AyurPhenoClusters define common molecular roots for rare diseases and uncover ciliary dysfunctions in syndromic conditions

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Abstract

Managing rare genetic diseases with organ centric focus presents a challenge in linking genotypes to phenotypic traits. Ayurveda on the other hand, diagnose diseases with multi-system perspective that are assessed by perturbations along three physiological dimensions viz- kinetic (*Vata*), metabolic (*Pitta*) and structural (*Kapha*) each with distinct phenotypic attributes and molecular correlates. This study explores how rare diseases, can be viewed from an Ayurvedic perspective by unifying the medical terminologies from both disciplines through Human Phenotype Ontology (HPO). Domain experts categorized 10,610 HPO terms into phenotypic groups based on Ayurvedic principles of *Vata* (V), *Pitta* (P), and *Kapha* (K) and used the Expectation Maximization (EM) algorithm to cluster and analyze 12,678 diseases. This revealed six distinct clusters collectively called "AyurPhenoClusters". 2814 diseases had unique memberships to single clusters showing enrichment for V/P/K phenotypes. Clusterwise functional annotation revealed the top processes as (i) embryogenesis and skeletal system, morphogenesis; (ii) endocrine and ciliary functions (iii) DNA damage response and cell cycle regulation (iv) inflammation and immune response (v) immune, hemopoiesis, telomere aging (vi) Small molecule metabolism and transport. Most noteworthy, K predominant cluster was significantly enriched for ciliary genes (43%) followed by a V predominant cluster (16 %). Our study also suggests that many rare diseases especially in the V cluster could be potential ciliopathies. This first of its kind of study provides an innovative framework that can bridge the gap between Ayurveda and modern medicine for improved mechanistic understanding of the rare diseases and pave the way for improved diagnostic and therapeutic strategies.

Ayurgenomics | rare diseases | integrative medicine | precision medicine | ciliopathy | phenomics

Significance Statement

Rare diseases, with an estimated global average of affecting 1 in 2500 persons, pose a substantial economic problem with frequent hospitalizations and expensive treatments. This study unifies Ayurveda-based principles with human phenotype ontologies to provide an innovative framework for understanding rare diseases. The study reveals six clusters of rare diseases with shared phenotypes and distinct molecular endophenotypes. Genes of two of the phenotypically distinct clusters converge to networks associated with ciliary dysfunctions highlighting the merit of this approach not only in identifying but endo-phenotyping ciliopathies. This offers new avenues for diagnosis, treatment, and drug repurposing and opens the possibility of adopting a system based holistic approach for reducing burden and improving quality of life.

Rare diseases characterized by complex symptoms, lack of definitive diagnostics, and limited treatment options present substantial challenges in healthcare (1). Also, the treatments are often organ-specific, symptom centric and do not address systemic health issues (2, 3). Large scale genome sequencing and genotype-phenotype correlations in rare diseases now reveal extensive overlap of clinical and molecular features that are gradually erasing the boundaries between seemingly unrelated diseases (4). This highlights the need for better disease classification methods that delineate genotype to phenotypic variations more accurately for improved diagnostic yields and therapeutic outcomes (5).

Ayurveda in contrast to modern medicine defines diseases from a system's perspective through examination of perturbation of three physiological entities,called "tridoshas",that govern the kinetic (V), metabolic (P) and structural attributes (K) of the system (6, 7). These imbalances affect multiple body systems and are discernible by the phenotypic attributes governed by each dosha. Ayurvedic treatment aims to bring doshas to their homeostatic thresholds through a holistic approach of drugs, diet and lifestyle modulation keeping in context the individuality of the person, the clinical history of the disease and the diseased individual (7, 8). Ayurveda identifies more than 140 phenotypic attributes originating from a single dosha imbalance, each representing a simplified classification of diverse symptoms. These are described as *"Nanatmaj Vikaras"* and herein referred as nV, nP and nK depending on the dosha involved. For example, pain, inflammation and obesogenic phenotype, regardless of its location in the body or general conditions, are each categorized under broad phenotypic groups of nV, nP and nK respectively. We hypothesized that the Ayurvedic concepts of doshic imbalances can provide a

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MM conceived the study, MM and LD developed the study design; AK and RS lead the Ayurveda annotation; DJ, HV, SK, SG,M, PJ, NR, RPS carried out HPO annotation, DJ annotated the *Nanantmaj Vikara*; MM and LD lead the data analysis; LD designed the computational methodology, and MM lead the genomics study; AJ and TA curated the diverse datasets and performed the data analysis with LD ; AS and AJ worked on ciliopathy and illustration; DJ, AK, AS, LD and MM synthesized the work; AJ, AS, LD and MM wrote the manuscript

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novel framework for understanding heterogenity seen in rare diseases, when integrated with the standardized phenotypic vocabulary of the Human Phenotype Ontology (HPO) (9, 10). This was built on multiple lines of evidence that demonstrate distinct functional enrichments of the doshas (6, 11) and we reasoned this approach could have the potential to simplify the complexity in disease categorization, leading to more targeted and stratified interventions.

Our initial exploratory analysis with a few dosha-specific phenotypic groups in the Human Phenotype Ontology (HPO) provided an approach for a more extensive exercise. For instance, syndromes associated with bleeding that is a nP feature were predominantly enriched in P-related phenotypes, whereas ataxic syndromes were linked to features that more commonly associate with V (Supplementary Note). With the help of domain experts, we assigned each of the 10610 HPO terms with a dosha label, as well as identified the HPOs that best described 140 "*Nanatmaj Vikaras*" (nV, nP and nK). 9269 syndromic diseases, each of which had at least one HPO identified as nV, nP or nK, were then EM clustered using the dosha labels assigned to the HPO terms. This led to six distinct "AyurPhenoClusters", each of which contained diseases enriched in distinct phenotypes and biological processes. We demonstrate the utility of this clustering in identification of syndromes/diseases that have a ciliary dysfunction either due to structural or functional disruption. This first of its kind of framework promises to (a) reconcile the gap between organ-centric and system-level medical perspectives (b) provide an assistive tool to Ayurveda practitioners for clinical assessment of modern diseases and (c) provide a framework for unifying rare diseases that have shared molecular endophenotypes for enhanced management and drug repurposing.

Results

Mapping of HPO terms to V/P/K phenotypes. The pilot study of integrating Ayurveda based clinical descriptions with modern medical terminologies using the interface of HPO revealed the potential of this approach in bridging the ontological links (Supplementary Note). Subsequently all 10,610 HPO terms associated to 12,678 diseases were annotated with V,P,K, and nV, nP, nK labels. 82% of them mapped to V, 11% to P and 7% to K(Table S1).Table S2 shows the distribution of these labels for all the diseases. All Nanatmaj features with exception of a few could be mapped to one or more HPO terms (Table S3). Since nV, nP, nK features denote extreme and distinguishing perturbations of V,P,K, 7135 diseases which had least one of them are selected for further analysis.

EM clustering reveals six clusters with distinct phenotypic and functional attributes. Using the label distributions of the 7135 diseases (Table S2), Expectation Maximization (EM) clustering algorithm yielded six distinct AyurPhenoClusters named as C0-C5. The distribution of the diseases to the different clusters based on their memberships, are shown in Fig.1. 2814 diseases, shown at the core, denotes the diseases with membership values 1 to a cluster, and 0 to others. 3857 have a high relative membership of 0.8 to a single cluster, shown in the lighter shaded region. Diseases at the intersection have equal memberships to two clusters. Only 14 diseases have membership to more than two clusters. Strikingly, C2 stood out as an isolated cluster with no overlaps.

A deeper analysis was carried out for the 2814 diseases that mapped uniquely to a cluster (Table S4). A clear distinction amongst the clusters emerges from the percentage of V/P/K and nV/nP/nK features of the diseases mapped to each cluster (Fig.1). Distinguishing set of features that are frequently observed in diseases of one cluster, but not as frequent in others, were identified (Table 1). Each of the six clusters is described below.

C0 with 1182 diseases is exclusively characterized by nV with 80% of the HPO terms annotated as V. The number of HPO terms associated with each disease range between 20 and 30 with anatomical as the most prevalent phenotypes. C1, with 479 diseases, had nV and V as the most common, although P/K are also present in minor fractions. This cluster displays a diverse range of phenotypes, not dominated by any specific anatomical features. C2, with 489 diseases, is distinctly defined by nP features and also the highest proportions of P features. The features are predominantly associated with inflammatory conditions affecting the skin and bones, alongside symptoms such as excessive sweating (hyperhidrosis) and increased thirst (polydipsia).C3, with 263 diseases, is also nP and P enriched. In addition to features shared with C2, it harbors a subset of V-related phenotypes, including vertigo, headaches, diarrhoea, and abdominal pain. C4, with 254 diseases, stands out with the highest percentage of nK among all clusters and a significant presence of K features in these diseases. Lastly, C5, with 147 diseases is very heterogeneous in terms of V/P/K with higher average number of HPO terms compared to other clusters. The diseases in this cluster also show a high prevalence of nV, alongside an equal representation of nP and nK features. 55% of the features are classified as V, the highest number of any single dosha across all clusters.

Functional enrichment of AyurPhenoClusters. Functional annotation of the genes associated with the 2814 diseases from the six clusters revealed some striking differences in enrichment with respect to the molecular functions, biological processes and pathways (Table 2). The genes within each cluster were also highly networked as evident from Metascape enrichments (Fig.2, Fig.S1 a-e).

The V predominant C0 cluster was significantly enriched in processes that govern anatomy from morphogenesis, differentiation to growth and development from embryo to adult. These included development of head, limb, skeletal system and sensory organ, development, cilium assembly, bone and muscle structure. It was also enriched in processes related to regulation of cell cycle processes, membrane potential smoothened signaling pathway, ossification and response to growth factor.

The cluster C1 was significantly enriched in processes related to cellular homeostasis, metabolism, primary immunodeficiency and renal system development. It also had processes related to response to small molecules, inorganic substances like nitrogen compounds, organic cyclic compounds as well as mechanical and light stimulus. SHP2 pathway that regulates important cellular pathways that control proliferation, migration, differentiation, growth, and survival was also enriched in this cluster. This cluster resonate

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with Ayurveda description of phenotypes associated with metabolism (P) and cellular processes (V) and could be described as a Vp cluster.

The P specific C2 cluster had enrichment of processes linked to regulation of body fluid levels, immune and inflammatory processes, cell activation, cytokine signaling and production, platelet activation and TH17 cell differentiation. The associated processes are significantly perturbed in DMD, lung fibrosis, cancer especially hematopoietic lineages and govern ECM organization, multi organism level homeostasis. Heightened inflammation is a characteristic of P as described in Ayurveda (Supplementary Note).

The C3 cluster had overlaps with C2 with respect to many P characteristics but also had more significant enrichment of hemopoiesis and myeloid cell differentiation, type 1 hemidesmosome assembly, telomere extension by telomerase, programmed cell death as well as response to viral and bacterial infection. Based on the phenotypic attributes, this had Pv features.

The K enriched C4 cluster was highly significant in genes related to ciliary functions as well as visual perception, determination of left right asymmetry and response and regulation of hormone, nutrient levels and metabolism of vitamin and cofactors especially Vitamin B12. These are prominent in ciliopathies, retinal dystrophy and Bardet Biedl syndrome.

Cluster C5 has abundance of all V,P,K features with a predominance of V features. The enriched processes include DNA repair, DNA damage response, chromatin organization and regulation of cell cycle as well as response to radiation, oxygen levels. Also significant was chordate embryo development, heart development, transcriptional regulation by TP53, aminoacyl biosynthesis and protein localization and associated with diseases like Fanconi anemia, diabetic cardiomyopathy and nucleic acid metabolism and innate immune sensing.

AyurPhenoClusters link many rare diseases to ciliopathies. Propelled by our observation that a collection of phenotypes labeled as K, defining the C4 cluster, showed an enrichment in ciliopathies, we decided to investigate the potential relationship between AyurPhenoClusters and ciliopathies. We observed that 385 genes associated with different Ayurpheno clusters were present in two prominent ciliary databases, the Cilacarta(12) and Ciliaminer, (13) and significantly enriched in C4 (Fig.3a, Table S5). Also 43% of the genes in C4, 16% of the genes in C0, 11.8% of C1, 9.1% of C5, 7.5% with C3 and 5.6% in C2 were associated with ciliary structure and functions.

Analysis using Metascape revealed extensive networks amongst the ciliary genes across all clusters (Fig.3b, Fig.S1 a-e). The processes within these ciliary genes are mapped to five major distinct functional hubs. These include network of genes related to (i) response to light, eye development, (ii) hedgehog signalling, embryonic development & cilium dependent cell mobility, (iii) centrosome & cell cycle regulation, (iv) regulation of cell projection & organelle assembly and (v) pathways associated with intraflagellar transport, cilium assembly, microtubule-based movement & dynein complex. There were four additional nodes that were mapped to pathways associated with protein localization. In the network, genes from C4 are prominently represented across all nodes, except those related to hedgehog signaling, embryonic development, and centrosome and cell cycle regulation in which genes from C0 have a greater contribution.

A conjoint analysis of two sets of C4 cluster genes, one mapping to reported ciliopathies and the second one comprising of remaining genes, revealed three major hubs (Fig.3c, Fig.S3a). Two of these hubs were connected, while the third, distinct hub was associated with vitamin metabolism. Among the connected nodes, one arm was specifically related to ciliary structure and function, majorly overlapping with the reported genes. Interestingly, the other arm, which mapped to the non-overlapping set, was associated with the regulation and response to large molecules (sugars, proteins, and hormones) within the same network. A similar conjoint analysis of the network from C0 with overlapped and non-overlapped genes from ciliary dataset revealed three distinct networks. A predominant fraction is associated with embryonic development, cell cycle and muscle movement (Fig.S3b). The overlapping genes from the ciliary databases are only contributing to a small part of the cluster networks associated with cilium assembly, interflagellar transport and hedgehog signaling.

Potential ciliopathies identified through AyurPhenoClusters. Across all the clusters, 251 diseases harbour genes reported in ciliary datasets described above (Table 3). However, only 38% (95 out of 251) are reported as ciliopathies in Cilaminer. We propose that the amongst the remaining 156 diseases some could be classified as ciliopathies as (1) they share extensive set of phenotypes with the reported ciliopathies (2) their genes are also members of the networks with ciliary structure and function. Based on Jacard's distance between phenotypes of reported ciliopathies and this set, we identified a few cases with high potential which include Robinow syndrome autosomal dominant 2 (OMIM:180700), Vissers-Bodmer syndrome (OMIM:619033), Griscelli syndrome type 1 (ORPHA:79476), progressive familial intrahepatic choleostasis (ORPHA 172) etc (Table 3). We also propose that the diseases whose genes do not map to ciliary datasets but have shared memberships in AyurPhenoClusters as well as connected to the ciliary networks (Fig.3c, Fig.S3 a-b) could also be due to ciliary dysfunctions. These include examples Obesity (OMIM;601665); Leptin deficiency or dysfunction (OMIM:614962); Macrocephaly/Autism syndrome (OMIM:605309); Choanal atresia and lymphedema (OMIM:6133611) etc. As is evident from Table 3, most of the potential ciliopathies are from C0 while the reported ones are in C4.

Discussion

This study presents a system-based approach to study rare genetic disorders that uses Ayurveda based characterization of HPOs and groups them into six phenotypically distinct clusters. Interestingly, many seemingly unrelated rare diseases were found to share molecular endophenotypes. We highlight the merit of this approach by demonstrating how this resolves the diagnostic dilemma of ciliopathies. The ayurvedic approach offers a holistic perspective of diseases which contrast with the focus on organ-level manifestations of modern medicine which often leaves rare disease patients with inadequate diagnostic and therapeutic options (14, 15).

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This first of its kind of study not only introduces a novel approach for identifying genes associated with pathogenesis but also reveals opportunities for repurposing treatments by grouping seemingly unrelated diseases.

Earlier studies using multi-omic approaches have revealed genome-wide differences in individuals with predominance of V, P and K doshas. These differences have been reported across biological scales of organization viz. expression, genetic, epigenetic, metagenomic, cellular, and even physiological levels (11, 16–20). The clusters defined in this study corroborate these observations, and the differential association of these clusters to various disease classes also resonates with textual descriptions in Ayurveda (Supplementary Note). The ability of *Nanatmaj* features to reduce dimensions in a cluster suggests that including many of these non-invasive attributes in clinical settings could further enhance stratification of a larger number of rare diseases into distinct groups. Inclusion of these features in prospective cohorts might further enhance endophenotype identification.

The use of the Expectation Maximization (EM) algorithm further enriches this study by probabilistically clustering diseases based on a flexible, data-driven approach (21). This method effectively handles the complexity and heterogeneity inherent in large-scale genomic data, allowing for the organic discovery of disease groupings based on underlying biological patterns rather than superficial symptoms or organ systems(22, 23). This approach reveals that conditions traditionally segregated into distinct categories may share underlying molecular mechanisms, suggesting a more interconnected biological network than previously recognized. These observations also resonate with earlier studies where unsupervised clustering using machine learning approaches as well as exome studies revealed inherent connectivity between multisystem phenotypic attributes(16, 24).

These findings have significant implications for diagnostics and therapeutic strategies in diseases exhibiting extensive clinical heterogeneity and could also become relevant in different organ specific syndromes. For instance, ciliopathies, which are often difficult to diagnose due to varied symptoms across different organs (25), were found to cluster predominantly in groups characterized by K or V features. Ciliary function plays a dual role in various diseases, acting as a cause in genetic disorders known as ciliopathies and consequential in other conditions where cilia are damaged by disease processes. Ayurveda ascribes transport and motility as functions governed by V, dysfunction of which leads to K manifestation (Supplementray Note). In ciliopathies like primary ciliary dyskinesia and polycystic kidney disease, dysfunctional or structurally abnormal cilia directly cause the disease by impairing cellular functions and signaling pathways (26). Conversely, in diseases such as COPD or severe asthma, ciliary dysfunction can occur as a secondary consequence of inflammation or other cellular damage, worsening the disease's symptoms and progression (27). Inclusion of clinical features that define the C4 cluster with genetic testing panels might enable better resolution of ciliopathies and lead to more targeted interventions addressing specific molecular pathways active in these clusters. Furthermore, the cluster analysis indicated that aberrant response functions of cilia could contribute to ciliary dysfunctions in diverse diseases with endocrine, retinal, renal and skeletal diseases as the most prominent manifestations. Inflammation and DNA damage response, like ciliopathy, are core processes in various diseases, potentially being the cause and symptomatic outcome. Our analysis identified two clusters, C2 and C3, that were enriched in immune and inflammatory processes, and C5, which was distinctly enriched in DNA damage (Fig.S4) with distinct phenotypes (Table 1).

Our study highlights the need to redefine diseases by considering systemic phenotypic effects and molecular mechanisms only traditional organ-specific categories. This study primarily focused on a subset of rare diseases and was based on the phenotypic observations from modern medicine. Future research will focus on validating the molecular attributes of the cluster, investigating potential ciliopathies, and incorporating Ayurvedic descriptions into clinical settings. In summary, integrating Ayurvedic dosha classifications with modern genomic data through advanced computational techniques offers a compelling new perspective on disease classification and treatment.

Materials and Methods

Annotation of HPO terms with respect to Doshas. Ayurveda classifies diseases into two broad groups based on involvement of single or multiple doshas as *Nanatmaj* and *Samanayaj* respectively. The phenotypes are more generic in the latter group (Supplementary Note). We explored these proportions in the HPO dataset (May version, dated 2022-10-05) that had 12678 diseases and 10610 non redundant features and associated genes. The following exercise was undertaken

1. **Mapping of HPO terms to dosha attributes: Clinical aspects**

A team of domain experts manually curated each of the HPO terms with respect to their correlation with either of the three doshas based on the foundational principles of Ayurveda as described in the ancient texts. This encompasses the entire spectrum from onset to progression to prognosis of disease. The correlation included a thorough assessment of disease mechanisms, causative factors including diet, lifestyle, and environmental influences, early warning signs, clinical symptoms at the onset, and treatment responses (Supplementary Note). Each dosha also bears specific attributes and deviation of phenotypic expressions from a baseline health during states of imbalance. For instance, attributes of dryness are a hallmark of V imbalance, manifesting across multiple organ systems as symptoms like dry skin (HP:0000958), dry mouth (HP:0000217), vaginal dryness (HP:0031088), dry cough (HP:0031246), and dry eyes (HP:0001097). On the other hand, an excess of P may present with bleeding (HP:0000421, HP:0040242) and burning sensations (HP:0032143, HP:6000420), while K imbalance might be reflected in symptoms of anorexia (HP:0002039), excessive salivation (HP:0003781), and lethargy (HP:0001254, HP:0011973).

2. **Mapping of *Nanatmaj Vikaras* to HPO terms: clinical aspects**

The experts referred to several textual references from Ayurveda literature (28) to match descriptions of diseases, or "*Vikaras*," from Ayurveda with HPO terms that represent corresponding phenotypic features of diseases. The features were identified based on the prominence of the organ or the system in the textual references. There are key differences

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between Ayurveda and modern medicine for defining diseases. This was taken into consideration during annotation of all *Nanatmaj Vikaras* as described in Supplementary Note. Table S3 provides mapping of all *Nanatmaj Vikaras* with the HPO terms. There were a few descriptions that did not have relevant matches.

3. **Re-annotation of rare syndromes from Ayurveda perspective**

Each Rare disease in HPO has multiple feature attributes. A new representation of each of the diseases was created in the dosha space using the HPO terms mapping to the dosha attributes as described in the Supplementary Note. The numbers of nV, nP or nK represented as percentages were also included for each of the diseases.

4. **Identification of clusters of diseases based on doshic proportions**

We used Expectation Maximization (EM) algorithm to explore whether there are distinct groups or "clusters" of diseases with similar patterns of dosha distributions. EM algorithm assumes that the data is generated from a mixture of several Gaussian distributions, with each representing a cluster in the data. The goal of the algorithm is to estimate the parameters of the underlying Gaussian distributions, including their means, covariances, and mixture weights or the prior probabilities. The algorithm outputs an optimal number of clusters along with a membership value between 0 and 1 for each disease to each cluster. The detailed algorithm is explained in SI Methods.

5. **Identification of distinguishing features for the clusters** To identify the distinguishing features of each cluster, we introduced a novel measure that could capture the significance σ of a feature f for a cluster c using a formula that assigns a high value to a feature that is unique for a cluster and frequent within the cluster. For each cluster c, let $\delta(f,c)$ denote the percentage of diseases in the cluster that contain the HPO feature f. The significance $\sigma(f,c)$ is calculated as below:

$$\text{If } x(f,c) = 0, \text{ then } \sigma(f,c) = 0,$$

$$\text{Otherwise, } \sigma(f,c) = x(f,c) \times \sum_{i \neq c} \frac{1}{1+\ln(x(f,i))}$$

It assigns a low value to features that are common across clusters. To identify the top n features of a cluster, the features are sorted in decreasing order of significance.

5. **GO and network analysis of OMIM genes associated with clusters**

In order to comprehensively understand the clusters at the molecular level we used Metascape. Along with functional enrichment it also performs interactome analysis and annotates the gene sets to functional modules based on information from over 40 independent knowledgebases (29). We also used Metascape to perform comparative analysis of functional modules/gene sets between and within the clusters.

6. **Analysis of AyurPhenoClusters in ciliopathy**

We downloaded data from CiliaMiner and CiliaCarta databases (12, 13), both of which are valuable resources for ciliopathy-related diseases and their genes. The CiliaMiner database has more than 500 diseases with their associated genes categorized into primary, secondary, motile, and atypical, on the basis of subcellular localization and functions. Among these, 274 genes are reported as potential ciliopathy candidates, as these are involved in the formation, function, and maintenance of cilia. On the other hand, Ciliacarta has a total of 956 genes, of which 302 are from the SYSCILIA gold standard, 677 from gene ontology and 285 from Bayesian predictions. We analyzed the genes from AyurphenoClusters that intersected with the above databases.

Cluster-wise network analysis was conducted to identify all pathways associated with the overlapping genes using METASCAPE. Additionally, a conjoint analysis with METASCAPE was performed on two sets of genes from each of the two clusters (C4 and C0) enriched in ciliary genes: one set consisted of reported ciliary genes, and the other set consisted of the remaining genes in the cluster. These genes were mapped to rare diseases in the AyurPhenoClusters and phenotypically compared with those reported in CiliaMiner. This led to identification of unreported potential ciliopathies in the set of rare diseases.

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Supporting Information Appendix (SI).

SI Note. Supplementary note

SI Information. Supplementary information

SI Datasets. Supplementary tables

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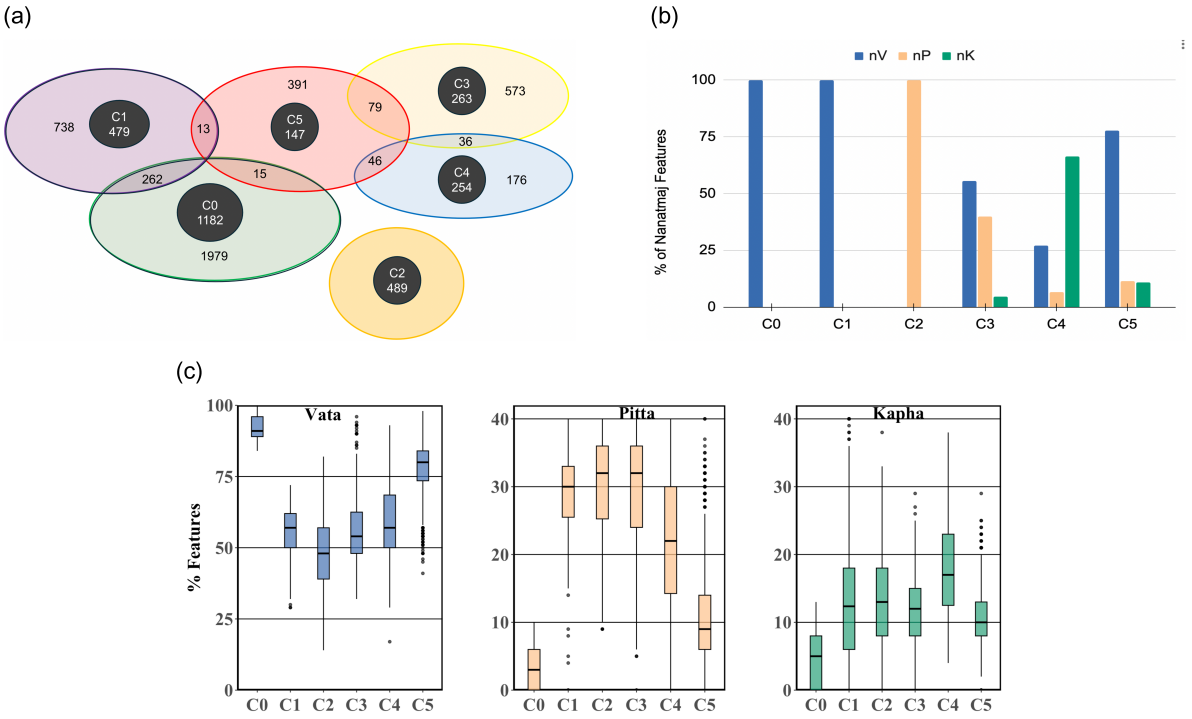

Fig. 1. Distribution of 7135 Diseases & associated HPO features assigned to V,P,K across clusters from 2841 core diseases (a) Distribution of diseases across AyurPhenoClusters. The darker core shows number of diseases with full membership (1.0) to a cluster. The lighter region denotes diseases with majority (0.8) membership to a cluster. Diseases at intersection have equal membership to both clusters. (b) The percentage of phenotypes classified as *Nanatmaj Vikaras* for each cluster corroborates with relative enrichment of *V, P* and K features. In Cluster C0 and C1, nV is nearly exclusive whereas C2 has nearly 100% nP. Clusters C3, C4, and C5 have relatively lower proportions of nV and nP and nearly equal proportions of nK. (c) The three panels of boxplots depict the percentage of HPO terms that map to *V, P* and K features across each cluster. The V features are highest in cluster C0 and C5; P is highest in C3 and C2; and K in C4 making them predominantly *V, P* and Kenriched clusters. Whereas C1 and C3 seem mixed *PV* types.

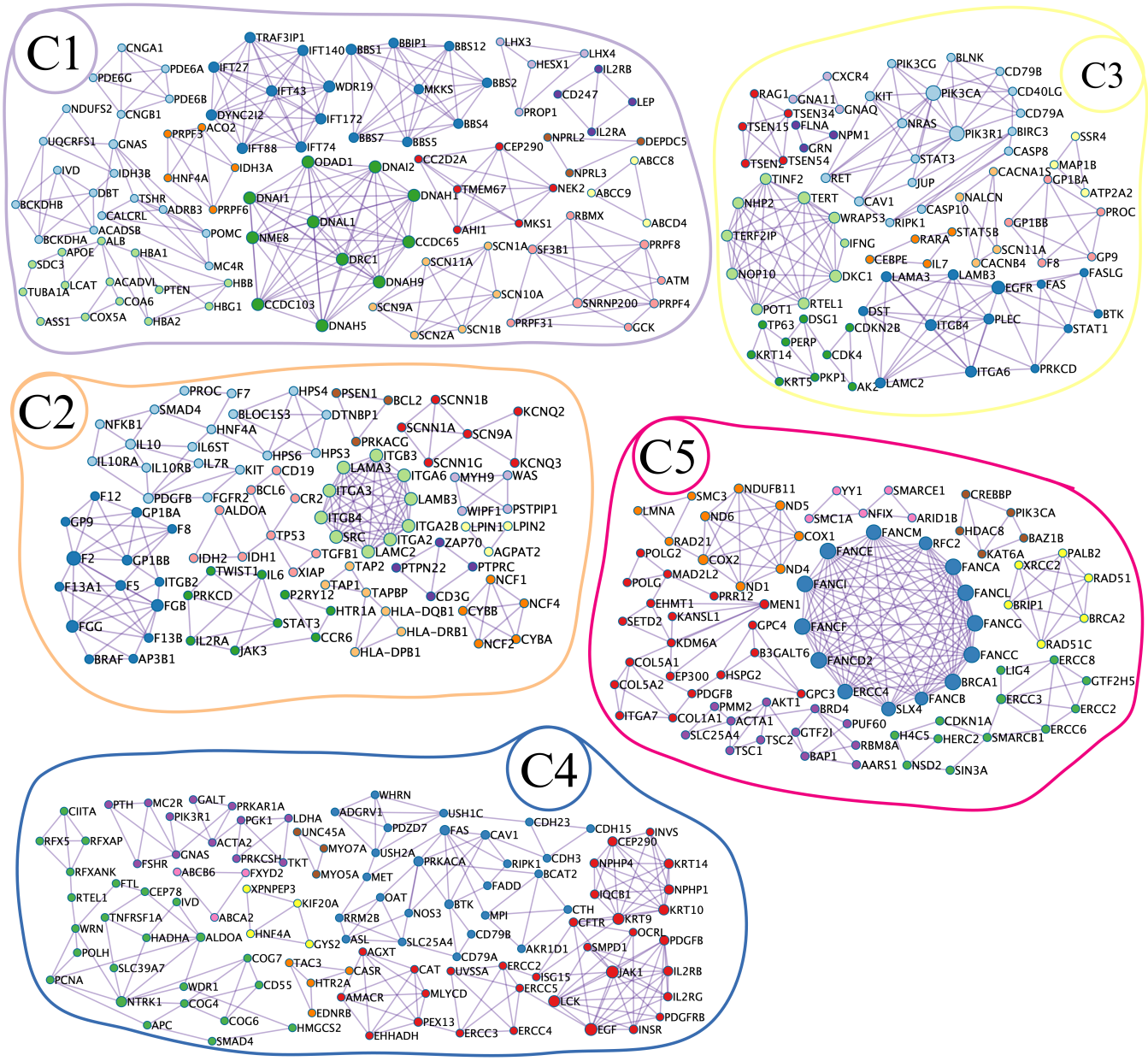

Fig. 2. Network of genes in each cluster from enriched Functional Modules from Metascape analysis in 2814 diseases. The nodes are colored by the enriched biological and functional processes (Fig.S1 a-e). For example, C2 (n=489), that is predominantly P is enriched with gene modules that correspond to hemopoiesis (dark brown), platelet formation (light blue), blood coagulation (dark blue) and rest related to immune response and inflammation. Cluster C4 (n=254) with dominance of K exhibits the modules related to ciliopathies (red and dark blue), transport and signaling (orange and yellow) and rest modules are associated with response and regulation of hormone, nutrient levels and metabolism. Cluster C5 (n =147) with V characteristics show modules that associate with DNA repair (blue, green, yellow, brown and pink), while modules in C1 (n =489) showed mix processes like homeostasis (yellow, blue and pink) as well as immune(green) and signaling. Cluster C3 (n=263), that is more P like have the modules involved in hemopoiesis and processes involved in telomere activity. We did not observe enriched functional modules in C0 (n =1182) in metascape

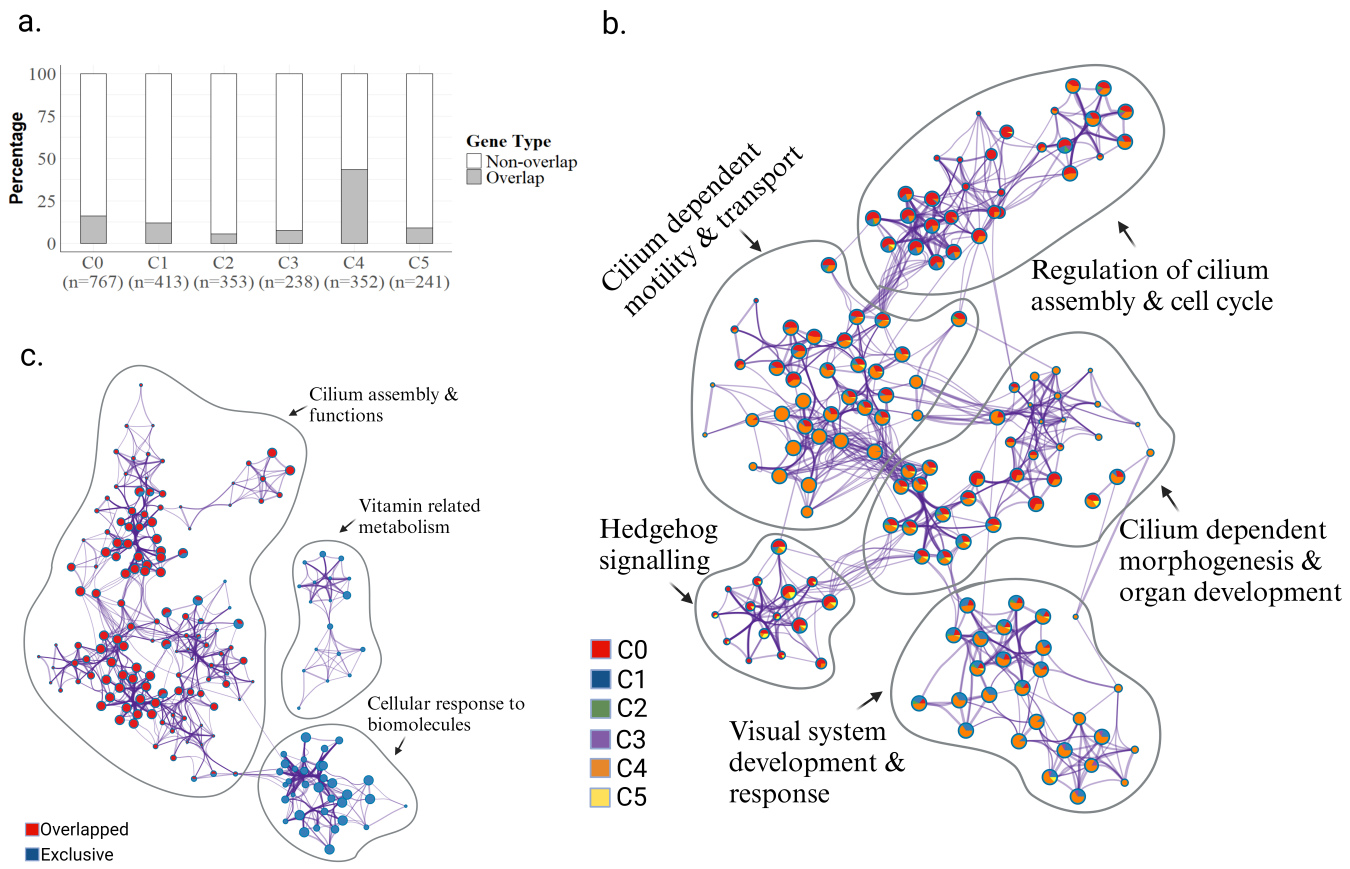

Fig. 3. Network analysis of ciliary genes from clusters. (a) The overlap between the genes in each cluster and known ciliary genes are depicted in the barplot. C4 has the highest overlap. (b) A network analysis of the ciliary genes in the C0-C5 clusters reveal different functional modules. Prominent networks include cilium dependent morphogenesis including visual system development and response, cilium motility, transport, signaling and cell cycle. The pie chart of each node shows a large fraction of genes from C4 (More detailed annotation inSupplementary Figure 4). (c) A network analysis of all the genes in cluster C4 (those that overlap with ciliary databases and exclusive) reveals three modules, the majority of which are related to cilia. Noteworthy, the exclusive set from C4 map to important cellular responses with connections to the cilia module.

Table 1. Top 20 phenotypes from the six clusters. The V,P,K features are colored as blue, yellow, and green, respectively. *Nanatmaj* features are underlined.

C0	C5	C1	C2	C3	C4
Seizure	**Seizure**	**Seizure**	**Fever**	**Fever**	**Pallor**
Short stature	**Short stature**	**Short stature**	**Abnormal bleeding**	**Abnormal bleeding**	**Lethargy**
Ptosis	**Ptosis**	**Ptosis**	**Abnormal skin blistering**	**Abnormal skin blistering**	**Excessive daytime somnolence**
Talipes equinovarus	**Talipes equinovarus**	**Diarrhea**	**Hyperhidrosis**	**Hyperhidrosis**	**Pericardial effusion**
Genu valgum	**Palmoplantar hyperkeratosis**	**Palmoplantar hyperkeratosis**	**Skin ulcer**	**Skin ulcer**	**Atherosclerosis**
Hypertelorism	Hypertelorism	**Headache**	**Purpura**	**Purpura**	**Hypothermia**
Low-set ears	Low-set ears	**Abdominal pain**	**Eczema**	**Eczema**	**Overweight**
Pectus excavatum	Pectus excavatum	**Abdominal distention**	**Polydipsia**	Arthritis	**Anorexia**
Depressed nasal bridge	Cryptorchidism	**Depression**	**Psoriasiform dermatitis**	Anemia	**Poor appetite**
Brachydactyly	Umbilical hernia	Vomiting	**Pustule**	Thrombocytopenia	**Obesity**
Micrognathia	Hypermetropia	Hypertension	**Skin Vesicle**	Meningitis	Nyctalopia
Epicanthus	Pes planus	Cataract	Gastroesophageal reflux	Skin rash	Hypercholesterolemia
Downslanted palpebral fissures	Atrial septal defect	Hepatomegaly	Epistaxis	**Seizure**	Facial edema
Long philtrum	Bicuspid aortic valve	Splenomegaly	Menorrhagia	**Diarrhea**	Polydactyly
Short neck	Ventricular septal defect	Elevated hepatic transaminase	Bruising susceptibility	**Vertigo**	Coma
Platyspondyly	Inguinal hernia	Jaundice	Erythema	**Headache**	Hypertrophic cardiomyopathy
Posteriorly rotated ears	Vesicoureteral reflux	Photophobia	Prolonged bleeding time	**Abdominal pain**	Hypogonadism
Scoliosis	Hip dysplasia	Metabolic acidosis	Joint hemorrhage	Nail dystrophy	Acanthosis nigricans
High palate	**Gastroesophageal reflux**	Proteinuria	Nail dystrophy	Lymphadenopathy	Hyperammonemia
Micromelia	**Obesity**	Conjunctivitis	Pruritus	Pruritus	Rod-cone dystrophy

Table 2. Enriched functional processes and pathways for the genes in clusters ordered by -log10(p-value). The bars and the numbers represent log transformed p values in each GO/pathway category obtained from Metascape.

Term	Description	C0	C4	C5	C2	C3	C1
GO:0001501	skeletal system development	68	0				
GO:0048598	embryonic morphogenesis	61	0				
GO:0060322	head development	56	13				
GO:0032989	cellular anatomical entity morphogenesis	38	0				
GO:0007423	sensory organ development	37	0				14
GO:0001503	ossification	37	0				
GO:0060173	limb development	36	0				
R-HSA-561783	Cilium Assembly	34	0				
GO:0061061	muscle structure development	32	0				
WP4803	Ciliopathies	33	100				
GO:0007601	visual perception		48				
WP5234	Bardet Biedl syndrome		42				
GO:0007368	determination of left/right symmetry		29				
GO:0046530	photoreceptor cell differentiation		26				
GO:0061512	protein localization to cilium		20				
GO:0009584	detection of visible light		17				
R-HSA-562092	Cargo trafficking to the periciliary membrane		17				
GO:0003352	regulation of cilium movement		17				
GO:0010817	regulation of hormone levels		16				
GO:0006281	DNA repair			36			
hsa03460	Fanconi anemia pathway			26			
WP4932	7q11 23 copy number variation syndrome			21			
GO:0006325	chromatin organization			20			
GO:1901987	regulation of cell cycle phase transition			19			
WP3651	Pathways affected in adenoid cystic carcinoma			19			
GO:0006302	double-strand break repair			19			
GO:0009314	response to radiation			17			
GO:0070482	response to oxygen levels			16			
GO:0043009	chordate embryonic development			16			
GO:0050878	regulation of body fluid levels				46	15	
GO:0001775	cell activation				45		
R-HSA-128021	Cytokine Signaling in Immune system				27		
GO:0001819	positive regulation of cytokine production				25	18	
GO:0002697	regulation of immune effector process				23	0	
WP5356	Disturbed pathways in Duchenne Muscular Dystrophy				23	0	
GO:0006954	inflammatory response				29	17	
GO:0050865	regulation of cell activation				29	20	13
GO:0002252	immune effector process				28	25	
GO:0050778	positive regulation of immune response				28	20	
hsa05200	Pathways in cancer				18	27	
GO:0030097	hemopoiesis					40	
GO:0030099	myeloid cell differentiation					20	
R-HSA-446107	Type I hemidesmosome assembly					20	
R-HSA-171319	Telomere Extension By Telomerase					15	
GO:0044282	small molecule catabolic process						15
GO:0050953	sensory perception of light stimulus						15
GO:0044283	small molecule biosynthetic process						16
GO:1901615	organic hydroxy compound metabolic process						17
GO:0030855	epithelial cell differentiation						17
R-HSA-382551	Transport of small molecules						18
GO:1901699	cellular response to nitrogen compound						18
GO:0048871	multicellular organismal-level homeostasis				19		20
hsa05340	Primary immunodeficiency					14	22
GO:0019725	cellular homeostasis						25

Table 3. Known and Potential Ciliopathies in Clusters

Clusters	Known Ciliopathies	Potential Ciliopathies Identified	
	Number of diseases	Number of Diseases Sharing Ciliary Genes	Top 5 Diseases Based on HPO Overlaps with Known Ciliopathies using Jaccard Similarity (Intersecting HPO set/Union of HPOs)
C0	38	74	Robinow syndrome autosomal dominant 2; Vissers-Bodmer syndrome; Mosaic variegated aneuploidy syndrome 2; Lissencephaly 4; Robinow syndrome, autosomal dominant 1
C1	3	26	Microcephaly and chorioretinopathy, autosomal recessive, 1; Griscelli syndrome, type 1; Lipodystrophy, congenital generalized, type 3; Cholestasis, progressive familial intrahepatic, 10; Usher syndrome type 1
C2	9	16	Crisponi/cold-Induced sweating syndrome 3; Bleeding disorder, platelet-type, 19; Diabetes mellitus, insulin-dependent-1; Pick disease of brain; Carney complex, type 1
C3	0	21	Deafness, neurosensory, autosomal recessive 2; Cholestasis, progressive familial intrahepatic, 9; Griscelli syndrome, type 2; Episodic ataxia, type 5; Autoimmune disease, multisystem, infantile-onset, 1
C4	38	7	Retinal dystrophy and obesity; Renal cysts and diabetes syndrome; Pseudohypoparathyroidism, type IB
C5	7	12	Glycosylphosphatidylinositol biosynthesis defect 18; Wolf-Hirschhorn syndrome; Congenital disorder of glycosylation, type Ia; Prader-Willi syndrome

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