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Applications of comparative evolution to human disease genetics

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Direct comparison of human diseases with model phenotypes allows exploration of key areas of human biology which are often inaccessible for practical or ethical reasons. We review recent developments in comparative evolutionary approaches for finding models for genetic disease, including high-throughput generation of gene/phenotype relationship data, the linking of orthologous genes and phenotypes across species, and statistical methods for linking human diseases to model phenotypes.

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Introduction

In a natural extension of the traditional model organism approach, new data sources and techniques are allowing connections to be drawn between human and model systems, even when phenotypes do not obviously match. As organisms diverge over evolutionary time, the relationship between genes and the phenotypes they encode often also diverge. Many novel phenotypes arise from repurposed gene networks, rather than novel genes [1,2], while, conversely, molecular networks can lose their associations with conserved phenotypes [3]. Such complexity gives rise to a wealth of potential model systems, each capable of providing useful insights into human disease.

Comparative evolutionary approaches to study human disease are rooted in the traditional use of experimental and genetic data from diverse organisms to explore mechanisms of human genetics. However, new methods for discovering relevant organismal models for human disease are being developed, most notably methods drawing on computer science and evolutionary analyses to incorporate the growing wealth of genetic and phenotypic data in increasingly diverse species.

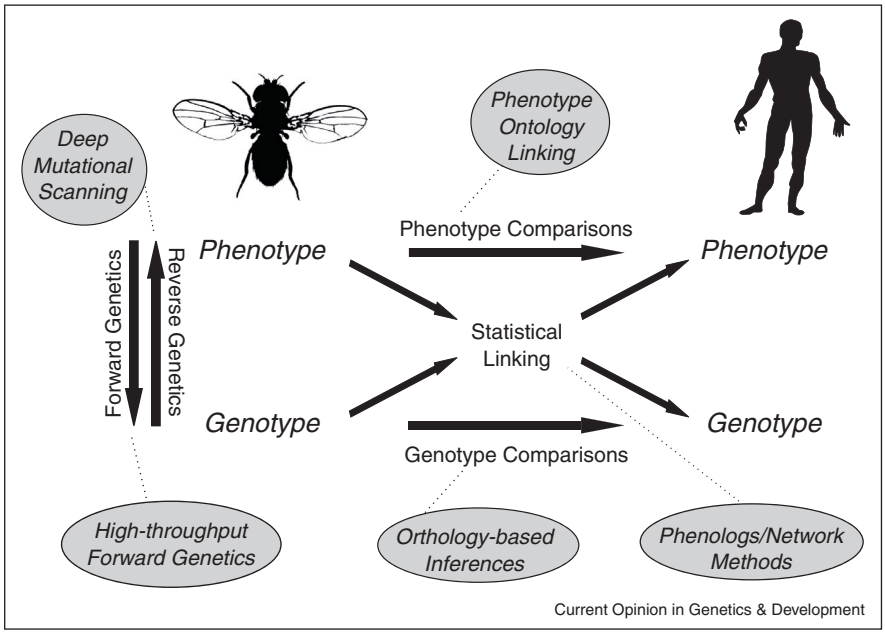
Here, we review recent advances in using phenotypic, genetic, and evolutionary information in both model and non-model organisms to rationally identify the genetic underpinnings of human disease. Figure 1 introduces a general framework that categorizes elements of comparative approaches. Typical approaches include identifying relationships between genes and phenotypes in a model organism via forward and/or reverse genetics, followed by comparison to human disease via gene orthology, phenotype similarity, or a combination of both. The different components have all been touched by an ever-increasing emphasis on high-throughput methods. Using the framework in Figure 1, we categorize the major approaches taken by researchers, and illustrate these approaches with several examples of how the new methods are applied to the study of human diseases.

Generating data with forward and reverse genetics

High-throughput identification of mutant phenotypes and their underlying genetics often provide the raw material for human disease model identification. The comparative approach often begins with a genetic screen in a model system to identify relevant pathways and genes. Genetic screens are traditionally divided into reverse genetics, which perturbs specific genes and looks for phenotypic effects, and forward genetics, which identifies phenotypes of interest and then uncovers their genetic basis. Generation of mutants by both approaches, and the corresponding large-scale identification of phenotypes, has been revolutionized by use of high-throughput sequencing, synthetic biology techniques, and image analysis.

In particular, over the last decade, reverse genetics has been scaled up by high-throughput knockdowns, especially RNAi screens and comprehensive gene knockout collections in model species that span the tree of life [4–8]. More recently, CRISPR screens, which are potentially amenable to any organism of interest, have been used to create libraries of human cell line knockouts [9,10], allowing reverse genetics to be applied to human systems;

Figure 1



Components of comparative methods for rationally identifying human disease genes. Silhouettes are from PhyloPic (URL: http://phylopic.org/).

phenotypic analysis of the resulting CRISPR libraries now seems to be the bottleneck. A group of methods termed 'Deep Mutational Scanning' allows the systematic switching of, for instance, every codon in an open reading frame to every other codon in search of phenotype-causing substitutions [11••,12,13].

Similar gains in throughput are now being seen in forward genetics screens as well. Often, forward genetic screens introduce untargeted mutations into a genome, and then identify lines with phenotypes of interest before screening for mutations. Recent efforts have utilized high-throughput sequencing to make this approach feasible in mammals [14] and on much larger scales than in previous generations [15]. Other methods utilize the diversity of natural populations as a basis for phenotypic screening [16•,17]. Platforms in yeast, plants, worms, and fruit flies now exist to record quantitative data on multiple levels, including morphology, metabolism, transcription, and translation [16•,18–21]. Combining these measurements make it possible not only to uncover the biology of model systems, but also to screen human genes and candidate disease alleles in a model system background, a method that Jasper Rine and colleagues termed 'surrogate genetics' [22,23•]. Although model organisms will remain a mainstay of human disease genetics, the advent of these novel molecular tools has raised the possibility of high-throughput screens of genotype/phenotype relations in any organism of interest, blurring the lines between model and non-model organism. Importantly, the advances in both forward and reverse genetics have produced hundreds of thousands of gene — phenotype associations across multiple organisms [24–27], providing deep datasets that now make computational analyses of new disease genes increasingly possible.

Finding models through phenotype comparison

Traditionally, non-human models of disease are often identified by the direct comparison of a model organism phenotype with traits of a human disease. However, such comparisons have historically relied only on the expertise of researchers, and tended to make use of organism-specific language to describe phenotypes. The development of ontologies, formal hierarchies of descriptive annotations [28–30], now allows researchers to find new human disease models by directly searching for homologous phenotypes, an approach easily scalable to large phenotypic datasets. Multiple ontologies [31–33] have been developed, enabling systematic analyses of phenotypes in a way that is descriptive, robust, programmatically accessible, and extensible across species. Notably, major organismal databases now use ontologies to describe phenotypes, for example as for the Worm [34], Human [35], and Mammalian [36] Phenotype Ontologies.

Formal ontologies allow phenotype databases to be cross referenced, much as researchers might search for homologous sequences across organisms. This functionality can significantly improve the throughput and sensitivity of the comparative approach, and can be used to identify

disease models on the basis of phenotypic qualities alone. As one such example, PhenomeNET [37], for instance, employs the Phenotype and Trait Ontology (PATO) developed by Gkoutos *et al.*, and was used to suggest novel genes involved in the Tetralogy of Fallot, a congenital heart defect. Other algorithms have also made use of phenotype annotations to facilitate the discovery of candidate disease genes [38•,39–42].

Finding models through genetic comparison

Just as phenotype ontologies can be used to identify disease models on the basis of phenotypes alone, appropriate models can also be selected using orthologs [43] of human disease genes identified in model organisms (Figure 1). Although this approach is limited by its reliance on *a priori* knowledge of the genetic basis of a disease, the basic step of determining gene orthology between organisms of interest still forms the core of most comparative studies. This is because orthologs, which are separated historically only by speciation events, tend to be more closely related in function than paralogs [44–46], which result from shared ancestral gene duplications and can often partition an ancestral function, or take on whole new functions [47–49].

New methods for inferring orthologs, and new databases for storing this information are proliferating. As of 2015, there are at least 37 different orthology databases using a variety of algorithms, reviewed in detail by Sonnhammer *et al.* [50••]. Benchmarking suggests that no one method outperforms all others, with methods differing in their precise definition of 'orthology' as well as in their tendency to favor either precision or recall for discovery of correct orthologs [51,52]. Meta-analyses that compare and compile information from different algorithms and databases are therefore expected to significantly improve performance [53,54]. Another promising direction is to use information about the species phylogeny to probabilistically inform gene tree inference [55–57]. When the gene of interest for a disease has not yet been identified, computational strategies now exist for prioritizing potential candidate genes, as we discuss next, but even these methods usually require knowledge of orthologs as a starting point.

Statistically associating genes and diseases

The methods described above either rely on prior information about the genetic nature of a human disease, or on a clear phenotypic similarity between organisms. However, phenotypes arising from conserved genetic pathways may have diverged so far that their homology is unrecognizable. A number of methods have been developed to derive useful information from such cases, as well as to facilitate the synthesis of data from multiple species (Figure 2). These methods have the added benefits of identifying both novel human disease genes and appropriate model systems for studying those genes. A common principle of these methods is to group genes together by some criterion that reports on function ('statistical association'). These groupings then enable the statistical inference of novel disease-associated genes. Methods vary in way that they group genes and associate them with phenotypes (Figure 2). Below, we highlight some of the most common methods, and some recent innovations in this area.

Phylogenetic profiles

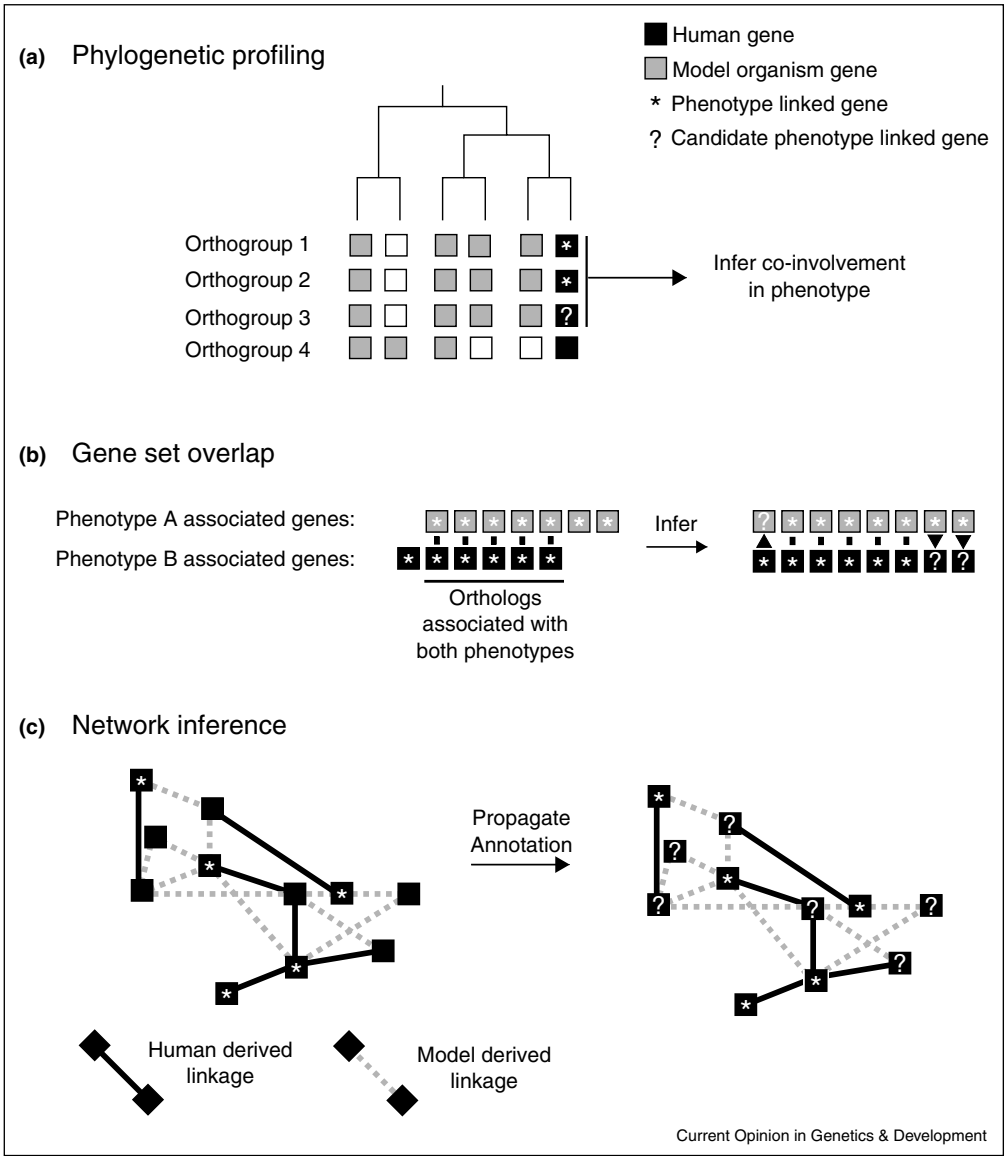
Genes with linked function tend to have similar patterns of presence/absence across species, and this presence/absence vector is termed a 'phylogenetic profile' (Figure 2a). Phylogenetic profiling allows the search for candidate genes which may have co-evolved with the disease-linked gene, and be involved in the same disease-causing process. Inferring gene functions by their phylogenetic profile, as proposed by Pellegrini *et al.*, is not new [58–60], however, these methods are increasingly being applied to the genetics of human disease [61••]. Recent improvements to this technique, such as using orthologous groups of genes, weighting by species divergence, and ancestral state inference, have increased the power of phylogenetic profiling methods, and by extension their application to candidate gene discovery [62••,63••,64,65]. As one recent example, Dey *et al.* applied phylogenetic profiling to discover genes involved in ciliary and centrosomal defects [62••].

Gene set overlap approaches

Gene set overlap methods determine if two groups of phenotype-associated genes in different species significantly share (orthologous) members (Figure 2b). These methods employ a statistical model to test the significance (commonly, the hypergeometric probability) of two phenotype-associated groupings from two species sharing a set of orthologous genes. This has proven to be an effective approach for identifying extremely divergent model phenotypes which employ the same genetic pathways involved in human diseases [27,66], such as, for example, the identification of a plant model of human Waardenburg syndrome [66]. Because these phenotypes employ orthologous genetic mechanisms, they have been termed 'phenologs' [66]. The original approach inferred pairwise phenologs [66], but has been subsequently improved upon by extension to multiple species [27]. The success of this extension indicates an important fact: more comparative data means more inferential power for discovering novel genes associated with human disease.

Involvement in a particular phenotype is not the only way to classify genes in overlap-based studies. Korcsmáros *et al.* used pathway annotations in model species to predict more complete, integrated human signaling pathways [67]. Increasingly, multiple sources of data are being

Figure 2



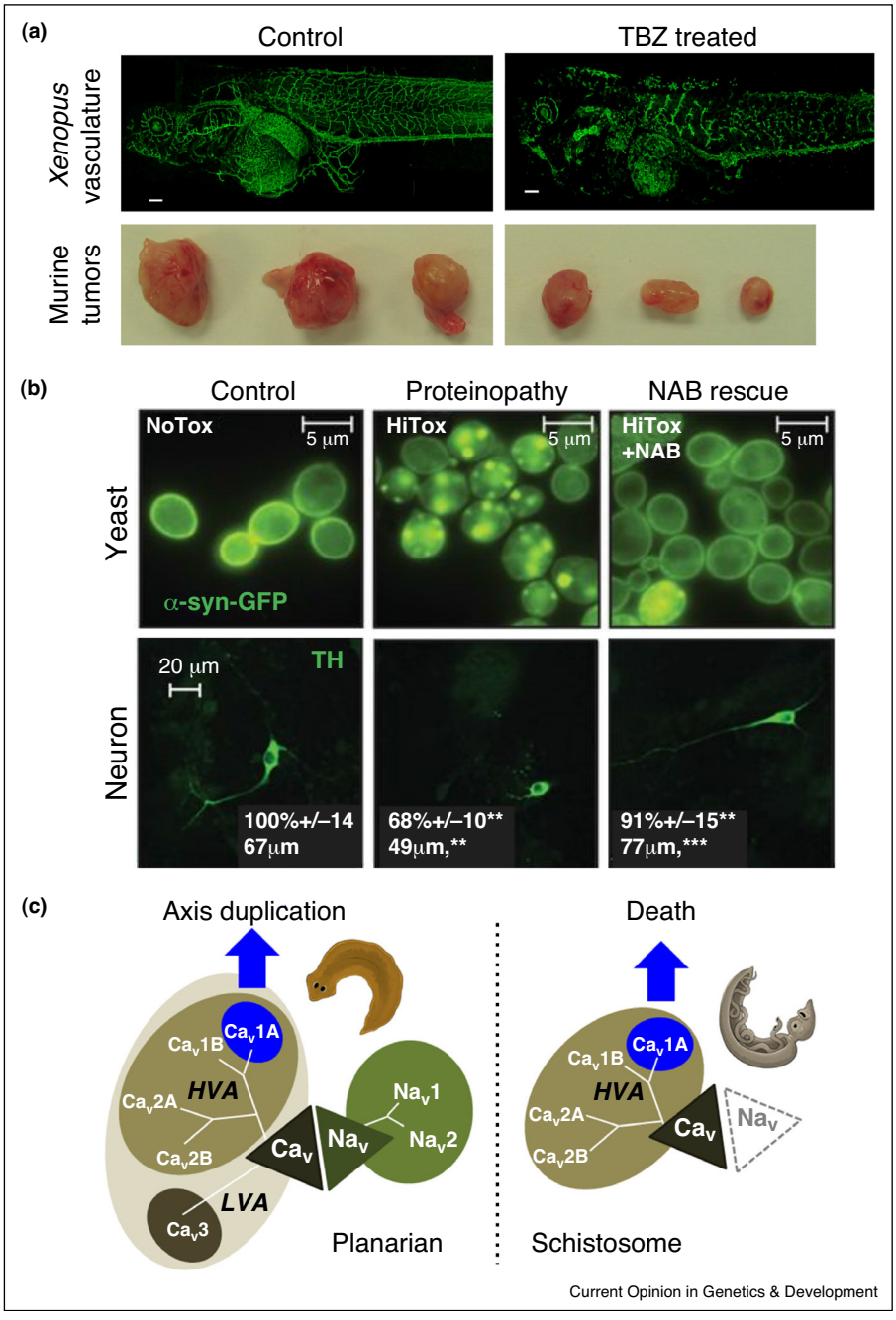
Examples of statistical linking methods for rationally identifying human disease genes.

combined in databases [68,69•] that allow comprehensive comparison of overlap between gene sets.

Network approaches

Gene network-based approaches use networks to provide statistical frameworks for inferring new gene functions or disease associations. A network is first built from interactions between genes (or their encoded proteins); in a comparative gene-discovery framework, these interactions may be experimentally derived from multiple species. The resulting network can then be used to propagate information from genes (network nodes) whose function is known, to genes of unknown function (Figure 2c [70]), using the interactions (network edges) to functionally annotate new genes [71,72]. In principle, edges in the network can incorporate interaction data gleaned from any data source or species, and are therefore often a preferred method of generating consensus annotations. Many kinds of functional annotations can be propagated and therefore predicted, including new gene annotations [73] and disease gene associations, such as might arise from genome-wide association scans, for example as shown for Crohn's disease using the human gene network HumanNet [71]. There are many methods used for information propagation (reviewed in depth in Wang and Marcotte [70]). Networks have also been constructed from genetic interactions, as might be gleaned from, for instance, double deletion screens [74], and used to find

Figure 3



Recent applications of statistical linking methods to identify and treat human disease. **(a)** Cha *et al.* [84••] used overlap between vasculature genes and genes linked to antifungal sensitivity in yeast to identify TBZ as a novel vascular disrupting agent. TBZ disassembled vasculature in *Xenopus* embryos (top panels) and slowed human fibrosarcoma tumor growth in mice (bottom panels). Adapted from Cha *et al.* [84••]. **(b)** Tardiff *et al.* [88] overexpressed α-synuclein and screened for phenotype rescuing compounds. One such compound, NAB, in turn ameliorated neuronal proteinopathies in worm neurons. Adapted from Tardiff *et al.* [88]. **(c)** Chan *et al.* [90••] identified divergent phenotypes in planarians and schistosomes in response to the small molecule PZQ. Ca_v, voltage-gated calcium channel; Na_v, voltage-gated sodium channel; HVA, high-voltage activated; LVA, low-voltage activated.
Adapted from Chan *et al.* [90••].

new genetic modifiers [75•]. Many gene networks are now available online that combine evidence from different interaction types, enabling the use of network-based inferences in most major model organisms [76,77,78•, 79,80••].

In one particularly interesting recent application of gene networks, the networks are not just used for candidate gene prioritization or annotation. Vidal *et al.* have suggested that disease phenotypes can be viewed as disruptions between interacting genes within the network structure ('edgetics') [81,82,83••], suggesting a wider use for gene networks in human disease research in guiding the disruption of only some, but not all, of a given gene's interactions to affect a specific biological outcome.

Recent applications

In reviewing the methods above, we have focused on the discovery of novel genes associated with human disease. One ultimate goal of these studies is to identify novel therapeutic agents that ameliorate the disease, which can be a challenge even when the target is known. We briefly highlight three recent studies that use the methods outlined above to identify novel drugs that target cancers, neurodegenerative diseases, and parasites (Figure 3).

One of the predictions of the original phenolog study [66] was a yeast gene set that models vertebrate angiogenesis, a key dependency of tumor growth. Cha *et al.* [84••] used prior information about gene-drug genetic interactions between the yeast pathway and a variety of small compounds [85] to prioritize drugs that might block blood vessel growth. They identified thiabendazole (TBZ) as a candidate angiogenesis inhibitor, and found that not only did it indeed prevent vascularization in *Xenopus* embryos, but it disrupted pre-existing immature vasculature and slowed fibrosarcoma tumor growth in a mouse model, making it the first such vascular disrupting agent with FDA approval for human use (here, for its antifungal activity). TBZ illustrates that guilt-by-association approaches can be predictive, even between yeast and vertebrates.

Yeast is especially useful for high-throughput drug and genetic screens, as shown by recent work on the protein α-synuclein. This protein is associated with Parkinson's disease and related neurodegenerative diseases, termed synucleinopathies [86]. Susan Lindquist *et al.* used drug screens to identify compounds that inhibited aggregation of the protein α-synuclein exogenously expressed in yeast [87]. They identified a class of compounds called N-Aryl Benzimidazoles (NABs) that inhibit α-synuclein aggregation in yeast cells and animal neurons [88]. They further utilized the genetic tractability of yeast to identify pathways affected by α-synuclein [89••], suggesting potential new therapeutic avenues for synucleinopathies.

Whereas these two comparative approaches were applied to understand human genetic disease, the same approaches can also inform on infectious disease. Chan *et al.* [90••] used planarians, a model platyhelminth worm, to identify the target of the drug praziquantel (PZQ), which kills schistosomes, the pathogenic platyhelminths that cause schistosomiasis, but whose molecular target is unknown. Remarkably, while PZQ kills schistosomes, it causes an axis-duplication phenotype in planarians. This axis duplication phenotype, unlike death, can be explored using RNAi screens, readily applied in planarians. Using this method, Chan *et al.* identified the cellular basis of the axis duplication phenotype and also identified novel gene targets, as well as new compounds that phenocopy the effect of PZQ and are therefore candidate anti-schistosomal agents.

Outlook for the future

We have touched on recent work using comparative approaches to relate human phenotypes to those in model organisms. We expect opportunities for connecting human genetics with the genetics of non-model organisms to increase considerably over the near time. In particular, data are increasingly available on human genetic variation, including familial inheritance, most recently across the Icelandic population [91], and increasingly provide a reference of human genetic variation for comparative approaches. It also seems a safe bet that the capacity for high-throughput CRISPR screens will dramatically increase known gene-phenotype associations from ever more diverse organisms, including non-traditional models. These developments will only increase in power and accuracy of comparative genomic approaches, and going forward, such methods will serve as a foundation to discover trends across life that point to the cause and treatment of human disease.

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