FOXP1 suppresses immune response signatures and MHC class II expression in activated B-cell-like diffuse large B-cell lymphomas

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Published in:
Leukemia

DOI:
10.1038/leu.2015.299

Publication date:
2016

Document version
Publisher's PDF, also known as Version of record

Document license
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Citation for published version (APA):
The FOXP1 (forkhead box P1) transcription factor is a marker of poor prognosis in diffuse large B-cell lymphoma (DLBCL). Here we report the results of a microarray analysis of 81 FOXP1-silenced DLBCL cell lines identified through differential regulation of immune response signatures and major histocompatibility complex class II (MHC II) genes as some of the most significant differences between germinal center B-cell (GCB)-like DLBCL with full-length FOXP1 protein expression versus activated B-cell (ABC)-like DLBCL expressing predominantly short FOXP1 isoforms. In an independent primary DLBCL microarray data set, multiple MHC II genes, including human leukocyte antigen DR alpha chain (HLA-DRA), were inversely correlated with FOXP1 transcript expression (P < 0.05). FOXP1 knockdown in ABC-DLBCL cells led to increased cell-surface expression of HLA-DRA and CD74. In R-CHOP (rituximab, cyclophosphamide, doxorubicin, vincristine and prednisone)-treated DLBCL patients (n = 150), reduced HLA-DRA (< 90% frequency) expression correlated with inferior overall survival (P = 0.0003) and progression-free survival (P = 0.0012) and with non-GCB subtype stratified by the Hans, Choi or Visco–Young algorithms (all P < 0.01). In non-GCB DLBCL cases with < 90% HLA-DRA, there was an inverse correlation with the frequency (P = 0.0456) and intensity (P = 0.0349) of FOXP1 expression. We propose that FOXP1 represents a novel regulator of genes targeted by the class II MHC transactivator CIITA (MHC II and CD74) and therapeutically targeting the FOXP1 pathway may improve antigen presentation and immune surveillance in high-risk DLBCL patients.

Leukemia (2016) 30, 605–616; doi:10.1038/leu.2015.299
uniformly treated series of 82 patients human leukocyte antigen DR alpha chain (HLA-DR)-positive DLBCL had a median OS of 16.2 years, while HLA-DR-negative patients had a much lower median OS of 4.2 years. Low levels of MHC II expression in DLBCL are proposed to reduce antigen presentation and thus facilitate tumor immune evasion, leading to decreased patient survival. Supporting data include a recent study using flow cytometry analysis of tumor-infiltrating lymphocytes in DLBCL that identified differences in the CD4/CD8 T-cell ratio on loss of HLA-DR. Low MHC II expression has also been associated with plasmacytic differentiation and ABC-DLBCL.

The expression of MHC II molecules is dependent on DNA-binding factors, the NF-Y complex, CREB and the RFX complex, which recruit the non-DNA-binding class II MHC transactivator (CIITA) protein. CIITA is the master regulator of MHC II transcription, acting as a transcriptional coactivator of MHC II through formation and stabilization of an ‘enhancosome’ with RFX and NF-Y transcription factors, as well as recruitment of histone acetyltransferases to alter chromatin accessibility. The ‘enhancosome’ complex not only acts on promoters of classical and non-classical MHC II genes but also on the promoters of additional genes involved in antigen presentation such as the invariant chain (CD74).

Loss of MHC II expression in immune-privileged (IP) DLBCL subsets occurs through deletions of the MHC II locus, while chromosomal translocations resulting in CIITA gene fusions in Hodgkin lymphoma cell lines lead to downregulation of MHC II molecules on the cell surface. No similar common genetic alterations have been found in MHC II genes or CIITA in non-IP DLBCL cases and cell lines to date. The mechanism of MHC II downregulation in most DLBCL is currently unknown but may involve a regulatory factor that coordinates MHC class II signature genes as MHC II and associated genes (for example, CD74) are localized on different chromosomes, yet both show reduced expression in DLBCL.

In this study, we have identified a novel relationship between FOXP1 and genes regulated by the CIITA complex, through microarray analyses of FOXP1-silenced DLBCL lines. We have also shown that FOXP1 silencing can lead to an increase in surface MHC II and CD74 in ABC-DLBCL. Furthermore, significant inverse relationships between MHC II molecules and FOXP1 at both the transcript and protein levels have been identified in primary DLBCL samples.

**PATIENTS AND METHODS**

**Patient samples and cell lines**

Reactive tonsils were provided by the John Radcliffe Hospital (Oxford, UK). DLBCL tissue microarrays comprising duplicate 1.0-mm cores from a series of patients uniformly treated in Denmark with R-CHOP with curative intent (n = 160) are as previously described. Table 1 lists clinical characteristics of all patients according to HLA-DRA expression. Informed consent was obtained from all patients in accordance with the Declaration of Helsinki, and local ethical approval was obtained from the Research Ethics Committee South Central—Oxford B (C02.162). DLBCL cell lines were sourced and maintained as described previously; they are regularly immunophenotyped and shown to be mycoplasma free.

**FOXP1 silencing by siRNA**

FOXP1 expression was silenced in DLBCL cell lines by Nucleofection program X-001 in an Amaxa Nucleofector II Device (Lonza, Slough, UK). Briefly, 2x10⁶ cells were electroporated in Solution L supplemented with 1 μM FOXP1-targeting HSS178308 (siFOXP1 #1) or HSS178309 (siFOXP1 #2) Stealth RNAi (Invitrogen, Carlsbad, CA, USA), or negative control siRNA duplex (Stealth RNAi Low GC, Invitrogen), and harvested after 48 h for western blotting and quantitative reverse-transcription PCR (qRT-PCR) analysis. Three independent experiments were performed for samples analyzed by microarray. For immune molecule fluorescence-activated cell sorting studies, OCI-Ly3 cells were subjected to consecutive rounds of silencing at 0 and 72 h, with flow cytometric analysis taking place at 144 h.

**Microarray hybridization for identification of FOXP1-regulated genes**

Triplicate-paired FOXP1 siRNA-treated and control siRNA-treated total RNA samples were hybridized to human whole-genome expression microarrays using a two-color system (Agilent Microarray Design Id:014850; Agilent Technologies LDA UK Limited, Stockport, Cheshire, UK). Arrays were scanned using Feature Extraction (Agilent version 10.5.1.1, Agilent Technologies LDA UK Limited), which applied intra-array linear and loess normalizations. Processed slide image data were imported to GeneSpring GX (Agilent, version 11.5, Agilent Technologies LDA UK Limited) where data derived from 41 078 probes were log₂-transformed and normalized for downstream analysis. The gene expression microarray data have been deposited in the NCBI Gene Expression Omnibus database with accession number GSE71526.

**Microarray data analysis**

To identify genes showing differential expression within cell lines and between subtypes, t-tests and analysis of variance were used. Significance

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**Table 1.** Clinicopathological characteristics of DLBCL patients stratified according to HLA-DRA expression

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>All cases (n = 150)</th>
<th>HLA-DRA &lt; 90% (n = 38)</th>
<th>HLA-DRA ≥ 90% (n = 112)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age (years)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Median</td>
<td>67</td>
<td>70</td>
<td>66</td>
<td>0.2574</td>
</tr>
<tr>
<td>Range</td>
<td>20–91</td>
<td>32–87</td>
<td>20–91</td>
<td></td>
</tr>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female (%)</td>
<td>70 (47)</td>
<td>19 (13)</td>
<td>51 (34)</td>
<td>0.6338</td>
</tr>
<tr>
<td>Male (%)</td>
<td>80 (53)</td>
<td>19 (13)</td>
<td>61 (40)</td>
<td></td>
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<tr>
<td><strong>Stage</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>I–II (%)</td>
<td>81 (54)</td>
<td>15 (10)</td>
<td>66 (44)</td>
<td>0.0376</td>
</tr>
<tr>
<td>III–IV (%)</td>
<td>69 (46)</td>
<td>23 (15)</td>
<td>46 (31)</td>
<td></td>
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<tr>
<td><strong>Performance status</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–1 (%)</td>
<td>129 (86)</td>
<td>31 (21)</td>
<td>98 (65)</td>
<td>0.3634</td>
</tr>
<tr>
<td>&gt; 2 (%)</td>
<td>21 (14)</td>
<td>7 (5)</td>
<td>14 (9)</td>
<td></td>
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<tr>
<td><strong>LDH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤ ULN (%)</td>
<td>89 (59)</td>
<td>16 (11)</td>
<td>73 (48)</td>
<td>0.0123</td>
</tr>
<tr>
<td>&gt; ULN (%)</td>
<td>61 (41)</td>
<td>22 (15)</td>
<td>39 (26)</td>
<td></td>
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<tr>
<td><strong>Extranodal sites</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0–1 (%)</td>
<td>126 (84)</td>
<td>31 (21)</td>
<td>95 (63)</td>
<td>0.6375</td>
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<tr>
<td>&gt; 2 (%)</td>
<td>24 (16)</td>
<td>7 (5)</td>
<td>17 (11)</td>
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<tr>
<td><strong>IPI</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0–2 (%)</td>
<td>89 (59)</td>
<td>25 (17)</td>
<td>80 (53)</td>
<td>0.5120</td>
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<tr>
<td>3–5 (%)</td>
<td>61 (41)</td>
<td>13 (9)</td>
<td>32 (21)</td>
<td></td>
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<tr>
<td><strong>COO (Hans)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCB (%)</td>
<td>88 (59)</td>
<td>14 (9)</td>
<td>74 (50)</td>
<td>0.0016</td>
</tr>
<tr>
<td>Non-GCB (%)</td>
<td>62 (41)</td>
<td>24 (16)</td>
<td>38 (25)</td>
<td></td>
</tr>
<tr>
<td><strong>COO (Choi; n = 147)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCB (%)</td>
<td>94 (64)</td>
<td>18 (12)</td>
<td>76 (52)</td>
<td>0.0135</td>
</tr>
<tr>
<td>Non-GCB (%)</td>
<td>53 (36)</td>
<td>20 (14)</td>
<td>33 (22)</td>
<td></td>
</tr>
<tr>
<td><strong>COO (Visco–Young; n = 148)</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.0088</td>
</tr>
<tr>
<td>GCB (%)</td>
<td>96 (65)</td>
<td>18 (12)</td>
<td>78 (53)</td>
<td></td>
</tr>
<tr>
<td>Non-GCB (%)</td>
<td>52 (35)</td>
<td>20 (13)</td>
<td>32 (22)</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: COO, cell-of-origin; DLBCL, diffuse large B-cell lymphoma; GCB, germinal center B-cell; HLA-DRA, human leukocyte antigen DR alpha chain; IPI, International Prognostic Index; LDH, lactate dehydrogenase; ULN, upper limit of normal. *Three cases (of 150) could not be classified for COO according to Choi algorithm. **Two cases (of 150) could not be classified for COO according to Visco–Young algorithm.
was determined using a P-value of < 0.05 after multiple testing correction (Benjamini–Hochberg) and log₂ ratio of minimum ≥ 0.5 (1.41-fold change). To identify common biological themes within siFOXP1-treated cell lines, Gene Ontology (GO) enrichment analysis was conducted on lists of differentially expressed genes (Supplementary Methods).

qRT-PCR and western blotting
Methods for qRT-PCR and western blotting experiments have been described previously.26 Details of TaqMan probes and gene expression quantification are described in Supplementary Methods, antibodies used for western blotting are shown in Supplementary Table S3.

Flow cytometry for immune cell surface markers
After FOXP1 or control siRNA treatment (144 h), OCI-Ly3 cells were incubated with anti-HLA-DRA-PE (12-9956-42, eBioscience, San Diego, CA, USA) or anti-CD74-PE (12-0748-42, eBioscience) or isotype control antibodies diluted 1:200 in phosphate-buffered saline/0.5% bovine serum albumin/2 mM EDTA. After a wash with phosphate-buffered saline and fixation in 1% formaldehyde, flow cytometric analysis was performed using the FACSCalibur (Becton Dickinson, San Jose, CA, USA) and FlowJo software (Treestar, San Carlos, CA, USA).

Data-mining from published microarray data sets
The Lenz microarray data set comprising gene expression profiling data for 414 DLBCL tumors was obtained from Gene Expression Omnibus (accession number: GSE10846). Further details are provided in Supplementary Methods.

Immunohistochemistry (IHC)
IHC labeling of DLBCL tissue microarrays for FOXP1, HIP1R and COO markers has been described previously.7 Staining for HLA-DRA expression, using 1:50 dilution of mouse monoclonal clone LN-3 (Leica Biosystems Ltd, Newcastle Upon Tyne, UK) was performed after dewashing and heat-mediated antigen retrieval in 50 mM Tris/2 mM EDTA pH9.0, using an EnVision Kit according to the manufacturer’s instructions (DakoCytomation, Glostrup, Denmark). HLA-DRA expression was independently scored by AHB/LL/EJS, who were blinded to the control characteristics. A qualitative score was generated where 3 = strong staining of comparable intensity to normal lymphocytes in tonsil controls (which exhibited homogeneously strong membrane staining) and 2 = moderate, 1 = weak and 0 = no labeling (tumors were only scored as negative when internal controls were positive). A quantitative score was generated for tumor cell positivity in 10% increments. Previous studies of HLA-DR expression in lymphomas selected an area of minimum intensity staining for scoring based on the rationale that these cells are more likely to escape immune surveillance.30 Thus lower frequency and intensity values were exhibited homogeneously strong membrane staining) and 2 = moderate, of comparable intensity to normal lymphocytes in tonsil controls (which

RESULTS
FOXPI depletion from DLBCL cell lines
GCB-DLBCL lines commonly express little FOXP1 protein, but when strongly expressed it is predominantly FOXP1S, while ABC-DLBCL are generally FOXP1+ and express detectable FOXP1, but mostly FOXP1L.8 To assess whether FOXP1S has a distinct role in ABC-DLBCL, knockdown of total FOXP1 expression was performed using two validated FOXP1-targeting siRNAs (Supplementary Figure S1) in two FOXP1+ GCB-DLBCL lines (DB and Karpas 422) and two ABC-DLBCL lines (HBL-1 and OCI-Ly3). For 48 h, FOXP1 proteins were efficiently depleted from these cell lines.

Gene expression profiling and validation of FOXP1 target genes
RNAs prepared from samples with validated FOXP1 silencing after 48 h were hybridized to Agilent human whole-genome expression microarrays, with each FOXP1 siRNA being compared with a non-targeting siRNA control. The two siRNAs used for targeting FOXP1 gave statistically reproducible results in each DLBCL cell line (Supplementary Figure S2). A comparison of individual FOXP1-repressed genes and FOXP1-induced genes (for example, genes induced or repressed, respectively, on FOXP1 silencing) with at least a twofold differential expression revealed few common targets across DLBCL lines, highlighting the difference between the two DLBCL subtypes (Figure 1a). Across all the four cell lines, there were no genes commonly repressed more than twofold by FOXP1, while 47 genes were commonly activated by FOXP1. Within the FOXP1-induced gene set, 76 of the 91 (84%) genes regulated in both ABC-DLBCL lines were also present in at least one other GCB-DLBCL line. In contrast, only 5 of the 31 (16%) genes within the FOXP1-repressed gene set in ABC-DLBCL lines were also present in another GCB-DLBCL line. Thus FOXP1-dependent activation appears conserved in both GCB- and ABC-DLBCL cells, while GCB/ABC-specific functions rendered by FOXP1 are likely achieved through repression of gene expression.

Several genes displaying greatest fold changes were selected for validation by qRT-PCR within the same samples used for the microarray analysis (Supplementary Figure S3) and in an independent sample set including four additional GCB- and ABC-DLBCL lines (Figure 1b). A subset of genes previously associated with FOXP1 in primary DLBCL through correlation with COO classification (LPP,34 NEIL135 and VNN235) were shown to be direct targets of FOXP1 by ChIP in one or more DLBCL lines (Figure 1c). However, where FOXP1 did not appear to bind the gene directly, despite regulating transcript expression (for example, LPP in K422 cells), it is possible that FOXP1 may act indirectly or via additional binding sites as only five promoter regions (with the highest numbers of FOXP consensus sites) were tested for each target. There are several clear differences in FOXP1-dependent activity between ABC- and GCB-DLBCL cells; for example, CHAC1 expression was upregulated in GCB-DLBCL lines but downregulated in a subset of ABC-DLBCL. The analysis of individual FOXP1 target genes validated that the microarray data were reproducible with an independent technique, that the genes were regulated in an extended DLBCL cell line panel and that the data set contained direct FOXP1 targets.

Comparison of biological processes associated with FOXP1 regulation in DLBCL cell lines
Studies involving B-cell receptor signaling and nuclear factor-kB pathway mutations show that multiple genes can be targeted to deregulate the activity of a pathway or biological process and that individual tumors achieve this in various ways.35–37 Thus further analyses were performed to identify biological processes associated with FOXP1 target genes that may be regulated by FOXP1 and their conservation or variation between DLBCL subtypes.
To identify FOXP1-regulated biological processes in GCB- and ABC-DLBCL cell lines, we applied GO enrichment analysis to FOXP1-repressed or FOXP1-induced gene sets with a fold change cutoff of ±1.41 (corresponding to ±0.5 on log2 scale), comparable to other studies. Genes commonly regulated by FOXP1 in GCB- or ABC-DLBCL cells were derived from several distinct biological processes (Figure 2). GO terms (false discovery rate <0.05) enriched in both DB and Karpas 422 (that is, specific for GCB-DLBCL) or both OCI-Ly3 and HBL-1 (that is, specific for ABC-DLBCL) were identified (Supplementary Table S1). GO terms enriched only in a single-cell line were excluded from further analyses as our aim was to identify common or subtype-specific rather than cell line-specific FOXP1 functions.

In the FOXP1-repressed gene sets, ABC-DLBCL cells showed enrichment of immune-related GO terms, including MHC II molecules, regulation of immune responses and leukocyte activation...
Gene expression microarray analysis of FOXP1-overexpressing human B cells has produced similar findings showing regulation of the immune response and leukocyte activation signatures, and thus FOXP1 appears to be a broad controller of multiple B-cell:T-cell interaction molecules in both normal and malignant B cells. FOXP1-dependent targets in GCB-DLBCL cell lines exhibited enrichment for distinct GO terms related to neuron components and regulation of metabolic processes.

Within FOXP1-induced gene sets, both GCB- and ABC-DLBCL cell lines showed enrichment of GO terms pertaining to cell movement (Figure 2b), suggesting a common function of FOXP1 in activating migration. These observations are consistent with the Venn diagrams described earlier (Figure 1a) in which a higher proportion of genes shared by GCB- and ABC-DLBCL cell lines was found in FOXP1-induced gene sets but not in the FOXP1-repressed gene sets.

Figure 2. GO enrichment analysis of the biological processes influenced by FOXP1 silencing in GCB- and ABC-DLBCL cells. (a) GO terms enriched in FOXP1-repressed gene sets (that is, genes upregulated by FOXP1 depletion). GO terms significantly enriched in ABC-DLBCL, but not in GCB-DLBCL, cells include MHC II complexes, regulation of immune responses and leukocyte activation. (b) GO terms enriched in FOXP1-induced gene sets (that is, genes downregulated by FOXP1 depletion). Both GCB- and ABC-DLBCL cells share GOs related to cell movement. The graphs were plotted on a negative log10 scale (higher −log10 value denotes more significant false discovery rate (FDR) value) and the actual linear FDR values are shown next to each bar.
FOXP1 silencing in ABC-DLBCL cells upregulates MHC II expression. MHC II genes were not individually among the most highly upregulated on FOXP1 silencing but were frequently repressed by FOXP1 in the ABC-DLBCL cell lines along with the non-MHC CIITA target gene CD74 and CIITA itself (Figure 3a). For example, in OCI-Ly3, 13 of the 18 (72%) MHC II transcripts were upregulated >1.41-fold on FOXP1 silencing, with 7 of the 18 (39%) being regulated in HBL-1. No MHC II genes were upregulated significantly in DB or Karpas 422 lines. To obtain a global view of transcript expression, we visualized the expression levels of selected MHC II genes against a background of 41,000 probes (excluding control probes) present on the microarray on scatter plots. None of the MHC II genes or the known direct FOXP1 target HIP1R were significantly upregulated in both GCB-DLBCL lines (Figure 3b), whereas HIP1R and five CIITA-regulated genes (CD74, HLA-DQB1, HLA-DQB2, HLA-DOA, HLA-DMA) were significantly upregulated in both FOXP1-depleted OCI-Ly3 and HBL-1 lines. The established contribution of MHC II downregulation to poor clinical outcomes and its correlation with the ABC-DLBCL subtype in primary DBLCL led us to further explore their relationship with FOXP1.\(^\text{13,17}\)

To validate the effect of FOXP1 depletion on MHC II expression at the protein level, flow cytometric analysis was performed on FOXP1-depleted OCI-Ly3 (Figure 4a). The surface levels of CD74 and HLA-DRA (the most abundant MHC II protein) were upregulated in both siFOXP1 #1- and #2-treated OCI-Ly3 compared with the control siRNA-treated cells. Supplementary Figure S4 illustrates similar data from additional ABC-DLBCL cell lines and downregulation of CD74 and HLA-DRA on FOXP1 silencing in the GCB-DLBCL cell line Karpas 422.

FOXP1 was inversely correlated with the antigen processing and presentation pathway and individual MHC II transcripts in primary DBLCL.

Gene Set Enrichment Analysis identified a significant inverse correlation between ‘antigen processing and presentation’ signature (entry no. hsa04612; KEGG database) and four independent FOXP1 probes in a primary DBLCL microarray data set \((n=414; \text{GSE10846: Figure 4b})\).\(^\text{19}\) MHC II genes contributing to the core enrichment of the gene set on a negative scale, in all four FOXP1 probes, included HLA-DRA, HLA-DMA, HLA-DQB1, HLA-DOA, and HLA-DPB1 (Supplementary Table S2). The relationship

Figure 3. Heat maps and scatter plots illustrating differential expression of MHC class II and other genes in FOXP1-depleted DBLCL cell lines. (a) Heat map showing differential expression of genes between ABC- and GCB-DLBCL cells involved in the MHC II protein complex and immune response (upregulated in FOXP1-depleted ABC-DLBCL cells) or metabolic processes, neuron projection and apoptosis (upregulated in FOXP1-depleted GCB-DLBCL cells). Each column in the heat map represents the fold-change in gene expression between the siRNA control and the FOXP1 targeting siRNA for two independent FOXP1 siRNAs (labeled si #1 and si #2) in each DLBCL cell line. Rows show individual genes. (b) Scatter plot analysis of gene expression profiling \((n=41\,000\) probes) for FOXP1-silenced DB (x axis) versus K422 (Karpas 422) (y axis) cell lines. The cutoff on the positive or negative scale on both x and y axis corresponds to ±1.41-fold cutoff change. Individual MHC II genes were not significantly upregulated but are illustrated because of the importance of the overall pathway. (c) Scatter plot analysis of gene expression profiling \((n=41\,000\) probes) for FOXP1-silenced OCI-Ly3 (x axis) versus HBL-1 (y axis) cell lines with ±1.41-fold as cutoff values for both x and y axis. Codes used to generate Figures 3b and c are available on request (by e-mail).
Figure 4. FOXP1 silencing increases HLA-DRA expression in ABC-DLBCL while FOXP1 transcripts are inversely correlated with antigen processing/presentation and with individual MHC II genes in primary DLBCL. (a) Knockdown of FOXP1 in OCI-Ly3 cells increased HLA-DRA and CD74 protein expression on the cell surface. Flow cytometry plots shown are representative of three independent experiments. (b) Gene Set Enrichment Analysis of primary DLBCL cases (n = 414; GSE10846) for gene sets associated with FOXP1 transcript expression; the ‘antigen processing and presentation’ signature was significantly enriched according to four independent FOXP1 probes (P < 0.05; false discovery rate < 0.25). (c) Significant (P < 0.05) inverse correlations between FOXP1 (223287_s_at) and selected MHC II transcripts (HLA-DRA, 210982_s_at; HLA-DMB, 217478_s_at and HLA-DQB1, 212999_x_at) in primary ABC-DLBCL (n = 167) and GCB-DLBCL (n = 183) cases derived from data set GSE10846.
between FOXP1 and individual MHC II genes was further evaluated within GCB (n = 183) or ABC (n = 167) molecularly defined DLBCL subtypes: FOXP1 displayed significant inverse relationships (r < -0.15; P < 0.05) with HLA-DRA, HLA-DMB and HLA-DQB1 in both DLBCL subtypes (Figure 4c). Thus, in contrast to our in vitro studies with pure lymphoma cell populations, primary DLBCL biopsies containing the tumor cells and their microenvironment exhibit a relationship between MHC II and FOXP1 gene expression independently of COO subtype. A differential relationship between FOXP1 transcripts and FOXP1 proteins in GCB- and ABC-DLBCL cells could also explain this phenomenon.

Analysis of HLA-DRA protein expression in primary DLBCL

We therefore specifically studied the relationship between FOXP1 and MHC II molecules and DLBCL subtype at the protein level in primary DLBCL using IHC. HLA-DRA was selected for further studies as it is the most highly expressed MHC II protein, there is a commercially available paraffin reactive monoclonal antibody (clone LN-3) and HLA-DRA has been previously demonstrated to have clinical relevance at both the transcript and protein level in CHOP-treated DLBCL.13,17,40 As there was no previously reported clinically relevant IHC cutoff for HLA-DRA expression in R-CHOP-treated patients, both the intensity and frequency of HLA-DRA expression were initially assessed. A number of DLBCL exhibited reciprocal patterns of FOXP1 and HLA-DRA expression (Figure 5a). COO subtyping was previously demonstrated to be clinically relevant in this series,7 and the frequency of HLA-DRA expression was significantly lower in non-GCB DLBCL subtyped using either the Hans,43 Choi44 or Visco–Young45 IHC algorithms (all P < 0.01; Figure 5b).

HLA-DRA expression was evaluable for 150/152 tissue microarray cases (98.7%). Quantitative frequency expression data were primarily used to investigate the clinical relevance of HLA-DRA expression as the qualitative intensity of expression was found to be less clinically relevant in initial tests (Figure 6). Testing different frequency cutoff scores indicated that cutoffs of 80% or 90% were most clinically relevant in terms of patients’ outcome. It was observed that more non-GCB DLBCL than GCB-DLBCL exhibited a score of 80% HLA-DRA positivity (Figure 5b), therefore the cutoff for HLA-DRA expression was set at ≥90% to capture this difference between the COO subtypes and its better prediction of progression-free survival (PFS).

Reduced frequency HLA-DRA expression was significantly associated with markers of high-risk disease and poor outcome HLA-DRA expression levels were independent of patients’ age, sex, performance status, the number of extranodal sites and the International Prognostic Index (IPI) (Table 1). Reduced HLA-DRA frequency of expression (≤90%) correlated with several indicators of high-risk disease, including elevated lactate dehydrogenase (P = 0.0123), higher stage (P = 0.0376) and a non-GCB phenotype (Hans, P = 0.0016; Choi, P = 0.0135; Visco–Young, P = 0.0088).

Figure 5. HLA-DRA expression and its relationship with FOXP1, COO and clinical outcome in primary DLBCL patients. (a) Representative DLBCL cases with inverse FOXP1 and HLA-DRA expression patterns by immunohistochemical labeling and photographed at ×200 magnification. DLBCL-1 biopsy was scored 100% for HLA-DRA positivity and 0% for FOXP1-positive cells. DLBCL-2 biopsy was scored 0% and 90% for HLA-DRA and FOXP1 labeling, respectively. (b) Frequency of HLA-DRA positivity in GCB- and non-GCB-DLBCL cases is significantly different (P < 0.05), as classified by Hans, Choi and Visco–Young algorithms. (c) Kaplan–Meier curves of OS (left panel) and PFS (right panel) in high (≥90%) or low (<90%) HLA-DRA expressing groups of DLBCL patients (n = 150) showed worse outcome for patients exhibiting < 90% HLA-DRA positivity.
Consistent with these findings, patients with reduced HLA-DRA expression (<90%) were found to have significantly worse OS (P = 0.0003) and PFS (P = 0.0012) (Figure 5c), corresponding to 5-year OS rates of 72% versus 38% and 5-year PFS rates of 63% versus 36%. Patients with reduced intensity HLA-DRA expression also exhibited poor OS (P = 0.0091) and PFS (P = 0.0103) (Supplementary Figure S5A), although this was less significant than the quantitative score.

Reduced frequency HLA-DRA expression identified patients with inferior outcome in low-risk IPI and COO subgroups

Reduced frequency of HLA-DRA expression identified a subgroup (23.8%) of high-risk patients in the low-risk IPI group (score 0–2) (P = 0.0008; Supplementary Figure S5B) and in the low-risk GCB subgroups (Hans (15.9%), P = 0.0089; Choi (19.1%), P = 0.0028; Visco–Young (18.8%), P = 0.0084; Supplementary Figure S6), irrespective of the subtyping algorithm used. No significant differences were observed within the high-risk IPI group or the non-GCB DLBCL subgroup, although there was a trend toward lower expression and worse outcome (Supplementary Figures S5B and S6). In multivariate analyses, the association of reduced (<90%) HLA-DRA expression with poor OS and PFS remained significant, being independent of a high IPI score and non-GCB phenotype (Table 2).

The reciprocal expression of FOXP1 and its direct target HIP1R is associated with HLA-DRA in primary DLBCL

There was significantly higher-intensity HLA-DRA protein expression in patients whose tumors lacked FOXP1 expression (P = 0.0373) or showed only weak FOXP1 expression (P = 0.0359) than in those with strong FOXP1 expression (Figure 6a). No significant correlation between the frequency of FOXP1 and HLA-DRA expression was observed (P = 0.2248; Supplementary Figure S7A). However, among DLBCL with reduced HLA-DRA expression (<90%) there was a reciprocal relationship between both their frequency (P = 0.0456) and intensity (P = 0.0349) in the non-GCB subtype (Figure 6b and Supplementary Figure S7B), which was not observed in GCB-DLBCL (Supplementary Figure S7C). There was a significant positive relationship between the frequency of expression of HLA-DRA and a direct FOXP1 target, HIP1R (P = 0.0008), although not with their intensity (Supplementary Figure S7D). We previously demonstrated that reciprocal frequency expression of FOXP1 (≥70%) and HIP1R (<10%), the FOXP1HIP1R phenotype, in this DLBCL series was more clinically relevant than either marker alone and hypothesized that this might represent a preferential measure of FOXP1S transcriptional activity.1 Interestingly, patients with reciprocal patterns of FOXP1 and HIP1R expression exhibited significantly reduced intensity (P = 0.0405) and frequency (P = 0.0300) of HLA-DRA expression (Figure 6c).

**DISCUSSION**

Here we compare the patterns of gene expression regulated by FOXP1, in GCB-DLBCL and predominantly FOXP1S expressed in ABC-DLBCL. Differences between FOXP1 targets in DLBCL molecular subtypes suggest that distinct FOXP1 isoforms in combination with their different genetic backgrounds generate significant functional differences. The analysis of individual FOXP1 target genes identifies several direct targets, in addition to HIP1R7.
whose expression contributes to the GCB-DLBCL COO signature, including \( \text{LPP}^{33} \), \( \text{VNN2}^{33} \) and \( \text{NEIL1}^{34} \). This is consistent with data from Sagardoy et al.,\(^{46} \) demonstrating that FOXP1 regulates genes involved in the GC reaction and that downregulation of FOXP1 is required for GCB function.

Although microarray analysis and ChIP-sequencing previously identified FOXP1 as a transcriptional repressor of immune signaling in the central nervous system,\(^{13} \) our study is the first to identify FOXP1 as a regulator of MHC II expression. Gene expression profiling studies in primary DLBCL identified an MHC class II gene expression signature conferring a favorable prognosis in CHOP-treated patients.\(^{47} \) This was presumed to be a consequence of effective presentation of tumor antigens to the immune system, as lower numbers of CD8\(^+\) tumor-infiltrating lymphocytes were previously observed in sporadic DLBCL that had lost one or more class I or class II HLA proteins\(^{48} \) and subsequently in those with low MHC II transcript and protein expression.\(^{41} \) Several studies have demonstrated a relationship between loss of MHC II expression in chemotherapy-treated DLBCL and poor outcome.\(^{13,17,40-42} \) However, other studies have found no relationship between HLA-DRA expression and clinical outcome.\(^{49,50} \)

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>OS (95% CI)</th>
<th>Hazard ratio</th>
<th>P-value</th>
<th>PFS (95% CI)</th>
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<tr>
<td>IPI ≥ 3</td>
<td>1.77–5.14</td>
<td>3.02</td>
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Abbreviations: CI, confidence interval; COO, cell-of-origin; DLBCL, diffuse large B-cell lymphoma; GCB, germinal center B-cell; HLA, human leukocyte antigen; IPI, International Prognostic Index; OS, overall survival; PFS, progression-free survival; R-CHOP, rituximab, cyclophosphamide, doxorubicin, vincristine, and prednisone. Note: IPI and low HLA-DRA expression (< 90%) were analyzed separately with regards to non-GCB phenotype determined using three different algorithms.

There have been few studies of the clinical relevance of HLA-DRA in the post-rituximab era. However, low transcript levels of HLA-DRB and HLA-DQA1 (< 20%) and high levels of MHC (≤ 80%), determined using a quantitative nuclease-protection assay, were predictors of poor prognosis in 116 R-CHOP-treated DLBCL.\(^{51} \) Interestingly, FOXP1 may functionally link these two observations, as repression of microRNA-34a by MYC has been reported to enable high-level FOXP1 protein expression,\(^{52} \) which may then functionally repress MHC II transcription. HLA-DRA expression (>1% cutoff for positive versus negative), assessed using the Dako M0746 antibody, did not predict outcome in either CHOP or R-CHOP cohorts from the large German RICOVER-60 trial.\(^{51} \) The Lunenburg Lymphoma Biomarker Consortium found HLA-DR expression, scored as negative versus positive, predicted OS in one of their two CHOP-treated cohorts and not in CHOP-treated patients who had received rituximab.\(^{54} \) In addition, a recent flow cytometry study of a small series of 36 Japanese patients reported that DLBCL patients with ‘not bright’ HLA-DR staining had a poor prognosis.\(^{35} \)

In the current series of 150 homogeneously R-CHOP-treated de novo DLBCL patients, reduced frequency of HLA-DRA protein expression predicted both poor OS and PFS. Previous studies have tended to compare tumors with complete loss of HLA-DRA expression or those with the lowest 10–20% expression (in some studies based on MHC II transcript analyses). We elected to use a 90% cutoff to distinguish cases with reduced HLA-DRA expression on the basis that this was the most predictive of outcome and would identify patients where tumor cells might be capable of escaping immune surveillance. However, >10% frequency of positivity cutoff in the current series was also able to significantly predict poor OS (\( P = 0.035 \)), while a ≥ 20% cutoff predicted both OS (\( P = 0.0067 \)) and PFS (\( P = 0.0379 \)).

Several components of the CIITA complex have been identified through their contribution to loss of MHC II gene expression in bare lymphocyte syndrome patients.\(^{56} \) However, the embryonic lethality associated with Foxp1 deletion in mice\(^{57} \) may explain why FOXP1 has no bare lymphocyte syndrome association. Unlike most DLBCL, testicular lymphomas commonly display genetic deletions of the MHC II genes. The recent identification of genetic rearrangements of CIITA and FOXP1 in primary testicular DLBCL\(^{58} \) provides independent evidence of their functional connection. Further studies are needed to determine the mechanism(s) by which FOXP1 regulates MHC II gene expression. Previous studies in DLBCL have suggested that the mechanism is not via regulation of CIITA expression but rather through an unknown transcriptional regulator.\(^{40,42} \) Certainly FOXP1 silencing in ABC-DLBCL can increase the transcription and cell-surface expression of molecules under the transcriptional control of the CIITA complex, such as HLA-DRA and CD74. A direct interaction with components of the CIITA complex may be one mechanism by which FOXP1 regulates its activity. Further studies are ongoing to explore this possibility, and our data mining of previously published FOXP1 ChIP-seq data\(^{39} \) has already confirmed that FOXP1 can indeed occupy HLA, CIITA and CD74 promoters in DLBCL cells, including the OCI-Ly3 cell line studied here (Supplementary Table S6).

To the best of our knowledge, we are the first to identify FOXP1 as a novel MHC II regulator. FOXP1 expression contributes to pathogenic MHC II downregulation in DLBCL and may also be important for its normal role in B cells where FOXP1\(^{33} \) is induced during B-cell activation/maturation.\(^{9} \) Targeting the FOXP1 pathway as both a useful biomarker and a novel therapeutic target for restoring antigen presentation and immune surveillance in DLBCL.

**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

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**Table 2. Multivariate analysis for OS and PFS in DLBCL patients treated with R-CHOP according to IPI, HLA-DRA expression and COO**

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ACKNOWLEDGEMENTS

We acknowledge the significant contributions made by Dr Philip Brown who sadly died before the completion of this study and drafting of the manuscript. This work was funded by a Programme grant from Leukaemia and Lymphoma Research (13047) and Research University grant (1001/PPSP/813054) from Universiti Sains Malaysia.

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Supplementary Information accompanies this paper on the Leukemia website (http://www.nature.com/leu)