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LETTER TO THE EDITOR

Differential impact of drugs on the outcome of *ETV6-RUNX1* positive childhood B-cell precursor acute lymphoblastic leukaemia: results of the EORTC CLG 58881 and 58951 trials

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In childhood B-cell precursor acute lymphoblastic leukaemias (BCP-ALL), the presence of an *ETV6-RUNX1* fusion transcript defines one of the most prevalent genetic subgroups, together with the high hyperdiploidy (HeH) ALL. Although *ETV6-RUNX1*^{pos} ALLs are associated with favourable outcome, their proper treatment strategies remain debatable, some groups suggesting crucial impact of upfront intensive treatment[1] while others favour low-intensity antimetabolite-based therapy.[2]

To address this question, we evaluated the long-term prognostic and predictive value of *ETV6-RUNX1* in *BCR-ABL1* negative *de novo* BCP-ALL children (1–17 years old) treated in the European Organisation for Research and Treatment of Cancer (EORTC) studies 58881, opened between January 1989 and November 1998[3] ($n = 1692$) and 58951 opened between December 1998 and August 2008[4,5] ($n = 1602$). Particular attention was given to the effects of the randomized treatments (Supplementary Figures S1 and S2) in the *ETV6-RUNX1*^{pos} subgroup as compared with those observed in the HeH and 'Others' BCP-ALL subgroups, in order to reveal specific drug response profiles related to distinct oncogenic process.

In total, 1887 BCP-ALL were screened for the presence of *ETV6-RUNX1*: 394 in study 58881 and 1493 in study 58951. In both studies, clinical features and outcome were similar to those of patients not screened (Supplementary Tables S1 and S2).

ETV6-RUNX1 was evidenced in 488/1887 patients (25.9%) and HeH in 595/1887 patients (31.5%). The 804 (42.6%) remaining patients ('Others') had others or unknown genetic abnormalities (Supplementary Figure S3). Clinical and biological features of patients according to the *ETV6-RUNX1* status and by genetic subgroups are presented in Supplementary Tables S3 and S4.

The median follow-up was 11.7 years and 6.7 years for study 58881 and 58951, respectively.

The 10-year event-free survival (EFS) rate was globally improved in study 58951 as compared with study 58881 (82.7% vs 73.1%). In both studies, the 10-year EFS was significantly higher in the *ETV6-RUNX1*^{pos} group than in the *ETV6-RUNX1*^{neg} group (Table 1 and Supplementary Figure S4). *ETV6-RUNX1*^{pos} patients had also a significantly higher 10-year overall survival (OS) rate (93.3 vs 82.0% in 58881, 95.3 vs 87.8% in 58951; Supplementary Figures S5 and S6).

The 10-year EFS of the *ETV6-RUNX1*^{pos} group was similar to that of the HeH group, but drastically superior to the one of the 'Others' subgroup (Figure 1).

Noteworthy, in the *ETV6-RUNX1*^{pos} group, EFS events mostly occurred after the end of the maintenance therapy, with very few events before, and virtually no event after 6 years from diagnosis.

In both studies, the higher EFS of the *ETV6-RUNX1*^{pos} group was mainly due to lower rates of induction failures and relapses and to treatment-related mortality rates below 1.5% (Supplementary Tables S3 and S4).

Erwinia-asparaginase (ASNase) vs E. coli-ASNase for all risk groups in study 58881,[6] and prolonged vs classical number of ASNase administrations for non-very-high-risk (VHR) patients in study 58951[7]

In *ETV6-RUNX1*^{pos} patients, the exact role of ASNase *in vivo* remains unclear. *In vitro* analyses have revealed that *ETV6-RUNX1*^{pos} cells are exquisitely sensitive to ASNase but similar outcomes have been described with[8] or without[9] intensive ASNase administration.

In study 58881, 94 patients were randomized for *E. coli*-ASNase ($n = 46$) or *Erwinia*-ASNase ($n = 48$), and 300 additional patients received *E. coli*-ASNase (Table 1 and Supplementary Table S5). The overall improvement of the 10-year EFS with *E. coli*-ASNase as compared with *Erwinia*-ASNase was approximately 10%, as in the main publication,[6] and around 33% in the HeH group. In contrast, in the *ETV6-RUNX1*^{pos} group, the 10-year EFS improvement was limited (3.7%). This is in line with results of the DFCI 95-01 study, showing no significant difference regarding EFS in 77 *ETV6-RUNX1*^{pos} patients treated with either *E. coli*- or *Erwinia*-ASNase.[8]

In study 58951, 1229 non-VHR patients were randomized for prolonged ('long-ASNase') vs classical ('short-ASNase') courses of asparaginase during consolidation/late intensification[7] (Table 1 and Supplementary Table S5). Overall, the 10-year disease-free survival (DFS) was 87.0% in the 'long-ASNase' arm and 83.6% in the 'short-ASNase' arm. In the *ETV6-RUNX1*^{pos} subgroup ($n = 333$), the impact of 'long-ASNase' was weak with a 10-year DFS rate of 94.8% in the 'long-ASNase' vs 91.2% in the 'short-ASNase' arm. In the HeH subgroup, 'long-ASNase' did not prolong the DFS as compared with 'short-ASNase'. St Jude obtained outstanding results (5-year EFS of 96.8%) in *ETV6-RUNX1*^{pos} patients treated with the Total XV regimen through intensified use of ASNase, vincristine and dexamethasone (DEX).[10] However, our results, while limited by the relatively low number of patients suggest that the benefit of ASNase intensification is low in *ETV6-RUNX1*^{pos} patients and that similar results can be reached without ASNase intensification.

Prednisone (PRED) (60 mg/m^2/day) vs DEX (6 mg/m^2/day) during induction in study 58951[5]

In the present analysis, the overall difference between DEX and PRED regarding EFS was not significant, as in the whole cohort analysis.[5] Similarly, no difference regarding EFS was observed in *ETV6-RUNX1*^{neg} patients, or in the HeH and 'Others' subgroups considered separately (Table 1 and Supplementary Figure S7A).

By contrast, *ETV6-RUNX1* status had a significant impact (test of heterogeneity: $P = 0.05$) on the treatment difference (Table 1 and Supplementary Figure S7A). In the *ETV6-RUNX1*^{pos} subgroup, the 10-year EFS was higher in the DEX group as compared with PRED (95 vs 87.2%). This difference remained practically unchanged when adjusting by sex, NCI risk group and EORTC risk group (VHR

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Table 1. Outcome by genetic subgroup according to the randomized questions of EORTC studies 58881 and 58951

	All	*ETV6-RUNX1^{pos}*	*ETV6-RUNX1^{neg}*	*HeH*	*Others*[a]	*Heterogeneity test ETV6-RUNX1^{pos} vs ETV6-RUNX1^{neg}*	*Heterogeneity test ETV6-RUNX1^{pos} vs HeH vs Others*
Erwinia-ASNase vs E. coli-ASNase for all risk groups in study 58881							
10-year EFS rates[b]							
Erwinia-ASNase	66.7%	80.0%	60.6%	56.3%	64.7%		
	(*n* = 48)	(*n* = 15)	(*n* = 33)	(*n* = 16)	(*n* = 17)		
E. coli-ASNase[c]	76.2%	83.7%	73.4%	89.5%	63.7%		
	(*n* = 346)	(*n* = 93)	(*n* = 253)	(*n* = 95)	(*n* = 158)		
HR[d]	0.63	0.78	0.56	0.09	0.96	*P* = 0.67	*P* = 0.02
95%* or 99%** CI	0.34–1.18*	0.13–4.54**	0.22–1.42**	0.02–0.58**	0.31–2.95**		
Long-ASNase vs Short-ASNase administrations during consolidation/late intensification for non-VHR patients in study 58951							
10-year DFS rates[e]							
Short-ASNase	83.6%	91.2%	80.5%	90.1%	72.8%		
	(*n* = 607)	(*n* = 177)	(*n* = 430)	(*n* = 188)	(*n* = 242)		
Long-ASNase	87.0%	94.8%	84.5%	88.2%	80.7%		
	(*n* = 622)	(*n* = 156)	(*n* = 466)	(*n* = 239)	(*n* = 227)		
HR[d]	0.85	0.65	0.85	1.45	0.71	*P* = 0.57	*P* = 0.13
95%* or 99%** CI	0.62–1.16*	0.22–1.97**	0.55–1.32**	0.65–3.23**	0.42–1.21**		
DEXA (6 mg/m^2/day) vs PRED (60 mg/m^2/day) during induction in study 58951							
10-year EFS rates[b]							
PRED	81.8%	87.2%	79.8%	88.8%	73.2%		
	(*n* = 745)	(*n* = 197)	(*n* = 548)	(*n* = 233)	(*n* = 315)		
DEXA	83.7%	95.0%	80.1%	88.0%	73.7%		
	(*n* = 748)	(*n* = 183)	(*n* = 565)	(*n* = 251)	(*n* = 314)		
HR[d]	0.92	0.46	1.00	1.19	0.96	*P* = 0.05	*P* = 0.11
95%* or 99%** CI	0.71–1.19*	0.18–1.17**	0.69–1.44**	0.59–2.47**	0.63–1.46**		
Monthly i.v. 6-MP (1 g/m^2) vs no i.v. 6-MP during maintenance therapy for non-high-risk patients in study 58881							
10-year DFS rates[e]							
No 6-MP i.v.	84.6%	100%	80.0%	91.7%	70.3%		
	(*n* = 102)	(*n* = 23)	(*n* = 79)	(*n* = 36)	(*n* = 43)		
6-MP i.v.	72.4%	71.4%	73.0%	79.3%	67.7%		
	(*n* = 98)	(*n* = 35)	(*n* = 63)	(*n* = 29)	(*n* = 34)		
HR[d]	1.91	5.82	1.47	1.89	1.32	*P* = 0.06	*P* = 0.15
95%* or 99%** CI	1.05–3.48*	1.12–30.22**	0.59–3.64**	0.37–9.80**	0.44–3.94**		
Vincristine-corticosteroid pulses vs no pulses during maintenance therapy for AR patients in study 58951							
10-year DFS rates[e]							
No pulse	82.8%	96.1%	75.7%	88.5%	71.1%		
	(*n* = 153)	(*n* = 53)	(*n* = 100)	(*n* = 26)	(*n* = 74)		
Pulse	87.5%	95.1%	84.3%	91.3%	82.3%		
	(*n* = 148)	(*n* = 44)	(*n* = 104)	(*n* = 23)	(*n* = 81)		
HR[d]	0.70	1.18	0.62	0.76	0.58	*P* = 0.54	*P* = 0.78
95%* or 99%** CI	0.39–1.27*	0.09–15.58**	0.27–1.40**	0.08–7.65**	0.24–1.38**		

Abbreviations: AR, average risk; ASNase, asparaginase; CI, confidence interval; DEX, dexamethasone; DFS, disease-free survival; EFS, event-free survival; HeH, high hyperdiploidy; HR, hazard ratio; i.v., intravenous; PRED, prednisone; VHR, very high risk; 6-MP, 6-mercaptopurine. [a] Including patients with t(4;11) BCP-ALL. [b] EFS was calculated from the date of CR to the date of first relapse or death. Patients who failed to reach CR by the end of induction-consolidation were considered as having an event at time 0. [c]Patients randomized or not for ASNase. [d]The estimated hazard ratio (HR) and its confidence interval (CI) were derived from log-rank test computations. Heterogeneities between these HRs were tested for significance using the Cochran's *Q* test. All analyses were based on the intent-to-treat principle. [e] DFS was computed from the date of randomization until first relapse or death in CR for patients who were randomized for a given question after the achievement of CR.

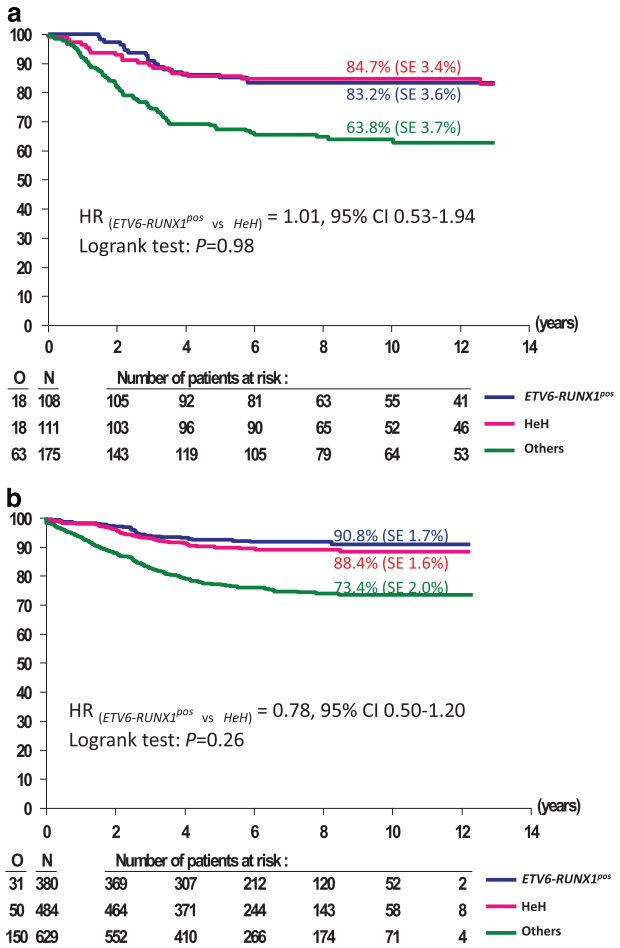

Figure 1. Kaplan–Meier curves of event-free survival by genetic subgroup (*ETV6-RUNX1*^{pos}, HeH or 'Others') in EORTC study (**a**) 58881 and (**b**) 58951.

vs non-VHR) by using a Cox model (HR = 0.47, 99% CI = 0.17–1.30; two-sided Wald test: $P = 0.055$). The 10-year OS was comparable in both arms (96.3 vs 94.5%, HR = 0.84, 99% CI = 0.21–3.37; two-sided log-rank test: $P = 0.74$).

A possible role for DEX in *ETV6-RUNX1*^{pos} patients had already been suggested by the St Jude group, who obtained outstanding results with DEX pulses during maintenance therapy.[10] In the randomized trial AIEOP-BFM ALL 2000,[11] higher 5-year EFS rates were observed in the *ETV6-RUNX1*^{pos} subgroup treated with DEX 10 mg/m^2 in induction when compared with PRED 60 mg/m^2, but this advantage did not translate into higher 5-year OS. In study 58951, the improvement in *ETV6-RUNX1*^{pos} patients regarding EFS did not either lead to an improvement in OS, since the majority of relapses occurred after the end of the maintenance therapy, and could then be salvaged with second-line therapies. However, toxicities of salvage therapies have to be balanced with those of first-line treatments and DEX at 6 mg/m^2 did not increase the incidence of infections and osteonecrosis in study 58951.[5] Furthermore, the majority of *ETV6-RUNX1*^{pos} patients, being less than 10-year-old, are at low risk of osteonecrosis.

Monthly intravenous (i.v.) 6-mercaptopurine (6-MP) (1 g/m^2) vs no i.v. 6-MP during maintenance therapy for non-high-risk patients in study 58881[12]

A total of 200 patients were randomized for the i.v. 6-MP question (Supplementary Table S5).[12] The addition of i.v. 6-MP was associated with a significantly lower 10-year DFS (two-sided log-rank test: $P = 0.03$) (Table 1).

Strikingly, in *ETV6-RUNX1*^{pos} patients, the 10-year DFS was 71.4% in the i.v. 6-MP group vs 100% in the classic maintenance group, whereas the treatment difference was less marked in the HeH and 'Others' subgroups (Table 1 and Supplementary Figure S7B). *ETV6-RUNX1*^{pos} patients treated with classic maintenance outside the randomization ($n = 47$) had a 10-year DFS from CR of 82.7%.

The addition of i.v. 6-MP was previously shown to lead to significantly worse outcome in study 58881.[12] The present analysis further showed that the deleterious effect of i.v. 6-MP was mainly observed in the *ETV6-RUNX1*^{pos} subgroup. *ETV6-RUNX1*^{pos} relapses have been suggested to arise from quiescent pre-leukaemic clones persisting after eradication of the overt leukaemia cells, and prolonged exposure to 6-MP/methotrexate during maintenance therapy increases the risk of second cancers.[13] Thus, i.v. 6-MP might have fostered the oncogenic process, leading to 'secondary leukaemia' relapses in *ETV6-RUNX1*^{pos} patients.

Alternatively, the deleterious effect of i.v. 6-MP could be related to a specific susceptibility of *ETV6-RUNX1*^{pos} cells to antileukaemic agents that inhibit *de novo* purine synthesis. High-doses of 6-MP result in a preferential increase in methylated metabolites via thiopurine methyl-transferase as compared with cytotoxic thioguanine nucleotides via hypoxanthine-guanine phosphoribosyltransferase. *ETV6-RUNX1*^{pos} cells express low levels of hypoxanthine-guanine phosphoribosyltransferase as compared with other ALL subgroups.[14] High-dose 6-MP could thus result in a higher production of methylated metabolites, especially in *ETV6-RUNX1*^{pos} cells. Because methylated metabolites inactivate *de novo* purine synthesis,[15] critical for cell progression, they could induce cell dormancy, protecting *ETV6-RUNX1*^{pos} cells from maintenance therapy. At completion of maintenance therapy, quiescent leukaemia cells could re-enter cell cycle and lead to relapse, which is consistent with the high rate of relapses occurring after the end of maintenance in *ETV6-RUNX1*^{pos} patients randomized in the i.v. 6-MP arm.

Vincristine-corticosteroid pulses vs no pulses during maintenance therapy for average risk (AR) patients in study 58951[4]

A total of 301 patients were randomly assigned for this question (Supplementary Table S5).

Overall, the 10-year DFS was higher in the pulse arm, as previously reported,[4] but the difference was not significant in this subanalysis (Table 1).

In the HeH subgroup, the 10-year DFS was approximately 90% in both arms. In the 'Others' subgroup, the pulses improved the 10-year DFS by approximately 11%, while *ETV6-RUNX1*^{pos} patients had similar outstanding outcomes in both arms (Table 1).

Noteworthy, these latter AR patients treated with *E. coli*-ASNase had already outstanding outcome with a 10-year DFS rate of 96.1%. If these data are confirmed, vincristine-corticosteroid pulses could be avoided in this specific subgroup.

In conclusion, our observations identified *in vivo* treatment sensitivities, which were specific to the *ETV6-RUNX1*^{pos} subgroup: the benefit of DEX instead of prednisone in induction, the limited role of asparginase intensification and the importance of low-intensity maintenance therapy. These results stress the benefit of analysing homogeneous oncogenetic subgroups when comparing different therapeutic schemes.

Of course, interpretation of such retrospective subgroup analyses needs to be done with caution as they were unplanned in the study design, so they were underpowered. Such findings are exploratory in nature, and require confirmation in other studies.

In future randomized studies one should aim not only to evaluate the overall treatment effect but also the possible heterogeneity of treatment difference according to the ALL subgroups.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1 Avigad S, Kuperstein G, Zilberstein J, Liberzon E, Stark B, Gelernter I *et al.* TEL-AML1 fusion transcript designates a favorable outcome with an intensified protocol in childhood acute lymphoblastic leukemia. *Leukemia* 1999; **13**: 481–483.
2 Rubnitz JE, Shuster JJ, Land VJ, Link MP, Pullen DJ, Camitta BM *et al.* Case-control study suggests a favorable impact of TEL rearrangement in patients with B-lineage acute lymphoblastic leukemia treated with antimetabolite-based therapy: a Pediatric Oncology Group study. *Blood* 1997; **89**: 1143–1146.
3 Vilmer E, Suciu S, Ferster A, Bertrand Y, Cave H, Thyss A *et al.* Long-term results of three randomized trials (58831, 58832, 58881) in childhood acute lymphoblastic leukemia: a CLCG-EORTC report. *Leukemia* 2000; **14**: 2257–2266.
4 De Moerloose B, Suciu S, Bertrand Y, Mazingue F, Robert A, Uyttebroeck A *et al.* Improved outcome with pulses of vincristine and corticosteroids in continuation therapy of children with average risk acute lymphoblastic leukemia (ALL) and lymphoblastic non-Hodgkin lymphoma (NHL): Report of the EORTC randomized phase 3 trial 58951. *Blood* 2010; **116**: 36–44.
5 Domenech C, Suciu S, De Moerloose B, Mazingue F, Plat G, Ferster A *et al.* Dexamethasone (6 mg/m2/day) and prednisolone (60 mg/m2/day) were equally effective as induction therapy for childhood acute lymphoblastic leukemia in the EORTC CLG 58951 randomized trial. *Haematologica* 2014; **99**: 1220–1227.
6 Duval M, Suciu S, Ferster A, Rialland X, Nelken B, Lutz P *et al.* Comparison of Escherichia coli–asparaginase with Erwinia-asparaginase in the treatment of childhood lymphoid malignancies: results of a randomized European Organisation for Research and Treatment of Cancer—Children's Leukemia Group phase 3 trial. *Blood* 2002; **99**: 2734–2739.
7 Mondelaers V, Suciu S, De Moerloose B, Ferster A, Mazingue F, Plat G *et al.* Prolonged E. Coli asparaginase therapy does not improve significantly the outcome for children with low and average risk acute lymphoblastic leukemia (ALL) and non Hodgkin lymphoma (NHL): Final Report of the EORTC-CLG Randomized Phase III Trial 58951. *Blood* 2012; **120**: abstract 134.
8 Loh ML, Goldwasser MA, Silverman LB, Poon WM, Vattikuti S, Cardoso A *et al.* Prospective analysis of TEL/AML1-positive patients treated on Dana-Farber Cancer Institute Consortium Protocol 95-01. *Blood* 2006; **107**: 4508–4513.
9 Rubnitz JE, Wichlan D, Devidas M, Shuster J, Linda SB, Kurtzberg J *et al.* Prospective analysis of TEL gene rearrangements in childhood acute lymphoblastic leukemia: A children's oncology group study. *J Clin Oncol* 2008; **26**: 2186–2191.
10 Bhojwani D, Pei D, Sandlund JT, Jeha S, Ribeiro RC, Rubnitz JE *et al.* ETV6-RUNX1-positive childhood acute lymphoblastic leukemia: improved outcome with contemporary therapy. *Leukemia* 2012; **26**: 265–70.
11 Möricke A, Zimmermann M, Valsecchi MG, Stanulla M, Biondi A, Mann G *et al.* Dexamethasone vs prednisone in induction treatment of pediatric ALL : results of the randomized trial AIEOP-BFM ALL 2000. *Blood* 2016; **127**: 2101–2113.
12 van der Werff Ten Bosch J, Suciu S, Thyss A, Bertrand Y, Norton L, Mazingue F *et al.* Value of intravenous 6-mercaptopurine during continuation treatment in childhood acute lymphoblastic leukemia and non-Hodgkin's lymphoma: final results of a randomized phase III trial (58881) of the EORTC CLG. *Leukemia* 2005; **19**: 721–726.
13 Schmiegelow K, Al-modhwahi I, Andersen MK, Behrendtz M, Hasle H, Heyman M *et al.* Methotrexate/6-mercaptopurine maintenance therapy influences the risk of a second malignant neoplasm after childhood acute lymphoblastic leukemia: results from the NOPHOALL-92 study. *Blood* 2012; **113**: 6077–6084.
14 Zaza G, Yang W, Kager L, Cheok M, Downing J, Pui CH *et al.* Acute lymphoblastic leukemia with TEL-AML1 fusion has lower expression of genes involved in purine metabolism and lower de novo purine synthesis. *Blood* 2004; **104**: 1435–1441.
15 Masson E, Synold TW, Relling MV, Schuetz JD, Sandlund JT, Pui C-H *et al.* Allopurinol inhibits de novo purine synthesis in lymphoblasts of children with acute lymphoblastic leukemia. *Leukemia* 1996; **10**: 56–60.

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