

# Mutations associated with a 17-gene leukemia stem cell score and the score's prognostic relevance in the context of the European LeukemiaNet classification of acute myeloid leukemia



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## ABSTRACT

Leukemia stem cells (LSC) are more resistant to standard chemotherapy and their persistence during remission can cause relapse, which is still one of the major clinical challenges in the treatment of acute myeloid leukemia (AML). A better understanding of the mutational patterns and the prognostic impact of molecular markers associated with stemness could lead to better clinical management and improve patients' outcomes. We applied a previously described 17-gene expression score comprising genes differently expressed between LSC and leukemic bulk blasts, for 934 adult patients with *de novo* AML, and studied associations of the 17-gene LSC score with clinical data and mutation status of 81 genes recurrently mutated in cancer and leukemia. We found that patients with a high 17-gene score were older and had more mutations. The 17-gene score was found to have a prognostic impact in both younger (aged <60 years) and older (aged ≥60 years) patients with AML. We also analyzed the 17-gene LSC score in the context of the 2017 European LeukemiaNet genetic-risk classification and found that for younger patients the score refined the classification, and identified patients currently classified in the European LeukemiaNet Favorable-risk category who had a worse outcome.

## Introduction

Acute myeloid leukemia (AML) is a heterogeneous disease.<sup>1-3</sup> Although many advances have been made in understanding the biology and treatment of AML, the long-term survival rates are still only ~40% for younger adults (aged <60 years), and ~10-15% for older patients (aged ≥60 years).<sup>1-3</sup> One major clinical challenge impeding improved outcome is relapse following achievement of complete remission (CR). It is hypothesized that relapse occurs because of the persistence of leukemia stem cells (LSC) and subsequent outgrowth of the leukemia clone.<sup>4,8</sup> Studies on the clinical relevance of LSC are still rare because no LSC-specific phenotype has been firmly established. Although the percentage of CD34<sup>+</sup>/CD38<sup>-</sup> expressing cells, which were initially assumed to include all LSC, was shown to affect prognosis,<sup>9,10</sup> the use of more permissive immunodeficient mouse models revealed that LSC can also be found in the CD34<sup>+</sup>/CD38<sup>+</sup> and CD34<sup>-</sup> compartments.<sup>4,7,9,11-15</sup> Instead of using surface markers to identify and quantify the presence

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of LSC, in 2011, Eppert *et al.*<sup>4</sup> described a LSC-related gene-expression signature comprising 44 genes that were deregulated in LSC. The derived stem cell-like signature was shown to associate with inferior outcome in adult patients with cytogenetically normal AML.<sup>4,16</sup> Recently, Ng *et al.*<sup>7</sup> used a similar approach to generate a LSC-derived gene-expression signature consisting of 17 genes that also associated with inferior outcome. However, it is still not fully determined whether this signature is associated with clinical characteristics and gene mutations. Moreover, the prognostic value of the 17-gene LSC score in the context of other, well-established risk classifications, for example the one by the European LeukemiaNet (ELN)<sup>1</sup>, has not, to our knowledge, been assessed.

We, therefore, derived the 17-gene score from a set of samples from adults with AML and determined associations between the signature and known prognosticators<sup>1,17,18</sup> as well as mutational data of 81 cancer- and leukemia-associated genes.<sup>19</sup> Moreover, we validated the prognostic impact of the 17-gene signature alone and in the context of the 2017 ELN genetic-risk classification.<sup>1</sup>

## Methods

### Patients and treatment

We investigated 934 adult patients with *de novo* AML (other than acute promyelocytic leukemia), for whom material for molecular analyses was available. Availability of material for analysis was the only criterion for inclusion in our study – we did not select AML patients based on their age, ELN risk group, specific clinical trial they were enrolled onto, etc. Because of differences in the treatment protocols between younger and older patients, we performed outcome analyses separately for these two groups of patients. Within each age group, patients were treated similarly, receiving a cytarabine/anthracycline-based induction on Cancer and Leukemia Group B (CALGB) trials.<sup>20-34</sup> No patient received an allogeneic stem cell transplant in first CR. Details of CALGB treatment protocols are provided in the *Online Supplementary Appendix* and *Online Supplementary Table S4*. There were no significant differences in CR rates, disease-free survival (DFS) or overall survival (OS) for younger patients enrolled onto CALGB 8525, 9222, 9621, 10503, 10603 and 19808 treatment trials (*Online Supplementary Table S2*) nor were there any significant differences in CR rates, DFS or OS among older patients enrolled onto CALGB 9420, 9720, 10201 and 10502 trials (*Online Supplementary Table S3*). CALGB is now part of the Alliance for Clinical Trials in Oncology (Alliance). All patients were enrolled on CALGB 8461 (cytogenetic studies), CALGB 9665 (leukemia tissue bank) and CALGB 20202 (molecular studies) companion protocols. Patients provided written informed consent, and study protocols were in accordance with the Declaration of Helsinki and approved by Institutional Review Boards.

### Transcriptome analyses and calculation of the 17-gene leukemia stem cell score

Pretreatment bone marrow and/or blood samples containing  $\geq 20\%$  leukemic blasts were obtained from all patients and mononuclear cells were enriched through Ficoll-Hypaque gradient centrifugation and cryopreserved until use. Total RNA was extracted from patients' samples using the TRIzol method according to the manufacturer's protocol and used for RNA-sequencing analyses (see also the *Online Supplementary Appendix*). RNA-sequencing libraries were prepared using the

Illumina (San Diego, CA, USA) TruSeq Stranded Total RNA Sample Prep Kit with Ribo-Zero Gold (n. RS1222201) according to the manufacturer's instructions. Sequencing was performed with Illumina HiSeq systems using the HiSeq version 3 sequencing reagents to an approximate cluster density of 800,000/mm<sup>2</sup>. Image analysis, base calling, error estimation, and quality thresholds were performed using HiSeq Controller software (version 2.2.38) and Real Time Analyzer software (version 1.18.64). Transcript abundance was quantified from the RNA-sequencing data using kallisto,<sup>35</sup> with a reference transcriptome consisting of *Homo sapiens* GRCh38 protein-encoding and non-coding transcripts except rRNA; the strand-specific option of "first read reverse" was chosen. Abundance values are represented in transcripts per million.

The 17-gene LSC score was derived similarly to that in the publication by Ng *et al.*<sup>7</sup> using RNA-sequencing data and the same weights that were published initially for a microarray platform.<sup>7</sup> Briefly, the 17-gene LSC score was calculated as the weighted sum of the normalized expression values of the 17 genes included in the signature: 17-gene LSC score =  $(DNMT3B \times 0.0874) + (ZBTB46 \times -0.0347) + (NYNRIN \times 0.00865) + (ARHGAP22 \times -0.0138) + (LAPTM4B \times 0.00582) + (MMRN1 \times 0.0258) + (DPYSL3 \times 0.0284) + (KIAA0125 \times 0.0196) + (CDK6 \times -0.0704) + (CPXM1 \times -0.0258) + (SOCS2 \times 0.0274) + (SMIM24 \times -0.0226) + (EMP1 \times 0.0146) + (NGFRAP1 \times 0.0465) + (CD34 \times 0.0338) + (AKR1C3 \times -0.0402) + (GPR56 \times 0.0501)$ .<sup>7</sup> The derived scores were used to divide patients into two groups using the median as the cutoff: a group with a high score (17-gene<sup>high</sup>) and a group with a low score (17-gene<sup>low</sup>).

### Cytogenetic and molecular analyses

Details of the cytogenetic and molecular analyses are provided in the *Online Supplementary Appendix*.

## Results

### Clinical and cytogenetic characteristics associated with the 17-gene leukemia stem cell score

Pretreatment characteristics of the 934 patients are shown in Table 1. For all patients, we determined the 17-gene LSC score, which indicates a stem cell-like gene-expression profile, and separated them into 17-gene<sup>low</sup> and 17-gene<sup>high</sup> groups using the median. Comparison between patients with a 17-gene<sup>low</sup> and 17-gene<sup>high</sup> score showed that the former were younger at diagnosis (median: 46 vs. 53 years;  $P < 0.001$ ) and had lower platelet counts (median: 50 vs.  $63 \times 10^9/L$ ;  $P < 0.001$ ). Cytogenetically, there was no difference in the frequency of the presence of cytogenetically normal AML between the groups. Among cytogenetically abnormal patients, those with a 17-gene<sup>low</sup> score more frequently had core-binding factor AML (CBF-AML;  $P < 0.001$ ), including all patients with t(8;21)(q22;q22) and 88% with inv(16)(p13q22) or t(16;16)(p13;q22). On the other hand, the group with a 17-gene<sup>high</sup> score included all patients with inv(3)(q21q26) or t(3;3)(q21;q26) and contained more patients with a complex karyotype than in the 17-gene<sup>low</sup> group ( $P < 0.001$ ). Most patients with a complex karyotype in the 17-gene<sup>high</sup> group had a typical complex karyotype (i.e., complex karyotype with unbalanced chromosome abnormalities leading to loss of material from 5q, 7q and/or 17p), whereas an atypical complex karyotype (i.e., complex karyotype without 5q, 7q and/or 17p abnormalities)<sup>36</sup> was found with a higher frequency among 17-gene<sup>low</sup> patients.

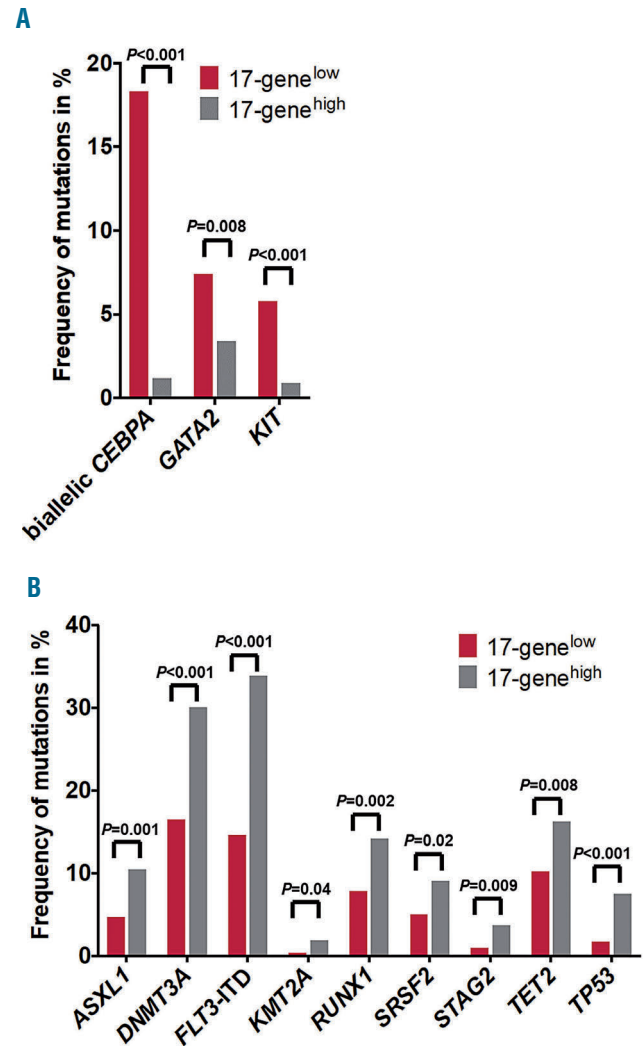
**Table 1.** Comparison of pretreatment clinical and cytogenetic characteristics in 934 patients with acute myeloid leukemia according to low and high 17-gene leukemia stem cell scores.

Characteristic	All patients (n=934)	17-gene <sup>low</sup> (n=467)	17-gene <sup>high</sup> (n=467)	P
Age, years				
Median	50	46	53	<0.001
Range	17-84	17-82	17-84	
Sex, n (%)				
Female	404 (43)	199 (43)	205 (44)	0.74
Hemoglobin, g/dL				
Median	9.2	9.2	9.1	0.31
Range	2.3-25.1	2.3-25.1	4.2-14.7	
Platelet count, x10 <sup>9</sup> /L				
Median	55	50	63	<0.001
Range	4-592	7-433	4-592	
WBC count, x10 <sup>9</sup> /L				
Median	24.1	24.1	23.9	0.46
Range	0.4-475.0	0.4-303.6	0.6-475	
% Blood blasts				
Median	54	54	54	0.18
Range	0-99	0-97	0-99	
% Bone marrow blasts				
Median	65	65	66	0.91
Range	0-97	0-97	4-97	
EM involvement, n (%)				
Present	220 (25)	112 (25)	108 (24)	0.88
FAB classification, n (%)				0.18
M0	40 (6)	16 (4)	24 (7)	
M1	150 (22)	82 (23)	68 (21)	
M2	185 (27)	100 (28)	85 (26)	
M4	189 (28)	107 (30)	82 (25)	
M5	113 (17)	52 (15)	61 (19)	
M6	1 (0)	0 (0)	1 (1)	
M7	1 (0)	0 (0)	1 (1)	
ELN group, n (%)				<0.001
Favorable	385 (45)	284 (64)	101 (24)	
t(8;21)	40	40	0	
inv(16)	69	61	8	
NPM1 mut/FLT3-ITD wt or low	211	123	88	
CEBPA mut	65	60	5	
Intermediate	188 (22)	69 (16)	119 (28)	
Adverse	291 (34)	89 (20)	202 (48)	
Cytogenetically normal, n (%)				0.17
Present	442 (47)	210 (45)	232 (50)	
CBF, n (%)				<0.001
Present	109 (12)	101 (22)	8 (2)	
t(8;21)	40	40	0	
inv(16)	69	61	8	
KMT2A-rearranged, n (%)				0.65
Present	46 (5)	21 (5)	25 (5)	
t(9;11)	19	9	10	
t(v;11)	27	12	15	
Complex karyotype, n (%)				<0.001
Present	79 (8)	19 (4)	60 (13)	
Typical	53	4	49	
Atypical	26	15	11	
t(6;9), n (%)				1.00
Present	5 (1)	2 (1)	3 (1)	
inv(3), n (%)				<0.001
Present	18 (2)	0	18 (4)	

WBC: white blood cell; EM: extramedullary; FAB: French-American-British; ELN: European LeukemiaNet; mut: mutated; ITD: internal tandem duplication; wt: wild-type; CBF: core-binding factor.

**Mutational landscape associated with the 17-gene leukemia stem cell score**

To obtain more detailed insights into the mutational patterns associated with the 17-gene LSC signature, we analyzed 81 cancer and leukemia-associated genes.<sup>19</sup> We found that 77 genes were mutated in at least one patient (*Online Supplementary Table S4*). Patients with a 17-gene<sup>low</sup> score had fewer mutations compared with patients with a 17-gene<sup>high</sup> score (median: 2 vs. 3;  $P<0.001$ ). Moreover, 12 gene mutations occurred at significantly different frequencies between patients with 17-gene<sup>low</sup> and 17-gene<sup>high</sup> scores (Figure 1). Biallelic *CEBPA* ( $P<0.001$ ), *GATA2* ( $P=0.008$ ), and *KIT* ( $P<0.001$ ) mutations were more frequent in the 17-gene<sup>low</sup> group of patients (Figure 1A). In contrast, patients with a 17-gene<sup>high</sup> score more frequently harbored mutations in *ASXL1* ( $P=0.001$ ), *DNMT3A* ( $P<0.001$ ), *KMT2A* ( $P=0.04$ ), *RUNX1* ( $P=0.002$ ), *SRSF2* ( $P=0.02$ ), *STAG2* ( $P=0.009$ ), *TET2* ( $P=0.008$ ) and *TP53* ( $P<0.001$ ) genes. Additionally, *FLT3*-internal tandem duplications were more frequent in these patients than in



**Figure 1.** Differences in the frequencies of gene mutations between patients with low and those with high 17-gene leukemic stem cell scores. Mutations that had a significantly higher frequency in the (A) 17-gene<sup>low</sup> or (B) 17-gene<sup>high</sup> group.

those with a 17-gene<sup>low</sup> score ( $P<0.001$ ) (Figure 1B and *Online Supplementary Table S4*), as previously described by Ng *et al.*<sup>7</sup>

### Outcome associated with the 17-gene leukemia stem cell score

All patients were assigned to the 17-gene<sup>low</sup> and 17-gene<sup>high</sup> groups based on the median of the initial analysis of the entire cohort of patients. We kept this initial grouping for all additional sub-analyses that could have potentially re-assigned some patients into different 17-gene score

groups. This led to differences in the sizes of the 17-gene<sup>low</sup> and 17-gene<sup>high</sup> score groups in younger and older patients.

Similarly to Ng *et al.*,<sup>7</sup> we found that the 17-gene LSC score was strongly associated with outcome in both the younger (Table 2; Figure 2A, B) and older (Table 2; Figure 2C, D) cohorts of patients. Among younger patients, those with a 17-gene<sup>low</sup> score had higher CR rates ( $P<0.001$ ) (Table 2) and longer DFS ( $P<0.001$ ) (Figure 2A) and OS ( $P<0.001$ ) (Figure 2B). Similar results were found in older patients: CR rates ( $P=0.004$ ) (Table 2), DFS ( $P=0.04$ ), (Figure 2C) and OS ( $P<0.001$ ) (Figure 2D).

**Table 2.** Comparison of outcomes according to the 17-gene leukemic stem cell score in younger adults (aged <60 years) and older adults (aged  $\geq 60$  years) with acute myeloid leukemia.

Endpoint	Younger patients (n=729)			Older patients (n=205)		
	17-gene <sup>low</sup> (n=403)	17-gene <sup>high</sup> (n=326)	P	17-gene <sup>low</sup> (n=64)	17-gene <sup>high</sup> (n=141)	P
Complete remission, %	87	63	<0.001	72	50	0.004
Disease-free survival			<0.001			0.04
Median, years	2.6	0.7		0.6	0.5	
% disease-free at 3 years	48	26		17	6	
95% confidence interval	43-53	20-32		8-30	2-13	
Overall survival			<0.001			<0.001
Median, years	6.5	1.1		1.1	0.6	
% alive at 3 years	59	27		27	9	
95% confidence interval	54-63	22-321		16-38	5-14	
Endpoint	ELN Favorable-risk group			ELN Intermediate-risk group		
	17-gene <sup>low</sup> (n=264)	17-gene <sup>high</sup> (n=78)	P	17-gene <sup>low</sup> (n=20)	17-gene <sup>high</sup> (n=23)	P
Complete remission, %	95	81	<0.001	90	78	0.42
Disease-free survival			0.008			0.09
Median, years	7.7	1.4		1.1	0.6	
% disease-free at 3 years	57	43		39	17	
95% confidence interval	50-63	31-55		17-60	4-37	
Overall survival			<0.001			0.05
Median, years	NR	2.4		2.4	1.1	
% alive at 3 years	68	49		50	17	
95% confidence interval	62-73	37-59		27-69	5-35	
Endpoint	ELN Adverse-risk group			ELN Intermediate-risk group		
	17-gene <sup>low</sup> (n=67)	17-gene <sup>high</sup> (n=123)	P	17-gene <sup>low</sup> (n=13)	17-gene <sup>high</sup> (n=23)	P
Complete remission, %	63	41	0.004	62	43	0.49
Disease-free survival			<0.001			0.92
Median, years	1.1	0.6		0.7	0.4	
% disease-free at 3 years	24	6		0	10	
95% confidence interval	12-37	2-15		0-29	1-36	
Overall survival			<0.001			0.48
Median, years	2.4	1.4		0.9	0.7	
% alive at 3 years	45	28		0	17	
95% confidence interval	31-57	20-37			5-35	

NR: not reached.

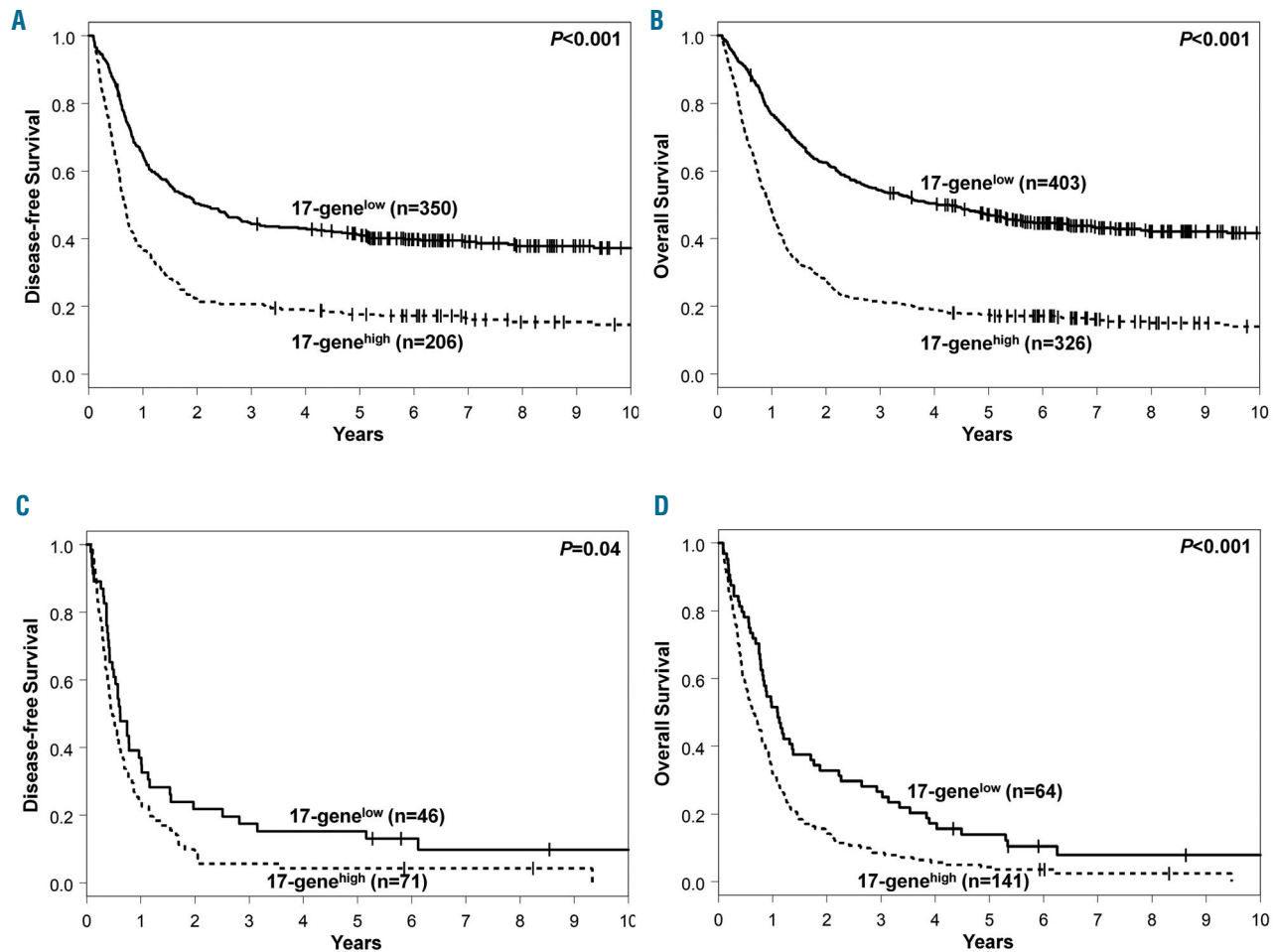
Next, we tested the prognostic impact of the 17-gene LSC score in multivariable analyses (Table 3). In younger patients, the 17-gene LSC score remained prognostically significant for all clinical endpoints, namely CR, DFS, and OS. In older patients, the score was prognostically significant only for OS, but it was not significant in the final models for achievement of a CR or DFS (Table 3).

### Prognostic impact of the 17-gene leukemia stem cell score in the context of the current European LeukemiaNet classification

To test the prognostic value of the 17-gene LSC score in the context of the current 2017 ELN classification, we classified all patients according to the published guidelines into ELN Favorable-, Intermediate- and Adverse-risk groups.<sup>1</sup> In both age cohorts, we found significant differences in the ELN risk-group distribution between patients with 17-gene<sup>low</sup> and 17-gene<sup>high</sup> scores ( $P < 0.001$  for younger and  $P = 0.009$  for older patients). Among the younger patients, two-thirds with a 17-gene<sup>low</sup> score were classified as having Favorable-risk, whereas 14% and 17% were classified as having, respectively, Intermediate- and Adverse-risk. On the other hand, younger patients with a 17-gene<sup>high</sup> score were most frequently classified in the

Adverse-risk group (41%), followed by the Intermediate- (32%) and Favorable-risk (26%) groups. Among the older patients, the majority in both the 17-gene<sup>low</sup> and 17-gene<sup>high</sup> score groups were classified in the Adverse-risk group (40% and 63%, respectively) (Online Supplementary Table S5), followed by Favorable- (36%) and Intermediate- (24%) risk groups in the 17-gene<sup>low</sup> group and by equal numbers for Favorable-risk (18%) and Intermediate-risk (18%) groups in the 17-gene<sup>high</sup> group.

Next, we tested whether the 17-gene LSC score can be used to refine the prognostic impact of the ELN classification. Among younger patients, we found that the 17-gene LSC score could refine the ELN classification for the ELN Favorable- and Adverse-risk groups, but not for the Intermediate-risk group. Younger patients with a 17-gene<sup>low</sup> score in the ELN Favorable-risk group had higher CR rates ( $P < 0.001$ ) (Table 2) and longer DFS ( $P = 0.008$ ) (Figure 3A) and OS ( $P < 0.001$ ) (Figure 3B) than the 17-gene<sup>high</sup> patients. Likewise, younger Adverse-risk patients with a 17-gene<sup>low</sup> score had higher CR rates ( $P = 0.004$ ) (Table 2), and longer DFS ( $P < 0.001$ ) (Figure 3E) and OS ( $P < 0.001$ ) (Figure 3F). On the other hand, among younger patients in the Intermediate-risk group, there was no significant difference in CR rates (Table 2) or DFS ( $P = 0.08$ )



**Figure 2. Differences in outcome between patients with low and those with high 17-gene leukemia stem cell scores.** (A) Disease-free survival (DFS) and (B) overall survival (OS) of younger adult patients (aged <60 years) according to the 17-gene leukemia stem cell (LSC) score. (C) DFS and (D) OS of older patients (aged ≥60 years) according to the 17-gene LSC score.

(Figure 3C), but those with a 17-gene<sup>low</sup> score had longer OS ( $P=0.03$ ) (Figure 3D).

Among older patients, the 17-gene score had almost no impact on outcome after classifying the patients according to the ELN recommendations. We found that only older patients in the Favorable-risk group with a 17-gene<sup>low</sup> score had longer OS than those with a 17-gene<sup>high</sup> score ( $P=0.05$ ) (Online Supplementary Figure S1, Table 2). The 17-gene score showed no prognostic impact in the Adverse- and Intermediate-risk groups.

## Discussion

The prognosis of AML patients is still poor, and relapse after achieving a CR is a major clinical challenge.<sup>1-4,7</sup> It is thought that leukemia relapse is caused by the persistence of LSC.<sup>4,7</sup> A better understanding of LSC and their prognostic impact in AML is necessary in order to improve patients' outcomes. However, the lack of a well-established phenotype has thus far impeded studies on the clinical relevance of LSC frequency. Ng *et al.*<sup>7</sup> recently developed a gene-expression signature, consisting of 17 genes that were found to be deregulated in LSC, to quantify the presence of LSC. They showed that the 17-gene LSC sig-

nature has a prognostic impact. In our study, we not only validated these data in an independent set of 934 adult patients with *de novo* AML, but also analyzed the prognostic impact of the 17-gene LSC score in the context of the current ELN classification. Moreover, we describe a detailed mutational landscape associated with the 17-gene LSC score.

Whereas the 17-gene score was initially derived using microarray data, Ng *et al.*<sup>7</sup> showed in a relatively small set of patients ( $n=169$ ) that RNA-sequencing data can also be used to derive the score. We validated this finding in a larger set of 934 AML patients with RNA-sequencing data using the same published weights of the score as Ng *et al.*<sup>7</sup> and demonstrated the robustness of the 17-gene score. We assigned the score to each patient and classified them into a 17-gene<sup>high</sup> or 17-gene<sup>low</sup> LSC group for all further analyses, using the median as the cut point.

Clinically, we found that patients with a 17-gene<sup>low</sup> score were younger and had lower platelet counts at diagnosis. Similar differences in age were also described by Ng *et al.*<sup>7</sup> Next, we compared cytogenetic findings between the groups of patients with 17-gene<sup>low</sup> and 17-gene<sup>high</sup> scores and although we did not find any difference in the incidence of cytogenetically normal AML, there was a different distribution of the specific cytogenetic abnormalities

**Table 3.** Multivariable models for outcome evaluating the 17-gene leukemia stem cell score and known prognosticators in younger (aged <60 years) and older (aged  $\geq 60$  years) adults with acute myeloid leukemia.

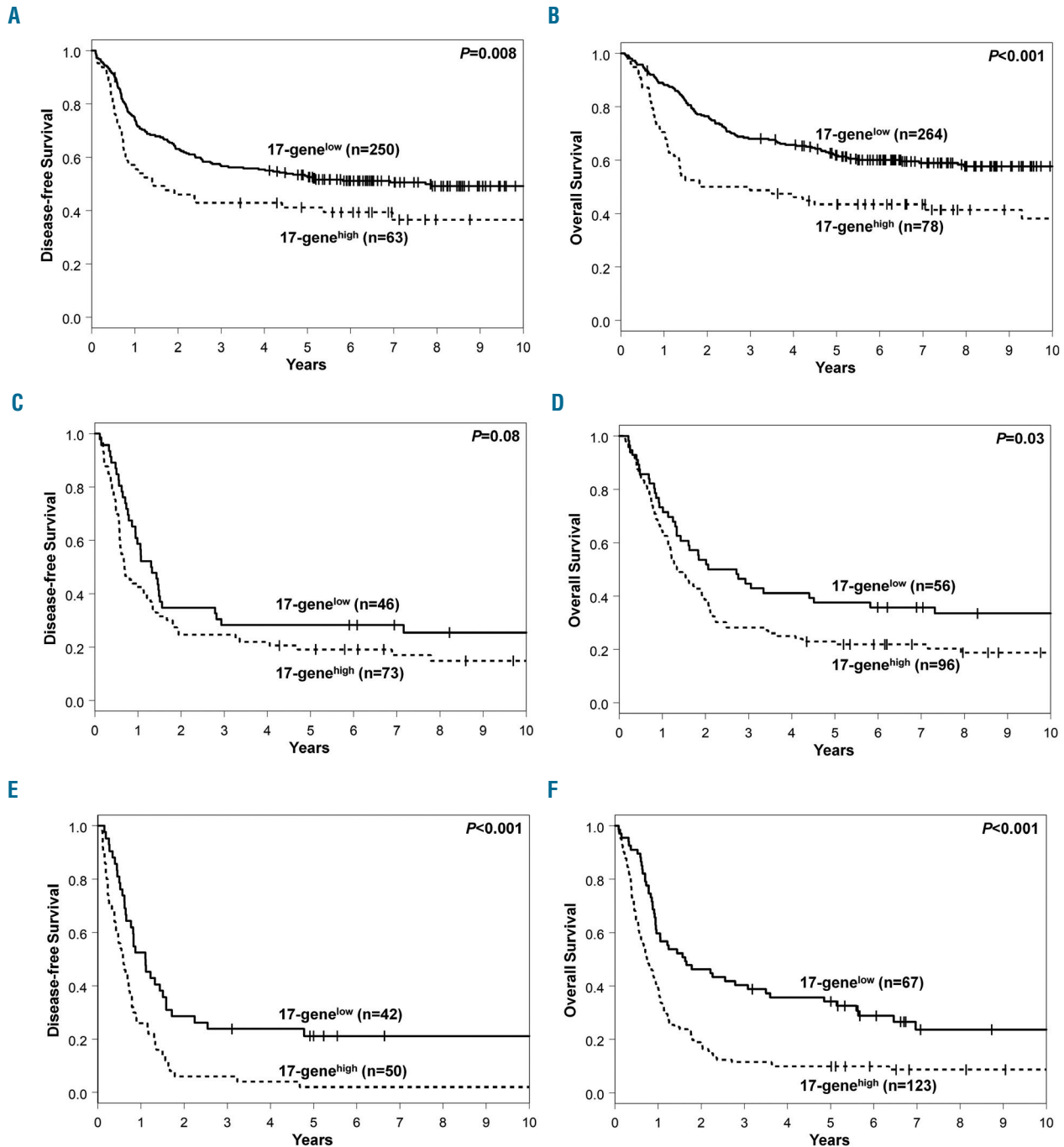
End point	Variable	Younger patients (n=729)		Older patients (n=205)	
		Odds ratio (95% CI)	P	Odds ratio (95% CI)	P
Complete remission	17-gene LSC score (high <i>vs.</i> low)	0.36 (0.23-0.56)	<0.001	*	*
	ELN 2017		<0.001		
	(Intermediate <i>vs.</i> Favorable), (Adverse <i>vs.</i> Favorable)	0.48 (0.26-0.86)			
	<i>WT1</i> (mutated <i>vs.</i> wild-type)	0.47 (0.24-0.92)	0.03		
	<i>ZRSR2</i> (mutated <i>vs.</i> wild-type)	0.44 (0.19-0.99)	0.05		
	<i>BAALC</i> expression (high <i>vs.</i> low)	0.60 (0.39-0.92)	0.02		
	Hemoglobin (continuous)	1.16 (1.03-1.30)	0.01		
		Hazard ratio (95% CI)	P	Hazard ratio (95% CI)	P
Disease-free survival	17-gene LSC score (high <i>vs.</i> low)	1.67 (1.31-2.13)	<0.001	*	*
	ELN 2017		<0.001		
	(Intermediate <i>vs.</i> Favorable), (Adverse <i>vs.</i> Favorable)	1.84 (1.39-2.42)			
	<i>DNMT3A</i> (mutated <i>vs.</i> wild-type)	2.87 (2.16-3.81)			
	<i>WT1</i> (mutated <i>vs.</i> wild-type)	1.41 (1.09-1.82)	0.008		
	Platelets (continuous, 50-unit increase)	1.94 (1.34-2.80)	<0.001		
Overall survival	17-gene LSC score (high <i>vs.</i> low)	0.87 (0.80-0.95)	0.003		
	ELN 2017		<0.001		
	(Intermediate <i>vs.</i> Favorable), (Adverse <i>vs.</i> Favorable)	1.88 (1.53-2.31)	<0.001	1.70 (1.19-2.41)	0.003
	<i>WT1</i> (mutated <i>vs.</i> wild-type)	1.77 (1.37-2.29)			
	Age (continuous, 10-year increase)	2.85 (2.26-3.60)			
	<i>BAALC</i> expression (high <i>vs.</i> low)	1.80 (1.33-2.44)	<0.001		
Platelets (continuous, 50-unit increase)	1.17 (1.07-1.27)	<0.001	1.71 (1.23-2.38)	0.001	
				0.86 (0.77-0.96)	0.007

95% CI: 95% confidence interval; ELN: European LeukemiaNet. An odds ratio >1 (<1) corresponds to a higher (lower) odds of achieving a complete remission for higher values of continuous variables and the first level listed of a dichotomous variable. A hazard ratio >1 (<1) corresponds to a higher (lower) risk for higher values of continuous variables and the first level listed of a dichotomous variable. Variables were considered for inclusion in the multivariable models if they had a univariable  $P$ -value of <0.20. Only markers for which there were at least eight mutated patients in each 17-gene score group (high/low) were included in the multivariable modeling. \* the 17-gene score does not remain statistically significant in the multivariable model for achievement of a complete remission and disease-free survival in older patients.

between the groups. Patients with CBF-AML were much more frequently classified in the 17-gene<sup>low</sup> score group, especially those with a t(8;21)(q22;q22) who were never found to have a 17-gene<sup>high</sup> score. As previously reported, patients with CBF-AML had a relatively favorable outcome compared with patients belonging to other cytogenetic subgroups.<sup>37-41</sup> On the other hand, patients in the 17-gene<sup>high</sup> score group more frequently carried cytogenetic

abnormalities associated with adverse outcome, such as a complex karyotype, especially a typical complex karyotype,<sup>36</sup> and inv(3)(q21q26) or t(3;3)(q21;q26).<sup>1,17,36,40-42</sup> Of note, patients with inv(3) or t(3;3) were classified exclusively in the 17-gene<sup>high</sup> score group.

Next, we looked for differences in the mutational patterns of 81 cancer- and leukemia-associated genes<sup>19</sup> between 17-gene<sup>low</sup> and 17-gene<sup>high</sup> score patients. Patients



**Figure 3.** Differences in outcome between younger adult patients (aged <60 years) with low and those with high 17-gene leukemic stem cell scores in the context of the current European LeukemiaNet 2017 classification. (A) Disease-free survival (DFS) and (B) overall survival (OS) of younger patients within the European LeukemiaNet (ELN) Favorable-risk group according to the 17-gene leukemia stem cell (LSC) score. (C) DFS and (D) OS of younger patients within the ELN Intermediate-risk group according to the 17-gene LSC score. (E) DFS and (F) OS of younger patients within the ELN Adverse-risk group according to the 17-gene LSC score.

with a 17-gene<sup>low</sup> score had a lower median number of mutations and only three genes, namely, *GATA2*, *CEBPA* and *KIT*, were found to be mutated more frequently in this group. *GATA2* mutations and biallelic *CEBPA* mutations are known to co-occur,<sup>45</sup> and the higher incidence of *KIT* mutations in 17-gene<sup>low</sup> patients can be at least in part explained by the elevated frequency of CBF-AML in this group, since *KIT* mutations are associated with CBF-AML.<sup>37</sup> Whereas both biallelic *CEBPA* mutations and *GATA2* mutations, which occurred frequently in the 17-gene<sup>low</sup> score group, are associated with a favorable outcome, mutations associated with adverse outcome, such as those in the *RUNX1*, *ASXL1*, and *TP53* genes,<sup>1,2,36,44-50</sup> were more frequently found in patients with a 17-gene<sup>high</sup> score.

We were also interested in characterizing further the prognostic significance of the 17-gene LSC score established by Ng *et al.*<sup>7</sup> We not only validated its prognostic impact in a larger independent cohort of patients, but also asked the question whether the 17-gene LSC score could refine the well-established 2017 ELN classification.<sup>1</sup> This is especially of interest because it appears that some patients classified as ELN Favorable-risk still have a poor outcome. These patients might benefit from other treatment options.<sup>1</sup> When we classified the patients according to the ELN guidelines, we found significant differences in the distribution of patients with 17-gene<sup>low</sup> and 17-gene<sup>high</sup> scores among specific ELN risk groups. In younger patients, the majority of 17-gene<sup>low</sup> score patients were classified as having Favorable-risk, whereas most patients in the 17-gene<sup>high</sup> score group were in the Adverse-risk group.

With regard to clinical outcome, we found that the 17-gene LSC score is capable of refining the ELN classification in younger patients. In the Favorable-risk group, application of the 17-gene LSC score led to the identification of approximately 20% of patients with a 17-gene<sup>high</sup> score who had a worse outcome than patients with a 17-gene<sup>low</sup> score. Prospective studies are needed to test whether these 17-gene<sup>high</sup> score patients might benefit from different induction. A similar ability of the 17-gene LSC score to

identify patients with different outcomes was shown for the Adverse-risk group, despite the fact that the outcome of patients in this group is in general poor. The usefulness of the 17-gene LSC score in the ELN Intermediate-risk group seems to be limited, with patients with a 17-gene<sup>low</sup> score having a better OS but not better CR rates or DFS. Likewise, the 17-gene LSC score could not improve the ELN classification in older AML patients, who are known to have a generally poor prognosis.<sup>1-3</sup>

In summary, we found that the 17-gene LSC score is associated with distinct clinical and molecular features. Moreover, we not only validated the prognostic impact of the 17-gene LSC score but also showed for the first time that the score can refine the current 2017 ELN classification, at least in younger patients. This is important because the 17-gene LSC score is associated with well-established prognostic markers that are included in the ELN guidelines. Prospective studies are needed to determine best treatment options for patients currently classified as having Favorable-risk who are identified to have a worse prognosis by the use of the 17-gene LSC score.

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