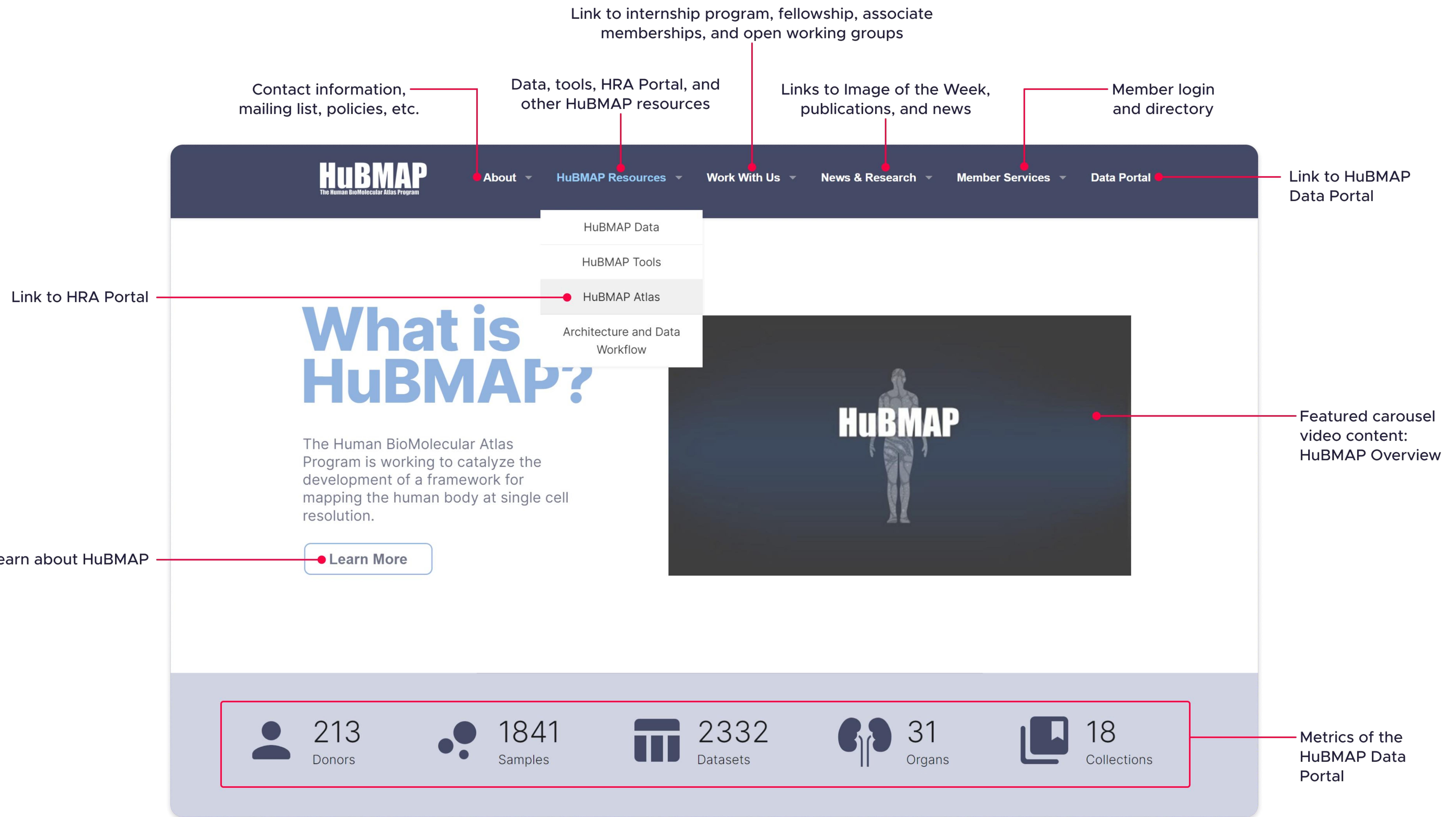


Supplemental Figure 1. Hybrid Cloud Microservices System Architecture

AWS

PSC

Globus



Supplemental Figure 2. HuBMAP Consortium Website

Explore HRA data: ASCT+B Tables, VCCF Files, 2D FTU Illustrations, 3D Reference Objects, OMAPs, and route to the HuBMAP Data Portal

Explore HRA applications

Explore HRA user interfaces

Explore HRA learning modules, standard operating procedures, events and more

HuBMAP Human Reference Atlas

Human Reference Atlas
3D Multiscale Biomolecular Human Reference Atlas

The 6th Release of the Human Reference Atlas (v2.0) is now available! See what's new in [HRA v2.0 in our Release Notes](#).

A Human Reference Atlas (HRA) is a comprehensive, high-resolution, three-dimensional atlas of all the cells in the healthy human body. The Human Reference Atlas provides standard terminologies and data structures for describing specimens, biological structures, and spatial positions linked to existing ontologies.

Map the human body at single-cell resolution

Learn more about the thousands of experts building the Human Reference Atlas.

Read the flagship paper of the Human Reference Atlas (HRA) published in *Nature Cell Biology*

Click the carousel buttons to view more slides about the HRA

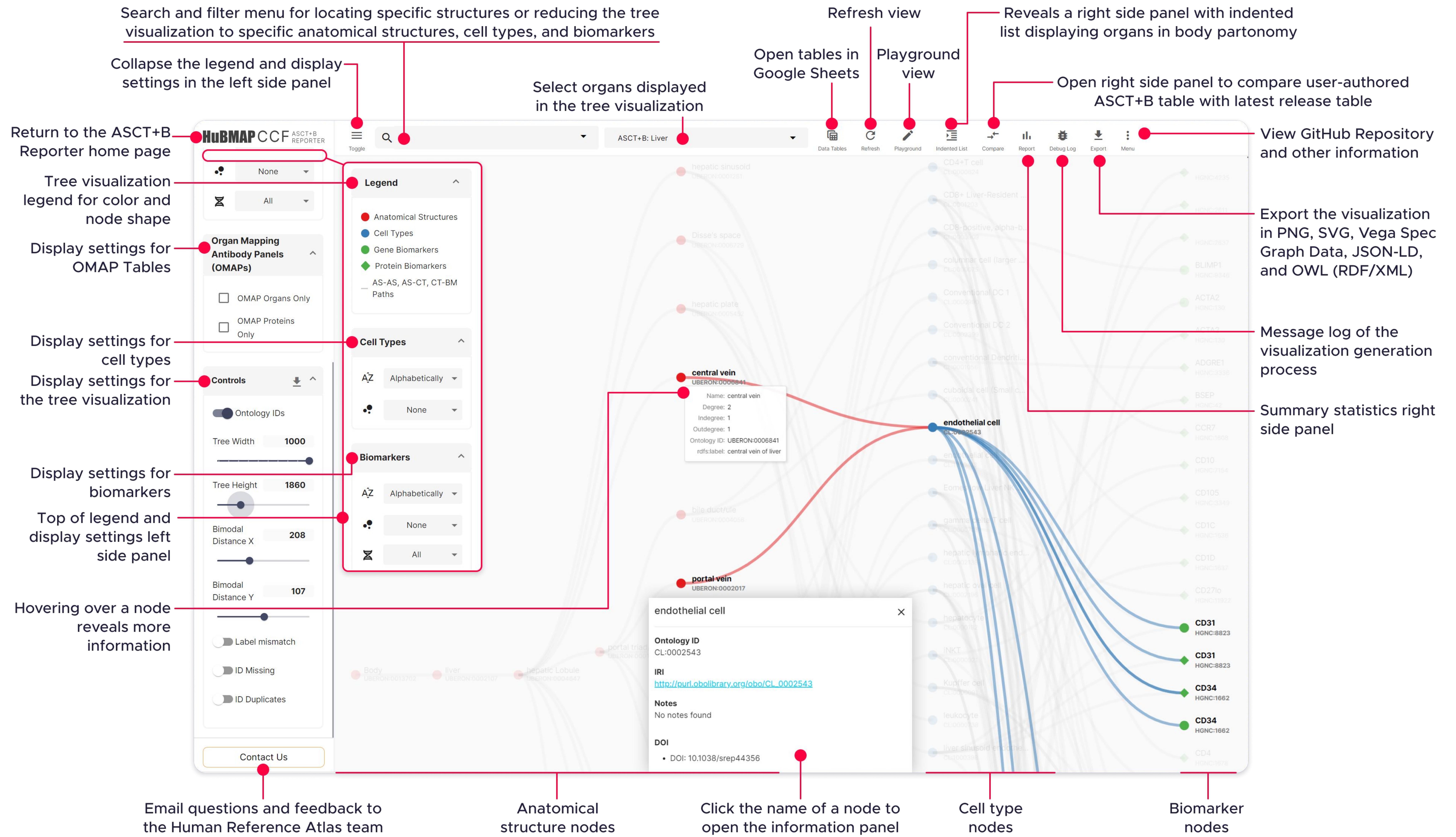
Metrics of the evolving Human Reference Atlas

Learn about the HRA team and editorial board

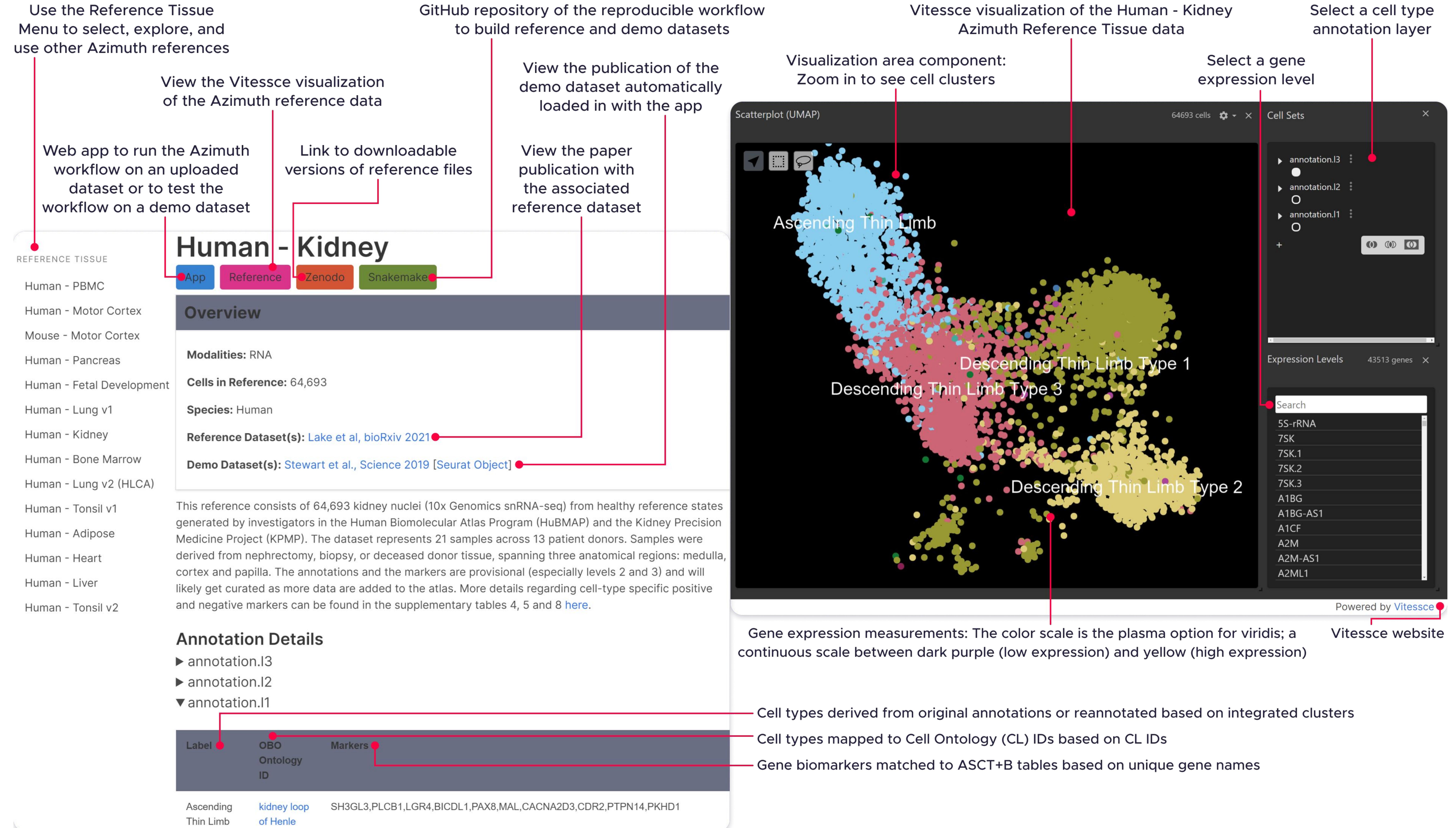
Access detailed release notes

A figure from the HRA flagship paper


Supplemental Figure 3. Human Reference Atlas Portal



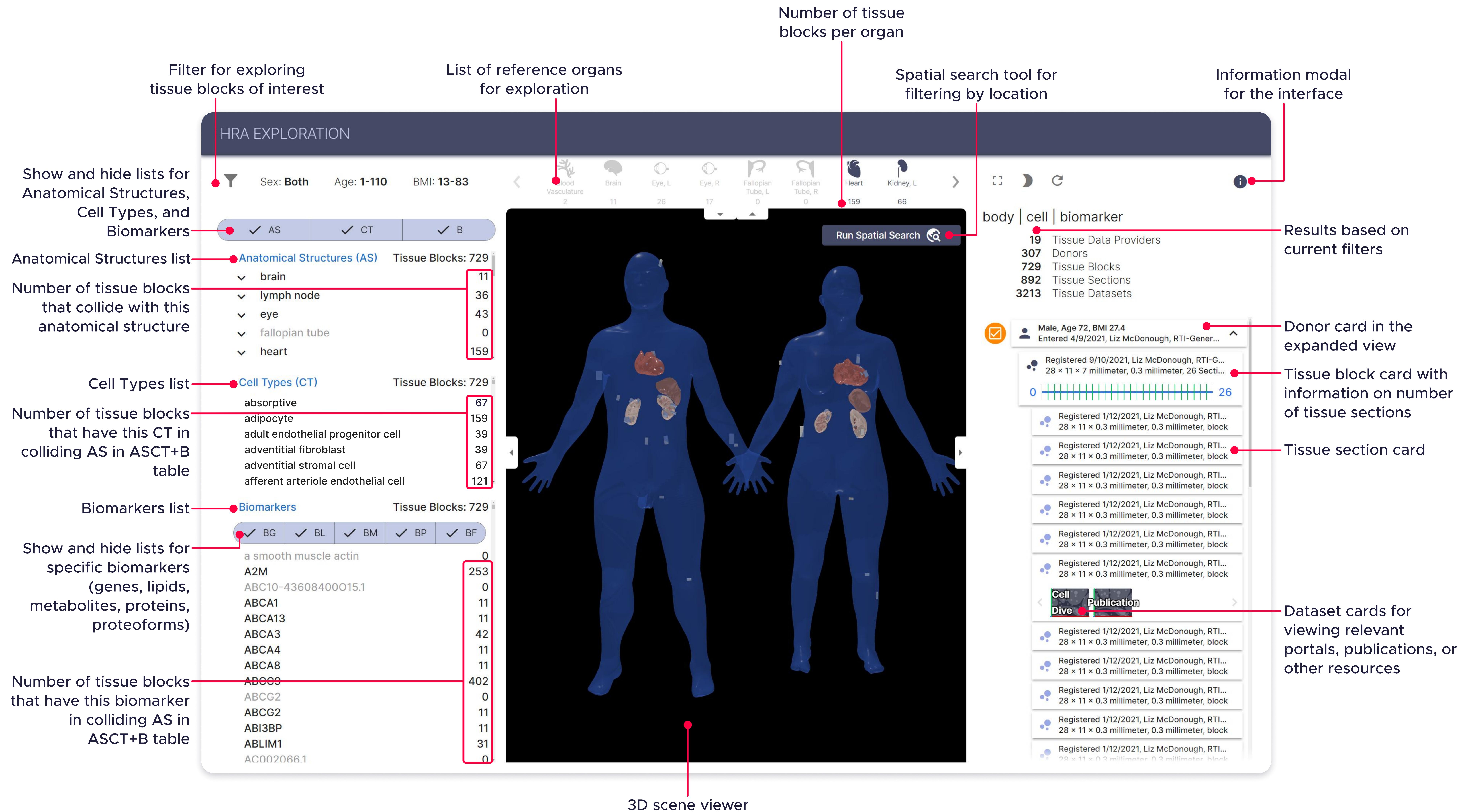
Supplemental Figure 4: ASCT+B Reporter User Interface



Supplemental Figure 5. Azimuth Portal and Reference Explorer User Interface



Supplemental Figure 6. Registration User Interface (RUI)



Supplemental Figure 7: Exploration User Interface (EUI)

HuBMAP HRA EXPLORATION

LOGIN

Sex: Both Age: 1-110 BMI: 13-83

Blood Vascularization Brain Eye, L Eye, R Fallopian Tube, L Fallopian Tube, R Heart Kidney, L Kidney, R Knee, L Knee, R Large Intestine

✓ AS ✓ CT ✓ B

Anatomical Structures (AS) Tissue Blocks: 446

- ✓ brain 0
- ✓ lymph node 35
- ✓ eye 0
- ✓ fallopian tube 0
- ✓ heart 24
- ✓ kidney 118

Cell Types (CT) Tissue Blocks: 446

- absorptive 65
- absorptive 57
- adipocyte 83
- adipocyte 12
- adipocyte 24
- adipocyte 1 0

Biomarkers Tissue Blocks: 446

- ✓ BG ✓ BL ✓ BM ✓ BP ✓ BF
- a smooth muscle actin 0
- A2M 114
- ABC10-43608400015.1 0
- ABCA1 0
- ABCA13 0
- ABCA3 10
- ABCA4 0
- ABCA8 0
- ABCC9 211
- ABCG2 0
- ABCG2 0
- ABI3BP 0
- ABLIM1 31
- AC002066.1 0
- AC002066.2 0

Run Spatial Search

body | cell | biomarker

7 Tissue Data Providers
140 Donors
446 Tissue Blocks
856 Tissue Sections
2359 Tissue Datasets

- Female, Age 67, BMI 30.2
Entered 12/27/2019, Yiling Lin, TMC-Stanford
- Female, Age 67, BMI 30.2
Entered 12/27/2019, Yiling Lin, TMC-Stanford
- Female, Age 14, BMI 19.7
Entered 2/16/2020, Marda Jorgensen, TMC-F...
- Female, Age 54
Entered 11/30/2021, Amanda Knoten, TMC-U...
- Female, Age 21, BMI 37.1
Entered 10/19/2020, Marda Jorgensen, TMC-...
- Male, Age 18, BMI 27.1
Entered 2/17/2020, Marda Jorgensen, TMC-F...
- Male, Age 47
Entered 8/3/2022, Marda Jorgensen, TMC-FI...
- Male, Age 18, BMI 27.1
Entered 2/17/2020, Marda Jorgensen, TMC-F...
- Male, Age 18, BMI 25.5
Entered 2/16/2020, Marda Jorgensen, TMC-F...
- Male, Age 20
Entered 6/6/2022, Marda Jorgensen, TMC-FI...
- Male, Age 45, BMI 33.1
Entered 12/11/2020, Yiling Lin, TMC-CalTech
- Male, Age 56, BMI 32.5
Entered 12/26/2019, Jamie Allen, TMC-Vande...
- Male, Age 43, BMI 41.3
Entered 2/10/2021, Yiling Lin, TMC-CalTech
- Male, Age 38, BMI 29.0
Entered 9/7/2021, Daniel Cotter, TMC-Stanford
- Male, Age 78, BMI 35.1
Entered 2/19/2020, Yiling Lin, TMC-Stanford
- Male, Age 78, BMI 35.1
Entered 2/19/2020, Yiling Lin, TMC-Stanford
- Male, Age 56
Entered 8/24/2022, Melissa Olmer, TMC-UC...

SenNet

Sex: Both

Age: 1-110

BMI: 13-83

	Blood Vasculation	0
	Brain	0
	Eye, L	0
	Eye, R	0
	Fallopian Tube, L	0
	Fallopian Tube, R	0
	Heart	0
	Kidney, L	0

AS CT B

Anatomical Structures (AS)

- brain
- lymph node
- eye
- fallopian tube
- heart

Cell Types (CT)

- absorptive
- absorptive
- adipocyte
- adipocyte
- adipocyte

Biomarkers

BG BL BM BP BF

a smooth muscle actin

A2M

ABC10-43608400015.1

ABCA1

ABCA13

ABCA3

ABCA4

ABCA8

ABCC9

ABCG2

ABCG2

ADAM20

body | cell | biomarker

1 Tissue Data Providers

2 Donors

2 Tissue Blocks

2 Tissue Sections

4 Tissue Datasets

Male, Age 37

Entered 11/4/2022, Matthew Wyczalkowski, W...

Registered 5/11/2023, Matthew Wyczalkowski...
20 x 15 x 10 millimeter, 10 millimeter, 1 Sections

Registered 4/27/2023, Matthew Wyczalko...
20 x 15 x 10 millimeter, 10 millimeter, Block

Female, Age 69

Entered 4/20/2023, Matthew Wyczalkowski, ...

Registered 5/11/2023, Matthew Wyczalkowski...
20 x 15 x 10 millimeter, 10 millimeter, 1 Sections

Registered 4/20/2023, Matthew Wyczalko...
20 x 15 x 10 millimeter, 10 millimeter, Block

GTEx Portal

Home Downloads Expression Single Cell QTL IGV Browser Tissues & Histology Documentation

Search Gene or SNP ID...

GTEx tissue sites mapped to the HuBMAP Human Reference Atlas

Sex: Both Age: 1-110 BMI: 13-83

Anatomical Structures (AS) Tissue Blocks: 475

- ✓ brain
- ✓ lymph node
- ✓ eye
- ✓ fallopian tube

Cell Types (CT)

- absorptive
- absorptive
- adipocyte
- adipocyte
- adipocyte

Biomarkers Tissue Blocks: 475

- ✓ BG ✓ BL ✓ BM ✓ BP ✓ BF
- a smooth muscle actin
- A2M
- ABC10-43608400015.1
- ABCA1
- ABCA13
- ABCA3
- ABCA4
- ABCA8
- ABCC9
- ABCG2
- ARCG2

Blood Vasculation 2

Brain 0

Eye, L 0

Eye, R 0

Fallopian Tube, L 0

Fallopian Tube, R 0

Heart 28

Kidney, L 66

Run Spatial Search

body | cell | biomarker

8 Tissue Data Providers

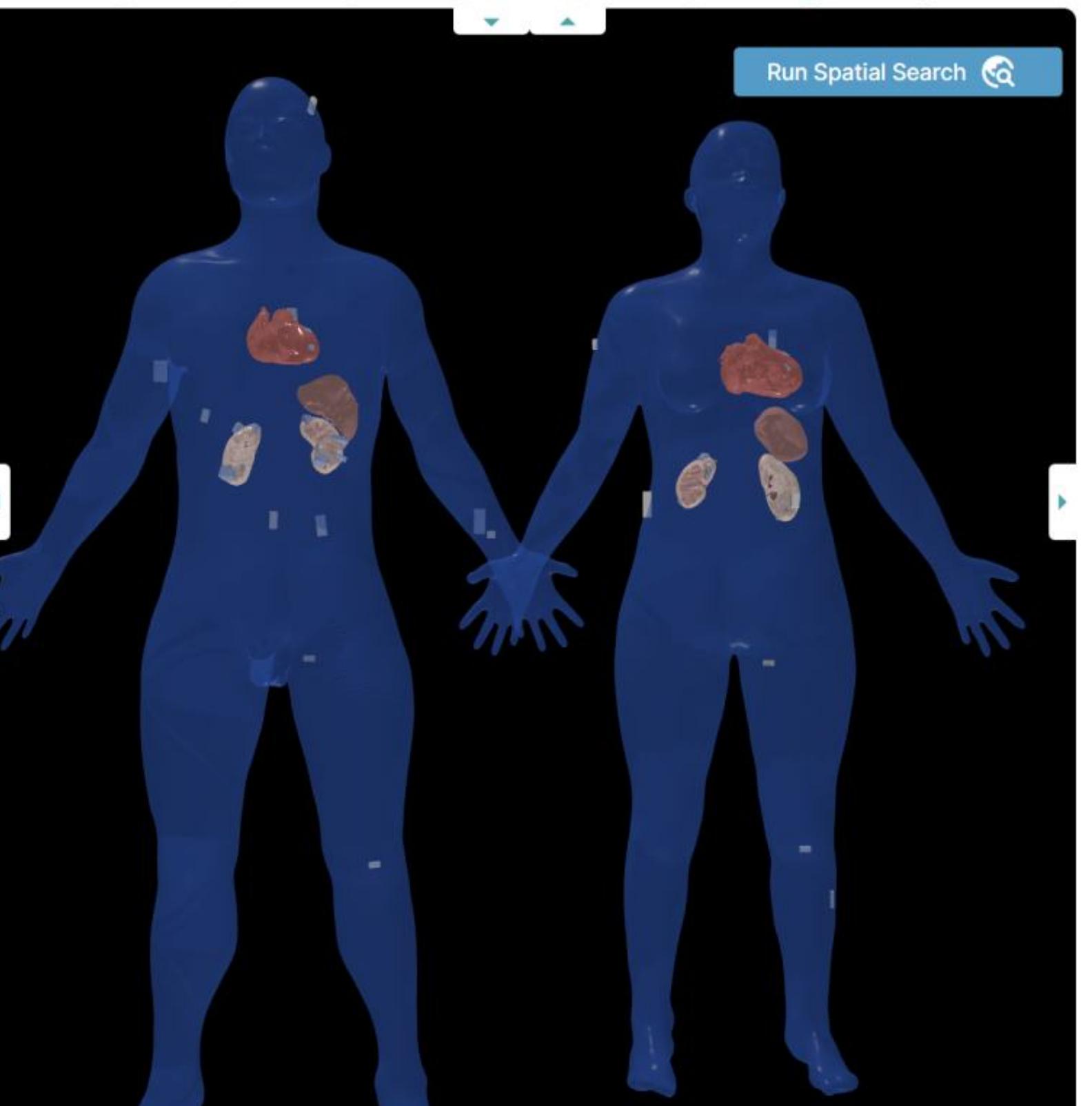
169 Donors

475 Tissue Blocks

856 Tissue Sections

2394 Tissue Datasets

- Females (n=94), Mean Age 53.5 (range 21-70)
Entered 1/26/2022, Kristin Ardlie, GTEx Project
- Males (n=146) Mean Age 54.3 (range 20 - 70)
Entered 1/26/2023, Kristin Ardlie, GTEx Project
- Females (n=297), Mean Age ? (range 20-79)
Entered 9/17/2021, Kristin Ardlie, GTEx Project
- Females (n=133) Mean Age 51.7 (range 21 - 7...
Entered 5/18/2021, Kristin Ardlie, GTEx Project
- Males (n=240) Mean Age 52.3 (range 20 - 70)
Entered 5/18/2021, Kristin Ardlie, GTEx Project
- Males (n=259) Mean Age 50.3 (range 21 - 70)
Entered 5/18/2021, Kristin Ardlie, GTEx Project
- Females (n=136) Mean Age 55 (range 21 - 70)
Entered 5/18/2021, Kristin Ardlie, GTEx Project
- Males (n=293) Mean Age 56.4 (range 20 - 70)
Entered 5/18/2021, Kristin Ardlie, GTEx Project
- Females (n=138) Mean Age 53.2 (range 21 - ...
Entered 5/18/2021, Kristin Ardlie, GTEx Project
- Males (n=294) Mean Age 54.9 (range 20 - 70)
Entered 5/18/2021, Kristin Ardlie, GTEx Project
- Females (n=19) Mean Age 56.4 (range 30 - 69)
Entered 9/17/2021, Kristin Ardlie, GTEx Project



The interface displays two 3D human silhouettes side-by-side, each with several translucent, colored tissue blocks (red, orange, yellow, green, blue) placed on specific anatomical locations. These blocks represent the spatial distribution of the selected tissue types across the human body. The left silhouette corresponds to the 'Anatomical Structures (AS)' section, and the right one to the 'Cell Types (CT)' section.

Select Registration UI for new HRA 3D Coordinate 

X Close 

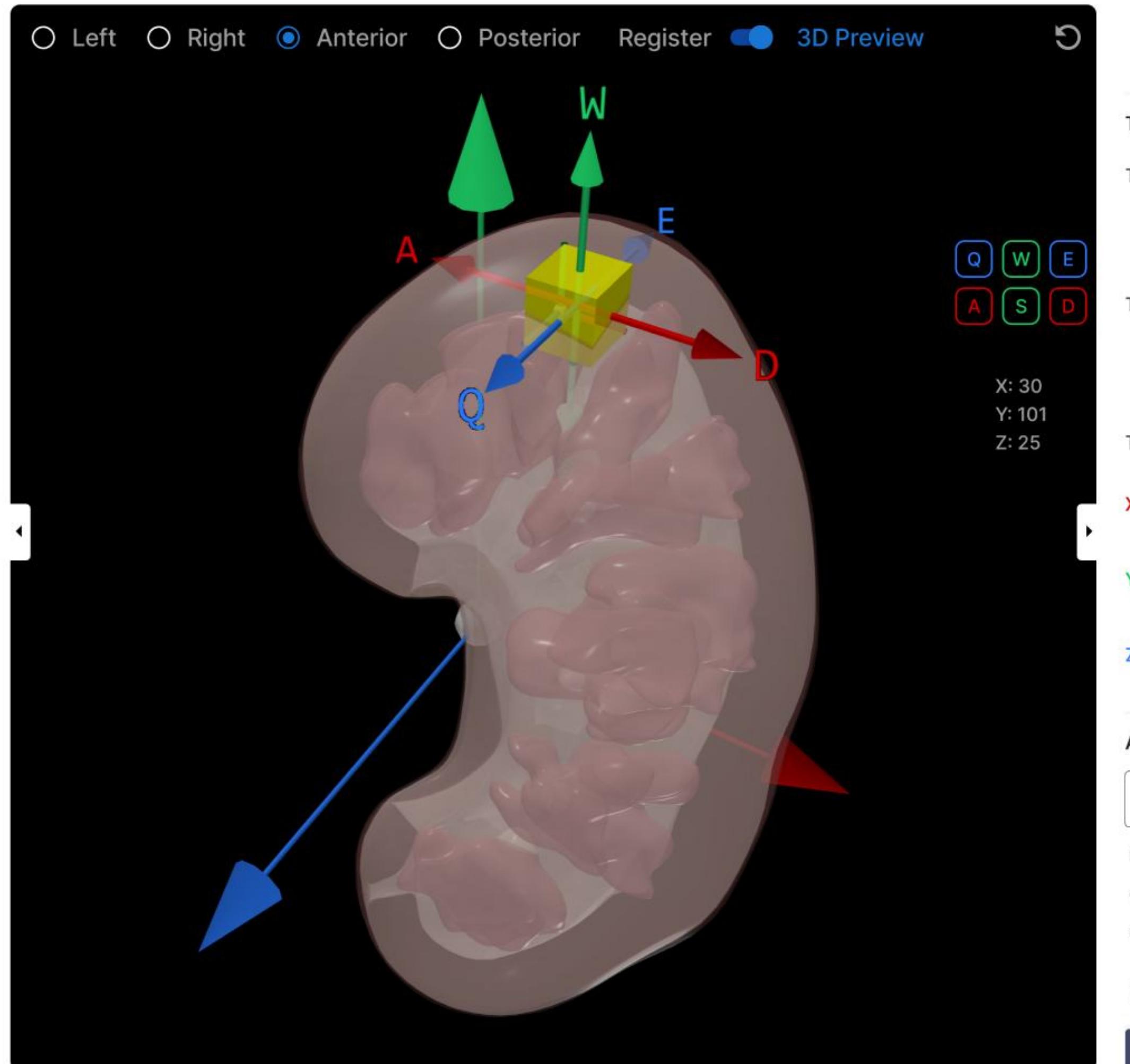
Anatomical Structures

Left Right Anterior Posterior Register  3D Preview 

 all anatomical structures
 kidney capsule
 hilum of kidney
 cortex of kidney
 renal column
 outer cortex of kidney
 renal medulla
 renal papilla
 renal pyramid

Landmarks

 all landmarks
 bisection line
 left renal artery
 left renal pelvis
 left renal vein
 left ureter
 major calyxes
 minor calyxes



The central image shows a 3D rendering of a kidney. A yellow rectangular tissue block is placed on the renal papilla (labeled 'Q'). Four points are marked: 'A' on the renal capsule, 'W' on the renal papilla, 'E' on the renal cortex, and 'D' on the renal medulla. A blue arrow points from point 'Q' towards the bottom left. The interface includes a legend for anatomical structures and landmarks, and various controls for tissue block dimensions, rotation, and registration.

Tissue Block Controls

Tissue Block Dimensions (mm)

Width (X)	Height (Y)	Depth (Z)
10	10	10

Tissue Sections

Thickness # Sections

Tissue Block Rotation

X: 0 Y: 0 Z: 0

Anatomical Structure Tags

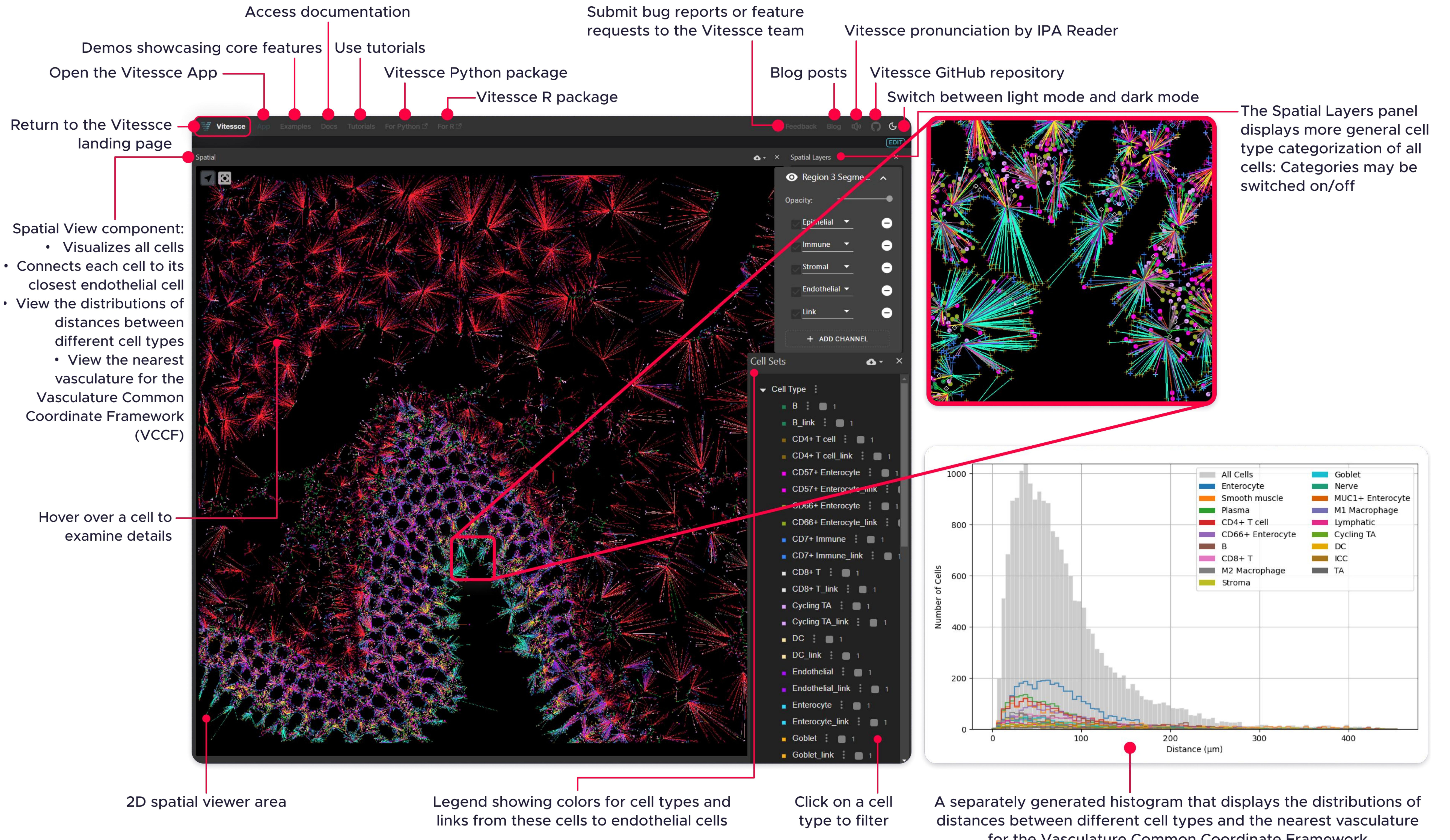
Add Anatomical Structures ... 

kidney capsule  cortex of kidney 
outer cortex of kidney  renal medulla 
renal pyramid 

 Assigned  Added

Review and Register

Supplemental Figure 8: Customized, Branded Deployment of EUI in HuBMAP, SenNet, GTEx, and RUI in GUDMAP



Supplemental Figure 9: Vasculature Common Coordinate Framework Distance Visualizations

Functional Tissue Units available for exploration

Name of the selected Functional Tissue Unit

2D Illustration viewer

Cell types by biomarkers table

Tabs to view tables for gene, protein, and lipids

Expand the table view

Cell types, cell counts, and associated biomarker columns

Hover for details on ontology IDs and expression values: Higher opacity means higher mean biomarker expression levels

Legend for cell types and biomarkers table: Hover over the information icons to reveal additional legend details

Collapse and expand Functional Tissue Unit listings within organs

Get the FTU Explorer web component via the HRA-UI GitHub Repository

View the selected illustration digital object metadata page

Show/hide specific source datasets in the cell types by biomarkers tables

Download the selected illustration in various formats

Sort source data by authors, year, paper title, and paper DOI

Publication title in which experimental data was published

Publication Digital Object Identifier URL linking directly to the experimental data

FTU Library

Human Reference Atlas

Functional Tissue Unit Explorer

FTU Explorer

renal corpuscle

Kidney

- loop of Henle ascending limb thin segment
- Cortical Collecting Duct
- descending limb of loop of Henle
- inner medullary collecting duct
- nephron
- outer medullary collecting duct
- renal corpuscle**
- thick ascending limb of loop of Henle

Large Intestine

- crypt of Lieberkühn of large intestine

Liver

- liver lobule

Lung

- bronchus submucosal gland
- alveolus of lung

Pancreas

- intercalated duct of pancreas
- islet of Langerhans
- pancreatic acinus

Prostate Gland

Embed Illustration

Download Illustration

Illustration Metadata

Glomerular visceral epithelial cell

Parietal epithelial cell

Epithelial cell proximal tubule

Macula densa epithelia cell

Afferent arteriole endothelial cell

Efferent arteriole endothelial cell

Glomerular capillary endothelial cell

Glomerular mesangial cell

50 µm

Cell Types by Gene Biomarkers

Cell Type	Cell Count	A2M [ENSG000...	AASS [ENSG00...	AKAP9 [ENSG0...	AKT3 [ENSG00...	AKT3 [ENSG00...	ALDHIA2 [ENS...	ALS2CL [ENSG...	ANKRD36 [LENS...	ANKRD36 [LENS...	ANKRD36C [EN...
glomerular capillary endothelial ...	344	●	●	●	●	●	●	●	●	●	●
glomerular mesangial cell	99	●	●	●	●	●	●	●	●	●	●
glomerular visceral epithelial cell	341	●	●	●	●	●	●	●	●	●	●
parietal epithelial cell	266	●	●	●	●	●	●	●	●	●	●

Cell Types by Protein Biomarkers

Cell Types by Lipid Biomarkers

Functional Tissue Unit Name: renal corpuscle

Uberon ID: <https://purl.humanatlas.io/2d-ftu/kidney-renal-corpuscle>

#Datasets: 1

Cell Type Name: parietal epithelial cell

CL ID: http://purl.obolibrary.org/obo/CL_1000452

Number of Cells: 266

Gene Name: ANKRD36 [ENSG00000291582]

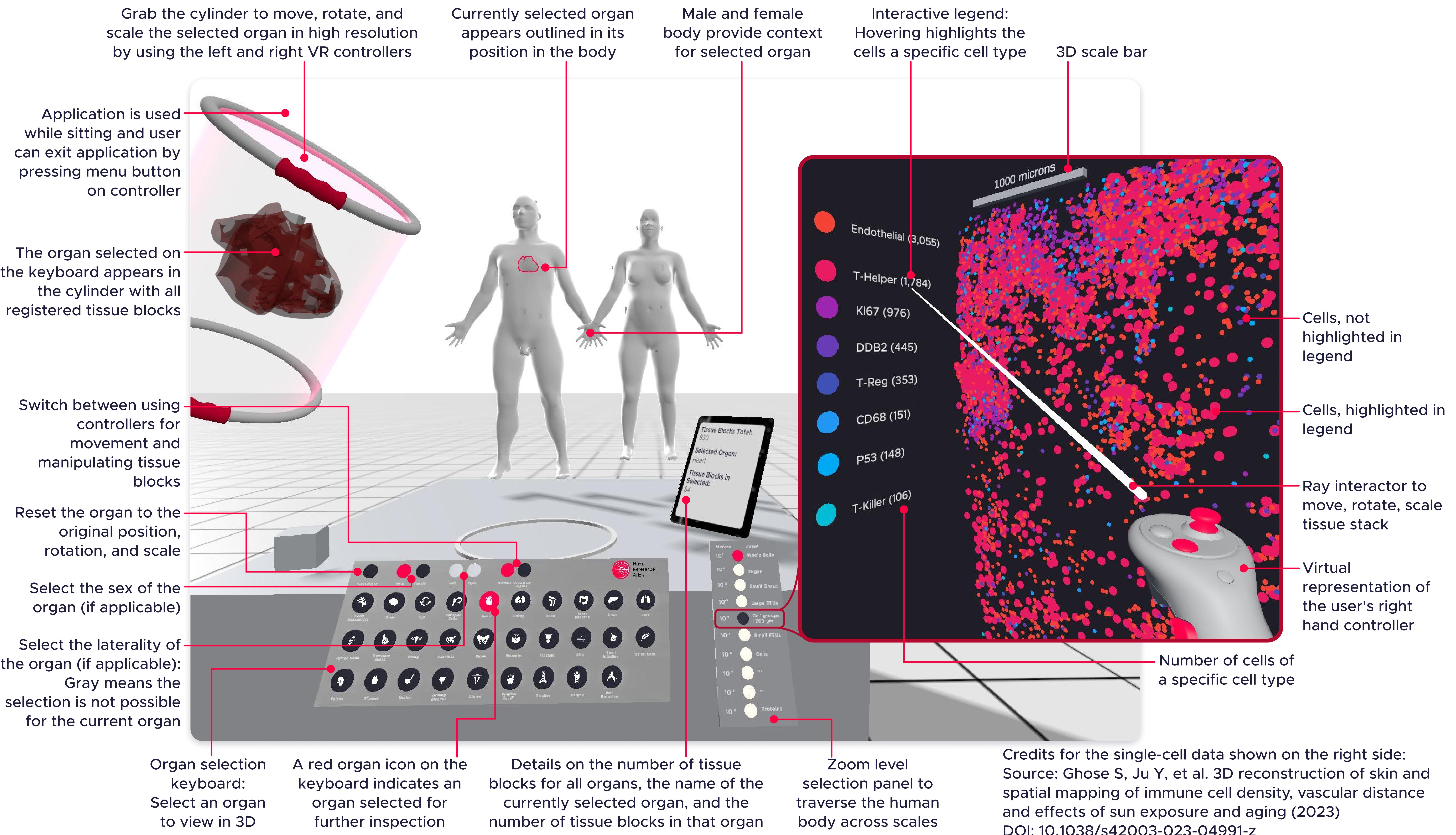
HGNC ID: HGNC:1982

Mean Expression Value: 0.294899

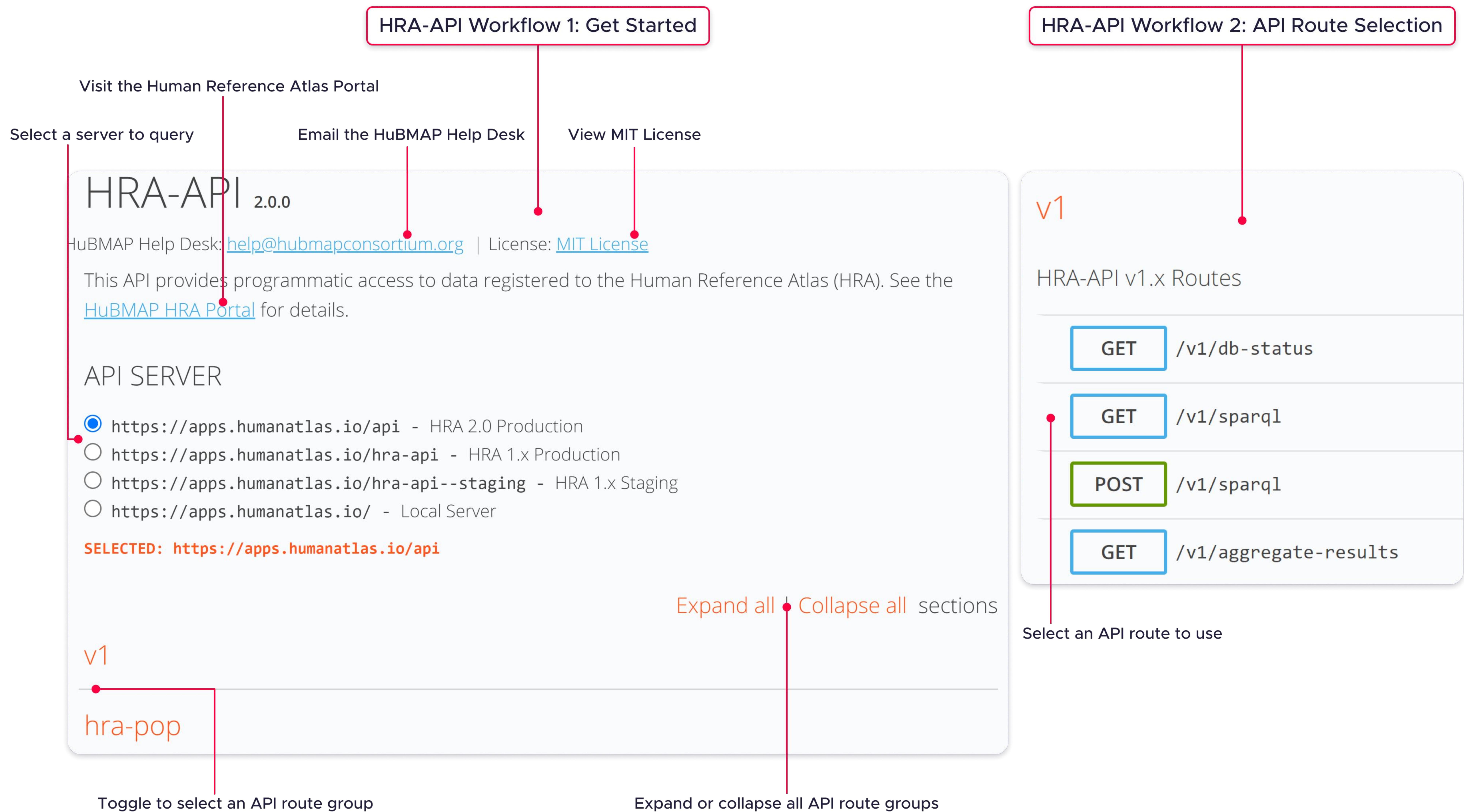
Source Data

<input checked="" type="checkbox"/> Authors	Year	Paper Title	Paper DOI
Yoshiharu Muto, Parker C. ...	2021	Single cell transcriptional ...	https://doi.org/10.103...

Supplemental Figure 10: Interactive FTU Explorer



Supplemental Figure 11: HRA Organ Gallery



Supplemental Figure 12: Human Reference Atlas Application Programming Interface: Get Started and API Route Selection

Input parameters for running an API query:

Fill in parameter values for the route

HRA-API Workflow 3: Run an API Query

v1

HRA-API v1.x Routes

GET /v1/db-status Get current status of database

GET /v1/sparql Run a SPARQL query

Run a SPARQL query

REQUEST

QUERY-STRING PARAMETERS

- * query string: SPARQL query to use
Examples: `SELECT * WHERE { ?sub ?pred ?obj . } LIMIT 10`
- token string: Authentication token to use for authenticated searches
- format enum: Allowed: application/json | application/ld+json | application/n-quads | application/n-triples | application/sparql-results+json | application/sparql-results+xml | application/trig | simple | stats | table | text/csv | text/n3 | text/tab-separated-values | text/turtle | tree
Override SPARQL response format (Note that not all formats are supported for all SPARQL query types)

API Server <https://apps.humanatlas.io/api>
Authentication Not Required

RESPONSE

200 404

Successful operation. SPARQL responses vary by format/content negotiation.

EXAMPLE SCHEMA

[
]
]

application/json

Copy

FILL EXAMPLE

CLEAR

TRY

Select a response code to view example response and schema doc

Example response tab

Schema documentation tab for the response

Run the API query

Reset parameters

Fill parameters with example options

Supplemental Figure 13: Human Reference Atlas Application Programming Interface: Run an API Query

HRA-API Workflow 4: View Query Response

GET /v1/sparql
Run a SPARQL query

Run a SPARQL query

REQUEST

QUERY-STRING PARAMETERS

* query string	SELECT * WHERE { ?sub ?pred ?obj . } LIMIT 10
SPARQL query to use Examples: SELECT * WHERE { ?sub ?pred ?obj . } LIMIT 10	
token string	
Authentication token to use for authenticated searches	
format enum	text/csv
Allowed: application/json application/ld+json application/n-quads application/n-triples application/sparql-results+json application/sparql-results+xml application/trig simple stats table text/csv text/n3 text/tab-separated-values text/turtle tree	
Override SPARQL response format (Note that not all formats are supported for all SPARQL query types)	

API Server <https://apps.humanatlas.io/api>
 Authentication Not Required

FILL EXAMPLE
CLEAR
TRY

View CURL command to reproduce query

View response headers

View real response from a query

Response Status: 200
 Took 173 milliseconds

RESPONSE

RESPONSE HEADERS

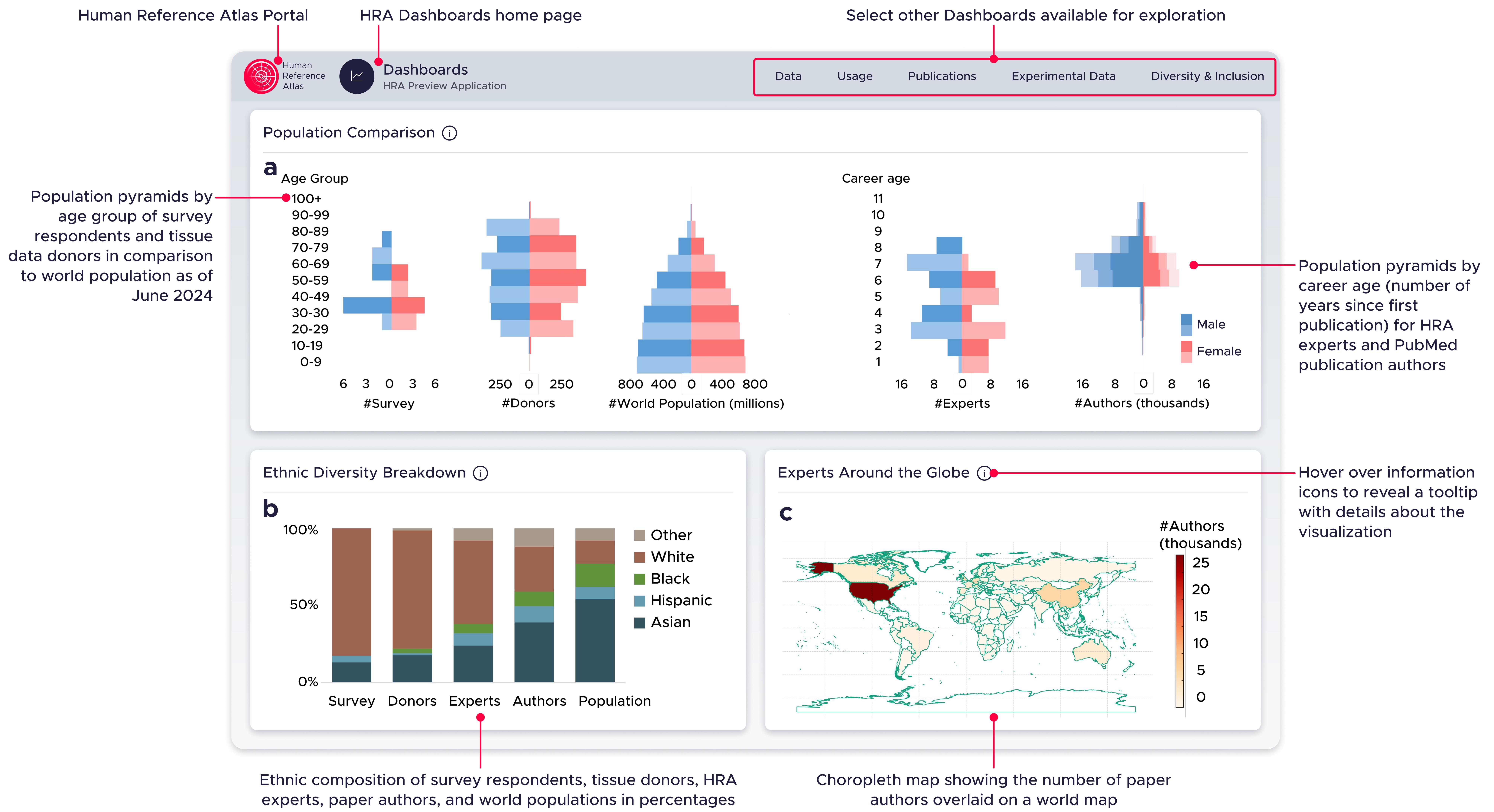
CURL

```
sub,pred,obj
http://ncicb.nci.nih.gov/xml/owl/EVS/Thesaurus.owl#C111241,http://www.w3.org/1999/02/22-rdf-syntax-ns#type,http://www.w3.org/2002/07/owl#NamedIndi
http://ncicb.nci.nih.gov/xml/owl/EVS/Thesaurus.owl#C111241,http://www.w3.org/1999/02/22-rdf-syntax-ns#type,http://www.w3.org/2004/02/skos/core#Cor
http://ncicb.nci.nih.gov/xml/owl/EVS/Thesaurus.owl#C111241,http://www.w3.org/2000/01/rdf-schema#label,Laser ablation
http://ncicb.nci.nih.gov/xml/owl/EVS/Thesaurus.owl#C111241,http://www.w3.org/2004/02/skos/core#broader,https://purl.humanatlas.io/vocab/hrav
http://ncicb.nci.nih.gov/xml/owl/EVS/Thesaurus.owl#C111241,http://www.w3.org/2004/02/skos/core#definition,"Removal, separation, detachment, extirp
http://ncicb.nci.nih.gov/xml/owl/EVS/Thesaurus.owl#C111241,http://www.w3.org/2004/02/skos/core#inScheme,https://purl.humanatlas.io/vocab/hrav
```

CLEAR RESPONSE • Reset the response

Copy • Copy the response

Supplemental Figure 14: Human Reference Atlas Application Programming Interface: View Query Response



Supplemental Figure 15. HRA Equity Dashboard

Course navigation menu

Collapse the course navigation menu

Account menu

Canvas Dashboard:

- View all courses
- View to do list

View recent feedback

View course grades

View upcoming assignments

List of courses

View calendars for all Canvas courses

Message inbox

Recent user history log menu

Use the Kaltura API to link Kaltura media to Canvas

Opens the external TimelyCare app for 24/7 virtual care

Help menu to use Canvas Guides, asking your instructor a question, submitting feature ideas and feedback

Minimizes global navigation menu

Title of the current course being viewed

HuBMAP-VHMOOC

No Expiration

Download course in alternative formats, such as ePub and electronic braille

HuBMAP Visible Human MOOC

Goals

The Visible Human Massive Open Online Course (VHMOOC) aims to:

- Communicate tissue data acquisition and analysis,
- Demonstrate single-cell analysis and CCF mapping techniques, and
- Introduce major features of the HuBMAP portal.

1st HuBMAP Portal Release (Oct. 2020)

HuBMAP Overview

- Project Goals, Setup, and Ambitions

Tissue Data Acquisition and Analysis

- Behind the Scenes at Vanderbilt University

Biomolecular Data Harmonization

- An Introduction to Seurat

Recent activity of messages from discussions, grading updates, private messages between you and other users, and more

VHMOOC course calendar

View Course Stream

View Course Calendar

View Course Notifications

To Do

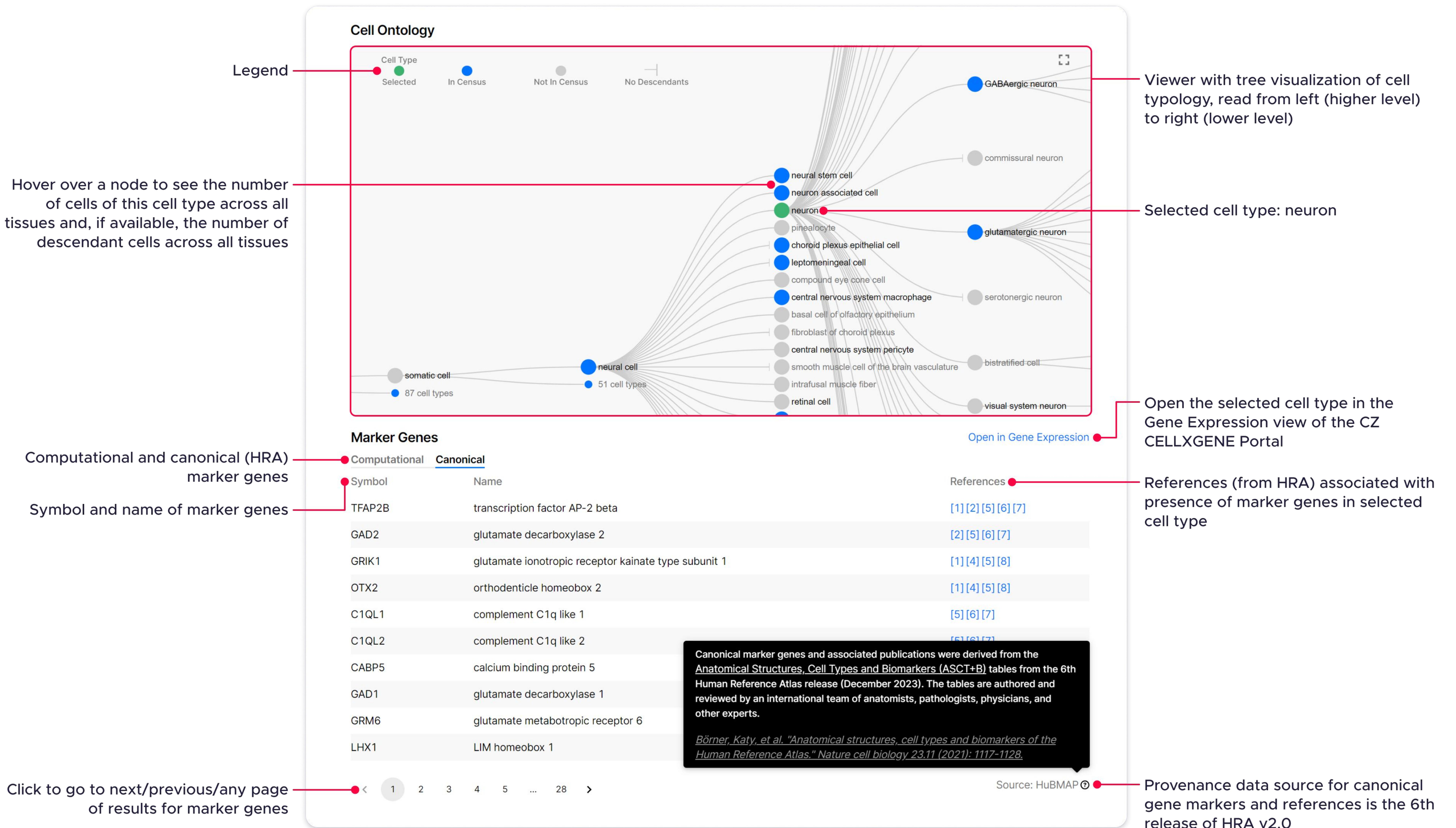
Nothing for now

Recent Feedback

Nothing for now

View and edit notification settings for this course

Supplemental Figure 16: Visible Human Massive Open Online Course (MOOC)



Supplemental Figure 17: CZ CellGuide Visualization With ‘Canonical’ Marker Genes And ‘References’ From The HRA