Computational workflow for predicting transcriptional modulation to achieve therapeutically desired cellular conversion for regenerative medicine

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Abstract

Introduction

Regenerative medicine promises cure for currently incurable diseases and pathological conditions. Its central idea is to leverage healthy cells to regenerate diseased cells, tissues or organs through the process of cellular conversion. The most common method to achieve this is by modulating the activity of specific transcription factors. However, the large number of protein-coding genes and transcription factors in humans and their complex interactions poses a challenge in identifying the most suitable ones for modulation. Here, we propose a computational workflow that facilitates the prediction of such transcription factors for achieving desired cellular conversion, along with highlighting their mechanistic basis in terms of the gene regulatory network of the target cell type.

Methods

The proposed workflow leverages three existing computational tools: TransSynW, PAGA and SIGNET, and uses single-cell transcriptome data of the starting and target cell types as inputs.

Results

We used this workflow on a sample dataset of human hindbrain neuroepithelial stem cells and midbrain medial floorplate progenitor cells to generate hypothesis for converting the former to the latter cell type. The workflow predicted the transcription factors for modulation and provided insight into their differential expression dynamics and influence on the predicted gene regulatory network of the target cells.

Conclusion

Our computational workflow helps extract meaningful predictive and mechanistic insights from high-dimensional biological data, which otherwise is difficult to accomplish from individual tools

alone. We believe this workflow can help researchers generate mechanistically founded hypotheses for achieving desired cellular conversions as a step towards regenerative medicine.

Key words

Transcriptional modulation; cellular reprogramming; cellular conversion; computational workflow; regenerative medicine

Abbreviations

TFs: Transcription Factors; scRNA-seq: single cell RNA sequencing; hNES: human hindbrain neuroepithelial stem cells; hProgFPM: human midbrain medial floorplate progenitor

1. Introduction

Regenerative medicine is an evolving branch of medicine aiming to address diseases without curative treatments [1]–[4].The central approach in regenerative medicine is to repair or replace the damaged and diseased cells, tissues and organs with the healthy ones [5] .

The first step towards generation of complex tissues and organs is the generation of healthy cells of specific types. This can potentially be achieved by cellular conversion through: (1) directed cellular differentiation of pluripotent cells occurring naturally (e.g. embryonic or adult stem cells) [6], [7], or developed artificially (e.g. iPSCs) [8], [9]; and (2) by transdifferentiation of somatic cells directly to the target cells [10].

Cells of a particular type maintain their identity and behavioral properties with the help of dynamic activities of transcription factors (TFs) and their corresponding target genes [11]. In line with this, cellular conversion from one type to another is shown to be achieved by modulating the activities of specific transcription factors [12], [13]. However, the challenge lies in identifying the correct TFs for modulation given that there are estimated 19,000 protein-coding genes [14] and ~1,600 TFs in humans [15]. Therefore, TF modulation for cellular conversions is typically based on prior knowledge, empirical intuition or purely trial and error, resulting in low efficiency of conversion [9], and tumorigenicity [1] and immune rejection [1], [4] of the target cells in the body.

Technologies such as single cell RNA sequencing (scRNA-seq) provide transcriptome information at single cell resolution [16]. This offers a means to understand the transcriptional signatures of different cell types as well as their intermediate transient cellular states during cellular interconversion [17] and thus, help in identifying TFs whose modulation can bring about the desired cellular conversions [18]. In fact, several computational tools exist (e.g. TransSynW [19], CellCartographer [20], NETISCE [21] and scREMOTE [22]) that utilize single cell transcriptome data alone or in combination with complementary biological data to predict the TF modulation required for desired cellular conversion. However, the hypotheses on TF modulation alone without understanding their molecular basis may be a black box and may have adverse consequence if progressed further towards clinical settings.

To gain holistic understanding of TF modulation, their mechanistic basis and the downstream effects, existing computational tools can be leveraged in the form of analysis workflows. In this study, we propose one such analysis workflow to generate hypotheses on TF modulation for cellular conversion and understand their mechanistic basis with respect to the transcriptional regulatory network of the target cell type.

We demonstrate the usefulness of this workflow using the sample dataset used by Okawa *et al.* [23]. The dataset corresponds to human hindbrain neuroepithelial stem cells (hNES) cell line (SAI2) [24] and human midbrain medial floorplate progenitor (hProgFPM) cells. The former was used as the starting cell type and the latter as the desired target cell type, thereby attempting cellular conversion from hindbrain progenitor cell line to a midbrain progenitor cell type.

2. Results and Discussion

We propose an analysis workflow consisting of TransSynW [19] for generation of hypotheses on TF modulation for cellular conversion, PAGA [25] for understanding the TransSynW predicted genes in the context of cellular conversion process from starting cell type to the target cell type, and SIGNET [26] to understand the gene modulation in the context of gene regulatory network of the target cell type, and gain insight into the mechanistic basis of the gene modulation hypothesis (see Figure 1). We detail this workflow below using the sample dataset of hNES to hProgFPM conversion as an example. The workflow generated hypothesis for converting hNES to hProgFPM cell type, revealed the differential expression dynamics of the hypothesized transcription factors and their interactions with the predicted gene regulatory network of the target cell type (hProgFPM).

2.1 Hypothesis generation on transcription factors whose activity modulation can achieve desired cellular conversion - TransSynW

TransSynW is a cell fate engineering tool, and we used it in the workflow to generate hypotheses on the TFs whose activity modulation can achieve cellular conversion of starting cell type (hNES) to the target cell type (hProgFPM). It uses single cell transcriptome data (e.g. scRNA-seq) of starting and target cell type populations to predict a synergistic list of TFs whose activity modulation can result in the desired cellular conversion.

TransSyn predicts core TFs required for cellular conversion and marker genes for the target cell type. Core TFs consist of specific and pioneer transcription factors, whose activity modulations

are hypothesized to bring about the cellular conversion. Specific TFs are predicted to be specifically expressed in the target cell type, and thus, are considered to be associated with cellular conversion and maintenance of target cell type identity. Pioneer TFs are generic in nature and consist of TFs previously reported to be involved in cell conversion protocols, for e.g. TFs associated with chromatin opening [19]. The marker genes (top10 shown by default) for the target cell type are predicted to enable assessing the performance of cell conversion experiments [19].

In the case of hNES to hProgFPM conversion, TransSynW predicted 8 core TFs (5 specific factors and 3 pioneer factors) (Table 1), whose activity modulations are hypothesized to bring about the desired cellular conversion. To gain insight into the relevance of these genes in the context of cellular conversion, we proceed to the next step of the workflow as detailed below. The marker genes predicted by TransSynW are shown in Table 2.

Table 1: Core transcription factors predicted by TransSynW

Gene	Fold Change	Type of Core Transcription Factor
OTX2	10.485	Specific
LMX1A	9.478	Specific
MSX1	6.99	Specific
DMRTA2	3.703	Specific
HEY1	3.182	Specific
SOX2	9.749	Pioneer
PBX1	5.604	Pioneer

SOX9	4.713	Pioneer

Table 2: Marker genes predicted by TransSynW. JSD Score: Jensen-Shannon Divergence score

Gene	JSD Score
DDC	78.61
NTN1	78.83
RND1	78.96
ELAVL4	78.97
PTPRO	79.03
APCDD1	79.04
RPS19	79.06
LDHA	79.17
PLOD2	79.17
EPHB2	79.24

2.2 Gaining insight into the differential expression dynamics of hypothesized transcription factors using pseudotime trajectory analysis - PAGA

We leveraged PAGA, a pseudotime trajectory inference tool, to understand the relevance of TransSynW predicted transcription factors in the context of cellular conversion from hNES to hProgFPM.

PAGA uses the starting cell type data (i.e. hNES) as the root (i.e. reference) and attempts to create a pseudotime trajectory representing the degree of conversion of each cell to the target cell type (hProgFPM) (see Figure 2). Overlaying the gene expression data of individual genes predicted by TransSynW on this pseudotime trajectory shows the difference in their expression as the cells transition from hNES to hProgFPM (see Figure 3, 4). Among the specific TFs, OTX2, LMX1A and MSX1 showed distinct change of expression between hNES and hProgFPM while DMRTA2 and HEY1 showed difference to a lesser extent. On the other hand, among the pioneer TFs, SOX2 and PBX1 showed no such change, while SOX9 showed minor differences in the expression between hNES and hProgFPM cells.

We hypothesized that this is because the specific TFs are characteristic of a specific lineage, midbrain in the case of hProgFPM, and thus are specifically expressed in them. In contrast, the pioneer TFs are generic and thus, are expressed in pluri- or multi- potent cells (in our case, by both, hNES and hProgFPM cell populations) for bringing about transcriptional alterations. To verify this, we studied the functional annotation of these genes in UniProt and the corresponding Gene Ontology terms (see supplementary file). The specific TFs were indeed found to be involved in dopaminergic and midbrain development except for HEY1. On the other hand, pioneer TFs - SOX2 and PBX1 are involved in suppressing neuronal differentiation in line with their multipotent nature, and it is the dynamic balance between specific and pioneer TFs that possibly acts as a switch for neuronal differentiation. For SOX9, we did not find any annotation relating it to neuronal differentiation.

2.3 Deciphering the mechanistic basis of transcription factors activity modulation - SIGNET

We used SIGNET to predict the gene regulatory network (GRN) of the target cell type (i.e. hProgFPM) that highlights the functional transcriptional regulation required for cellular functions (see Table 3). Assessing the TransSynW hypothesized TFs and marker genes in the context of this GRN revealed the likely molecular basis of their effect on cellular conversion. We used TRRUST database to identify the corresponding TFs and the target genes of the genes obtained from TransSynW and SIGNET such that indirect interactions can be captured.

Combining these genes and their corresponding regulatory TFs and the target genes in a network (see Figure 5) highlights the hypothesized TFs and marker genes in the context of hProgFPM GRN. For instance, (1) MSX1 (a specific TF) and SOX9 (a pioneer TF) predicted by TransSynW, seems to jointly regulate the expression of HES1 (a TF in hProgFPM GRN), which in the downstream, regulates the expression of a marker gene, PTPRO; (2) Similarly, OTX2 (another specific TF) and SOX9 jointly regulates the expression of another marker gene, DDC in the downstream; and (3) NR2F6 and HMGA2 are two of the TFs predicted by SIGNET, and are shown to be regulating the expression of two of the pioneer TFs, SOX9 and SOX2, respectively. Overall, the network helps reveal the direct and indirect effects of modulation of the TransSynW hypothesized genes, and their interaction with hProgFPM GRN, which together culminate into the regulation of few of the marker genes predicted by TransSynW.

Table 3: Regulons predicted by SIGNET for target cell type, hProgFPM.

Transcription Factor	Target Gene
HES1	PLEKHM2, SARNP, KIAA0226, VDAC3
HES5	HSD11B1L, VDAC3
HMGA2	RAP1B, SMARCA1
NR2F6	CBX5, EHBP1, GGCX, MAGI2, SOX9
PBX1	RCC2, IMMP1L, FBXL20, ATP5E, RPS14
TEAD2	RTN3, BCAT1, SLC39A10

3. Discussion

Efficient cellular conversion of therapeutically suitable starting cell types (e.g. stem cells, skin fibroblasts) to the desired target cell types (e.g. dopaminergic neurons, cardiomyocytes, pancreatic beta cells [27]) lies at the center of regenerative medicine. We proposed an analysis workflow that leverages three disparate computational tools to generate not just hypotheses of gene modulation for cellular conversion, but also infer their mechanistic basis.

Although, scientific literature is replete with examples of using multiple tools to address their specific use cases in stem cell research and regenerative medicine, to the best of our knowledge, such defined workflows are not present. We believe that the proposed workflow is reusable and can help researchers formalize new and mechanistically founded hypotheses for achieving desired cellular conversions.

It is important to note that the presented workflow is one of the possible workflows, and many more such workflows can be devised to address this or other challenges in the regenerative medicine field. We would like to draw parallels to genomic data analysis workflows that have streamlined such analyses and have contributed greatly in accelerating the progress of the field.

4. Conclusion

In this study, we leveraged diverse computational tools together to navigate through high-dimensional transcriptomic data and propose hypotheses on transcription factors modulation for achieving desired cellular conversion. We believe that the proposed workflow would benefit researchers in generating mechanistically founded hypotheses that addresses the common pitfalls of cellular conversion including low efficiency of conversion, and the risk of tumorigenicity and immunogenicity in the target cells. Furthermore, we believe integrating already existing resources (computational tools are an example) can in general provide deeper and diverse insights than individual tools. The proposed workflow is a start, and can be further extended with other combinations of tools, prior biological knowledge, etc. based on their suitability to specific use-cases.

5. Materials and Method

5.1 scRNA-seq based gene expression data of starting and target cells

The data used in the study were obtained from NCBI GEO: hNES from GSE114670 and hProgFPM from GSE76381. In both, gene expression values are expressed as counts of detected mRNA molecules from each gene in each cell.

The hNES and hProgFPM datasets consist of 15212 genes x 288 samples (i.e. cells) and 19531 genes x 1977 samples respectively. The genes common in both datasets were identified (= 15036) and used for further analysis.

5.2 TransSynW

TransSynW [19] was set up locally using code available at: https://git-r3lab.uni.lu/mariana.ribeiro/transsynw. scRNA-seq data of starting and target cells were provided separately as input to TransSynW. The target cell scRNA-seq data file is appended with starting cell data, which serves as the background cluster required by TransSynW.

5.3 PAGA

PAGA [25] requires the scRNA-seq data in the form of a *samples x genes* matrix as input. For this, the starting and target cell scRNA-seq data were merged, creating a matrix of 370 samples *(288 hNES + 82 hProgFPM)* x 15036 genes.

Scanpy (https://scanpy.readthedocs.io/en/stable/index.html) was used for PAGA analysis, and the steps are based on its tutorial (https://scanpy-tutorials.readthedocs.io/en/latest/paga-paul15.html). Briefly, dimensionality reduction was performed using Principal Component Analysis, followed by construction of neighborhood graph of the samples. The data was further denoised using Diffusion map. Starting cell type (i.e. hNES) data is used as the root for computing the pseudotime trajectory. The gene expression values of TransSynW predicted genes were overlaid on the trajectory to visualize the expression changes of each gene in the context of the trajectory.

5.4 SIGNET

Signet [26] requires scRNA-seq data in the form of *samples x genes* matrix as input, and list of transcription factors based on the species (*Homo sapiens* in our case). The steps followed were in accordance with the SIGNET tutorial (https://github.com/Lan-lab/SIGNET/tree/main/SIGNET_Tutorial). In brief, SIGNET predicts the relationship between TF and non-transcription factor genes, and then uses RcisTarget (https://bioconductor.org/packages/release/bioc/html/RcisTarget.html) for motif analysis and thereby filtering out the false positive ones.

Data availability

We downloaded the gene expression data from Gene Expression Omnibus (GEO) under accession codes GSE114670 and GSE76381.

Authors' contributions

V.S. conceived the study, V.S. and A.M. designed the experiments. A.M. conducted the experiments. A.M. and V.S. analyzed and interpreted the results. A.M. and V.S. wrote the manuscript.

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Conflict of interest

All authors are affiliated with Thoughtworks.

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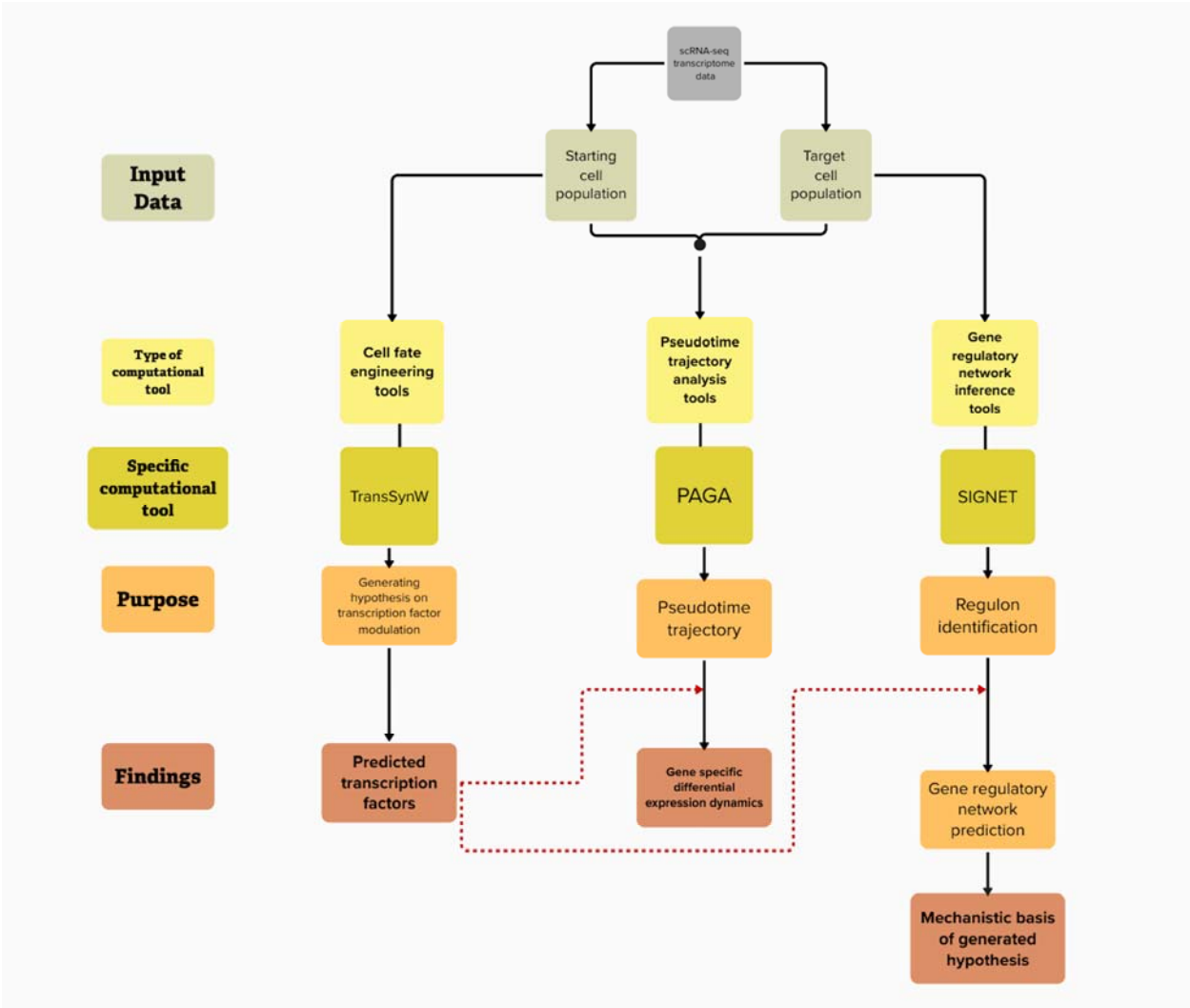

Figure 1: Proposed analysis workflow.

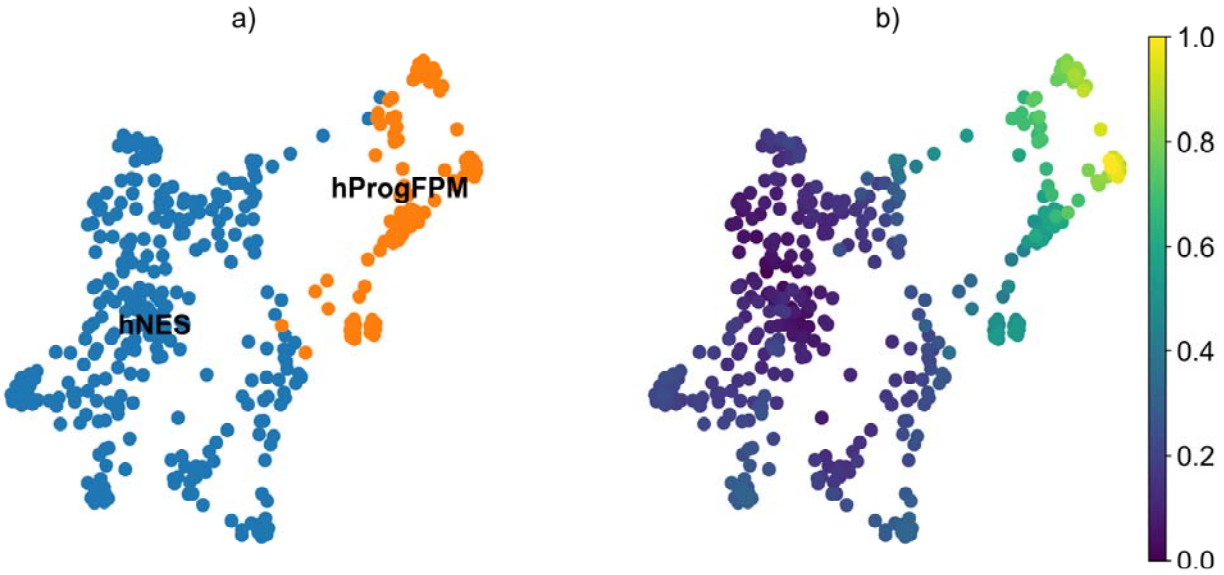

Figure 2: Pseudotime trajectory of hNES to hProgFPM conversion. a) Clustering of hNES and hProgFPM cells; Blue: hNES cells, Orange: hProgFPM cells; b) Pseudotime trajectory showing the progression from hNES cells (dark shades) to hProgFPM cells (lighter shades).

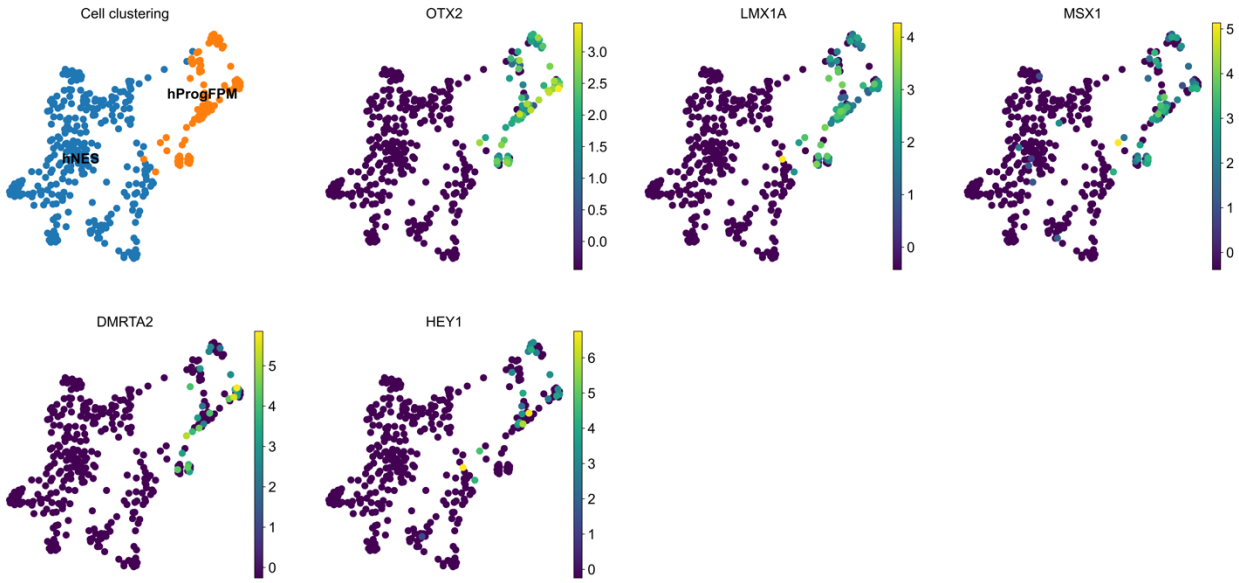

Figure 3: Differential expression dynamics of hypothesized specific transcription factors with reference to the pseudotime trajectory. Clustering of hNES and hProgFPM cells is provided for reference; Blue: hNES cells, Orange: hProgFPM cells.

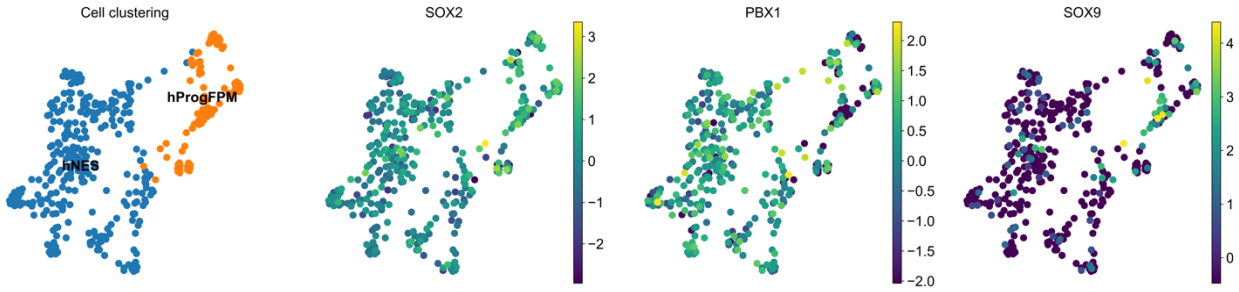

Figure 4: Differential expression dynamics of hypothesized pioneer transcription factors with reference to the pseudotime trajectory. Clustering of hNES and hProgFPM cells is provided for reference; Blue: hNES cells, Orange: hProgFPM cells.

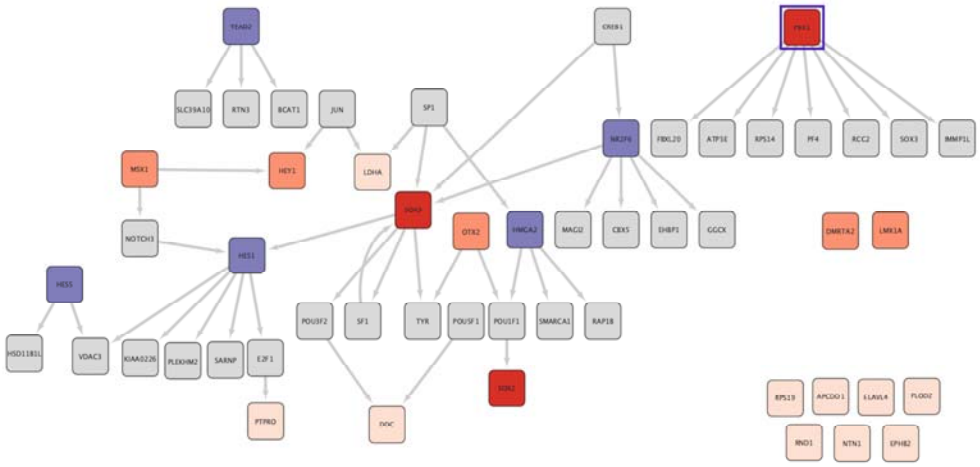

Figure 5: Transcriptional regulatory network based on the genes obtained from TransSynW and SIGNET. Red: Pioneer transcription factors, Orange: Specific transcription factors, Light Orange: Marker genes, Purple: Transcription factors predicted by SIGNET, Red with Purple box: Common transcription factors between hypothesized genes and SIGNET, Grey: Additional interacting genes obtained from TRRUST database.