

An atlas connecting shared genetic architecture of human diseases and molecular phenotypes provides insight into COVID-19 susceptibility

iCPAGdb Web App Supplement

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Two primary objectives guided the design of the iCPAGdb web app (the web app): quick accessibility of precomputed cross-phenotype analysis of GWAS (CPAG) results for select GWAS studies and the ability to discover new cross-phenotype relationships between researcher uploaded GWAS data sets and those maintained in the iCPAGdb database (the database). We will refer to the browsing and upload modes simply as “review” and “compute,” respectively. Once the data content and public interaction objectives were established, architecture design choices were made, drawing on experience gained while developing a web app for a prior GWAS project (Wang et al., 2018). Primary software components for the web portion of iCPAGdb are the R statistical programming language (R Core Team, 2020), the R package *Shiny* for interaction of web pages with R scripts (Chang et al., 2020), *Shiny Server* as a 24/7 multi-user platform to make Shiny apps publicly accessible (RStudio, 2020), the database environment *SQLite* for efficient querying of GWAS and CPAG results (Hipp, 2020), and the R package *RSQLite* to execute SQL queries from within R scripts (Muller et al., 2020). CPAG computations, as described in the iCPAGdb section of the paper and (Wang et al., 2015), are implemented in the Python programming language, external to the web app, and are executed using parameterized system calls constructed from values supplied by the user through on-screen controls. The results of a CPAG execution are read by the R script, processed, and presented to the viewer in various tables and graphs on a web page. Shiny conducts the interaction between web pages, R scripts, and the CPAG functions. The SQLite database is primarily used by the CPAG functions, but is also a source of identifiers and other values used to populate selection lists within the web app.

Program flow 1 outlines the major processing steps for review mode. Basically, the user requests an existing CPAG result set from which a corresponding table and heatmap are generated and displayed. Various filtering and graph construction controls are available for iterative sub-setting of data and selection of significance measure and number of top significant phenotype pairs to plot. The “Download” button enables the researcher to make a local copy of records appearing in the currently displayed results table. Important packages used in this mode are DT (Xie et al., 2020) for construction of and interaction with tables and ggplot2 (Wickham, 2016), plotly (Sievert, 2020), and heatmaply (Galili et al., 2017) for basic plotting, interactive plotting (hover labels), and heatmap generation, respectively.

Program flow 1, review mode

1. Query available precomputed CPAG results and construct table with selectable rows, one per study
 2. Present table in web app
 3. When table row is selected, read corresponding study results, prepare table of results and heatmap for review
 4. Interact with user, iterating through on-screen control settings to sort, filter, and modify results table while synchronizing heatmap with tabular data
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Although the packages employed are relatively full-featured and robust, several custom algorithms had to be developed to overcome specific limitations of various functions of these packages when used with our

data. For example, the clustering algorithm used by the `heatmaply()` function to add dendrogram lines to a graph generated errors when used with the distance matrix computed by the base R `distance()` function. A substitute vector distance algorithm was developed to overcome domain errors reported by `heatmaply()`. Figure 1 shows an example review session.¹ The table in the upper section of the form lists precomputed CPAG results available for review. Below that are the filter and graph controls. When a row in the CPAG table is selected, a table of corresponding results appears in the “Table” tab (bottom of the image) and a corresponding heatmap that relates pairs of inter-GWAS phenotypes by the selected significance measure (Fisher, Bonferroni, etc.) appears in the “Heatmap” tab. Figures 2 and 3 show the table and heatmap that appear after clicking the “Molecular traits vs. Human disease” row of the selection table, which is accessed by scrolling down.

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Review iCPAGdb Upload GWAS and compute CPAG Bibliography

1. Select a data set to review

Description	Source (GWASs)	Source (GWASs)	P _{threshold} (GWASs)	P _{threshold} (GWASs)	LD Population	Reference
COVID-19	Elzinghaus	NHGRI, H2P2, Metab, Mol, Clin	1x10 ⁻⁵	5x10 ⁻² (NHGRI), 1x10 ⁻⁵	EUR	Elzinghaus et al., 2020
Human disease	NHGRI-EBI GWAS catalog		5x10 ⁻⁵		EUR	Buniello et al., 2019
Host-pathogen traits	H2P2		1x10 ⁻⁵		EUR	Hi-HOST Phenome Project; Wang et al. 2019
Host-pathogen traits	H2P2		1x10 ⁻⁵		AFR	Hi-HOST Phenome Project; Wang et al. 2019
Host-pathogen traits	H2P2		1x10 ⁻⁵		EAS	Hi-HOST Phenome Project; Wang et al. 2019

2. Filter

☐ Include all SNPs in table

Trait filter:

SNP filter:

EFO filter select multiple:

☐ Include compound EFOs

Apply filters Clear filters Download filtered records

Heatmap metric

☒ Fisher ☐ Bonferroni ☐ FDR ☐ Jaccard ☐ Chao-Sorensen

Display top significant phenotype pairs in heatmap

☐ 10 ☒ 25 ☐ 50 ☐ 100 ☐ 250 ☐ 500 ☐ 1,000 ☐ all

Table Heatmap

Figure 1: iCPAGdb web app Review tab

Table Heatmap

Show 25 entries

Trait ₁	Trait ₂	Nshare _{direct}	Nshare _{LD}	Nshare _{all}	-log ₁₀ (P _{Fisher})	-log ₁₀ (P _{Bonferroni})	-log ₁₀ (P _{LD})	SNP _{shared}	Jaccard	ChaoSorensen	Trait1_EFO
selenium measurement	betaine	6	2	8	32.9707	26.7055	26.7055	rs921943rs558133rs16876394-rs17823744rs1706979	0.1455	0.7697	Other measurement
dehydroepiandrosterone sulphate measurement	dehydroisoandrosterone sulfate (DHIA-S)	0	6	6	23.9325	17.6673	17.9683	rs36139342-rs794614rs80193476-rs17277546rs296396	0.1364	0.8711	Other measurement
blood metabolite measurement	1-inoeoylglycerophosphoethanolamine*	3	4	7	22.2541	15.9889	16.466	rs4149056-rs2199680rs174548-rs174535rs2727271-rs	0.0398	0.1961	Other measurement
blood metabolite measurement	glutaryl carnitine	4	4	8	22.0174	15.7521	16.3542	rs8012rs2070630-rs4690909rs246234-rs2062541-rs87	0.0359	0.2072	Other measurement
blood metabolite measurement	1-arachidonoylglycerophosphoinositol*	1	6	7	21.2813	15.0161	15.7696	rs11045905-rs12829704rs2727271-rs2727270rs968567	0.0378	0.1919	Other measurement
hormone measurement	andosterone sulfate	1	4	5	21.2567	14.9914	15.7696	rs2637125-rs2972516rs17277546rs2185570-rs1752362	0.1087	0.3706	Other measurement
bilirubin measurement	X-11793	0	6	6	20.7647	14.4995	15.3446	rs1587493-rs8330rs6431630-rs11563251rs2361502-rs	0.0732	0.366	Other measurement
serum metabolite measurement	X-11317	1	6	7	20.6788	14.4136	15.3167	rs9939224-rs7499892rs183130-rs3764261rs10159255-	0.0407	0.2104	Other measurement
blood metabolite measurement	1-arachidonoylglycerophosphoethanolamine*	5	2	7	20.4046	14.1394	15.1337	rs2727271rs4149056rs11045906-rs12829704rs104680	0.0357	0.1807	Other measurement
bilirubin measurement	X-11529	1	5	6	20.399	14.1337	15.1337	rs7303743-rs2417940rs4149056rs1604542-rs1995409	0.0674	0.3305	Other measurement
total cholesterol measurement	X-03094	4	4	8	20.2117	13.9465	14.9879	rs9958734-rs3786247rs964184rs4938303-rs23679709	0.0175	0.0928	Lipid or lipoprotein measurement
blood metabolite measurement	X-12063	2	5	7	19.4609	13.1956	14.2748	rs1934963-rs4917639rs7809615-rs10278040rs4149056	0.033	0.166	Other measurement

Figure 2: iCPAGdb web app. Table generated by selecting a precomputed CPAG result.

¹Screen-shots were taken from the iCPAGdb website, <http://cpag.oit.duke.edu>

Program flow 2, compute mode

Upload a GWAS section

Researcher:

1. Browses local computer for a GWAS file to upload
2. Specifies file structure (delimiter type, GWAS SNP and significance columns)
3. Clicks “Upload file” to prepare uploaded data for CPAG processing

Compute section

Researcher:

4. Selects iCPAGdb GWAS study (GWAS source two) to be used for investigation of cross-GWAS associations
5. Selects p-thresholds (to filter phenotypes and SNPs) for each GWAS and specifies a linkage disequilibrium (LD) population
6. Clicks “Compute CPAG”

The R script:

7. Composes a CPAG (Python) function call, using researcher supplied values
8. Creates an asynchronous future() environment for CPAG execution
9. Passes control to the CPAG function and waits on returned (promise piped) results
10. Generates a table of results and heatmap using current on-screen configuration values

Researcher:

11. Reviews and interacts with results as on the Review tab
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[Review iCPAGdb](#) [Upload GWAS and compute CPAG](#) [Bibliography](#)

1. Upload a GWAS file

Choose File

Delimiter ☐ Comma ☒ Tab

Trait (phenotype) column

SNP column

P (significance) column

[Upload file](#)

2. Compute

GWAS source one

GWAS source two

p-threshold₁ (1X10⁻⁴)

p-threshold₂ (1X10⁻⁴)

p-threshold adjustments
H2P2 min = 1X10⁻²
NHGRI min = 5X10⁻³
All others, min = 1X10⁻³

LD 1000 Genomes population
☒ European ☐ African ☐ Asian

[Compute CPAG](#)

3. Filter

☐ Include all SNPs in table

Trait filter

SNP filter

EFO filter select multiple

☐ Include compound EFOs

[Apply filters](#) [Clear filters](#) [Download filtered records](#)

Heatmap metric
☒ Fisher ☐ Bonferroni ☐ FDR ☐ Jaccard ☐ Chao-Sorensen

Display top significant phenotype pairs in heatmap
☐ 10 ☒ 25 ☐ 50 ☐ 100 ☐ 250 ☐ 500 ☐ 1,000 ☐ all

[Table](#) [Heatmap](#)

Figure 4: iCPAGdb web app. Upload and Compute tab..

In initial testing, the app was found to perform efficiently, giving researchers convenient access to both precomputed CPAG results and newly computed values for uploaded GWAS data. Cross-phenotype relationships presented by the app agree with those known to researchers with expert knowledge of data sets employed during verification. It is hoped that the app will become a recognized and useful tool for researchers conducting exploratory cross-phenotype analysis of GWAS.

Complete R and Shiny scripts for the iCPAGdb web app, along with additional design information, are available at <https://github.com/tbalmat/iCPAGdb>.

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