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A HaemAtlas: characterizing gene expression in differentiated human blood cells

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Hematopoiesis is a carefully controlled process that is regulated by complex networks of transcription factors that are, in part, controlled by signals resulting from ligand binding to cell-surface receptors. To further understand hematopoiesis, we have compared gene expression profiles of human erythroblasts, megakaryocytes, B cells, cytotoxic and helper T cells, natural killer cells, granulocytes, and monocytes using whole genome microarrays. A bioinformatics analysis of these data was performed focusing on transcription factors, immunoglobulin superfamily members, and lineage-specific transcripts. We observed that the numbers of lineage-specific genes varies by 2 orders of magnitude, ranging from 5 for cytotoxic T cells to 878 for granulocytes. In addition, we have identified novel coexpression patterns for key transcription factors involved in hematopoiesis (eg, GATA3-GFI1 and GATA2-KLF1). This study represents the most comprehensive analysis of gene expression in hematopoietic cells to date and has identified genes that play key roles in lineage commitment and cell function. The data, which are freely accessible, will be invaluable for future studies on hematopoiesis and the role of specific genes and will also aid the understanding of the recent genome-wide association studies. (BLOOD. 2009;113:e1-e9)

Introduction

The hematopoietic system represents one of the best-studied cellular differentiation processes in mammals. The differentiation of the hematopoietic stem cell (HSC) into the blood cell lineages, which is depicted as a stepwise process, generates diverse types of cells that perform many different functions. Historical observations of the blood, made in the late 18th century using some of the first microscopes, revealed that blood is composed of a heterogeneous population of cells that are distinct in number, morphology, and function. Since these early studies, the application of both technological and methodologic advances to the investigation of blood has led to an ever-increasing understanding of the nature and function of the different types of blood cells. For example, the use of monoclonal antibodies (mAbs) and the designation of the cluster of differentiation (CD) markers, of which there are now more than 300, allows hematologists to assign detailed phenotypes to malignant blood cells, which form the basis of decisions on therapeutic intervention.

The value of the current understanding of the hematopoietic system to patient care is perhaps best illustrated in the field of malignancy where gene and protein expression profiles permit rapid and routine patient stratification. It is now possible to stratify patients with leukemia and lymphoma with unprecedented accuracy using gene expression profiles. Signature gene expression profiles may be used for diagnosis and predicting disease prognosis. In addition to studies in patients, gene expression profiles are available for a wide range of healthy tissue types. However, many of these resources, although broad in tissue coverage, are limited in the number of samples analyzed for each tissue type (eg, Symatlas). Consequently, the false-positive and false-negative discovery rates are high, and limited reliable information is available regarding variation in gene expression profiles between healthy persons. Similarly, platform differences between studies do not facilitate rapid comparison between datasets.

We set out to generate a focused gene expression atlas for cells of the hematopoietic system from healthy persons, a so-called Hematology Expression Atlas (HaemAtlas). We have taken advantage of recent advances in cell purification, RNA amplification, and microarray technologies that allow the study of gene expression of purified subsets of cells on a genome-wide scale. Using whole-genome expression arrays, we have compared the gene expression...
profiles of the precursors of erythrocytes and platelets (erythroblasts [EBs], megakaryocytes [MKs]) and of B cells, cytotoxic T cells (Tc), helper T cells (Th), natural killer (NK) cells, granulocytes, and monocytes. In total, 50 expression profiles were obtained using the Illumina HumanWG-6 version 2 Expression BeadChip (Illumina, San Diego, CA), which have more than 48,000 probes, targeting genes and known alternative splice variants from the RefSeq database release 17 and UniGene build 188.

The data described represent an extremely useful resource for the clinical hemat-oncologist and for the research community as a whole. In addition, we demonstrated the utility of this dataset by performing a focused bioinformatic analysis of transcription factor and immunoglobulin superfamily (IgSF) member gene expression. The dataset has already been used in conjunction with genome-wide association studies and in the characterization of tetraspanins. Finally, by comparing expression profiles between cell types, we have identified sets of transcripts that are lineage specific and show, in an accompanying manuscript, the expression and function of 4 novel proteins in arterial thrombus formation.

Methods

Cell purification and purity assessment

Whole blood units (~ 450 mL) from 7 healthy volunteer donors of the Cambridge BioResource at National Health Service (NHS) Blood and Transplant were obtained with informed consent in accordance with the Declaration of Helsinki. The study was approved by the United Kingdom National Health Service Blood and Transplant. Donors were included only if they had a hemoglobin more than 12.5 g/dL for women and 13.5 g/dL for men, were negative for HepB, HepC, HIV1, and HIV2 antibodies, negative for syphilis, and negative for hepatitis C virus (HCV) by nucleic acid testing. Donors Epstein-Barr virus and cytomegalovirus status were not selection criteria. Blood was taken by venipuncture into a bag containing acid citrate dextrose anticoagulant according to the NHS Blood and Transplant procedures. CD4⁺ Th and CD8⁺ Tc lymphocytes, CD14⁺ monocytes, CD19⁺ B lymphocytes, CD56⁺ NK cells, and CD66b⁺ granulocytes were isolated using an automated magnetic labeling protocol (RoboSep; StemCell Technologies, Vancouver, BC) as described in “Supplementary Materials and Methods” in Document S1 (available on the Blood website; see the Supplemental Materials link at the top of the online article). Details of the CD markers used for cell isolation together with quality control data for the processed samples are given in Tables S1 and S2. The culture conditions of the 4 cord blood hematopoietic progenitor cell (HPC) preparations and the purification protocol of the MKs and EBs have been described previously.

RNA purification, amplification, and hybridization

Purified cell populations were lysed in Trizol following the manufacturer’s instructions (Invitrogen, Paisley, United Kingdom) using 1 mL Trizol reagent per 10⁶ cells. Isolated total RNA was then purified further using the RNeasy MinElute Cleanup Kit (QIAGEN, Dorking, United Kingdom). Each purified RNA sample was assessed for quality and integrity using the 2100 Bioanalyzer (Agilent Technologies, Palo Alto, CA). All information on RNA processing and quality assessment is available in Table S1. Total RNA (500 ng) was amplified using the Illumina Total Prep RNA Amplification Kit (Ambion, Austin, TX) according to the manufacturer’s instructions. The biotinylated cRNA (1500 ng per sample) was applied to Illumina HumanWG-6 v2 Expression BeadChips and hybridized overnight at 58°C. Chips were washed, detected, and scanned according to the manufacturer’s instructions.

Statistical analysis of gene expression data

Present genes. The Illumina BeadStudio software calculates a Detection Score equivalent to 1 – P value for detection for each probe, which is an estimate of the confidence limit of detection relative to the local background. Probes were considered as present if they had a detection score more than 0.99 in all samples of a given cell type.

Differentially expressed genes. We performed pairwise comparisons between one cell type and every other cell type used in the study. These comparisons are exhaustive but necessary to identify transcripts that are unique to each of the cell types or common between different cell types. In comparing the expressions between cell types, we performed a paired t test (or 2-sample t test in the case of nonpaired samples) coupled with multidimensional false-discovery rate control (FDR2D). FDR2D was used to guard against false-positive results from transcripts whose variance is underestimated by chance, whereas their fold changes are small. Analysis of the results obtained suggests that the method is effective in identifying true differentially expressed (DE) transcripts.

Cell unique and unspcific genes. To identify transcripts that are specifically enriched or depleted in a given blood cell lineage, so-called “unique” and “unspecific” genes, respectively, we performed a comparison between the lists of DE genes using an “AND” operator. In such a way, genes that were consistently up- or down-regulated vs all other cell types were identified.

Bioinformatic analysis

Biologic processes. The Protein Analysis Through Evolutionary Relationships (PANTHER) classification scheme (http://www.pantherdb.org/) was used to infer involvement in biologic process for the present genes as described in “Supplementary Materials and Methods” in Document S1.

IgSF proteins. The identification of the IgSF repertoire expressed by blood cells was based on matching microarray probes to 2 existing reference sets: (1) our manually curated human IgSF reference set defined previously; and (2) the subset of Homo sapiens Ensembl v46, gene predictions that received significant hits by either PFAM or SUPERFAMILY, hidden Markov models that represent IgSF domain sequences.

The functional presence of an IgSF gene was established using conservative signal threshold cutoff values. Furthermore, the analysis of IgSF expression was primarily focused on the identification of those cell types in which the presence of a transcript was particularly marked. This was achieved by comparing relative signal intensity values for the same probe across the cell types and, using the ratio of the mean intensity to the SD, indicative skews in the distribution were identified when such an index was less than 1.

Transcription factor networks. We generated a dataset of transcription factors by combining (1) a manually curated list of known transcription factors and (2) sequence-specific DNA-binding transcription factors using the most recent version of our transcription factor prediction database (http://transcriptionfactor.org/). The combined transcription factor set contains 2528 transcripts, all of which are present on the Illumina HumanWG-6 version 2 Expression BeadChips.

Evolutionary conservation of gene expression profiles. To identify evolutionary conservation of gene expression profiles in blood cells, we compared the human hematopoietic expression data generated in this study with that in mice obtained by Chambers et al. The murine study included hematopoietic stem cells, activated Tc and Th cells, in addition to the cell types analyzed here, but did not include MKs. A comparative analysis of the expression profiles for the cell types common to both studies was conducted. Notwithstanding that the tissue and membrane antigens used for cell isolation differed between the 2 studies, greater than 98% of all human-mouse orthologous transcripts were represented in both datasets.

The data described in this manuscript are available at ArrayExpress (www.ebi.ac.uk/microarray-as/aef/) under accession number E-TABM-633 or at the Bloodomics project website (www.bloodomics.org).

Results

Sample processing

In total, we purified peripheral blood cells from 43 volunteers from which 7 sets that met strict quality control criteria were selected for
For each cell population, purity was more than 95% as assessed by flow cytometry together with a morphologic assessment of May-Grunwald-Giemsa (Romanovsky)–stained cytocentrifuge preparations using light microscopy (Figure 1). After cell isolation, RNA was purified and quality assessed using an Agilent BioAnalyzer before amplification. A total of 50 samples were amplified and hybridized onto the Illumina Human WG-6 version 2 Expression BeadChips as described. This represents 6 cell types isolated from peripheral blood from the 7 volunteer donors (n = 42) and MKs and EBs differentiated from CD34+ HPCs obtained from 4 umbilical cord blood samples (n = 8).6

Genes expressed in differentiated blood cells

For each cell type, we first determined the number of present probes by applying rigorous criteria to reduce false-positive discoveries (Figure 2; Table S3). As can be seen, the number of present probes ranged from 7302 for granulocytes to 10 314 for MKs. The lower number of present transcripts in granulocytes could not be attributed to any features of the microarrays (data not shown).

Hierarchical cluster analysis of all samples based on the probes with the highest variance across the 50 samples recapitulated the known hematopoietic differentiation pathway, with the exception that the NK-cell samples were more closely related to the Tc samples (Figure 2B) than Th. On the basis of this clustering, we defined genes that were common to (1) the 2 precursor cells, (2) granulocytes and monocytes, and (3) Tc, Th, and NK lymphoid cells and performed an overlap analysis with those present in B cells (Figure 2C). A total of 5396 genes were detected in all blood cells, with transcripts from an additional 1860 genes being present in all cells except for monocytes and granulocytes (Figure 2C). As expected, more than 1000 more transcripts were detected in the transcriptomes of the 2 precursor cells (MKs and EBs), with Gene Ontology (GO) analysis indicating enrichment for genes involved in cell cycle (GO, 0007049), mitotic cell cycle (GO, 0000278), and cell-cycle process (GO, 0022402). This observation is in agreement with the active cell proliferation and differentiation processes that are underway in these 2 elements that normally reside in the bone marrow environment.

Using PANTHER classification, we observed that genes in “nucleoside, nucleotide and nucleic acid metabolism,” “immunity and defense,” and “protein metabolism and modification” are overrepresented in hematopoietic cells but that categories such as “signal transduction” and “developmental process” are underrepresented (Figure 2D). The enrichment for genes involved in “immunity and defense” is consistent with our understanding that immune responses are one of the primary...
functions of the myeloid and lymphoid blood cell types. In addition, genes classified as being involved in “signal transduction” are underrepresented in all cell types studied.

Expression of CD markers

The CD markers constitute the most widely studied hematopoietic markers, with known protein expression patterns confirmed by antibody staining of normal and malignant hematopoietic cellular elements. Of the 339 currently described CD markers, 44 are not represented on the Illumina HumanWG-6 v2 Expression BeadChips (data not shown). We clustered the samples on the basis of CD marker gene expression. The samples cluster largely as expected, with a clear distinction between cells of the myeloid and lymphoid lineages (Figure 3). Interestingly, again, the CD56⁺ NK cells cluster most closely to the CD8⁺ Tc cells, confirming the results of the hierarchical clustering based on transcripts with a high variance (Figure 2), and compatible with the notion that these 2 cells are more closely related than the CD4⁺ and CD8⁺ T cells at the transcript level. Similarly, the CD66b⁺ granulocytes and CD14⁺ monocytes cluster together as do the MK and EB samples (Figure 3).

Combinatorial patterns of transcription factor expression

Transcriptional regulation is a key mechanism controlling fate commitment of HPCs and their progeny and ultimately in controlling intermediate phenotypes, such as volumes and numbers of the mature blood cell elements. Both gain- and loss-of-function studies have been used to demonstrate the role of transcription factors in controlling the specification and differentiation of HSCs (eg. SCL/TAL1, GATA2, c-MYB, PU.1, RUNX1, ETV6, GFI1). However, much remains to be learned about the way these key regulators interact with each other and thus form the transcriptional networks that specify the various mature lineages. We therefore explored the potential utility of our gene expression profiles to gain new insights into hematopoietic transcriptional control mechanisms.

We initially catalogued sequence-specific, DNA-binding transcription factors expressed in all cell types using the most recent version of our transcription factor prediction database DBD (http://transcriptionfactor.org/). The expression profiles of known key hematopoietic transcription factors and their related family members are shown in Figure S1. An immediate conclusion from this analysis was that key hematopoietic transcription factors are expressed in multiple hematopoietic lineages, consistent with the notion that hematopoietic lineages are generally not specified by single transcription factors. Instead, specific combinatorial interactions between key transcription factors are vital to control cellular identity.

To explore the combinatorial theme further, we next identified those transcription factors that share their expression profiles with 6 well-characterized transcription factors with distinct roles in the development of the 8 blood lineages profiled in this study. This approach was based on the rationale that coexpression of transcription factor pairs might reveal new regulatory links as it would be consistent with either direct regulation (transcription factors upstream or downstream of each other) or placement within the same regulatory pathways. Our analysis demonstrated that the numbers of coexpressed transcription factors (TFs) varied greatly for the 6 TFs chosen, ranging from one for GATA1 to 35 for GATA2.
Coexpression in several cases was consistent with known interactions (GATA2-Tal1 or GATA1-GFI1) and also suggested as yet unreported interactions between known key regulators (GATA3-GFI1; GATA2-KLF1). Moreover, many putative links with totally uncharacterized transcription factors were revealed, such as the various zinc finger families (Figure 4). Taken together, therefore, our analysis suggested that comprehensive genome-wide expression surveys provide an important resource to reveal new links in hematopoietic regulatory networks, particularly with respect to the combinatorial control of gene expression.

IgSF member expression in hematologic cells

The IgSF represents a family of proteins that play key roles in hematopoiesis and blood cell function. Analysis of the HaemAtlas expression data shows that 170 (~30%) of the approximately 600 known IgSF genes show significant expression across the 8 blood cell types investigated (Figure 5). The highest cumulative expression (and largest unique protein repertoire) of IgSF molecules was found in the granulocyte, whereas the erythroblast showed the lowest level of IgSF deployment. This detailed analysis of the expression of IgSF members in blood cells has identified several novel findings relating to their various functions.

IgSF members involved in boundary interactions

Several IgSF family members are involved in interactions at cell boundaries, and we investigated the expression of these in the HaemAtlas data. Blood cell-surface IgSF protein interaction with the vascular wall and epithelia is primarily mediated and modulated via molecules, such as PECAM-1, MCAM, CD47, SIRPs, and the families of the intercellular adhesion and junctional adhesion molecules, ICAM and JAM, respectively. PECAM-1, MCAM, and JAM molecules are crucial for interaction with the endothelium, binding both homotypically and to other non-IgSF ligands. PECAM-1 is known to interact with the non-IgSF CD177, which is considered to be granulocyte-specific. In our data, CD177 showed very low expression levels across the 8 cell types, whereas PECAM1 transcription was found at increasing levels in megakaryocytes, monocytes, and granulocytes. PECAM-1 is also known to play a collaborative role with JAM-A in the transmigration of granulocytes, and JAMA expression was predominant in the granulocyte. JAM-C, on the other hand, was well represented in all lymphoid cells as well as the megakaryocyte. JAML, which binds the Coxsackie adenovirus receptor (CxADR) during blood cell migration across the mucosal barrier, was among the most highly expressed cell adhesion molecules in monocytes and granulocytes. MCAM (typically up-regulated in activated T cells), VCAM1, and MADCAM1, which are known to be specifically expressed in endothelial cells, were not detected.

The ICAMs are known for their deployment on luminal endothelial and apical epithelial surfaces and for their interaction with leukocytic integrins. However, signaling from ICAMs is also known to play a role in blood cell development. In the...
current study, ICAM4 was exclusively expressed in megakaryocytes and erythroblasts, ICAM3 was present in all differentiated blood cells (somewhat prominently in the granulocyte), and ICAM2 had a moderate signal intensity level in all cell types except for granulocytes. Transcription levels were low for ICAMs-1 and -5 in all cells tested.

Interestingly, we observed a notable overlap between the blood cell IgSF cell surface sensors and those associated with neural development. Moderate intensity levels of NCAM-1 and low levels of ICAMs-1 and -5 were observed in all cell types tested, with yellow boxes indicating the size of the font and the green-to-red color intensity are both indicative of the strength of mean expression across the cells.

Identification of differentially expressed genes

A statistical analysis was performed to identify transcripts that are differentially expressed between each cell type as described. For this analysis, we considered a transcript to be differentially expressed between each cell type as described. For this analysis, we considered a transcript to be differentially expressed if it had a P value less than .05 and a fold change more than 2. The outcome of this analysis for MKs is shown in Figure 7. An average of 2206 features were up-regulated (range, 1091-3763) and 1986 down-regulated (range, 750-3058) between MKs and each other cell type. As expected when the MK was used as a reference, the smallest number of DE features was observed in the comparison with EBs. Interestingly, we observed that the CD66b+ granulocytes had the greatest number of DE features in each
comparison, reflecting the significant differences between the myeloid cells and the other cells tested. The complete lists of DE features are given in Table S4.

**Cell-specific transcripts**

We also performed an overlap analysis of the lists of DE transcripts to identify those that are consistently up-regulated in one cell type compared with all others (Table S5). The lists of genes thus generated are considered “unique” for each cell type analyzed. We observed that the number of transcripts uniquely expressed in a given cell type varies by more than 2 orders of magnitude, with CD8⁺ cells expressing only 5 unique transcripts and CD66b⁺ cells expressing 878. Similarly, the CD66b⁺ cells have the highest number of unspecific transcripts, whereas CD8⁺ cells express the least (data not shown).

The CD8⁺ T cell–specific genes included both CD8A and CD8B, although low-level expression of CD8A was also observed in the NK-cell population, but this was in the absence of CD8B. The other CD8⁺ T cell–specific transcripts were CD248, DKK3 (dickkopf homolog 3), and the T-cell receptor alpha V gene segment TRA1-2. CD248, also known as endosialin, has previously been reported as a fibroblast and pericyte marker where it plays a role in tissue remodelling and repair.37 The function of DKK3, which is divergent from the 3 other dickkopf family members (DKK1, 2, and 4), is unknown, although a role as a tumor suppressor has been suggested because it is down-regulated in several tumor cells.38 Interestingly, Dkk3 knockout mice, which do not show enhanced tumorigenesis, have several unique hematologic features compared with wild-type mice, including the frequency of NK cells and IgM levels.39 More recently, a role for DKK3 in TGF-β signaling has been identified40; however, its role as a secreted molecule in cytotoxic T-cell function remains to be elucidated.

We hypothesized that the identification of cell-specific transcripts would lead to the discovery of novel genes that play important roles in cellular functions. We tested this hypothesis for 2 of the cell types used in this study, CD8⁺ T cells and MKs. CD248-specific monoclonal antibodies, we were able to demonstrate the surface expression of CD248 on CD8⁺CD45RA⁻ T cells (Figure 8), confirming the lineage specificity of this protein. The reason for the differential expression of CD248 between human and mouse T cells is unknown but warrants further investigation.

For MKs, we selected 4 MK-specific transcripts for study in a zebrafish thrombosis model. Knockdown of all 4 genes, which are uniquely expressed in MKs, significantly affected thrombus formation in the caudal artery after laser-induced vessel injury. Using this model, combined with the selection of MK-specific genes identified using the HaemAtlas, we have demonstrated a role for BAMBI and LRRRC32 in promotion and DCBLD2 and ESAM in inhibition of thrombus formation.5

**Discussion**

In this study, we have generated a gene expression atlas for 8 cells of the hematopoietic system in what represents the most comprehensive study of gene expression in blood cells from normal healthy persons published to date. We envisage that the future use of the
HaemAtlas will primarily be that of a reference resource for gene expression in blood cells. We developed standardized protocols and stringent quality-control measures for cell isolation before microarray analysis to ensure the quality of this gene expression atlas. All cell types used in this study were more than 95% pure based on flow cytometry analysis and inspection by microscopy. The granulocyte population consists of 3 cell types (neutrophils, eosinophils, and basophils), all of which express CD66b and would therefore be copurified. Interestingly, we did observe variation in the levels of eosinophils in the granulocyte preparations from 15% to 30%. The effect of this variation on the transcriptome data is unknown, but it is probably most apparent in the determination of lineage-specific transcripts. Such an effect was observed for the single CD56+ NK sample with platelet contamination, as this NK sample showed the presence of transcripts deemed MK-specific (data not shown). This observation highlights the importance of maintaining a high level of cell purity when identifying lineage-specific genes. However, the presence of a single, platelet-contaminated sample had minimal effect because of the number of replicates used and the high purity of the other samples.

Our analysis of this comprehensive dataset was focused on transcription factors and IgSF members as these proteins play key roles in both blood cell differentiation and function. An analysis of the coexpression of all TFs with 6 well-characterized TFs that have distinct roles in blood cell development confirmed known interactions and identified as yet unreported ones between known key regulators of transcription. This analysis highlights the utility of genome-wide expression in revealing new links in hematopoietic regulatory networks. Similarly, the IgSF analysis confirmed known expression patterns and identified several previously unreported ones in hematopoietic cells. Of particular interest is the expression of many transcripts involved in neural development. Furthermore, we were able to identify genes that are unique to each cell type studied. These lists of unique genes include the classic lineage-specific CD transcripts and novel lineage-specific transcripts recently identified by both others and us (eg, G6B, G6F, LRRC32, and SUCNR1 in MKs5) and also identify novel lineage-specific transcripts for further study. Having established a catalog of lineage-specific transcripts is important for several reasons. First, it provides reassurance of the accuracy of the data presented in this manuscript. A close inspection of the lineage-specific transcripts encoding transmembrane proteins in EBs and MKs identified the presence of lineage-specific CD transcripts, confirming the excellent sensitivity of the array platform. Second, proteins encoded by lineage-specific transcripts are ideal drug targets allowing for pharmacologic manipulation of cell function in a cell-specific manner. Third, sequence variation of transcripts for transmembrane proteins, which alter the amino acid sequence of cell-specific membrane proteins, may be alloantigens, such as the human platelet antigens.41 It is probable that, by an approach of inverted immunology, novel clinically relevant alloantigens may be uncovered. Finally, lineage-specific transcripts may play a key role in cell function, as highlighted by the fact that all the novel MK-specific transcripts that we have tested in a zebrafish thrombosis model have a clear role in thrombus formation.5

Unlike previous studies performed with pooled cells isolated from inbred strains of mice, we performed each hybridization with RNA obtained from a single person. In addition, samples in this study were isolated from unrelated donors; hence, it is possible to ascertain the extent of biologic variation in gene expression. A parallel study, in which gene expression profiles of monocytes from 40 persons were compared, has identified those monocyte genes with the greatest variation in expression (data not shown). Such studies, combined with genome-wide genotyping, will allow the identification of cis- and trans-regulatory genetic variants that control gene expression in primary cells, as has recently been determined for immortalized lymphoblastoid B-cell lines.42,43

The analysis of the HaemAtlas data reported here is based on statistical comparisons performed on a cell-by-cell basis. It is possible to analyze the data by making use of the known hematopoietic hierarchy such that opposite “arms” in the hematopoietic lineage tree would be combined. This strategy would potentially allow the identification of DE genes in in silico–generated precursor cells that are not readily accessible for analysis.

In conclusion, the HaemAtlas that we have generated serves not only as a reference library for gene expression in human blood cells but also as a resource for identifying key genes with roles in blood cell function.

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Authorship

Contribution: N.A.W. performed and designed research, analyzed data, and wrote paper; A.G. performed statistical analysis of the data; B.d.B. performed analysis of immunoglobulin superfamily expression and wrote the paper; S.D. and D.M.-S. performed
analysis of transcription factor expression and wrote the paper; W.G.J.A. and A.P.A. provided critical bioinformatic support; D.L.H., C.M.I., and C.D.B. performed T-cell experiments; P.D.E. performed amplifications and microarray hybridizations; W.E. analyzed morphology of blood cells and provided critical expertise; N.S.F. isolated cells and RNA and wrote the paper; W.G.J.A. and A.P.A. provided critical bioinformatic support; analysis of transcription factor expression and wrote the paper; and W.H.O. designed research and wrote the paper.

A complete list of the members of the Bloodomics Consortium appears in Document S1, available on the Blood website.

Conflict-of-interest disclosure: The authors declare no competing financial interests.

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References

1. Zola H, Swart B, Nicholson I, et al. CD molecules 2005: human cell differentiation molecules. Blood. 2005;106:3213-3216.
2. Li S, Cho Y, Chang KA, et al. Large-scale analysis of the human and mouse transcriptionomes. Proc Natl Acad Sci U S A. 2002;99:4465-4470.
3. Potty MB, Watkins NA, Colombo D, et al. Identification of Sphk1 as a novel platelet tetrascerin and the collagen receptor GPVI as a component of tetrascerin microdomains. Biochem J. 2009;417:391-400.
4. Soranzo N, Rendon A, Gieger C, et al. A novel variant on chromosome 7q22.3 associated with mean platelet volume, counts and function. Blood. 2009;113:3831-3837.
5. O’Connor MN, Salles II, Cvejic A, et al. Functional genomics in zebrafish permits rapid characterization of novel platelet membrane proteins. Blood. 2009;113:4754-4762.
6. Macaulay IC, Tijssen MR, Thijssen-Timmer DC, et al. Comparative gene expression profiling of in vitro differentiated megakaryocytes and erythroblasts identifies novel activatory and inhibitory platelet membrane proteins. Blood. 2007;109:3260-3269.
7. Ploner A, Calza S, Gusnanto A, Pawitan Y. Multidimensional logistic false discovery rate for microarray data. Biostatistics. 2006;7:556-569.
8. de Bono B, Chothia C. Exegesis: a procedure to understand protein domains. Nucleic Acids Res. 2006;34:D247-D251.
9. Mann CJ, Hinits Y, Hughes SM. Comparison of cancer gene expression profiles from microarrays and quantitative reverse transcriptase polymerase chain reaction. Genomics. 2004;33:5331-5342.
10. Dangerfield J, Larbi KY, Huang MT, Dewar A, Nourshargh S. PECAM-1 (CD31) and homophilic interaction up-regulates alpha beta 1 on transmigrated neutrophils in vivo and plays a functional role in the ability of alpha integrins to mediate leukocyte migration through the perivascular basement membrane. J Exp Med. 2002;196:1201-1211.
11. Gueguzbes V, Vigneron P, Lamerant N, Kieda C, Jaffredo T, Dunon D. Dual role of melanoma cell adhesion molecule (MCAM)/CD146 in lymphocyte endothelium interaction: MCAM/CD146 promotes rolling via micropillar induction in lymphocyte and is an endothelial adhesion receptor. J Immunol. 2007;179:6673-6685.
12. Weber C, Fraemohs L, Dejana E. The role of adhesion molecules in vascular inflammation. Nat Rev Immunol. 2007;7:467-477.
13. Sachs UU, Andrei-Selmer CL, Maniar A, et al. The neutrophil-specific antigen CD177 is a counter-receptor for platelet endothelial cell adhesion molecule-1 (CD31). J Biol Chem. 2007;282:23603-23612.
14. Woodfin A, Reichel CA, Khandoga A, et al. JAM-A mediates neutrophil transmigration in a stimulus-specific manner in vivo: evidence for sequential roles for JAM-A and PECAM-1 in neutrophil transmigration. Blood. 2007;110:1848-1856.
15. Zen K, Liu Y, McCall IC, et al. Neutrophil migration across tight junctions is mediated by adhesive interactions between epithelial occludin and adenosin receptor and a junctional adhesion molecule-like protein on neutrophils. Mol Biol Cell. 2005;16:2694-2703.
16. Cook-Mills JM. VCAM-1 signals during lymphocyte migration: role of reactive oxygen species. Mol Immunol. 2002;39:499-508.
17. Dando J, Wilkinson KW, Ortlepp S, King DJ, Brady RL. A reassessment of the MADCAM-1 structure and its role in integrin recognition. Acta Crystallogr D Biol Crystallogr. 2002;58:233-241.
18. Paessens LC, Singh SK, Fernandes RJ, van Kooyk Y. Vascular cell adhesion molecule-1 (VCAM-1) and intercellular adhesion molecule-1 (ICAM-1) provide costimulation in positive selection along with survival of selected thymocytes. Mol Immunol. 2008;45:42-48.
19. Sumagin R, Sarelius IH. A role for ICAM-1 in maintenance of leukocyte-endothelial cell rolling interactions in inflamed arterioles. Am J Physiol Heart Circ Physiol. 2007;293:H2786-H2789.
20. Zakian J, Parkos CA. Leukocyte-epithelial interactions. Curr Opin Cell Biol. 2003;15:557-564.
21. Mann CJ, Hints S, Hughes SM. Comparison of neuramin (ALCAM) and neuramin-like cell adhesion molecule (NLCAM) expression in zebrafish. Gen Exp Patterns. 2006;6:952-963.
22. Woodfin A, Reichel CA, Khandoga A, et al. The leucine-reint sequel protein LRI01 is a negative regulator of Elast cell receptor tyrosine kinases. J Biol Chem. 2004;279:47050-47056.
23. Kenagy RD, Plass A, Wight TN. Vesicular degranulation and vascular disease. Trends Cardiovasc Med. 2006;16:209-215.
24. Toeka K, Nakamura K, Hirohata S, et al. Vesicant is induced in infiltrating monocytes in myocardial infarction. Mol Cell Biochem. 2005;280:47-56.
25. Bhat R, Eissmann P, Endt J, Hoffmann S, Watzl C. Fine-tuning of immune responses by SLAM receptors. J Leukoc Biol. 2006;79:417-424.
26. Veillette A. Immune regulation by SLAM family receptors and SAP-related adaptors. Nat Rev Immunol. 2006;6:546-566.
27. MacFadyen JR, Haworth O, Roberston D, et al. Endosialin (TEM1, CD248) is a marker of stromal fibroblasts and is not selectively expressed on tumour endothelium. FEBS Lett. 2005;579:2569-2575.
28. Tuji T, Miyazaki M, Sakaguchi M, Inoue Y, Nabma M. A REIC gene shows down-regulation in human immortalized cells and human tumor-derived cell lines. Biochem Biophys Res Commun. 2000;268:20-24.
29. Barrantes Idel B, Montero-Pedrazuela A, Guadano-Ferraz A, et al. Generation and characterization of dickkopf3 mutant mice. Mol Cell Biol. 2006;26:2317-2326.
30. Princo S, Neehs C. Dkk3 is required for TGF-beta signaling during Xenopus mesoderm induction. Differentiation. 2007;75:957-967.
31. Metcalfe P, Watkins NA, Ovenden WH, et al. Nomenclature of human platelet antigens. Vox Sang. 2003;85:240-245.
32. Stranger BE, Forrest MS, Clark AG, et al. Genome-wide associations of gene expression variation in humans. PLoS Genet. 2005;1:e78.
33. Stranger BE, Forrest MS, Dunning M, et al. Relative importance of nucleotide and copy number variation on gene expression phenotypes. Science. 2007;315:848-853.