Molecular characterisation of lupus low disease activity state (LLDAS) and DORIS remission by whole-blood transcriptome-based pathways in a pan-European systemic lupus erythematosus cohort

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ABSTRACT

Objectives To unveil biological milieus underlying low disease activity (LDA) and remission versus active systemic lupus erythematosus (SLE).

Methods We determined differentially expressed pathways (DEPs) in SLE patients from the PRECISESADS project (NCT02890121) stratified into patients fulfilling and not fulfilling the criteria of (1) Lupus LDA State (LLDAS), (2) Definitions of Remission in SLE remission, and (3) LLDAS exclusive of remission.

Results We analysed data from 321 patients; 40.8% were in LLDAS, and 17.4% in DORIS remission. After exclusion of patients in remission, 28.3% were in LLDAS. Overall, 604 pathways differed significantly in LLDAS versus non-LLDAS patients with an false-discovery rate-corrected p (q)<0.05 and a robust effect size (dr)>0.36. Accordingly, 288 pathways differed significantly between DORIS remitters and non-remitters (q<0.05 and dr>0.36). DEPs yielded distinct molecular clusters characterised by differential serological, musculoskeletal, and renal activity. Analysis of partially overlapping samples showed no DEPs between LLDAS and DORIS remission. Drug repurposing potentiality for treating SLE was unveiled, as were important pathways underlying active SLE whose modulation could aid attainment of LLDAS/remission, including toll-like receptor (TLR) cascades, Bruton tyrosine kinase (BTK) activity, the cytotoxic T lymphocyte antigen 4 (CTLA-4)-related inhibitory signalling, and the nucleotide-binding oligomerization domain leucine-rich repeat-containing protein 3 (NLRP3) inflamasome pathway.

Conclusions We demonstrated for the first time molecular signalling pathways distinguishing LLDAS/remission from active SLE. LLDAS/remission was associated with reversal of biological processes related to SLE pathogenesis and specific clinical manifestations. DEP clustering by remission better grouped patients compared with LLDAS, substantiating remission as the ultimate treatment goal in SLE; however, the lack of substantial pathway differentiation between the two states justifies LLDAS as an acceptable goal from a biological perspective.

INTRODUCTION

Systemic lupus erythematosus (SLE) is a multi-system autoimmune disease that is characterised by heterogeneity of immunological aberrancies and clinical manifestations.1 The disease exhibits relapsing-remitting patterns, with acute inflammatory tissue injury that needs prompt and effective therapy, aiming for remission which is characterised by quiescence in terms of clinical features. Treating to remission, or to low disease activity when
remission is not achievable, emerged as a conceptual framework for the management of SLE in 2014,2 which was later endorsed in the 2019 and the 2023 European Alliance for Associations for Rheumatology (EULAR) updates of the recommendations for the management of SLE.3 4 5

Several definitions of remission have been proposed, yet the prevailing definition by the Definitions of Remission in SLE (DORIS) taskforce6 is the one most frequently used in studies.5 Likewise, several criteria have been proposed to define low disease activity, with the lupus low disease activity state (LLDAS)6 7 being the most frequently used. Attainment of DORIS remission and LLDAS has been coupled with prevention of organ damage8 9 and favourable experience of health-related quality of life,10 which substantiates their relevance as treatment goals, but the biological milieu underlying these states and how these differ from lupus biology during active disease have yet to be explored.

RNA from whole-blood samples collected with RNA stabilisers allows the study of large populations in multicentre studies, mitigating technical and source variability that limits the reproducibility of results and introduces methodological bias,11 and has therefore been proven useful in the context of autoimmune diseases.12-14 RNAseq data are commonly interpreted on analysis of differentially expressed (DE) genes at a single-gene level, which substantially limits statistical power as well as interpretability due to redundant results not accounting for similarity across genes. Gene-set analysis has been proposed as an attempt to overcome this issue,15 through grouping similar transcripts belonging to specific pathways, thus allowing the interpretation of results in the context of biologically related groups of genes (ie, DE pathways (DEPs)). Among several existing methods, the Functional Analysis of Individual Microarray Expression (FAIME) algorithm has proven particularly powerful,16 as shown in our previous results from a multicohort study.12 Along with this analysis, the Reactome Knowledgebase17 that systematically links protein-coding genes to their molecular functions can be used to annotate pathways of interest and to discover functional biological relationships.

The above formed the scope of the present investigation, where we aimed at determining DEPs in LLDAS versus non-LLDAS as well as in remission versus non-remission states in European patients with SLE.

METHODS

Patients and controls

Patients with a diagnosis of SLE according to the revised 1997 American College of Rheumatology (ACR) classification criteria18 and/or the 2012 Systemic Lupus International Collaborating Clinics (SLICC) criteria,19 who participated in the PRECISESADS project20 (NTC02890121) were included in the present study. Clinical data were extracted from the PRECISESADS SLE substudy case report forms and included Systemic Lupus Erythematosus Disease Activity Index 2000 (SLEDAI-2K) scores,21 Physician Global Assessment (PGA; scale 0–3), and detailed information about therapies, which allowed stratification of the study population into patients fulfilling and not fulfilling the criteria of (1) LLDAS,2 (2) DORIS remission,2 and (3) LLDAS after exclusion of patients in remission. As per study protocol, none of the patients had been treated with cyclophosphamide within 6 months and/or deleterious therapies within 12 months prior to sampling.

The study protocol was reviewed and approved by local ethics committees at all recruiting centres. All patients provided written informed consent for participation in the PRECISESADS project. The present research has been reviewed and approved by the Swedish Ethical Review Authority (registration number: 2022-03907-01).

Procedures

A detailed description of the methodology followed for the RNAseq, DEP, and druggability analyses, including statistical procedures, can be found in the online supplemental material, pages 3–10.

RESULTS

Clinical characteristics

Complete clinical data were available for 321 patients (n=310 for LLDAS; n=321 for DORIS remission). Baseline characteristics and demographics are summarised in table 1. A total of 131 patients (40.8%) were in LLDAS, while 56 (17.4%) were in DORIS remission; 75 of 265 non-remission patients (28.3%) were in LLDAS. Patients in LLDAS (n=23/131 (17.6%) vs n=79/179 (44.1%); p=0.013) as well as patients in DORIS remission (n=10/56 (17.9%) vs n=96/265 (36.2%); p=0.013) were less likely to be currently treated with immunosuppressants compared with patients not fulfilling the criteria of LLDAS or DORIS remission, respectively.

No differences regarding the use of hydroxychloroquine (HCQ), anti-dsDNA positivity, or complement consumption...
were observed between patients in DORIS remission and non-remission individuals. By contrast, LLDAS patients were less frequently hypocomplementemic (n=50/131 (38.2%) vs n=107/179 (59.8%); p<0.001) and positive for anti-dsDNA (n=27/131 (20.6%) vs n=94/179 (52.5%); p<0.001) compared with non-LLDAS subjects, but no difference was noted regarding the proportion of patients on HCQ between the two groups. Patients fulfilling the LLDAS criteria had a mean dose of prednisone equivalents of 1.54 (±2.32) mg/day, patients in DORIS remission had a mean dose of 0.71 (±1.56) mg/day, and patients in LLDAS exclusive of remission had a mean dose of 2.08 (±2.58) mg/day. Patients not in LLDAS had a mean dose of prednisone equivalents of 4.59 (±5.14) mg/day, and patients not in DORIS remission had a mean dose of 3.83 (±4.68) mg/day.

**Reactome pathway analysis in LLDAS versus non-LLDAS**

Overall, 604 pathways differed significantly between patients who fulfilled the LLDAS criteria and patients who did not with a false-discovery rate (FDR)-corrected p (q)<0.05 and a robust effect size (dr)≥0.36 (online supplemental material, sheet 1; figure 1A); of those, 226 pathways were downregulated and 378 were upregulated in patients in LLDAS compared with the non-LLDAS population; 218 and 366 pathways, respectively, fulfilled the statistical selection criteria for root comparison (count of Reactome roots>3; online supplemental material, sheet 2). The proportion of pathways among those with a positive correlation with LLDAS exceeded the proportion of pathways among those with a negative correlation within three roots: DNA repair (n=34/366 (9.3%) vs n=1/218 (0.3%); q=4.1×10⁻⁵), metabolism of RNA (n=31/366 (8.5%) vs n=0/218 (0.0%); q=1.8×10⁻⁸), and cell cycle-related pathways (n=41/366 (11.2%) vs n=2/218 (0.9%); q=1.8×10⁻⁸). Conversely, higher proportions among pathways with negative correlations with LLDAS were observed within roots for the immune system (n=44/218 (20.2%) vs n=24/366 (6.6%); q=3.5×10⁻⁹), extracellular matrix organisation (n=6/218 (2.8%) vs n=0/366 (0%); q=0.007), and metabolism-related pathways (n=52/218 (23.9%) vs n=21/366 (5.7%); q=4.9×10⁻⁸).

After clustering analysis, three distinct groups of patients could be identified, as illustrated in figure 2A (separation of classes among clusters: χ²=25.3; p<0.001). Clusters 1 and 2 comprised the highest proportions of patients in LLDAS (n=49/91 (53.8%) and n=70/148 (47.3%), respectively), while cluster 3 had the lowest LLDAS prevalence (n=12/71 (16.9%)). Clusters 1 and 3 were distinctly different in terms of enriched pathways, while cluster 2 was characterised by a mixed pattern.

The prevalence of clinical features in the musculoskeletal, mucocutaneous, and renal domains differed across the three biological clusters, as did the use of immunosuppressants, the latter being less prevalent in the LLDAS-enriched clusters 1 and 2 (table 2). Cluster 3 was characterised by an increased prevalence of hypocomplementemia and anti-dsDNA positivity compared with the LLDAS-enriched clusters 1 and 2.

**Reactome pathway analysis in DORIS remission versus non-remission**

A total of 1465 unique Reactome pathways were selected for analysis. Overall, 288 pathways differed significantly (q<0.05 and dr≥0.36) between DORIS remitters and non-remitters with a FDR-corrected p (q)<0.05 and a robust effect size (dr)≥0.36 (online supplemental material, sheet 3; figure 1B); of those, 97 were found to be downregulated and 191 upregulated in DORIS remitters compared with the non-remission population;
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82 and 172 pathways, respectively, qualified for statistical analysis, that is, they had Reactome roots with >5 entries (online supplemental material, sheet 4). The proportion of pathways among those with a positive correlation with DORIS remission exceeded the proportion of pathways among those with a negative correlation within four roots: DNA repair (n=21/172 (12.2%) vs n=0/82 (0.0%); q=6.7×10^{-4}), metabolism of RNA (n=20/172 (11.6%) vs n=0/82 (0.0%); q=6.7×10^{-4}), signal transduction (n=32/172 (18.6%) vs n=5/82 (6.1%); q=0.015), and gene expression (n=9/172 (11%) vs n=1/82 (1.2%); q=0.005). Conversely, higher proportions of negative correlations with DORIS remission were observed for roots within the immune system (n=39/82 (47.6%) vs n=16/172 (9.3%); q=2.2×10^{-11}) and metabolism-related pathways (n=22/82 (26.8%) vs n=7/172 (4.1%); q=6×10^{-7}).

After clustering analysis of significant pathways, three distinct groups of patients could be identified, as illustrated in figure 2B (separation of classes among clusters, \( \chi^2=12.3; p=0.002 \)). Cluster 1 encompassed the highest proportion of patients in DORIS remission (n=25/93; 26.9%), while cluster 3 encompassed the lowest proportion of DORIS remitters (n=6/86; 7%); these two clusters showed distinctly different biological phenotypes and separation of over-expressed and under-expressed Reactome pathways. Cluster 2 had an intermediate number of

Figure 2 Clusters of individualised Reactome pathways. Individualised Reactome pathways after clustering of selected features associated with (A) LLDAS or (B) DORIS remission. The bars to the right illustrate the distribution of relevant clinical features across clusters. Cluster 1, LLDAS/DORIS remission-enriched cluster; cluster 2, mixed cluster; cluster 3, non-LLDAS/DORIS remission cluster; DORIS, definitions of remission in systemic lupus erythematosus; LLDAS, lupus low disease activity state.

Table 2 Summary of clinical features in Reactome pathway clusters

<table>
<thead>
<tr>
<th>Feature, n (%)</th>
<th>Clusters by LLDAS (n=310)</th>
<th>Clusters by DORIS remission (n=321)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORIS remission</td>
<td>21 (23.1%)</td>
<td>31 (20.9%)</td>
<td>4 (6.6%)</td>
</tr>
<tr>
<td>LLDAS</td>
<td>49 (53.8%)</td>
<td>70 (47.3%)</td>
<td>12 (16.9%)</td>
</tr>
<tr>
<td>CNS</td>
<td>8 (8.8%)</td>
<td>13 (8.8%)</td>
<td>5 (7.0%)</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>8 (8.8%)</td>
<td>21 (14.2%)</td>
<td>19 (26.8%)</td>
</tr>
<tr>
<td>Renal</td>
<td>11 (12.1%)</td>
<td>30 (20.3%)</td>
<td>24 (33.8%)</td>
</tr>
<tr>
<td>Mucocutaneous</td>
<td>38 (41.8%)</td>
<td>73 (49.3%)</td>
<td>44 (62%)</td>
</tr>
<tr>
<td>Serositis</td>
<td>1 (1.1%)</td>
<td>3 (2.0%)</td>
<td>3 (4.2%)</td>
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<tr>
<td>Positive serology</td>
<td>59 (64.8%)</td>
<td>86 (58.1%)</td>
<td>52 (73.2%)</td>
</tr>
<tr>
<td>Low C3/C4 levels</td>
<td>42 (46.1%)</td>
<td>70 (47.3%)</td>
<td>45 (63.4%)</td>
</tr>
<tr>
<td>Anti-dsDNA (+)</td>
<td>33 (36.3%)</td>
<td>51 (34.5%)</td>
<td>37 (52.1%)</td>
</tr>
<tr>
<td>Altered CBC</td>
<td>18 (19.8%)</td>
<td>28 (18.9%)</td>
<td>17 (23.9%)</td>
</tr>
<tr>
<td>Leucopenia</td>
<td>16 (17.6%)</td>
<td>21 (14.2%)</td>
<td>14 (19.7%)</td>
</tr>
<tr>
<td>Thrombocytopenia</td>
<td>3 (3.3%)</td>
<td>11 (7.4%)</td>
<td>6 (8.4%)</td>
</tr>
<tr>
<td>Hydroxychloroquine</td>
<td>68 (74.7%)</td>
<td>102 (69.0%)</td>
<td>53 (74.6%)</td>
</tr>
<tr>
<td>Immunosuppressors</td>
<td>18 (19.8%)</td>
<td>44 (29.7%)</td>
<td>40 (56.3%)</td>
</tr>
</tbody>
</table>

Prevalence of clinical and laboratory features in clusters from significantly differential Reactome pathways. P values are derived from Pearson’s χ² squared (χ²) or Fisher’s exact tests. Significant results are in bold.

DORIS remitters (n=25/142; 17.6%) and a biological mixture of pathways without a clear-cut distinct biotype. The three clusters were characterised by a different prevalence of musculoskeletal and renal activity, as well as use of immunosuppressants, with an apparent trend across clusters from the lowest prevalence in DORIS remission-enriched cluster 1, to intermediate prevalence in the mixed cluster 2, and the highest prevalence in cluster 3 that comprised the lowest proportion of DORIS remitters, as summarised in table 2. Differences were observed concerning positive serology, hypocoomplementemia, and anti-dsDNA positivity, yet with no clear trend (lower prevalence in cluster 2). No other differences were observed.

Reactome pathway analysis in DORIS remission versus LLDAS exclusive of remission versus non-LLDAS

Analysis of adjacent levels of disease activity using forward difference coding in linear regression models showed no DEPs between patients in DORIS remission compared with patients in LLDAS after suppression of patients in DORIS remission. This comparison was deemed sufficient for testing the null hypothesis of equivalence of the means between the partially overlapping samples of patients in DORIS remission and patients in LLDAS. Of contrast, 662 DEPs were documented between patients in LLDAS after suppression of DORIS remitters and the non-LLDAS patient population (online supplemental material, sheet 5).

Analysis of Reactome pathways in relation to renal involvement and other clinical manifestations

The expression of Reactome pathways within the renal domain showed that 223 pathways were differentially expressed with q<0.05 and dr≥0.36 (online supplemental material, sheet 6); of these, 141 were upregulated and 82 were downregulated in patients with current renal activity versus patients no renal activity, 123 and 77, respectively, qualifying for association analysis (online supplemental material, sheet 7). Renal involvement was positively associated with enriched metabolic (renal involvement: n=39/123 (31.7%)) vs no renal involvement: n=177 (1.3%); q=4.8×10⁻⁴) and signal transduction pathways (renal involvement: n=37/123 (30.1%) vs no renal involvement: n=3/66 (3.9%); q=4.8×10⁻⁴) and negatively associated with cell cycle processes (renal involvement: n=0/123 (0.0%) vs no renal involvement: n=10/777 (14.0%); q=1.1×10⁻⁴), DNA repair (renal involvement: n=0/123 (0.0%) vs no renal involvement: n=18/77 (25.0%); q=4.8×10⁻⁴), and metabolism of RNA (renal involvement: n=37/123 (30.1%) vs no renal involvement: n=37/77 (3.9%); q=1.1×10⁻⁴). Only 19 pathways were found to be associated with haematological manifestations, which limited us from conducting association tests. Exploratively, it was found that four immune system pathways related to IFN functions were positively correlated with haematological manifestations, including IFN-α/β signalling (q=0.046; dr=0.417) and IFN-γ signalling (q=0.0488; dr=0.414). No other associations were found between Reactome pathways and musculoskeletal, mucocutaneous, pulmonary, neurological, and serological features of disease.

Exploratory analysis showed that several pathways were correlated with SLEDAI-2K scores (online supplemental material, sheet 8), although with a small effect size (Cohen’s f²≥0.02); of these, 121 had a negative correlation and 92 a positive correlation, 114 and 80, respectively, qualifying for association analysis (online supplemental material, sheet 9). Consistent with LLDAS and DORIS remission, which incorporate SLEDAI-2K, increasing scores were negatively associated with DNA repair mechanisms (positive correlation: n=0/80 (0.0%) vs negative correlation: n=22/114 (19.3%); q=3.9×10⁻¹); but positively associated with immunological functions (positive correlation: n=20/80 (25.0%) vs negative correlation: n=5/114 (4.4%); q=5.4×10⁻⁴). The overlap of DEPs by LLDAS, DORIS remission, and SLEDAI-2K scores is depicted in the online supplemental figure S1. Comparing the frequencies of pathways that were positively or negatively associated with the different
Systemic lupus erythematosus outcomes (online supplemental material, sheet 10), DORIS remission was more strongly associated with a negative regulation of the immune system than LLDAS or low SLEDAI-2K scores. Heatmaps depicting immune system pathways in relation to LLDAS- and DORIS remission-enriched clusters are illustrated in figure 3, where inhibitory pathways are shown to be

![Figure 3](image-url)

**Figure 3** Immune system Reactome pathways according to biological clusters and main functions. Distribution of individualised immune system Reactome pathways in clusters (A) by LLDAS and (B) by DORIS remission. The coloured bars represent manual annotation according to the main functions of each pathway cluster, with pink denoting pathways with inhibitory functions on the immune system, red denoting inflammasome/inflammatory pathways enriched in cytokines, grey denoting toll-like receptor (TLR) and related functions, blue denoting type I interferon (IFN) pathways, and purple denoting antigen processing and B-cell pathways. DORIS, definitions of remission in systemic lupus erythematosus; LLDAS, lupus low disease activity state.
Table 3  Summary of relevant mechanisms and supporting evidence

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Finding</th>
<th>Supporting literature</th>
</tr>
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<tbody>
<tr>
<td>DNA repair</td>
<td>Increased in LLDAS/DORIS remission; downregulated in active SLE.</td>
<td>Defective in SLE;23–25 defective DNA repair predisposes to RA;26 ameliorates with symptom improvement in RA.26</td>
</tr>
<tr>
<td></td>
<td>Reduced GG-NER and TC-NER in active renal SLE.</td>
<td>Defective DNA-repair in lupus nephritis.25</td>
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<td></td>
<td>Reduced POLB-dependent long patch base excision repair pathway in active renal SLE.</td>
<td>Mutations in POLB associated with SLE;26 defective POLB caused nephritis27 and correlated with severe glomerulonephritis in murine lupus.28</td>
</tr>
<tr>
<td>RNA metabolism</td>
<td>tRNA processing and post-transcriptional modification of mRNA metabolism of non-coding mRNA associated with LLDAS/DORIS remission.</td>
<td>Altered RNA metabolism in inflammation and autoimmune diseases;31–33 mutations in NMD elicit type I IFN responses;34 inhibition of NMD increases p53,35 linked to SLE activity36 via promoting apoptosis;37 inhibition of p53-dependent apoptosis reverses alveolar haemorrhage in murine lupus.38</td>
</tr>
<tr>
<td>Gene expression</td>
<td>Reduced carpastel-related apoptosis in active renal SLE.</td>
<td>Reduced apoptosis in kidney biopsy samples from patients with lupus nephritis.39</td>
</tr>
<tr>
<td></td>
<td>Increased in LLDAS/DORIS remission.</td>
<td>Transcription of death genes impaired in remittent patients.39</td>
</tr>
<tr>
<td>Immune system Type I IFN</td>
<td>Reduced type I IFN responses in LLDAS/DORIS remission.</td>
<td>Type I IFN pathways induce inflammation;40 correlating with SLE activity.41</td>
</tr>
<tr>
<td></td>
<td>No association with active neurological, respiratory, musculoskeletal, mucocutaneous, or renal SLE.</td>
<td>No correlation with musculoskeletal, mucocutaneous, or renal manifestations in phase III trials of anifrolumab.41</td>
</tr>
<tr>
<td></td>
<td>Associations with haematological activity.</td>
<td>Subgroup analysis of phase III anifrolumab trial demonstrated an effect of anti-IFN therapy on leucopenia and thrombocytopenia.42</td>
</tr>
<tr>
<td>Immune system TLR pathways</td>
<td>TLRs downregulated in LLDAS/DORIS remission.</td>
<td>TLR7/8 and TLR9 elicit B-cell proliferation and function43 and associate with anti-TNF therapy44</td>
</tr>
<tr>
<td></td>
<td>Association between SLE activity and TLR1:TLR2 and TLR6:TLR2 heterodimers.</td>
<td>TLR1:TLR2 and TLR6:TLR2 heterodimers promote type I IFN production.45</td>
</tr>
<tr>
<td></td>
<td>TLR2 associated with active renal SLE.</td>
<td>TLR2 promotes ischemia/reperfusion injury in the kidneys.46</td>
</tr>
<tr>
<td></td>
<td>Activation of TLR3, TLR4, and TLR5 cascades in patients with active disease.</td>
<td>TLR3 and TLR4 promote inflammation and production of type I IFN;47,48 TLR5 associated with IL-17 and IL-22 production in tissues.49</td>
</tr>
<tr>
<td>Immune system Interleukins</td>
<td>IL-1, IL-4, IL-13, IL-6, IL-7, IL-10, IL-17, and IL-20 family associated with active SLE.</td>
<td>Interleukins associated with SLE activity and pathogenesis;50–52</td>
</tr>
<tr>
<td></td>
<td>IL-2, IL-3, IL-5, and GM-CSF signalling associated with LLDAS/DORIS remission.</td>
<td>Inverse association with SLE activity thoroughly described.50–52</td>
</tr>
<tr>
<td>Immune system Inflammasome</td>
<td>Inflammasome and related pathways associated with active SLE.</td>
<td>Inflammasome implicated in SLE pathogenesis;53 potential therapeutic target.60</td>
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<tr>
<td></td>
<td>NLRP3 showed a trend toward an association with active renal SLE.</td>
<td>NLRP3 pathway activated in tissue samples from lupus nephritis patients.60</td>
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<td>Immune system CTLA-4</td>
<td>CTLA-4 pathway upregulated in LLDAS/DORIS remission.</td>
<td>Polymorphisms reducing CTLA-4 function increase type I IFN.45</td>
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<td>Immune system DAP-12</td>
<td>DAP-12-related pathways upregulated in LLDAS/DORIS remission.</td>
<td>DAP-12 exerts inhibitory signals on natural killer cells and regulates natural immunity.64</td>
</tr>
<tr>
<td>Immune system PD-1</td>
<td>PD-1 pathway function increased in LLDAS/DORIS remission.</td>
<td>PD-1 negatively regulates B-cell and T-cell function.66</td>
</tr>
<tr>
<td>Metabolism</td>
<td>Acetylation increased in LLDAS/DORIS remission.</td>
<td>Epigenetic mechanisms linked to acetylation control autoimmunity;77,79 defective histone acetylation in murine models promotes dsDNA production and tissue injury.77</td>
</tr>
<tr>
<td></td>
<td>Eicosanoid reduction linked to the absence of renal involvement.</td>
<td>Eicosanoids suggested as potential targets in renal disease.71</td>
</tr>
<tr>
<td></td>
<td>Reduction of eicosanoids and leukotrienes linked to LLDAS/DORIS remission.</td>
<td>Eicosanoids suggested as potential targets for SLE.72</td>
</tr>
</tbody>
</table>

The table lists the main mechanisms that were found to be associated with systemic lupus erythematosus (SLE) or specific clinical manifestations and LLDAS or DORIS remission based on differential Reactome pathway analysis. CTLA-4, cytotoxic T lymphocyte antigen 4; DAP-12, 12kDa transmembrane protein; DORIS, definitions of remission in SLE; dsDNA, double-strand DNA; GG-NER, general genome NER; GM-CSF, granulocyte-macrophage colony-stimulating factor; IFN, interferon; IL, interleukin; LLDAS, lupus low disease activity state; mRNA, messenger RNA; NER, nucleotide excision repair; NLRP3, nucleotide-binding oligomerisation domain leucine-rich repeat-containing protein 3; NMD, nonsense-mediated mRNA decay; PD-1, programmed death-1; POLB, DNA polymerase beta; RA, rheumatoid arthritis; SLEDAI, systemic lupus erythematosus disease activity index; TC-NER, transcription-coupled NER; TLR, toll-like receptor; IRNA, transfer RNA; UV, ultraviolet.

upregulated in patients in LLDAS and DORIS remission, while IFN, inflammatory, and toll-like receptor (TLR) signalling pathways are shown to be upregulated in the non-LLDAS and non-remission groups.

Associations of interest between LLDAS or DORIS remission states, or disease manifestations, and immune mechanisms are summarised in table 3, along with literature relating to the findings.

Illustrative examples of druggable Reactome pathways

As LLDAS and DORIS remission were positively associated with several TLR cascades (online supplemental material, sheets 1 and 3), we explored known drug–target interactions within these pathways (https://idg.reactome.org/PathwayBrowser/#/R-HSA-168898). TLR7/8 and TLR9 cascades interact with two drugs: HCQ, an antagonist of both TLR7 and TLR9, and imiquimod, an agonist of TLR7 (figure 4A–C; detailed in online supplemental figure S2).

The TLR2 cascade as well as TLR1:TLR2 and TLR6:TLR2 heterodimer cascades do not have direct drug interactions, neither do TLR5 and TLR10, yet all these pathways converge to the MyD88-MAL(TIRAP) cascade that is initiated on the plasma membrane, which was also associated with renal involvement (dr=0.361; q=0.033) (https://reactome.org/PathwayBrowser/#/R-HSA-166058). Bruton tyrosine kinase (BTK) is a key player in these pathways; its activity is affected by at least three inhibitors, that is, acalabrutinib, ibrutinib, and zanubrutinib (figure 4D,E; detailed in online supplemental figure S2).

DISCUSSION

In the present study, several Reactome pathways were able to distinguish between LLDAS and non-LLDAS, as well as between DORIS remission and non-remission states, lending support to the clinical meaningfulness of LLDAS and DORIS remission as treatment goals. We herein coupled these states of disease with underlying biology for the first time. DORIS remission yielded...
more distinct separations across differentially enriched pathways and biological clusters compared with LLDAS, presumably owing to the greater degree of stringency of remission, corroborating the concentric distribution of LLDAS and DORIS remission, also at a biological level. However, a non-substantial pathway differentiation was demonstrated between DORIS remission and LLDAS exclusive of remission, suggesting a minimal added modulation at a biological level between these two states. Collectively, these observations suggest that although management of SLE should aim for DORIS remission, LLDAS is an acceptable goal in biological terms when remission is not achievable.

We documented associations between LLDAS or DORIS remission and several immune mechanisms. Evidence indicates that DNA repair is defective in patients with SLE, with implications in SLE pathogenesis.23 24 Interestingly, defective DNA repair mechanisms were here found to be associated with renal activity, corroborating previous literature.25 Mutations in the POLB genes have been associated with SLE and replicated in independent genome-wide association studies,26 while POLB defective function has been shown to cause lupus in murine models,27 also correlating with severe glomerulonephritis.28 In line with these previous findings, the POLB-Dependent Long Patch Base Excision Repair Reactome pathway was found in our sample to be defective in patients with renal involvement. Defective DNA repair has also been linked to loss of T cell tolerance, predisposing individuals to rheumatoid arthritis.29 Notably, this deficiency has been found to be reversible following treatment, with a tendency to decrease along with symptom improvement.30 This aligns with our findings of hampered DNA damage mechanisms in patients fulfilling the LLDAS or DORIS remission criteria.

Another mechanism that was enriched in patients in LLDAS or DORIS remission was RNA metabolism. Different processes involved in RNA transcription products were found to be associated with LLDAS and DORIS remission, including transfer RNA (tRNA) processing, post-transcriptional modification of messenger RNA (mRNA), as well as pathways involved in the metabolism of non-coding mRNA. Dysregulation of RNA metabolism has been linked to inflammation and autoimmunity.31 32 Mutations in NMD affecting the quality control of aberrant mRNA mutations may predispose to an autoimmune phenotype via type I IFN signalling.33 Inhibition of NMD upregulates the tumour suppressor protein p53,34 which has been correlated with SLE activity,35 likely through induction of apoptosis,36 and targeting p53-dependent apoptotic mechanisms was shown effective in treating murine diffuse alveolar haemorrhage.37 Our finding of reduced NMD pathways in patients not fulfilling the LLDAS or DORIS remission criteria is well in line with the aforementioned evidence, further corroborating the relevance of these targets at the biological level.

LLDAS and DORIS remission were also associated with increased gene-expression processes, and apoptotic processes...
related to caspases and caspase activators were downregulated in patients with renal involvement compared with SLE patients quiescent in the renal domain. This accords with reports of reduced apoptosis in kidney tissue from patients with lupus nephritis.38 Interestingly, remission has been linked with impaired transcription of death genes, but preserved transcription and regulation of DNA repair.39

Not unexpectedly, LLDAS and DORIS remission were associated with reduced activity of immune system processes. Induction of type I IFN pathways and elicited inflammatory responses, a mechanism of known importance in SLE pathogenesis,40 which also correlates with the degree of SLE activity,41 42 was here found to be upregulated in SLE patients not fulfilling the LLDAS or DORIS remission criteria. This is the first report describing a relative to counter states downregulation of the IFN signature in SLE patients in LLDAS and DORIS remission. Interestingly, renal activity correlated poorly with IFN-related pathways, as also observed in a post-hoc analysis of the phase III trials of anifrolumab, a human monoclonal antibody targeting the type I IFN receptor, approved for the treatment of active SLE.43 On the contrary, haematological alterations were found to correlate with INF-related pathways, also in accordance with findings from the same study, where anifrolumab was found to improve leucopenia and thrombocytopenia.44

Furthermore, a wide range of TLR cascades were downregulated in remittent patients. This pertains to the known rote of TLR7/8 and TLR9 in B-cell functions and proliferation,45 as well as to a previous report on their association with SLEDAI scores in a small population of untreated SLE subjects.46 We herein describe for the first time associations between TLR pathway signalling and renal involvement, also in accordance with findings from the same study, where anifrolumab was found to improve leucopenia and thrombocytopenia.44

Inflammatory and regulatory cytokine signalling pathways were herein found to be associated with active SLE, including several that previously have been coupled with SLE pathogenesis or activity.52–54 In contrast, IL-2, IL-3, IL-5, and granulocyte-macrophage colony-stimulating factor signalling was associated with LLDAS and DORIS remission, also corroborating previous literature.55–57

The inflammasome and inflammasome-related pathways were here associated with active SLE. Importantly, the inflammasome pathway has been advocated to be relevant in SLE pathogenesis and disease progression,58 59 with therapeutic implications.60 We found that the inhibitory signalling related to cytotoxic T lymphocyte antigen 4 (CTLA-4) was upregulated in SLE patients in LLDAS or DORIS remission. Defective CTLA-4 function coupled with a genetic polymorphism has been linked to increased type I IFN activity.61 Abatacept, a CTLA-4/ IgG fusion protein with inhibitory functions on T cell proliferation and cytokine production, failed to demonstrate efficacy in lupus nephritis, but was effective in reducing the occurrence of articular flares.62 Associated with LLDAS and DORIS remission were also inhibitory signals such as the innate-immunity inhibitor DAP12, which primary acts on natural killer (NK) cells, and the programmed cell death 1 signalling pathway, which attenuates signalling downstream of the T cell receptor (TCR) and the costimulatory receptor CD28, suppressing cellular functions such as activation, proliferation, metabolic regulation, cytotoxicity, and cytokine production.63 64

Finally, our data provide implications of targeting certain pathways to ameliorate disease. We demonstrated examples of druggable Reactome pathways pointing to inhibitors of TLR cascades as putative drug candidates. These results are independent of HCQ use, a well-known modifier of TLR7 and TLR9 functions,65 and further stress the need to globally tackle immune system activation to promote remission. Nevertheless, the use of HCQ in our population may explain the lack of association between TLR pathway signalling and renal involvement, as this drug is known to be beneficial in the treatment of lupus nephritis in conjunction with mycophenolate mofetil66 and is recommended for all SLE patients unless contraindicated, especially those with kidney involvement.67 68 In our analysis, BTK emerged as a potential target of downstream mediators of TLR pathway signalling. The use of BTK inhibitors has been advocated in lupus,69 with evidence from animal models indicating that they may ameliorate renal lupus.70 71 It is worth mentioning that a phase II RCT of the dual TLR7/8 inhibitor enpatoran is currently ongoing (NCT05162586).

Our study has strengths but is not exempt from drawbacks. The lack of replication in independent cohorts or in vitro experiments, the cross-sectional study design, and the overall limited numbers of SLE patients with high disease activity constitute main limitations. The lack of longitudinal data precluded investigation of restoration or reversal of biological aberrancies while shifting from active SLE to disease quiescence defined by LLDAS or DORIS remission, which would be of interest to study in a future work. Another important limitation was the lack of data on the duration of LLDAS and DORIS remission prior to sampling, which may be expected to affect the extent and depth of transcriptome alterations that are associated with these states. Strengths include the large number of patients and a multitude of results corroborating previous research, which provides reassurance while contributing to the robustness of current evidence. Importantly, this was the first thorough analysis of pathways in SLE patients in association with low disease activity and remission, providing biological relevance to current treatment goals in SLE management. We demonstrated how pathways can be explored to gain insights into SLE pathogenesis, substantiate the distinction between quiescent and active disease, and reveal potential therapeutic targets.

In summary, we demonstrated for the first time molecular signalling pathways distinguishing LLDAS and DORIS remission from active SLE. Compared with active disease, LLDAS and remission were associated with downregulated biological processes related to SLE pathogenesis and biological processes linked to specific disease manifestations. While DEP clustering by DORIS remission better grouped patients than clustering by LLDAS, substantiating the conceptual testimonial of remission being the ultimate treatment goal in SLE, the lack of substantial pathway differentiation between the two states justifies LLDAS as an acceptable goal from a biological perspective when remission is not achievable. Notably, DORIS remission was associated with a higher proportion of pathways with negative regulatory effects on the immune system compared with LLDAS or low SLEDAI-2K, underlining the importance of reversing immune system activation to attain adequate clinical control of the
disease. The study revealed the potentiality of existing drugs that could be repurposed to treat SLE and important pathways underlying active SLE whose modulation could aid attainment of disease quiescence. Among those, TLR cascades, BTK activity, CTLA-4-related inhibitory signalling, and the NLRP3 inflammasome pathway were of particular interest.

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Acknowledgements
The authors express gratitude to the clinical investigators of the PRECISESADS Clinical Consortium listed in the online supplemental material page 12 and Bayer GmbH for performing RNAseq and providing preprocessed data. The authors would also like to thank all participating patients.

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PRECISESADS Clinical Consortium: Jacques-Olivier Pers, Alain Saraut, Valérie Devauchelle-Pensec, Sandrine Jousse-Joulin/Centre Hospitalier Universitaire de Brest, Hospital de la Cavale Blanche, Brest, France; Bernard Lauwereys, Julie Ducrée, Anne-Lise Maudoz (Pôle de pathologies rhumatismales systémiques et inflammatoires, Institut de Recherche Expérimentale et Clinique, Université catholique de Louvain, Brussels, Belgium); Ana Tavares, Isabel Almeida (Department of Autoimmune Diseases, Hospital Clínic, Institut d’Investigacions Biomèdiques August Pi i Sunyer, Barcelona, Catalonia, Spain); Ignasi Rodríguez-Saraux, Valérie Devauchelle-Pensec, Sandrine Jousse-Joulin (Université catholique de Louvain, Brussels, Belgium); Csongrad Megyei (Kormányhivatal, University of Szeged, Szeged, Hungary); Comite Ético de Investigación Clínica del Hospital Clinic de Barcelona, Hospital Clinic I Provincia, Institut d’Investigacions Biomèdiques August Pi i Sunyer, Barcelona, Spain; Comité de Ética y Investigación en Centro de Granada (CEI—Granada), Servicio Andaluz de Salud, Hospital Universitario Reina Sofia Cordoba, Spain; Comité de Ética y Investigación en Centro de Granada (CEI—Granada), Servicio Andaluz de Salud, Hospital Universitario Reina Sofia Cordoba, Spain; Commission de Études et de Recherche, hospital Hôpitaux universitaires de Genève, Hôpitaux Universitaires de Genève, Switzerland; Andalusian Public Health System Biobank, Granada, Spain; Comissió Medica Ethique UZ KU Leuven/Onderzoek, Katholieke Universiteit Leuven, Belgium; Ethikkommission, Charité, Berlin, Germany; Ethikkommission, Medizinische Hochschule Hannover, Germany. All patients provided written informed consent for participation in the study. The study protocol for the present analysis was reviewed and approved by the Swedish Ethical Review Authority (approval no. 2022-03907-01). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review
Not commissioned; externally peer reviewed.

Data availability statement
Data are available upon reasonable request. Data are available on reasonable request. Raw data are property of the PRECISESADS consortium and protected under the European General Data Protection Regulation (GDPR). Metadata and aggregated processed data are available upon reasonable request from the corresponding author and from the EGA (European Genome-phenome Archive).

Supplemental material
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Ann Rheum Dis: first published as 10.1136/ard-2023-224795 on 19 February 2024. Downloaded from http://ard.bmj.com/
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**Systemic lupus erythematosus**


SUPPLEMENTAL MATERIAL

Molecular characterisation of Lupus Low Disease Activity State (LLDAS) and DORIS remission by whole-blood transcriptome-based pathways in a pan-European systemic lupus erythematosus cohort
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**RNA sequencing**

Total RNA was extracted from whole-blood (WB) samples collected in Tempus tubes using Tempus Spin technology (Applied Biosystems). Samples were processed in 5 batches, randomised to four 96-well plates with respect to diagnosis, recruitment center, and RNA extraction date. The samples were depleted of alpha- and beta-globin mRNAs using globinCLEAR protocol (Ambion) and 1 µg of total RNA as input. Subsequently, 400 ng of globin-depleted total RNA was used for library synthesis with TruSeq Stranded mRNA HT kit (Illumina). The libraries were quantified using qPCR with PerfeCTa NGS kit (Quanta Biosciences), and equimolar amounts of samples from the same 96-well plate were pooled. Four pools were clustered on a high output flow cell (two lanes per pool) using HiSeq SR Cluster kit v4 and the cBot instrument (Illumina). Subsequently, 50 cycles of single-read sequencing were performed on a HiSeq2500 instrument using a HiSeq SBS kit v4 (Illumina). The clustering and sequencing steps were repeated for a total of three runs in order to generate sufficient number of reads per sample. The raw sequencing data for each run were preprocessed using bcl2fastq software and the quality was assessed using FastQC tools. Cutadapt was used to remove 3’ end nucleotides below 20 Phred quality score and extraneous adapters; additionally, reads below 25 nucleotides after trimming were discarded. Reads were then processed and aligned to the UCSC Homo sapiens reference genome (Build hg19) using STAR v2.5.2b. A 2-pass mapping with default alignment parameters was used. To produce the quantification data, we used RSEM v1.2.31 resulting in gene level expression estimates (Transcripts Per Million [TPM] and read counts). A sample would pass the RNA single quality control (QC) if (i) the number of reads mapped to the genes was more than 7 million, and (ii) the RNA integrity number (RIN) value was higher than 7.
**Gene-set functional annotation**

To characterise functional annotations at the patient level, individualised functional annotation was performed by means of the Functional Analysis of Individual Microarray Expression (FAIME) algorithm\[5, 6\] that translates gene-level measurements of each sample into individual molecular function profiles. First, data were transformed by means of Variance Stabilising Transformation (VST)\[7\] via the DESeq2 package.\[8\] FAIME scores were then built considering Reactome\[9\] pathways mapped by at least 5 genes/transcripts; Entrez IDs that had no official gene symbols were dropped from the analysis. Reactome annotations were downloaded from the Reactome website.\[10\]

**Differential expression pathway analysis**

The main outcomes were Lupus Low Disease Activity State (LLDAS; reference: non-LLDAS) and Definitions of Remission in SLE (DORIS) remission (reference: non-remission). We also employed forward difference coding to compare LLDAS exclusive of remission with (i) non-LLDAS and (ii) DORIS remission. Importantly, the first comparison i.e., between patients fulfilling the DORIS remission criteria and patients fulfilling the criteria for LLDAS upon exclusion of those fulfilling the criteria for DORIS remission, given the fact that the two populations are independent, is the method of choice for testing the hypothesis of no difference between the overlapping samples of patients in LLDAS and patients in DORIS remission.\[11\] Differences between groups were calculated using linear models with a procedure akin to the voom method described by Law *et al.*\[12\], as described below.
An ordinary least square (OLS) regression model was fit to FAIME scores taking into account sequencing batch, gender, age, disease duration, and the use of hydroxychloroquine as covariates, along with the respective outcome (note that other therapies were not included as confounding factor in the models to avoid collinearity since they constitute components of the outcomes or are more prevalent in non-LLDAS/non-remission patients). OLS eigenvalues were checked and the variable in the design matrix with scores $< 1.10^{-4}$ were iteratively removed so as that individual variance inflation factors (VIF) were all $< 5$, to avoid multicollinearity and inflation of coefficient estimates. Residual standard deviations for OLS with the multicollinearity-weighted design matrix were then calculated and plotted against average FAIME scores.

A locally weighted scatterplot smoothing (LOWESS) trend was fitted to the residual standard deviations. To better account for ties, trends in the upper and lower 5% percentiles were independently calculated. The pathway-wise square-root residual standard deviations plotted against average FAIME scores and the LOWESS fit is represented here below:

The LOWESS trend was then used to predict the standard deviation of each individual FAIME score; the inverse squared predicted standard deviation was retained as individual weight/pathway.
A weighted least square (WLS) model was fitted for each pathway using the same design matrix used to run the OLS above and the individual weights as calculated above.

Summary data from WLS models were then used to calculate a moderated t-test statistic, according to the eBayes method described by Smyth *et al.*[13], as described below.

The ordinary t-test statistic for the $p$th pathway and $k$th contrast is given by:

$$
(1) \quad t_{pk} = \frac{\beta_{pk}}{SE(\beta_{pk})} = \frac{\beta_{pk}}{s_p u_{pk}} \quad ; \quad \tilde{s}_p^2 = \frac{RSS}{d_p} \quad ; \quad u_{pk} = \frac{SE(\beta_{pk})}{s_p}
$$

where $\beta_{pk}$ is the regression coefficient and $SE(\beta_{pk})$ its standard error, equivalent to the sample residual standard deviation $s_p$ (i.e the square root of the sample residual variance $s_p^2$), multiplied by $u_{pk}$ the unscaled standard deviation. In the equation, RSS is the residual sum of squares and $d_p$ the degree of freedom of the model given by $n - k - 1$.

The moderated t-test statistic is the weighted version of the t-test that accounts for extra information borrowed from all the pathways and is given by:

$$
(2) \quad \tilde{t}_{pk} = \frac{\beta_{pk}}{\tilde{s}_p u_{pk}} \quad ; \quad \tilde{s}_p^2 = \frac{d_p s_p^2 + d_0 s_0^2}{d_p + d_0} \quad ; \quad \frac{1}{\tilde{s}_p^2} \sim \frac{1}{d_0 s_0^2} \chi^2_{d_0}
$$

Where $\tilde{s}_p$ represents the posterior value of the residual variance. A scaled inverse chi-square prior is assigned to $\tilde{s}_p^2$ and the hyperparameters $d_0$ and $s_0^2$ represent the prior degrees of freedom and location of the distribution.
According to Smyth et al. [13], the marginal distribution of $s_p^2$ follows a scaled F-distribution with degrees of freedom $d_o$ and $d_p$ and is described by:

$$E(\log s_p^2) = \log s_0^2 + \psi \left(\frac{d_p}{2}\right) - \psi \left(\frac{d_o}{2}\right) + \log \left(\frac{d_0}{d_p}\right)$$

$$\text{var}(\log s_p^2) = \left(\frac{d_p}{2}\right) + \psi' \left(\frac{d_0}{2}\right)$$

Let $e_p$ be the adjusted logarithm of sample variance of pathway $p$:

$$e_p = \log s_p^2 - \psi \left(\frac{d_p}{2}\right) + \log \left(\frac{d_p}{2}\right)$$

It has an expected value of:

$$E(e_p) = \log s_0^2 - \psi \left(\frac{d_o}{2}\right) + \log \left(\frac{d_p}{2}\right)$$

And variance:

$$\text{var}(e_p) = \psi' \left(\frac{d_p}{2}\right) + \psi' \left(\frac{d_o}{2}\right)$$

Thus, solving eq. (7) and applying Bassel’s correction, we obtain:

$$\psi' \left(\frac{d_0}{2}\right) = \frac{1}{p} \sum_{p=1}^{p} \left(\frac{p}{p-1} (e_p - \bar{e})^2 - \psi' \left(\frac{d_p}{2}\right)\right)$$

From (8), $d_o$ can be found solving the inverse trigamma function.

Finally, $s_0^2$ can be estimated by Newton’s formula:

$$s_0^2 = \exp \left\{ \bar{e} + \psi \left(\frac{d_o}{2}\right) - \log \left(\frac{d_0}{2}\right) \right\}$$

$s_0^2, s_p^2$ and $d_o, d_p$ are thus used to estimate $s_p^2$ and $\xi_{pk}$ as described in eq. (2).
From $t_{pk}$ values, the corresponding moderated $p$ values are computed from the $t$ distribution with $d_o + d_p$ degree of freedom. The $p$ values are then corrected for multiple tests via the false discovery rate (FDR) method ($q$).[14]

Winsorised 20% data were used to determine a robust moderated t-test $\tilde{t}_{pk(r)}$ and the robust effect size ($d_r$).[15] To this end, winsorisation was independently applied to cases and controls (e.g., LLDAS/non-LLDAS, DORIS remission/non-remission), and OLS, WLS, and the eBayes procedures were run as described above.

From $\tilde{t}_{pk(r)}$, pathway-related unscaled $d_r$, $d^*_r$, were calculated according to Rosnow:[16]

$$d^*_r = \frac{n \tilde{t}_{pk(r)}}{\sqrt{d_o(r)} + d_p(r) + \sqrt{n_{out}} \overline{n}_{out}}$$

Where $n$ is the total number of cases, $n_{out}$ the number of subjects with the outcome of interest, and $\overline{n}_{out}$ the number of subjects without the outcome.

The $d^*_r$ found in (12) is then scaled according to Algina et al.[17] to produce the robust estimator $d_{rp}$:

$$d_{rp} = .642 \, d^*_r$$

As an additional measure of effect size, we also calculated the probability of superiority[18] ($A$), defined as the probability that a person picked at random from the case group will have a higher score than a person picked at random from the control group:

$$A = \phi \frac{d_{rp}}{\sqrt{2}}$$
where $\Phi$ is the cumulative distribution function of the standard normal distribution.

Annotations with $q < 0.05$ and a $|dr| \geq 0.36$, which corresponds to a moderate effect size,[19] were considered significant.

Reactome pathways were annotated to their root terms and their different distribution in relation to a negative or positive $dr$, suggesting a downregulation or an upregulation in patients in LLDAS/DORIS remission compared with patients who were not in LLDAS/remission, was calculated by means of the chi-squared ($\chi^2$) test with FDR-adjusted p values; root terms with low prevalence were eliminated.

**Pathway analysis with quantitative traits**

For explorative purposes, associations between Reactome pathways and Systemic Lupus Erythematosus Disease Activity Index 2000 (SLEDAI-2K) scores were assessed. For each pathway, a *moderated robust t-test statistic* $\tilde{t}_{pk}$ and relative $q$ values were calculated as described above from winsorised data. To determine the effect size or multivariable WLS regression, the (robust) Cohen’s $f^2$ was calculated from *moderated robust t-test statistic* $\tilde{t}_{pk(r)}$ values calculated from winsorised data.

$$f^2 = \frac{r^2_{part}}{1 - r^2_{part}}; \quad r^2_{part} = \frac{\tilde{t}_{pk(r)}^2}{\tilde{t}_{pk(r)}^2 + d_0(r) + d_p(r)}$$

(15)

Where $r^2_{part}$ is the partial coefficient of determination for the $p$th pathway and $k$th contrast.

Thresholds for $f^2$ interpretation are provided by Cohen[20] and are 0.02 for small, 0.15 for medium, and 0.35 for large effect size.
For all the analyses, custom codes written in python by LB built on top of the scikit-learn[21] and Statmodels[22] modules were used.

For visualisation of data, confounding factors were removed calculating residuals from WLS in a procedure akin to the removeBatchEffect function of the Limma R package;[23] clustering by means of the k-means algorithm and heatmap representation was made via the Python library Matplotlib;[24] the number of clusters was selected to obtain the highest statistical separation (e.g., chi-squared test values) of the binary outcome status across groups.

**Druggability of Reactome pathways**

Exploration of druggable Reactome pathways i.e., drug-target interactions was explored via the Reactome pathway browser as described in: https://idg.reactome.org/documentation/userguide#drug-target-interactions. Examples are provided to illustrate potential implications inferred from our findings.
Supplemental Figure S1. Venn diagram delineating differentially enriched pathways across different outcomes and SLEDAI-2K scores.

The numbers indicate differentially enriched Reactome pathways in systemic lupus erythematosus (SLE) patients with different outcomes. DORIS: Definitions of Remission in SLE; LLDAS: Lupus Low Disease Activity State; SLEDAI-2K: Systemic Lupus Erythematosus Disease Activity Index 2000.
**Supplemental Figure S2.** Druggable Toll-Like Receptor (TLR) cascades. Drug-pathway interactions within TLR cascades associated with definitions of remission in systemic lupus erythematosus (DORIS) remission (from: https://idg.reactome.org, with modifications); irrelevant pathways are blurred. Panel A depicts TLR 7/8, TLR9, TLR2, TLR5, and TLR10 pathways; pathway-drug interactions with TLR7 and TLR9 are highlighted with red squares (the number of related drugs is indicated) and detailed in panels B and C. The MyD88:MAL(TIRAP) cascade initiated on the plasma membrane, highlighted with red arrows and detailed in panel D, is the terminal effector of TLR2, TLR5, and TLR10 pathways. Within this pathway, Bruton Tyrosine Kinase (BTK) is a key druggable component, whose inhibitors are detailed in panel E.
List of local investigators from the participating clinical sites

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