(5R)-5-Hydroxytriptolide (LLDT8) induces substantial epigenetic mediated immune response network changes in fibroblast-like synoviocytes from rheumatoid arthritis patients

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(5R)-5-Hydroxytriptolide (LLDT-8) induces substantial epigenetic mediated immune response network changes in fibroblast-like synoviocytes from rheumatoid arthritis patients

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Tripterygium is a traditional Chinese medicine that has widely been used in the treatment of rheumatic disease. (5R)-5-hydroxytriptolide (LLDT-8) is an extracted compound from Tripterygium, which has been shown to have lower cytotoxicity and relatively higher immunosuppressive activity when compared to Tripterygium. However, our understanding of LLDT-8-induced epigenomic impact and overall regulatory changes in key cell types remains limited. Doing so will provide critically important mechanistic information about how LLDT-8 wields its immunosuppressive activity. The purpose of this study was to assess the effects of LLDT-8 on transcriptome including mRNAs and long non-coding RNA (lncRNAs) in rheumatoid arthritis (RA) fibroblast-like synoviocytes (FLS) by a custom genome-wide microarray assay. Significant differential expressed genes were validated by QPCR. Our work shows that 394 genes (281 down- and 113 up-regulated) were significantly differentially expressed in FLS responding to the treatment of LLDT-8. KEGG pathway analysis showed 20 pathways were significantly enriched and the most significantly enriched pathways were relevant to immune reaction, including cytokine–cytokine receptor interaction ($P=4.61\times10^{-13}$), chemokine signaling pathway ($P=1.01\times10^{-5}$) and TNF signaling pathway ($P=2.79\times10^{-4}$). Furthermore, we identified 618 highly negatively correlated lncRNA-mRNA pairs from the selected significantly differential lncRNA and mRNA including 27 cis-regulated and 591 trans-regulated lncRNA-mRNAs modules. KEGG and GO based function analysis to differential lncRNA also shown the enrichment of immune response. Finally, lncRNA-transcription factor (TF) and lncRNA-TF-mRNA co-expression network were constructed with high specific network characteristics, indicating LLDT-8 would influence the expression network within the whole FLS cells. The results indicated that the LLDT-8 would mainly influence the FLS cells systemically and specially in the process of immune related pathways.

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Rheumatoid arthritis (RA) is the most common chronic inflammatory disease with complex etiology. The inflammation makes the synovium thicken and causes swelling around the joints. Thus, it induces the damage of cartilage. Recent findings indicate that remission of symptoms is more likely when treatment begins early with medications. Although several widely-used anti-rheumatic drugs, such as methotrexate, steroids, anti-IL-6R and anti-TNFα monoclonal antibodies, have demonstrated some degree of efficacy in the treatment of RA, a substantial proportion of patients exhibit poor response and the incidence of adverse reactions is substantial. The use of plant- and microbial-based compounds to treat a variety of pathologies has an extensive history and includes digitalis, L-Dopa, taxol, quinine, ephedrine, codeine, and penicillin. In our clinical practice, we found a traditional Chinese medicine Tripterygium could be applied to decrease the severity of RA. Tripterygium is a genus of plants from the Euonymus Family. This Traditional Chinese medicine has been used in the treatment of autoimmune disease, rheumatic disease, and systemic lupus erythematosus (SLE). Triptolide is an extracted compound from Tripterygium, which has strong immunosuppressive activity. Triptolide can inhibit interleukin-6 (IL-6) and reduce osteoclastogenesis by inhibiting NF-κB signaling. An optimized structured analog of Triptolide, (5R)-5-hydroxytriptolide (LLDT-8), has been shown to have both low toxicity and high immunosuppressive ability. Previous studies also demonstrated that LLDT-8 can suppress the immune responses on peripheral blood mononuclear cells (PBMC) and T cells. Importantly, LLDT-8 also inhibited the differentiation of Th1 and Th17 cells and has effect on the immune responses of RA patients. Increasing evidence indicates that activated synovial fibroblasts, together with macrophage and lymphocyte secreted factors, as part of a complex cellular network, play an important role in the pathogenesis of rheumatoid arthritis. Meanwhile, the pharmacological effect of LLDT-8 on synovial fibroblasts has not been investigated. Further, elucidating the underlying molecular mechanisms of how LLDT-8 generates immunosuppression without a high degree of toxicity may provide a platform for the development of novel anti-rheumatologic therapeutics.

Long non-coding RNAs (IncRNAs) are a recently discovered class of non-coding functional RNA and some important roles of IncRNAs as regulators in a wide spectrum of biological processes were identified in the past several years. There are over 16,000 IncRNAs in humans and the functions of majority of them are unknown. Recent evidence also suggests the role of IncRNAs in the pathophysiology of disease processes, especially in cancer and immune disease. In the previous studies, IncRNA have been reported to be related to the pathogenesis of RA due to its association of major pathways linked to Inflammation, such as NFκB and TLR signaling. However, whether IncRNA is involved in the mechanism of therapy of LLDT-8 to rheumatoid arthritis is still unknown.

The aim of this study was designed to identify the mechanism of immuno-impressive function of LLDT-8 and identify potential ncRNA targets of LLDT-8. We applied TNF-α and IL-17 to induce an inflammatory status in the cells so that we can observe the LLDT-8 effect easily compared with treatment to normal FLS cell directly. We then assessed the effects of LLDT-8 on the regulation of gene expression on mRNAs and long non-coding RNAs in FLS isolated from RA patients. Agilent Human IncRNA (4 × 180 K, Design ID: 062918) was applied in present study to provide genome-wide ncRNA and mRNA expression profile. With this study, we aimed to demonstrate how LLDT-8 treatment significantly impacts the process of immune regulation.

### Material and Methods

#### Patients, cell culture and LLDT-8 treatment.

FLS cells were derived from the synovial tissues of patients with RA in Guanghua hospital who had undergone total joint replacement surgery during June to August 2015. Written informed consent to collect FLS cells for LLDT-8 studies was obtained from all participating RA patients. This study was approved by the academic advisory board of Guanghua Hospital (No. 2015-SRA-01) and all methods were performed in accordance with the relevant guidelines and regulations. All patients were randomly enrolled and all of them fulfilled the American College of Rheumatology classification criteria for RA. Clinical data were collected at the time of sample collection. The detail clinical information is shown in Table 1.

An overview of the cellular processing is shown in Fig. 1. Briefly, joint tissues were minced into 1 × 1 × 1 mm pieces and treated for 2 hours (h) with 2–4 mg/ml of collagenase (Serva, GERMANY) in DMEM at 37 °C in 5% CO2. Dissociated cells were then centrifuged at 500 × g, re-suspended in DMEM supplemented with 10% FCS (Gibco, USA), and plated in 75 cm² flasks. The cultures were kept at 37 °C in 5% CO2 and the culture medium was replaced every 2–3 days. Mycoplasma assay was performed on synovial fibroblasts to avoid mycoplasma contamination. When cells approached confluence, they were passed after diluting 1:3 with fresh medium until used. The purity of the cells was verified by flow cytometric analysis. The FLS cells of passages 4th were seeded in 6-well plates. As the control group, the FLS cells were cultured in DMEM including 10 ng/ml TNF-α and 10 ng/ml IL-17.

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</table>

(PeptoTech, USA) for 12 h. In the treatment group, LLDT-8 (Shanghai Pharma, Shanghai) was dissolved with 2% DMSO and diluted with DMEM (with TNF-α and IL-17) to 100 nM/ml for 24 hours. 100 nM LLDT-8 does not have obvious FLS cytotoxic effect while producing a slight apoptosis effect for FLS (Supplementary Fig. 1) which is consistent with a previous report 11,29. In the process to validate the microarray data, TNF-α treatment was applied to simulate a pro-inflammatory reaction and then LLDT8 treatment was applied to evaluate the effect of LLDT-8 on the inflammatory reaction as measured by real-time PCR (RT-PCR).

**RNA extraction and microarray hybridization.** The total RNA was extracted by TRizol reagent and quantified by the NanoDrop ND-2000 (Thermo Scientific, Waltham, MA, USA). The integrity of RNA was assessed using the Agilent Bioanalyzer 2100 (Agilent Technologies Inc, Santa Clara, CA, USA).

Customized Agilent Human IncRNA microarray (4×180 K, Design ID: 062918) was used in this study. 30,656 probes located in mRNA transcripts from Entrez Gene and 78,243 probes in IncRNA. the catalog of the IncRNA were collected from the integration of Broad Institute, Human Body Map IncRNA, TUCP catalog, UCSC IncRNA Transcripts, GENCODE 18, NONCODE V4.0, Ensembl, RefSeq, Ultra-conserved region encoding LncRNA (UCR), IncRNAdb and ncRNA database. The total RNA was transcribed to double-stranded cDNA, synthesized into cRNA (Low Input Quick-Amp Labeling Kit, one-color, Agilent), and labeled with Cyanine-3-CTP. The labeled cRNAs were then hybridized onto the microarray. After washing, the arrays were scanned by the Agilent Scanner G2505C (Agilent Technologies Inc., Santa Clara, CA, USA). Other parameters in ncRNA labeling, microarray hybridization, and washing procedure were performed according to the manufacturer’s standard protocols. RT-PCR was applied to validate parts of significant differential genes within same samples with > 3 times technical repeats.

**Image scanning and data analysis.** The array images were analyzed using Feature Extraction software (version 10.7.1.1, Agilent Technologies Inc., Santa Clara, CA, USA), and the raw data were obtained and basically analyzed with Genespring. The raw data were initially normalized with the quantile algorithm. The probes that at least in one out of two conditions had flags in “P” were chosen for further data analysis. Differentially expressed genes or IncRNAs were identified through a combination of fold change and p-values calculated from a t-test (details in the Statistical analysis section). The threshold set for upregulated and downregulated genes was a fold change ≥ 2.0 and a P ≤ 0.05.

**Identification of cis-regulated mRNAs of the differential IncRNAs.** Based on these 5 biological replications with or without LLDT-8 treatment, differential expressed IncRNA, cis-regulatory genes/mRNAs were identified. The mRNAs were identified as “cis-regulated mRNAs” when (1) the mRNA loci are within 100 k windows up- and down-stream of the given IncRNA, and (2) the Pearson correlation of IncRNA–mRNA expression is significant (P ≤ 0.01). GO analysis and KEGG analysis were applied to determine the roles of these differentially expressed mRNAs. Finally, Hierarchical Clustering was performed to display the distinguishable genes’ expression pattern among samples.

**Functional prediction of selected differential IncRNAs.** The overall gene function distribution (co-expression, ontology and pathway) of the differential IncRNAs obtained in the experiment was identified as follows. For each differential IncRNA, the Pearson correlation of its expression value with the expression value of each mRNA was calculated, and a P < 0.05 was selected. The enrichment of functional terms in annotation of
Results

Genome-wide mRNA profile of before and after LLDT-8 treatment. We describe the project with the flowchart as Fig. 1. By analyzing genome-wide IncRNA microarray of RA FLS responding to LLDT-8, we found 394 differentially expressed genes (p < 0.05, fold change > 2). 71% (281) of them were down-regulated and 28.7% (113) were up-regulated (Supp. Table 1). Volcano plot for the differential express genes was shown in Fig. 2A. Supervised cluster analysis (Heatmap) showed differentially expressed genes could distinguish the samples before and after LLDT-8 treatment (Fig. 2B). In order to check the quality of the microarray data, we validated several canonical immune response relate genes, such as NFKB1 (P = 1.80 × 10^{-19}), MYD88 (P = 1.26 × 10^{-5}), JUN (P = 1.09 × 10^{-14}) and FOS (P = 4.41 × 10^{-22}) with qPCR and we found the result were highly consistent with microarray results (Fig. 2C). These down-regulated T-cell receptor signaling pathway (NFKB1, JUN, FOS) and Toll-like receptor signaling pathway (MYD88) genes indicate LLDT-8 could provide highly consistent with microarray results (Fig. 2C). These down-regulated T-cell receptor signaling pathway (NFKB1, JUN, FOS) and Toll-like receptor signaling pathway (MYD88) genes indicate LLDT-8 could provide significantly immunosuppressive activity with multiple molecular networking approaches. KEGG pathway analysis (Fig. 2D) of the differentially expressed genes showed 20 pathways were significantly enriched (P < 0.05, FDR < 0.01). Interesting, the top 4 enriched pathways were significantly relevant to Immune reaction, including cytokine-cytokine receptor interaction (P = 4.61 × 10^{-34}), chemokine signaling pathway (P = 1.90 × 10^{-9}), chemokine signaling pathway (P = 1.01 × 10^{-3}), and TNF signaling pathway (P = 2.79 × 10^{-9}). These findings indicated that the LLDT-8 would greatly influence the RA FLS in the process of immune regulation. By analyzing interaction networks based on STRING (Fig. 3A), BioGRID (Fig. 3B) and KEGG (Fig. 3C), we found that these differentially expressed genes were significantly interacting with each other and constructed specific and explicit networks (Fig. 3).

Genome-wide IncRNA profile of RA FLS before and after LLDT-8 treatment. The IncRNAs with both fold change ≥ 2.0 and P-value ≤ 0.05 from the t-test were identified as differentially expressed IncRNAs. Our results showed that 360 IncRNAs of RA FLS were significantly changed with LLDT-8 treatment. Those P-values ranged from 4.88 × 10^{-2} to 2.92 × 10^{-7}, and the fold change spanned from 2.00 to 18.44. Among these IncRNAs, 56% (203) were downregulated and 44% (157) were upregulated (Supp. Table 2). Our result indicates not only mRNAs but also IncRNA transcripts would be widely changed during the treatment of LLDT-8. In addition, we found the target genes of the differential IncRNAs that could also be a strong indication of the change caused by LLDT-8 treatment. In addition, as Fig. 2E shows, cluster analysis based on the 30 co-expression genes of differential IncRNA (ENST00000584923) could separate the samples quite accurately with or without LLDT-8 treatment, indicating that the IncRNA network and the mRNA network in the cells were highly interacted and coordinately changed by LLDT-8 treatment.
Co-expression network analysis between mRNA and lncRNA. The IncRNAs co-expressed function was identified through the correlation of IncRNA-mRNA. For each of the IncRNA, we calculate the Pearson correlation of its expression value with the expression value from every different mRNA. The pair of IncRNA and
mRNA was selected if their correlation test reached the threshold (P-value < 0.05). Also, in order to ensure the selected pairs is meaningful, we only kept those correlated pairs which show strong negative correlation (correlation coefficient < −0.9). Our result indicated that there were 9,666 pairs of lncRNA-mRNA with strong negative correlation. Moreover, 618 of them were also identified as the significantly differential mRNA and lncRNA from the t-test in which 70 pairs of them were located in the same chromosome. Furthermore, 13 out of those 70 pairs were located in chromosome-6, and 10 out of those them were located in chromosome-17. Such kind of chromosome-distribution disequilibrium suggests the influence of the LLDT-8 is not a random effect but with specific target and influence to FLS. 27 cis-regulated (Table 2 and Supp. Table 3) and 591 trans-regulated lncRNA-mRNAs modules were identified (Table 3 and Supp. Table 4).

Functional prediction of selected differential lncRNAs analysis were conducted both with GO and KEGG strategies. Gene Ontology analysis showed that the term of innate immune responses was significantly enriched and 17 differential lncRNAs were identified to be involved (Supp. Table 5). KEGG analysis identified term of rheumatoid arthritis was significant enriched and 4 differential lncRNAs (NONHSAG028996, NONHSAT142637, ENST00000584934 and NR_028330.1) were identified to be involved (Supp. Table 6).

We also identified large number of co-expressed lncRNA and TFs. The co-expression network between TF and lncRNA was shown in Fig. 4A. We discovered one large sub-network and large number isolated interaction between TFs and lncRNA. This network indicated lncRNA and TF would regulate the gene expression together in FLS cells. When we build lncRNA, TF, target gene network together (Fig. 4B), the result is quite similar as our expectation, and large numbers of genes were identified regulated by lncRNA and TF simultaneously.

**Cellular regulation effect of LLDT-8 treatment to FLS involved in NF-κB pathway.** In order to validate our discoveries that LLDT-8 could provide pharmacological effect to RA therapy via the interaction with rheumatology related pathway (Fig. 2D), we validate the effect of LLDT-8 to one of most important
Table 2. Most significant trans-lncRNA-mRNA regulation pairs for the significant differential lncRNA.

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<th>FC</th>
<th>R</th>
<th>P-value</th>
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<tr>
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<tr>
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<tr>
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Table 3. Most significant cis-lncRNA-mRNA regulation pairs for the significant differential lncRNA.

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Discussion

*Tripterygium* is a traditional Chinese medicine, which has widely been used in the treatment of rheumatic disease. (5R)-5-hydroxytriptolide (LLDT-8) is an extracted compound from *Tripterygium* and has shown lowered cytotoxicity and relatively higher immunosuppressive activity. However, how LLDT-8 influences RA FLS cells is still unknown, especially in levels of lncRNAs. In this study of genome-wide microarray assay, we identified large number of lncRNA and mRNAs responding to the LLDT-8 treatment. In addition, the first LLDT-8
related cis-regulated and trans-regulated lncRNA-mRNA modules were identified. We also constructed the first lncRNA-TF-mRNA co-expression network and demonstrated that LLDT-8 influenced the expression network within the whole FLS cells and therefore provided potential molecular and cellular mechanisms that LLDT-8 could be considered as potential rheumatoid arthritis drugs.

As we know, this is the first study to elaborate the genome-wide lncRNA and mRNA changes with or without LLDT-8 treatment. Our study provided an important landscape to design further studies to investigate the medical applications for lncRNAs in RA therapy. Although, genome-wide association studies (GWAS) have identified hundreds of variants associated with RA, our understanding of the disease mechanisms is still limited. Notably, more than 90% of the risk variants lie in non-coding regions, and almost 10% are corresponding to lncRNA

Figure 4. Co-expression network of lncRNA-TF and lncRNA-TF-targetGene within LLDT-8 differential response transcriptional regulatory network. (A) Co-expression network of lncRNA-TF, (B) Co-expression network of lncRNA-TF-Target Genes.
Considering that our result showed the significant change of the lncRNA during LLDT-8 treatment, lncRNA would be play important role in the pathogenesis and therapy of RA.

Our microarray data are consistent with protein results in our previous study in which we found LLDT-8 inhibited IL-1β, IL-6, IL-21 and IL-23 while LLDT-8 increased the IL-10 protein level. Meanwhile, our research were supported by numerous of previous research, such as Dr. Karouzakis and colleagues found synovial fibroblasts from early rheumatoid arthritis shown DNA methylation changes37. Our research demonstrate the immuno-suppressive function of LLDT-8 was related to the interaction with ncRNA network. Our results were also consistent with n'sh (PMC2833606) in which they found CCL8 are abundantly-expressed in RA synovial tissue while we found LLDT-8 could significant decrease CCL8 (Table 3). In another study38, p38 MAPK inhibition treatment showed increased TNFRSF18 which is similar with LLDT-8 treatment in our study which also highlights the anti-inflammatory function of LLDT-838. What's more, FAM129A was demonstrated low-expression in RSK2 deficiency mice which have earlier and exacerbated inflammation of bone destruction and in our study, we found FAM129A was significantly up-regulated after LLDT-8 treatment39. All these evidence support our conclusion that LLDT-8 own immune-suppressive function and epigenetic regulation mediated by IncRNA might play important roles.

We conducted the power analysis to estimate the minimum samples size to identify significant (q-value < 0.5) mRNA changes based on our dataset GSE84074 with bootstrap resampling. In the bootstrap resampling, we selected several important rheumatoid arthritis genes such as MMP genes (MMP1, MMP3), CCL genes (CCL3, CCL4, and CCL26), and IL genes (IL6, IL8, IL19, and IL24). We found when the sample size is larger than 4, majority of these rheumatoid arthritis genes can be detected with power > 0.8 (Supplementary Fig. 2), therefore, we believe our sample size is sufficient to identify the most interesting inflammation and autoimmune associated signals.

Our study also provided a probability to compare the IncRNA profiles with RA, primary Sjögren’s syndrome40, gastric carcinogenesis41, endometrial carcinoma42, bladder cancer43, esophageal squamous cell carcinoma44, non-small-cell lung cancer45 and cervical cancer46, since our data has been deposited to GEO database. These diseases might share some common aberrant IncRNAs relevant with inflammation and immune response and therefore provide some special insight to the therapy of RA.

In summary, our results provided a good prospect in further clinical tests of LLDT-8 for its therapeutic potential in the treatment of RA. We also suggest that more studies need to be done in order to further investigate the biological functions of IncRNAs in more patient samples. However, those initial results suggest that IncRNA would be a good biomarker and drug target in the future drug discovery, especially for LLDT-8. Our study also demonstrate epigenetics including DNA methylation47–49 and IncRNA50,51 are playing important roles in etiology and therapy of RA.

**Conclusion**

Genome-wide IncRNA and transcriptome analysis of response to treatment with (5R)-5-Hydroxytriptolide (LLDT-8) in cells shown LLDT-8 would mainly influence the RA cells systemically and especially in the process of immune network regulation.

**Data Availability**

The microarray data was deposited in the Gene Expression Omnibus (GEO accession: GSE84074).


Acknowledgements

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Author Contributions

D.H. and S.G. contributed to the conception, design and final approval of the submitted version. S.G., J.L. and T.J. contributed to the integrated analysis of multiple microarray datasets, batch effect elimination and statistical analysis. D.L., T.J., Y.L., R.W., Y.S., X.Z., Y.W., F.B., Q.D., J.Z., G.W. and X.Z. collected samples and helped to data cleaning, statistic and draft the manuscript. J.L., X.Z., Y.J. conducted cellular experiences. The final manuscript was completed by S.G., S.S. and D.H. All authors read and approved the final manuscript.

Additional Information

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