figures 5A and 5B).

To further evaluate this potential association, we investigated the impact of \textit{PRAME} expression on the clinical outcome of an independent cohort of younger AML patients.
treated with ATRA within the randomized phase III study AMLSG 07-04. In this cohort, ATRA treatment in *PRAME*-high patients was significantly associated with improved outcome in comparison to all other cases, and ATRA treated *PRAME*-high patients tended to have a better outcome than ATRA treated *PRAME*-low AML (*P*=0.029 and *P*=0.13, respectively; log rank test; Figures 5C and 5D).
DISCUSSION

PRAME is an important target structure in tumors as this tumor-associated antigen is frequently expressed in different solid tumors and hematological malignancies, whereas no expression is seen in most normal tissues or CD34-positive hematopoietic stem cells. While the function and clinical relevance of PRAME is still not completely understood, in our current work we could demonstrate that cell proliferation and differentiation was associated with the level of PRAME expression and can be influenced by ATRA, thereby suggesting that PRAME expression has an impact on the clinical outcome of ATRA-treated AML patients.

PRAME, a dominant repressor of retinoic acid receptor (RAR) signaling, binds to the RAR in the presence of retinoic acid (RA), thus preventing ligand-induced receptor activation and target gene transcription. RA induces transcription of a set of target genes through the binding and activation of its receptor, resulting in a differentiation and cell cycle arrest in responsive cells. Therefore, loss of RA responsiveness might provide beneficial selection bias for cancer cells. In accordance, Oehler et al. showed that PRAME overexpression can contribute to leukemogenesis by inhibiting myeloid differentiation through the blockage of the RARA signaling pathway. Thus, the regulation of RAR signaling by PRAME seems to be also very likely in primary AML, but this of course warrants further investigation.

In our study, analysis of different AML cell line models suggests that PRAME expression does not only impact differentiation, but also proliferation of the leukemic cells. Likely playing an important role, in PRAME-low AML cell lines a high differentiation rate could already be achieved following the treatment with ATRA at low concentrations, thereby suggesting that the RAR signaling pathway is responsive and not blocked in these cells. Similarly, in PRAME-low AML cases excess ATRA might have no additional beneficial effect as RAR signaling induced differentiation is not blocked to begin with and other yet unknown mechanisms account for the differentiation block, which cannot be overcome by ATRA. In accordance, differentiation reflected by the expression of CD66b could not be further increased by using higher ATRA doses. In contrast, AML cells characterized by high PRAME expression levels showed only a low increase in the differentiation rate when treated with low-dose ATRA concentrations. However, CD66b expression could be notably increased by treating cells with higher ATRA concentrations. This suggests that in these cells PRAME inhibits cellular differentiation and by increasing ATRA concentrations the PRAME-induced block might be overcome and RAR signaling restored, thereby again enabling ATRA-dependent cell differentiation induction.
With regard to a potential impact on apoptosis, it recently has been shown that the TRAIL response to RA can be blocked by PRAME in chronic myeloid leukemia (CML).(28) In CML, BCR-ABL-mediated up-regulation of PRAME is leading to decreased TRAIL expression, thereby impairing TRAIL-induced apoptosis. However, in our AML patients we observed no inverse correlation of *PRAME* and *TNFSF10* (encoding for TRAIL) expression (see Supplementary Table 2), thereby suggesting different mechanisms of apoptosis deregulation in AML. Notably, we also detected no relevant differences for the induction of apoptosis in *PRAME*-high or *PRAME*-low cell lines treated with ATRA. Therefore, in AML mechanisms of ATRA action seem to be mainly influencing *PRAME*-mediated proliferation and differentiation changes, but not apoptosis.

Based on these observations further studies are warranted to unravel the exact mechanisms of ATRA action in *PRAME*-high non-APL cases. One might hypothesize that *PRAME* overexpression phenocopies PML-RAR translocations in that both interfere with RAR signaling under physiological concentrations of RA, and like in APL, ATRA might then trigger degradation of the inhibitory RARA/PRAME complex. While RA-induced transcriptional activation is directly coupled to proteasome-mediated RARα degradation, this pathway accounts for RA-induced degradation of both RARα and APL-associated RARα fusions and such RARα proteolysis is best seen with high doses of RA.(29)

With regard to a potential impact of PRAME on RAR signaling in primary AML patients (n=80), our microarray-based observations in an ATRA-treated elderly AML cohort (n=39) was in line with our *in vitro* data. These pointed to a PRAME-dependent effect of ATRA in AML, and in accordance we observed a trend towards improved outcome within a previously published Phase III study investigating the effect of ATRA in untreated elderly AML patients (61 years or older).(7) In the respective HD98B trial we could show that addition of ATRA to conventional therapy can significantly improve the CR rate, EFS and OS in AML patients with the genotype *NPM1* mutation without concomitant *FLT3*-ITD mutation. This genotype has been associated with favorable outcome,(6) and also seems to be a predictive marker for a response to ATRA.(7) In the current analysis, we did not find a correlation of *PRAME* expression with neither *NPM1* nor *FLT3*-ITD mutational status (see above). However, the ATRA response signature revealed a prominent induction of a gene expression pattern similar to the one observed in *NPM1*-mutated AML.(17) These gene expression changes might confer a cellular state rendering the leukemia cells again more sensitive to chemotherapy, similar to the good chemotherapy response observed in *NPM1*-mutated *FLT3*-ITD-negative AML irrespective of ATRA treatment.

While the treatment with ATRA in high PRAME expressing patients did not reach statistical significance in the elderly AML cases, an independent study of younger AML patients entered within the AMLSG 07-04 trial with high PRAME expression (n=13) showed a
significant clinical benefit when treated with ATRA as compared to all other patients (n=56, \( P=0.029 \)).

In conclusion, PRAME seems to play a critical role in cell proliferation and differentiation and in addition may be of therapeutic use. In AML cases with higher PRAME expression levels the addition of ATRA to chemotherapy and probably also the use of ATRA as maintenance therapy might further contribute to the elimination minimal residual disease in \emph{PRAME}-high AML cases. Thus, in the future a combination of immunotherapy and ATRA as targeted therapy against PRAME-mediated blockage of RAR-signaling might further improve patient management in PRAME-expressing AML cases.
ACKNOWLEDGMENTS

We would like to thank the members of the German-Austrian AMLSG for their continuous support of the treatment protocols.

GRANT SUPPORT

This work was supported by generous grants from the German José Carreras Leukemia Foundation to J.G. and L.B. (DJCLS A 10/01, R07/15v and R09/13) and the German Research Foundation (DFG GR 2676/3-1, TP B03 SFB 1074 and BU 1339/3-1)
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Figure legends

Figure 1: PRAME-associated gene expression pattern and functional annotation.
(A) Western blot analysis of PRAME expression in AML cell lines compared to mRNA expression levels as determined by microarray analysis. This exemplary figure shows a dilution series of the AML cell line KG1 with low PRAME expression (pink bar) and the cell line K562 with high PRAME expression (purple bar). (B) Comparison of microarray-based and quantitative RT-PCR (qRT-PCR)-based PRAME expression measurement of randomly selected cases (n=29) reveals a good correlation (P<0.001, linear regression analysis; depicted gene expression values are log2-transformed mean-centered expression changes). (C) For data visualization the top 100 ClassComparison analysis-derived PRAME expression-associated genes (rows) and AML samples (columns) were hierarchically clustered (average linkage clustering; similarity metric: correlation, uncentered; selected gene names are depicted). Cases with low and high PRAME expression (indicated by green and red bars, respectively) grouped together as indicated (for annotated probe sets gene symbols are provided). (D) Selected results of a functional annotation analysis of the PRAME expression-associated signature using DAVID (Enrichment Score: tells the overall enrichment of an annotation cluster with considering each of its members; Count: indicates number of genes contained in the respective gene ontology term). (E) PRAME expression levels in cell lines defined as low- and high-PRAME expression cell lines, respectively (plotted are log2 transformed centered gene expression ratios).

Figure 2: Proliferation and differentiation of PRAME-high or -low AML cells in response to ATRA treatment.
(A) PRAME-low AML cell line Kasumi-1 shows a low proliferation rate measured by BrdU treated with ATRA at different concentrations in contrast to (B) PRAME-high THP-1 cells. The proliferation of PRAME-low cells did not intensively decrease with higher ATRA concentrations in contrast to PRAME-high cells where a markedly reduced proliferation could be detected in these cells treated with higher ATRA concentration. (C) CD66b cell-surface FACS analysis showed also a relatively dose-independent differentiation of PRAME-low cells as a high differentiation rate was already observed at low ATRA concentration and the differentiation/expression of CD66b did not increase with high ATRA doses. (D) In contrast, PRAME-high cells showed a low differentiation rate at low ATRA concentrations, but the CD66b expression could be increased using high ATRA doses.
Figure 3: siRNA mediated PRAME knock-down in PRAME-high cell line: impact on ATRA induced differentiation.

(A) Transfection of PRAME-high leukemic cells (K562) with different siRNAs directed against PRAME. The most significant reduction in PRAME expression measured by real-time RT-PCR was obtained with siRNA#8 following 24 and 72 h after transfection (~50% reduction, scrRNA = scrambled RNA control). (B) CD66b cell surface expression of leukemic cells treated with ATRA at a concentration of 10⁻⁷ mol/l following PRAME knock-down using siRNA#8. After 72 h cell differentiation as indicated by CD66b expression could only be mildly increased in PRAME-high K562 cells treated with scrRNA. However, PRAME knock-down significantly increased the ATRA-induced differentiation with results resembling findings in PRAME-low cells, thereby further suggesting a PRAME-blocked RAR-differentiation. (C) In accordance, cell growth as measured by cell counts was also more effectively inhibited by low-dose ATRA treatment in PRAME-high leukemia cells following siRNA-mediated PRAME knock-down.

Figure 4: Gene expression changes associated with siRNA-mediated PRAME knock-down and ATRA treatment

(A) ClassComparison findings comparing siRNA knock-down and scrRNA K562 samples are depicted as Volcano plot that combines the t-test P-value with the magnitude of the expression change following PRAME knock-down. On the y-axis the negative log₁₀ of the P-value, and on the x-axis the log of the fold change following siRNA-mediated PRAME knock-down (down-regulated genes are plotted on the left). (B) Volcano plot depicting ClassComparison findings for ATRA treated/untreated K562 samples.

Figure 5: Kaplan Meier analyses based on PRAME expression and ATRA treatment in two randomized clinical trials (AML HD98B and AMLSG 07-04).

(A) - (D) Kaplan Meier analyses based on PRAME expression defined grouping and ATRA treatment in AML HD98B, (A) and (B), and AMLSG 07-04 patients, (C) and (D), respectively (P-values are indicated; PRAME expression groups have been defined based on the median PRAME expression).
Figure 1
Figure 2

A

B

C

D
Figure 4

A

B

Log2(Fold change)

-0.5 0.0 0.5

Log2(Fold change)

-2 0 2 4 6

PRAME

-Log(10 p-value)

0 1 2 3 4 5 6

-Log(10 p-value)

0 1 2 3 4 5 6
Clinical Cancer Research

PRAME induced inhibition of retinoic acid receptor signaling-mediated differentiation - a possible target for ATRA response in AML without t(15;17)

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Clin Cancer Res  Published OnlineFirst February 26, 2013.

Updated version  Access the most recent version of this article at: doi:10.1158/1078-0432.CCR-11-2524

Supplementary Material  Access the most recent supplemental material at: http://clincancerres.aacrjournals.org/content/suppl/2013/02/26/1078-0432.CCR-11-2524.DC1

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