Image Guided Therapy (IGT) and robot registration

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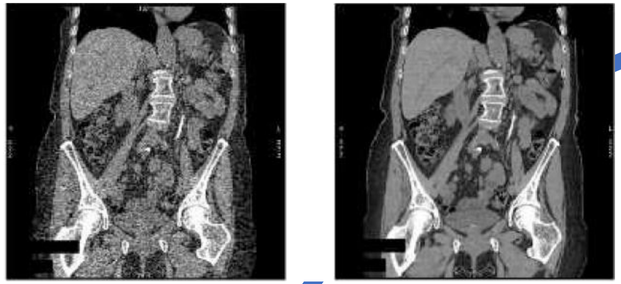
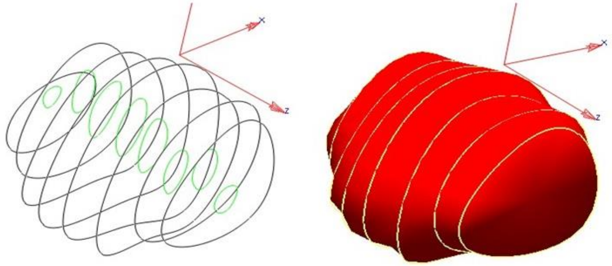
- **Image-guided surgery** (**IGS**) is any surgical procedure where the surgeon uses *tracked surgical instruments* in conjunction with *preoperative or intraoperative* images in order to directly or indirectly guide the procedure. Image guided surgery systems use cameras,ultrasonic, electromagnetic or a combination or fields to capture and relay the patient's anatomy and the surgeon's precise movements in relation to the patient, to computer monitors in the operating room. This is generally performed in real-time though there may be delays of seconds or minutes depending on the modality and application. (Wikipedia)

Research topics

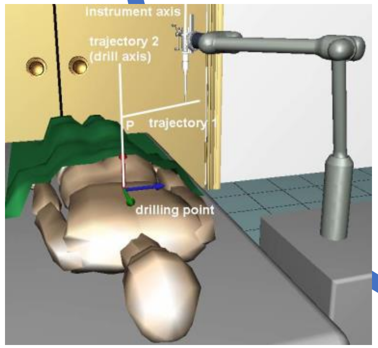


Imaging

Sensors



Modeling



Robotics

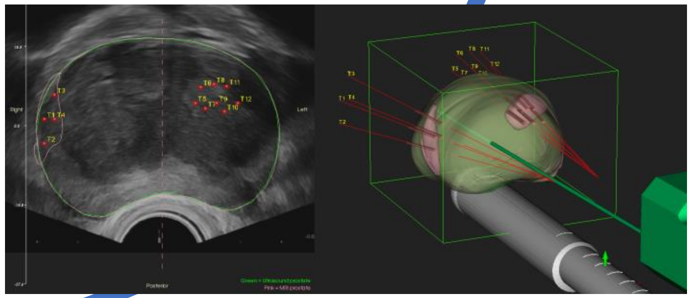
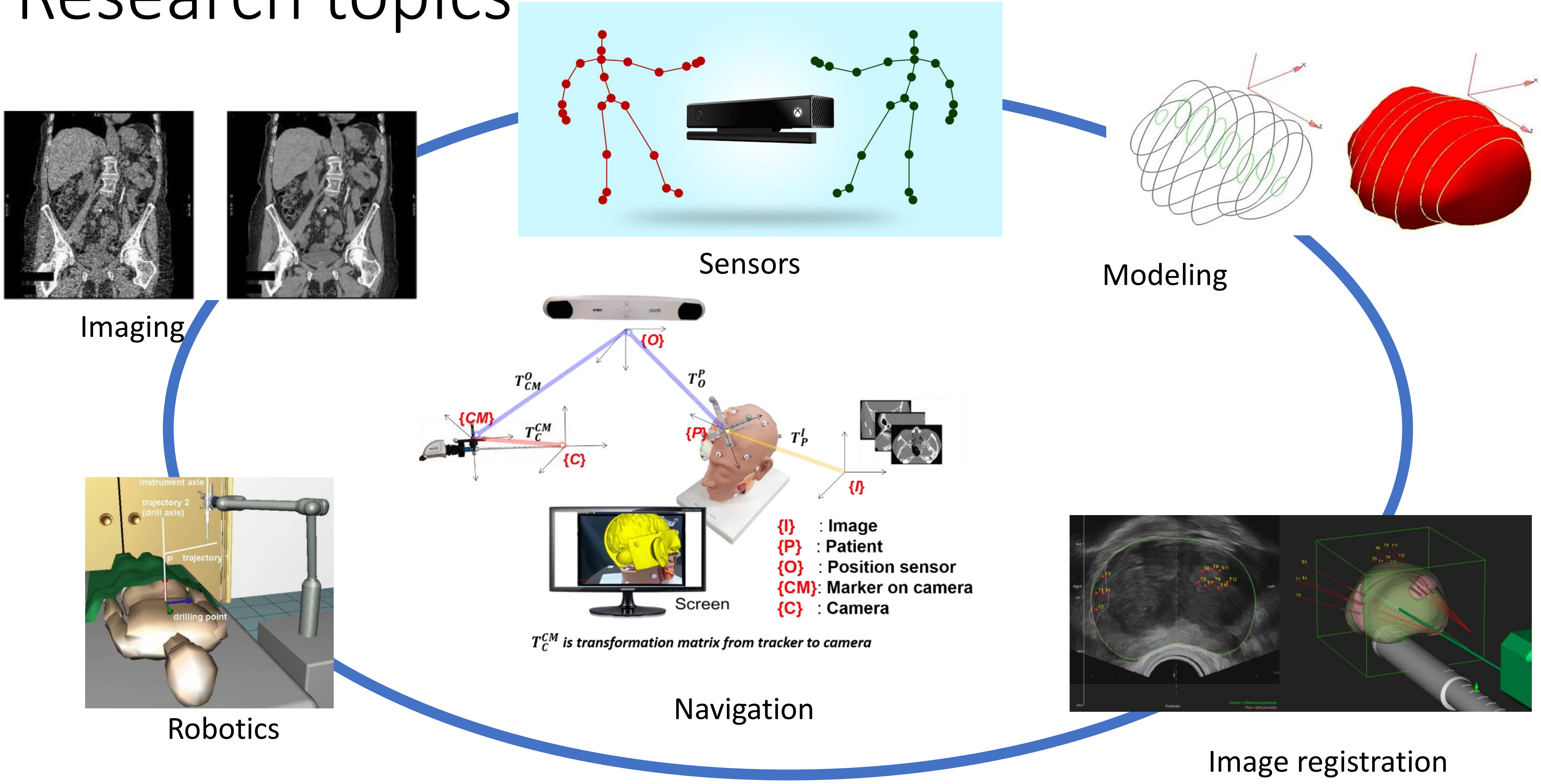


Image registration

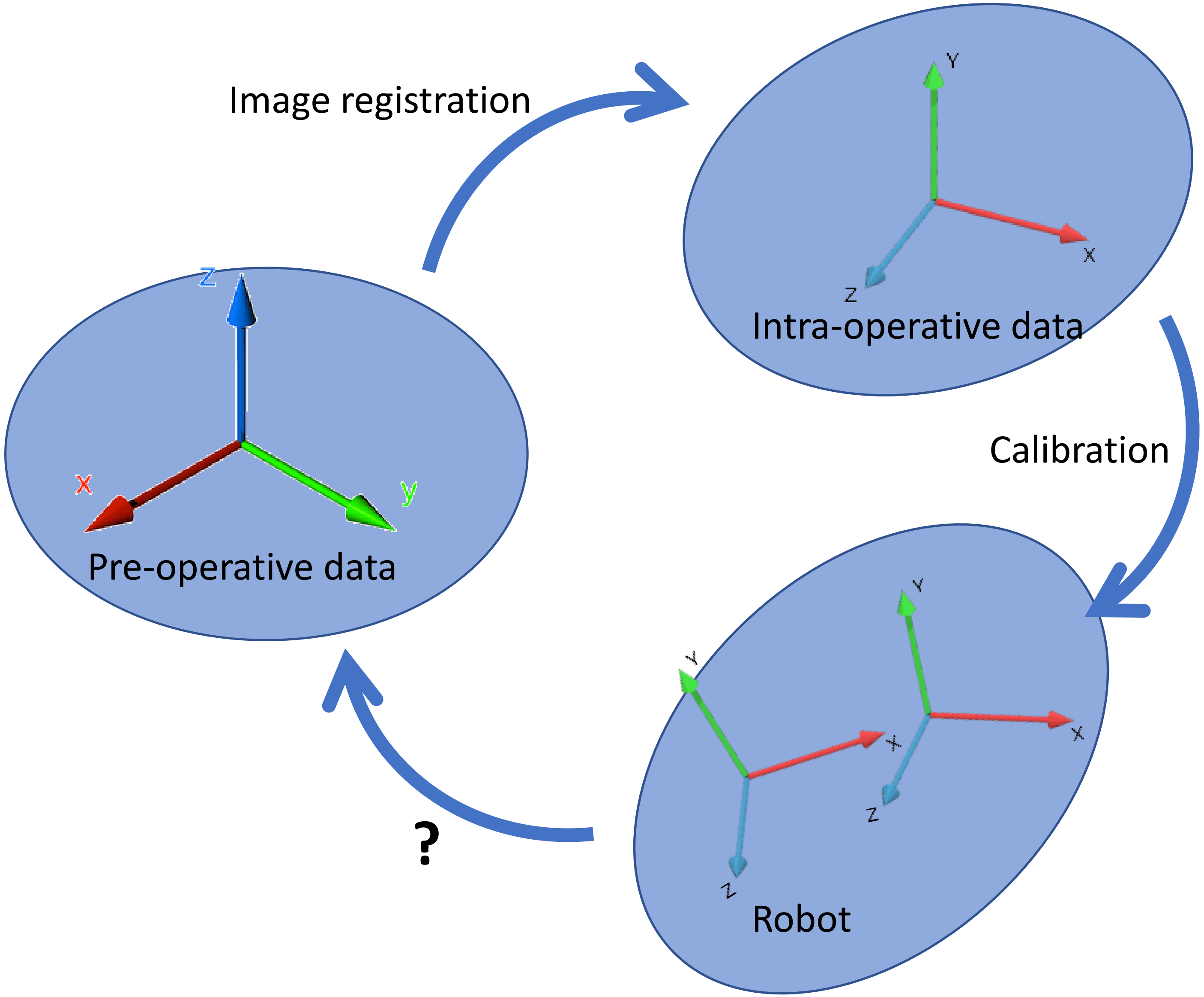
Research topics



What is robot registration?

- Registration consists in determining the geometric relationships between two reference frames

- Robot registration consists in transferring the planning to the robot coordinate system



Tools

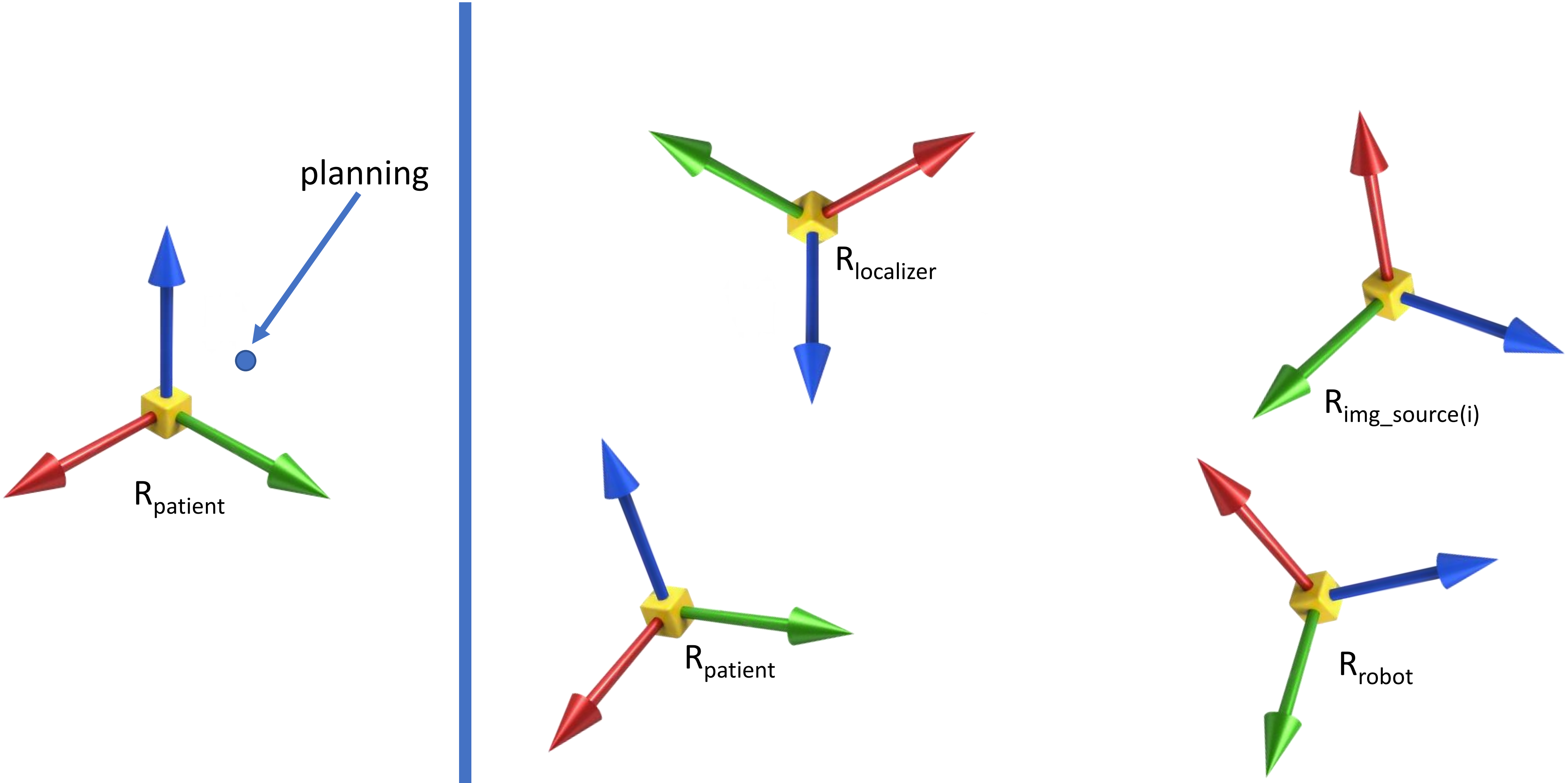
- Calibration
- Tracking
- Data registration

Using:

- Patient’s data
- External objects

We assume that the robot is intrinsically calibrated

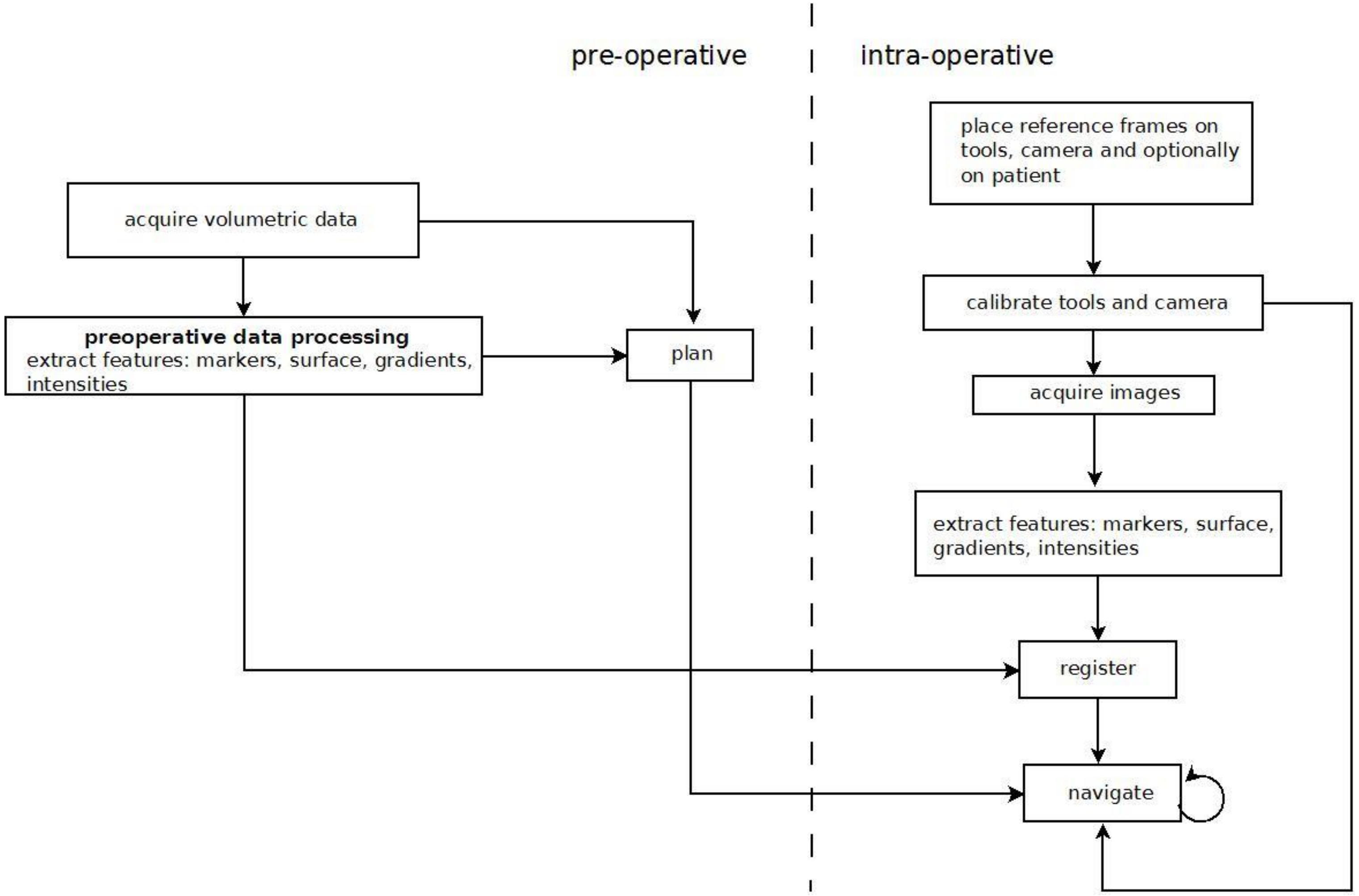
Reference frames of interest



Pre-operatively

Intra-operatively

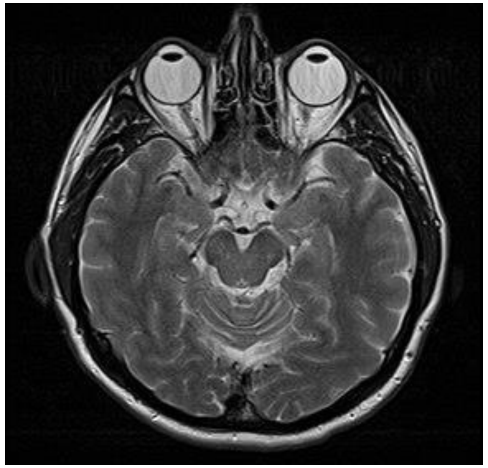
Image guided systems



Hardware

- Localizers:
  - Optical, magnetic, mechanical arm,

- Imaging sensors:
  - X-Ray, ultrasound (US), Magnetic resonance (MRI)



Medical imaging

- **CT images**: 3D image of the inside of an object from a large series of 2D X-ray images taken around a single axis of rotation
- **MRI images** uses a magnetic field causing the nuclei at different locations to rotate at different speed. 3D spatial information can be obtained by providing gradients in each direction.
- **US images**: the reflected ultrasound wave is used to measure the discontinuity in the tissue density. Applications: soft tissues, blood flow (Doppler), 3D US
- Other types of images: **2D X-Ray, fMRI, PET, SPECT**
- The data standard is *DICOM* (Digital Imaging and Communications in Medicine) and the files are organized as *data sets* (e.g. chest data set).

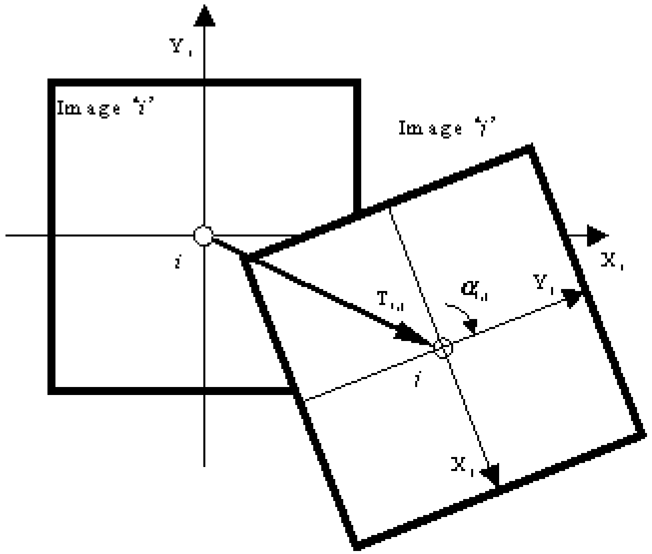
Registration basics

- Two reference frames R_A and R_B and a transform ${}^{B}T_A$ to be determined
- Selection of features F_A in R_A and F_B in R_B
- Definition of a similarity measure (or distance) between F_A and F_B
- Determination of ${}^{B}T_A$ such that the similarity is maximum (or distance minimum)

$$ {}^{B}T_A = \arg\min d(F_A, {}^{B}T_A(F_B)) $$

Registration output (transformation)

- Rigid registration:
    - Preserve distances
    - Preserve the straightness of lines and the angles
    - In 3D may be specified by 6 parameters



Registration output (transformation)

- Rigid registration:
  - In 3D (homogeneous coordinates)

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = [\boldsymbol{R}] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} + \boldsymbol{t} = \begin{bmatrix} \boldsymbol{R} & t \\ \mathbf{0}^T & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = [\boldsymbol{T}] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

Registration output (transformation)

- Rigid registration
    - Rotation rapresentations:
        - Rotation matrix: 9 parameters
        - Euler angles: 3 parameters
        - Axis-angle: 4 parameters
        - Unit Quaternions: 4 parameters

Registration output (transformation)

- Non-rigid registration:
  - Affine transformation (linear transformation):
    - Preserve parallel lines
    - Preserve straightness of lines
    - Does not preserve distances
    - Does not preserve angles

Registration output (transformation)

- Non-rigid registration:
  - Affine transformation representation in 2D (6DOF):

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & x_{off} \\ d & e & y_{off} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

Registration output (transformation)

- Non-rigid registration:
  - Affine transformation representation in 3D (12 DOF):

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} a_{xx} & a_{xy} & a_{xz} & a_{xt} \\ a_{yx} & a_{yy} & a_{yz} & a_{yt} \\ a_{zx} & a_{zy} & a_{zz} & a_{zt} \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}$$

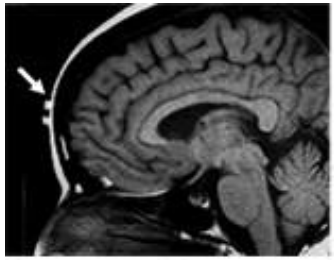
Registration output (transformation)

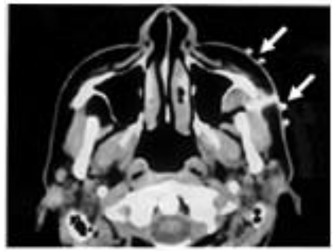
- Non-rigid registration:
  - Non linear transformation (does not preserve the lines):
    - Quadratic transformations (second order polynomials) (30DOF in 3D):

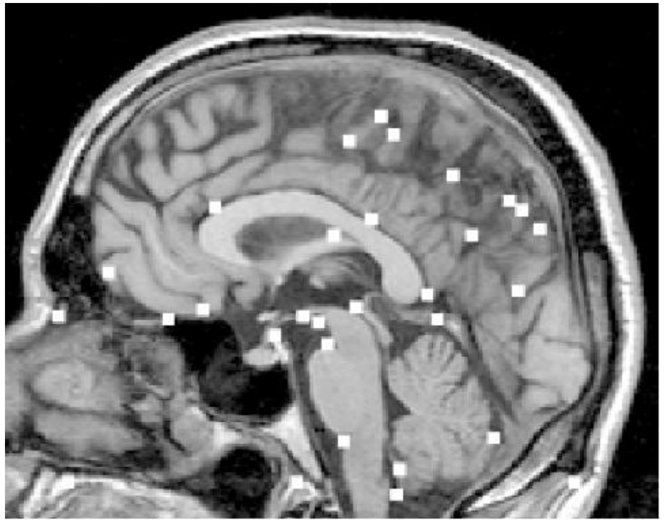
$$\mathbf{T}(x,y,z) = \begin{pmatrix} a_{00} & \dots & a_{08} & a_{09} \\ a_{10} & \dots & a_{18} & a_{19} \\ a_{20} & \dots & a_{28} & a_{29} \\ 0 & \dots & 0 & 1 \end{pmatrix} \begin{pmatrix} x^2 \\ y^2 \\ \dots \\ 1 \end{pmatrix}$$

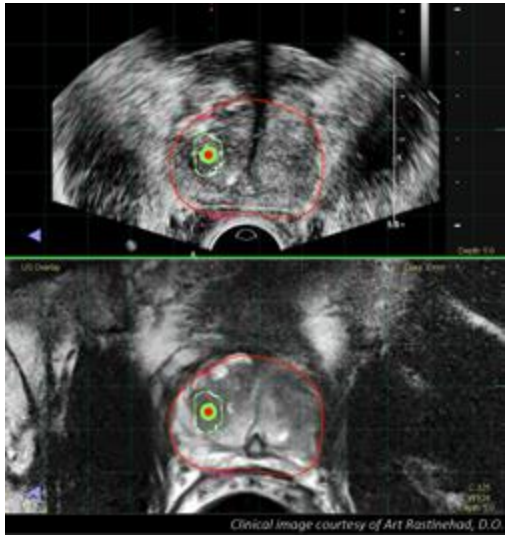
Typical 3D/3D rigid registration methods

- Point to point (Procrustes)
  - External fiducials
  - Anatomical landmarks
- Surface registration
  - Anatomical surface (e.g. Iterative Closest Point ICP)
  - Principal axis registration
- Intensity-based registration (for images only)



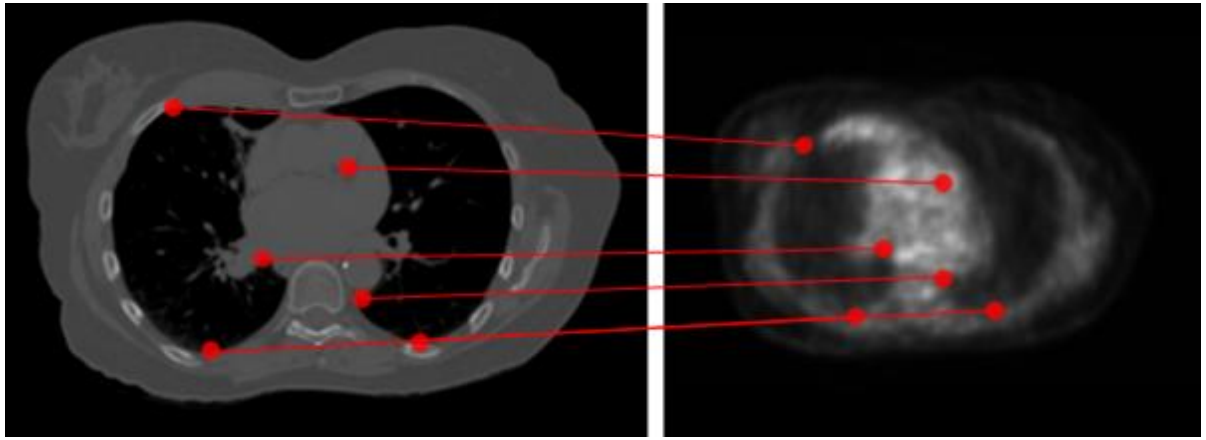






Point to point registration

- The points usually correspond to a set of features in the two (or more) objects (fiducial markers, anatomical markers).
- The measure to be optimized is the distance between the features.



Point to point registration

- Given two sets of n points A and B, the Procustes problem is to find a matrix R, a vector t, and scalar *s* such that:

$$X_i = s(RY_i + t) \text{ for i =1, …, n} \qquad (1)$$

We consider the 3D case, therefore R is a 3x3 rotation matrix and t is a 3x1 translation vector.

- The registration objective is to solve:

$$\min_{R,t,s} \sum_{i=1}^{n} \| X_i - s(RY_i + t) \|^2 \qquad (2)$$

- Several methods to solve (2), we’ll see the method based on SVD

Point to point registration

- Compute t from (1):

$$t = \frac{1}{s}\left(\frac{1}{n}\sum_{i=1}^{n} X_i\right) - R\left(\frac{1}{n}\sum_{i=1}^{n} Y_i\right) \quad (3)$$

- Plug (3) into (1):

$$\overline{X_i} = sR\overline{Y_i} \quad (4)$$

where $\overline{X_i} = X_i - \frac{1}{n}\sum_{i=1}^{n} X_i$ and $\overline{Y_i} = Y_i - \frac{1}{n}\sum_{i=1}^{n} Y_i$

- Compute the norm of both sides in (4):

$$\|\overline{X_i}\| = s\|\overline{Y_i}\|$$

Point to point registration

- It remains only R to be computed
- Let's define:

$\bar{X}$=($\overline{X_1}$ … $\overline{X_n}$) and $\bar{Y}$=($s\overline{Y_1}$ … $s\overline{Y_n}$) two 3xn matrices

- Then:

$\boldsymbol{\varepsilon} = \sum_{i=1}^{n} \|\overline{X_i} - sR\overline{Y_i})\|^2 = \|\bar{X} - R\bar{Y})\|^2$ (5)

where the second norm is the Frobenius norm.

- It can be proven that the solution of (5) is:
- $R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \det(VU^T) \end{pmatrix} U^T$

where $UDV^T = \bar{Y}\overleftarrow{\bar{X}}^T$ is the SVD of the matrix $\bar{Y}\overleftarrow{\bar{X}}^T$

Point to point registration: drawbacks

- Most of the times the correspondences are not known
- The number of landmarks may not be the same
- The solution was proposed by Besl&McKay, 1992 : ICP algorithm

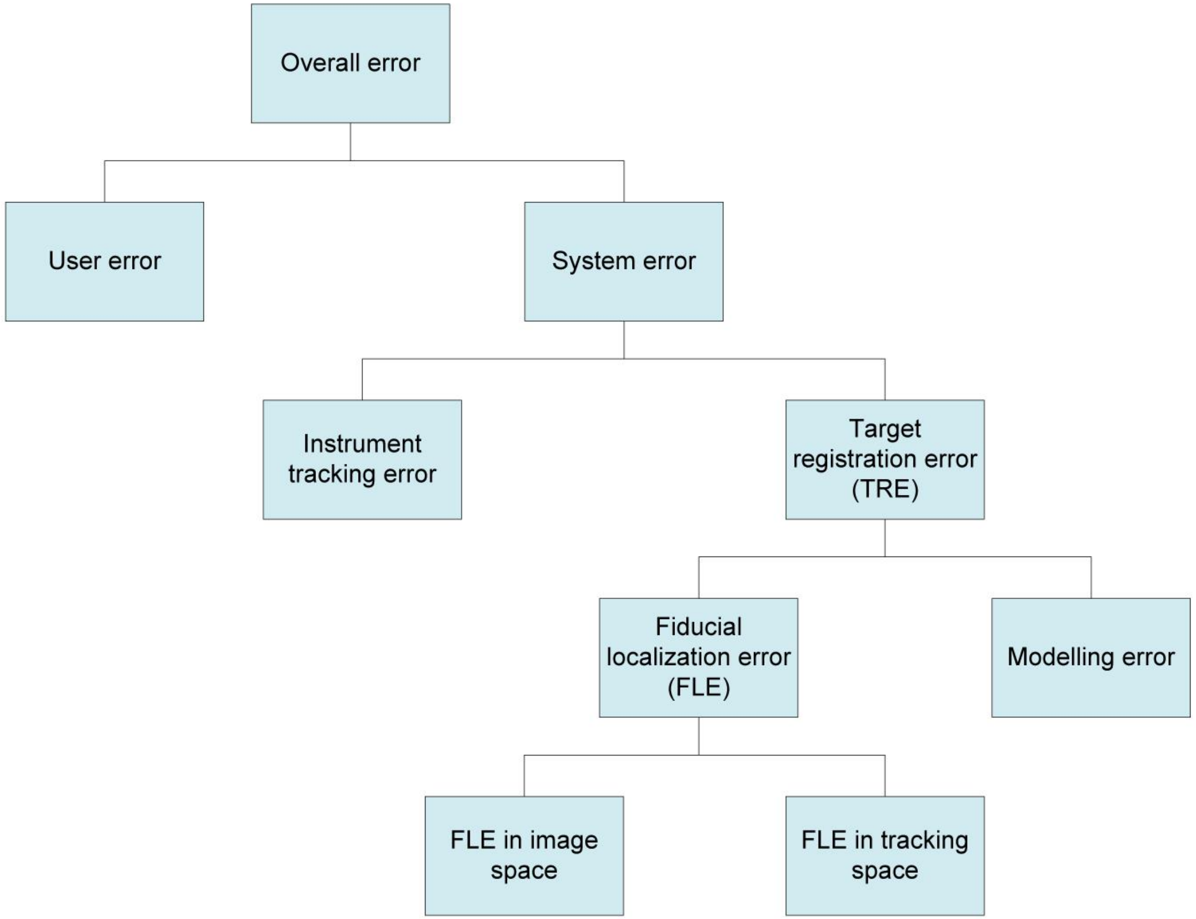
ICP algorithm

- Input: A, B two sets of 3D points
- Output: a rigid transform that aligns A and B

1. For every point in B compute the closest point in A
2. For all the correspondences found in 1. compute (R,t)
3. Apply (R,t) to B
4. Compute the quadratic error **ε** (equation (2)) between A and B
5. Check if **ε** is less than a threshold of if the maximum number of iterations were reached. If yes, output (R,t), otherwise go to 1.

Accuracy analisis

- Tracking errors +
- Calibration errors +
- FRE, FLE errors+
- Noise



Software for IGT: Matlab

- Implemented methods for registration: procrustes(X,Y), pcregistericp(X,Y).
- Interface with external hardware (e.g. tracker, US system).
- Reads and display DICOM files
- Easy to prototype
- No need to compile
- The execution may be slower

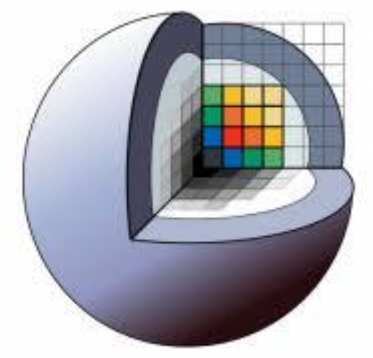
Software for IGT: Mevislab

- Medical Image Processing and Visualization
- “MeVisLab represents a powerful modular framework for image processing research and development with a special focus on medical imaging. It allows fast integration and testing of new algorithms and the development of clinical application prototypes.”

- Advanced methods for registration and segmentation
- Programmed through scripts and blocks
- Personalized GUI for every application
- Approved for clinical use
- Not so easy to interface with external hardware
- Not so well documented
- Expensive (but also free version)

Software for IGT: 3DSlicer

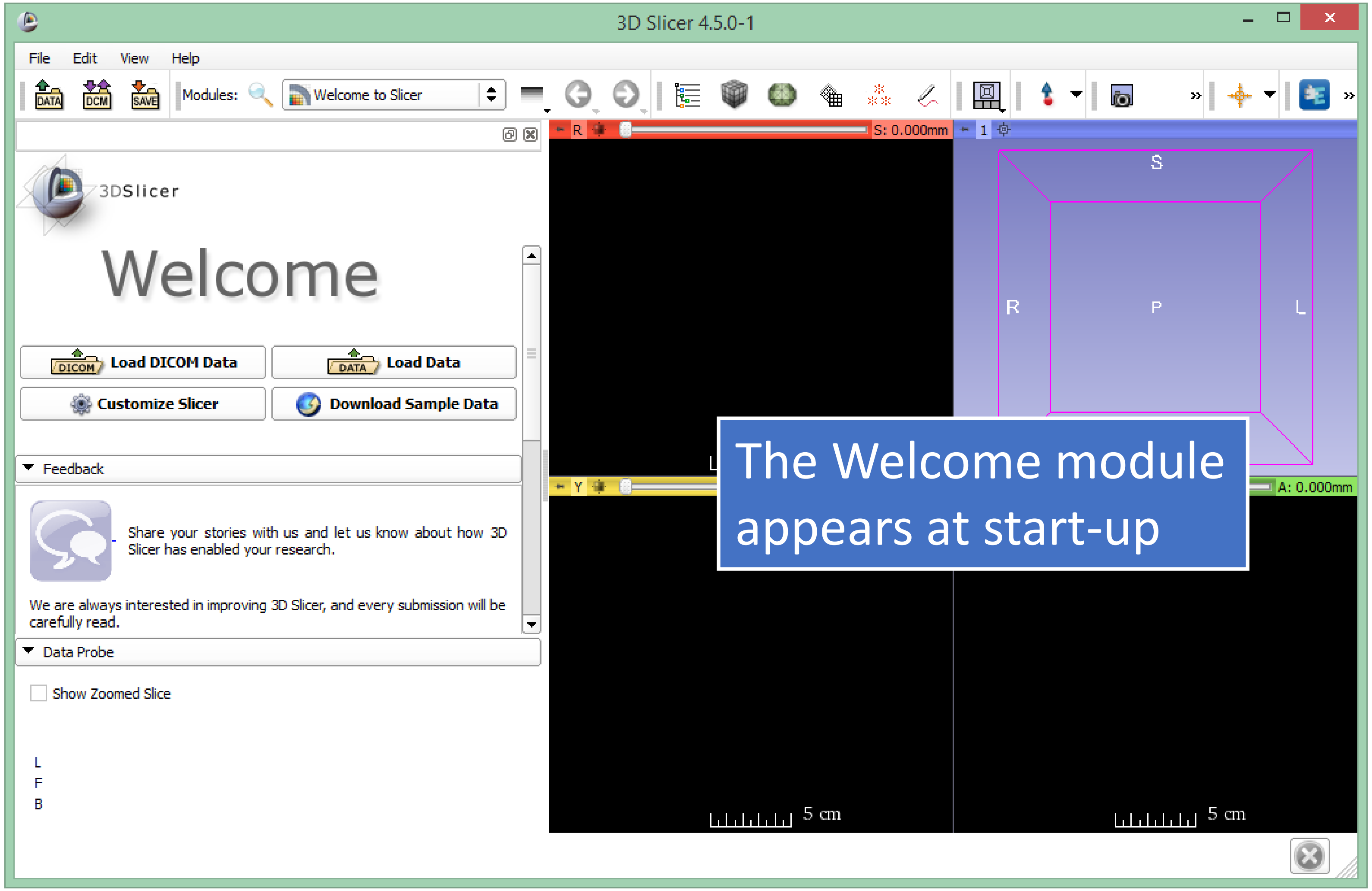
- 3D Slicer is:
- A software platform for the analysis (including registration and interactive segmentation) and visualization (including volume rendering) of medical images and for research in image guided therapy.
- A free, open source software available on multiple operating systems: Linux, MacOSX and Windows
- Extensible, with powerful plug-in capabilities for adding algorithms and applications.
- Features include:
- Multi organ: from head to toe.
- Support for multi-modality imaging including, MRI, CT, US, nuclear medicine, and microscopy.
- Bidirectional interface for devices.
- Well documented
- Slicer is not approved for clinical use and intended for research



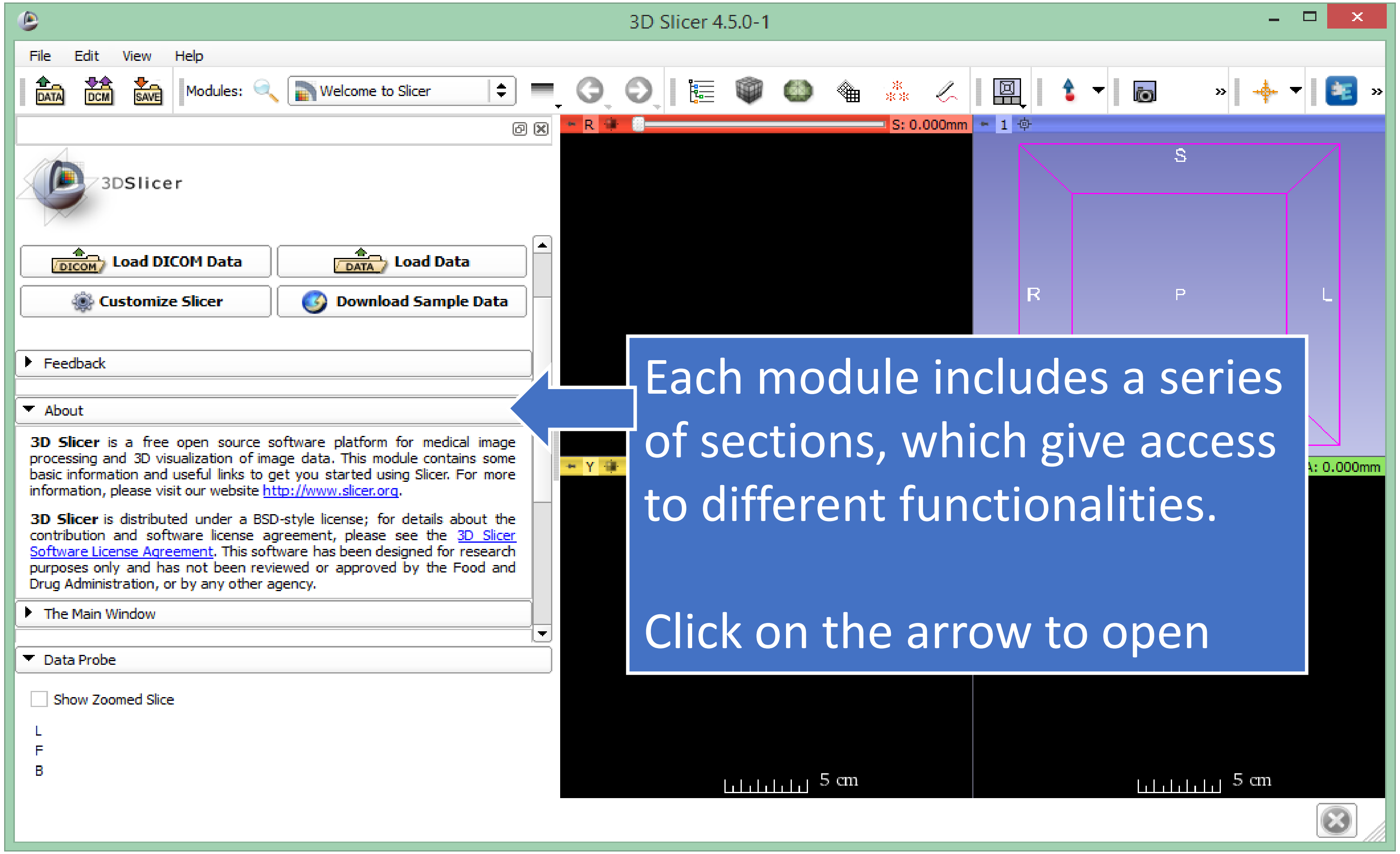
Platform and hardware

- Developed and maintained on Windows 64bit, Mac OSX, and Linux 64bit & 32bit
- Slicer requires
  - Minimum 2GB RAM
  - Graphics accelerator with 64MB of memory
  - 64 bit strongly suggested

3D Slicer version 4.5



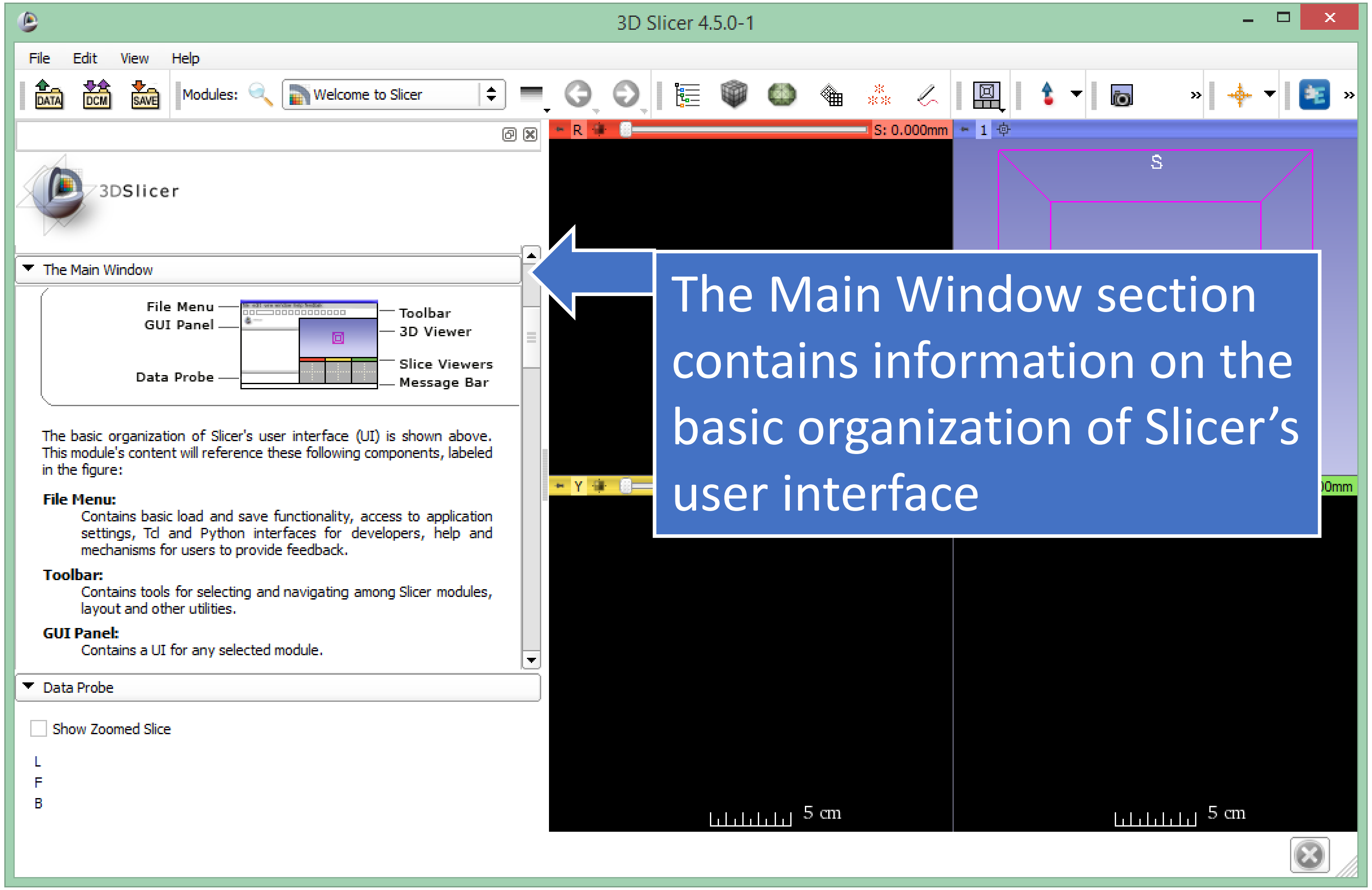
Welcome to Slicer



Each module includes a series of sections, which give access to different functionalities.

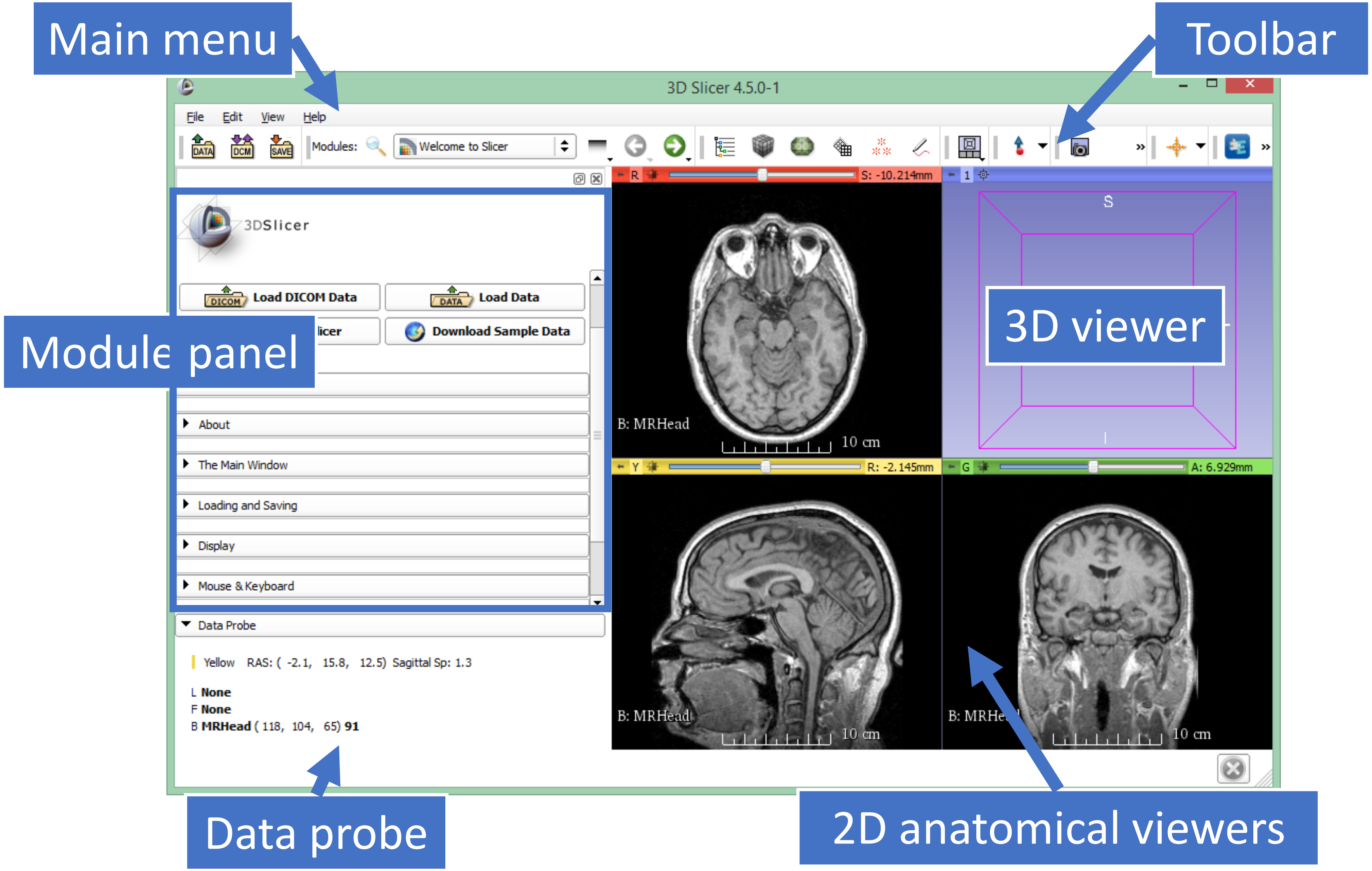
Click on the arrow to open

Welcome to Slicer

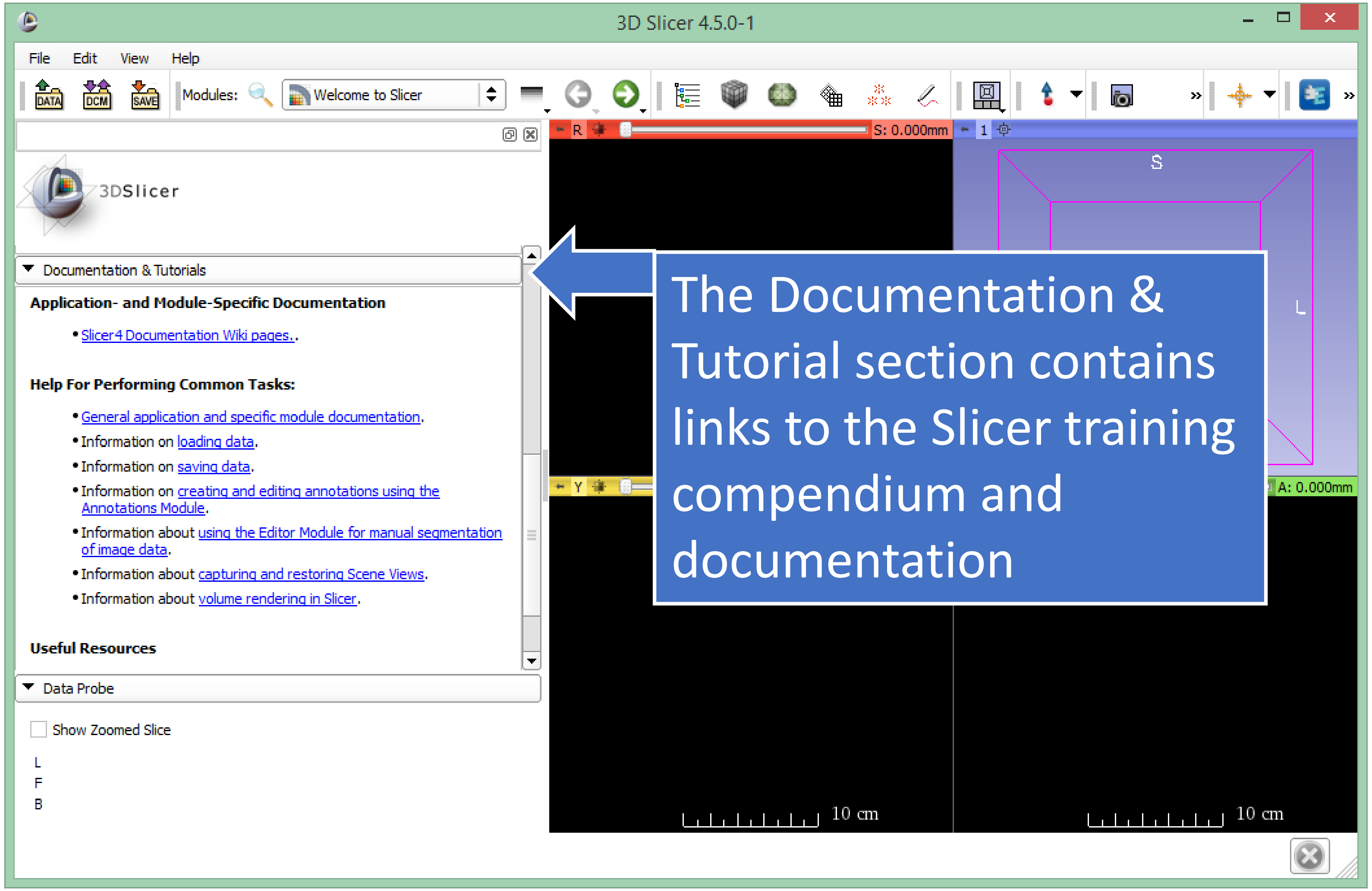


The Main Window section contains information on the basic organization of Slicer's user interface

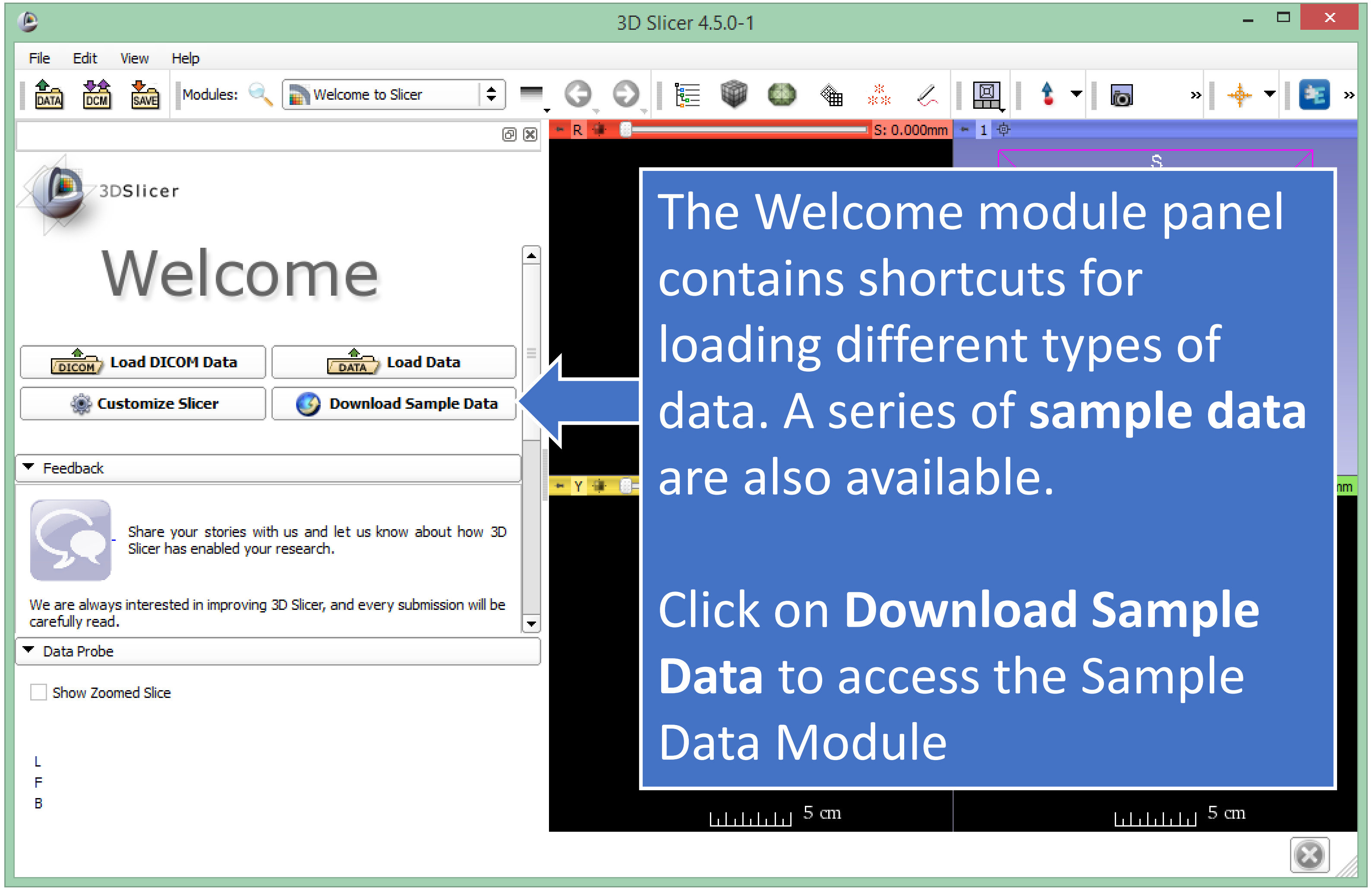
Slicer user interface



Welcome module



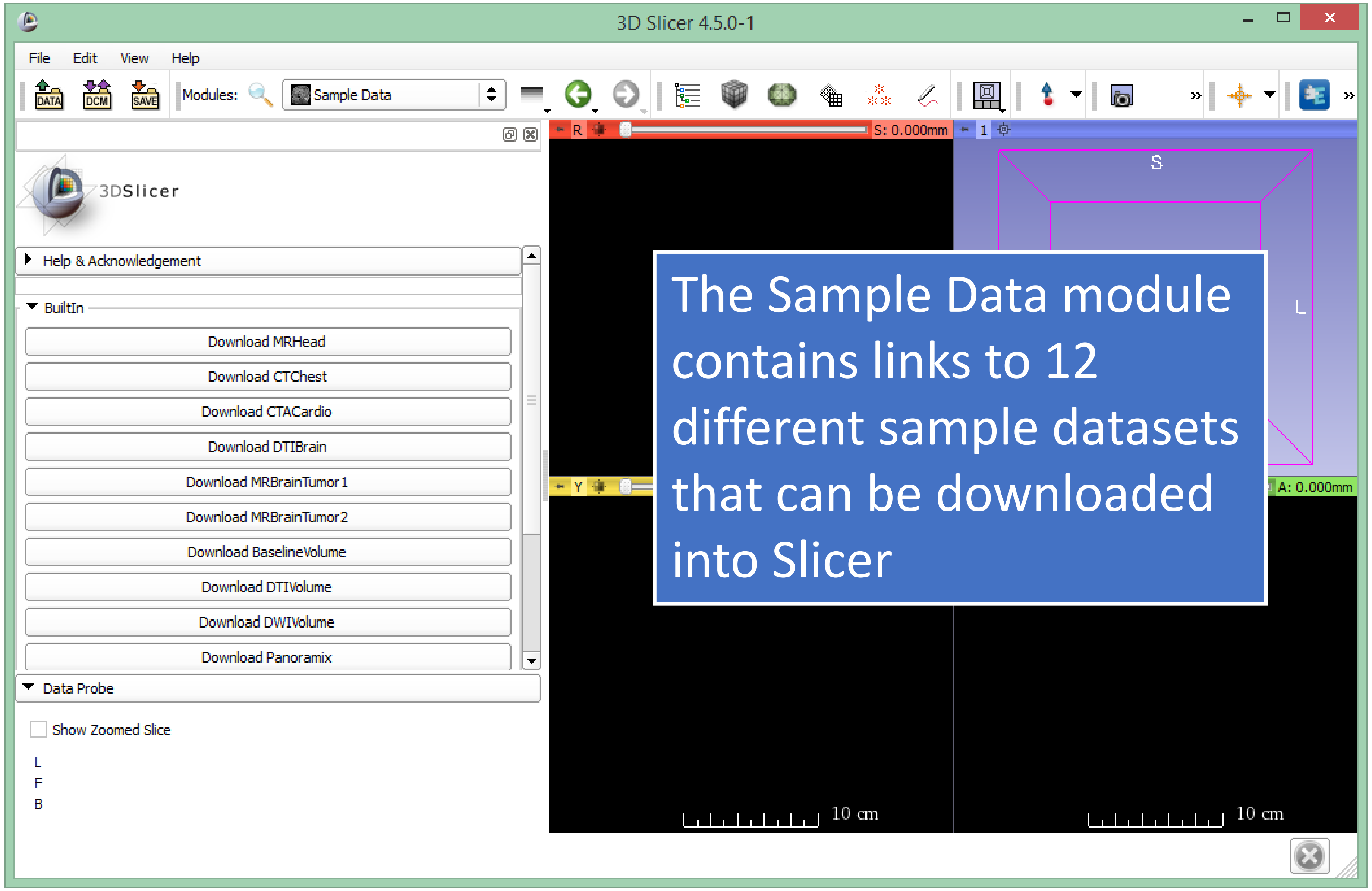
Welcome module



The Welcome module panel contains shortcuts for loading different types of data. A series of **sample data** are also available.

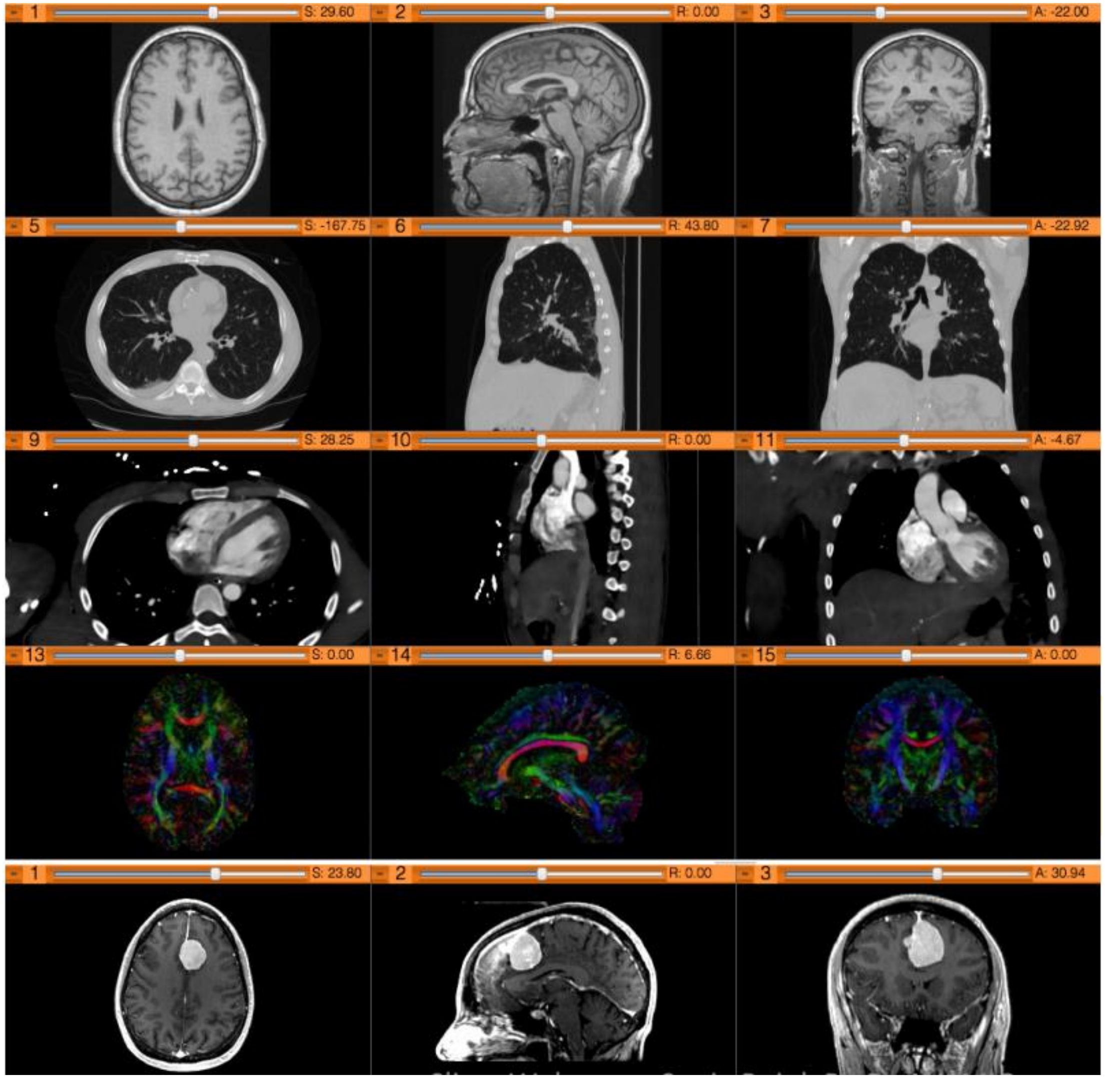
Click on **Download Sample Data** to access the Sample Data Module

Sample Data



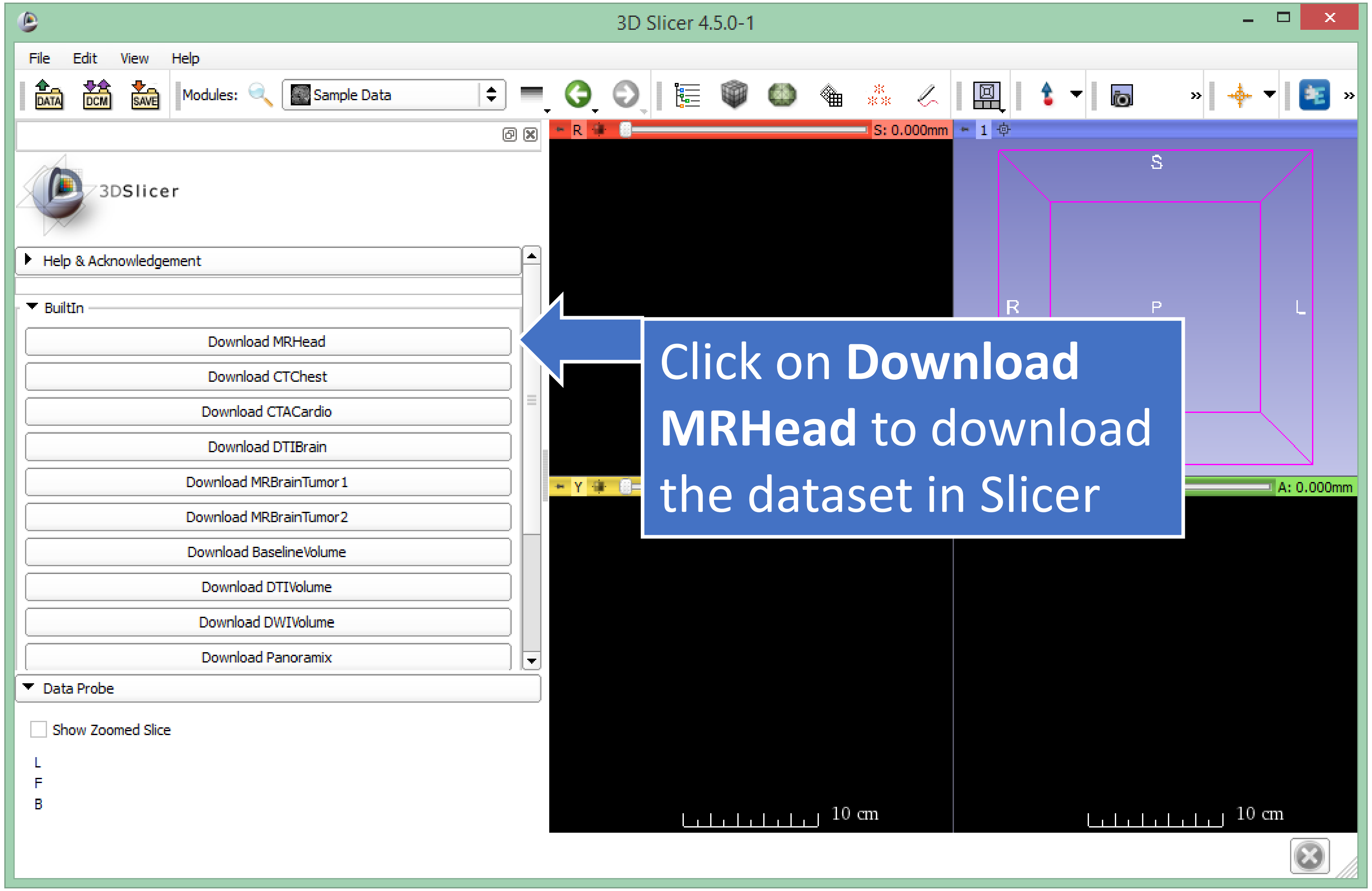
The Sample Data module contains links to 12 different sample datasets that can be downloaded into Slicer

Sample Data

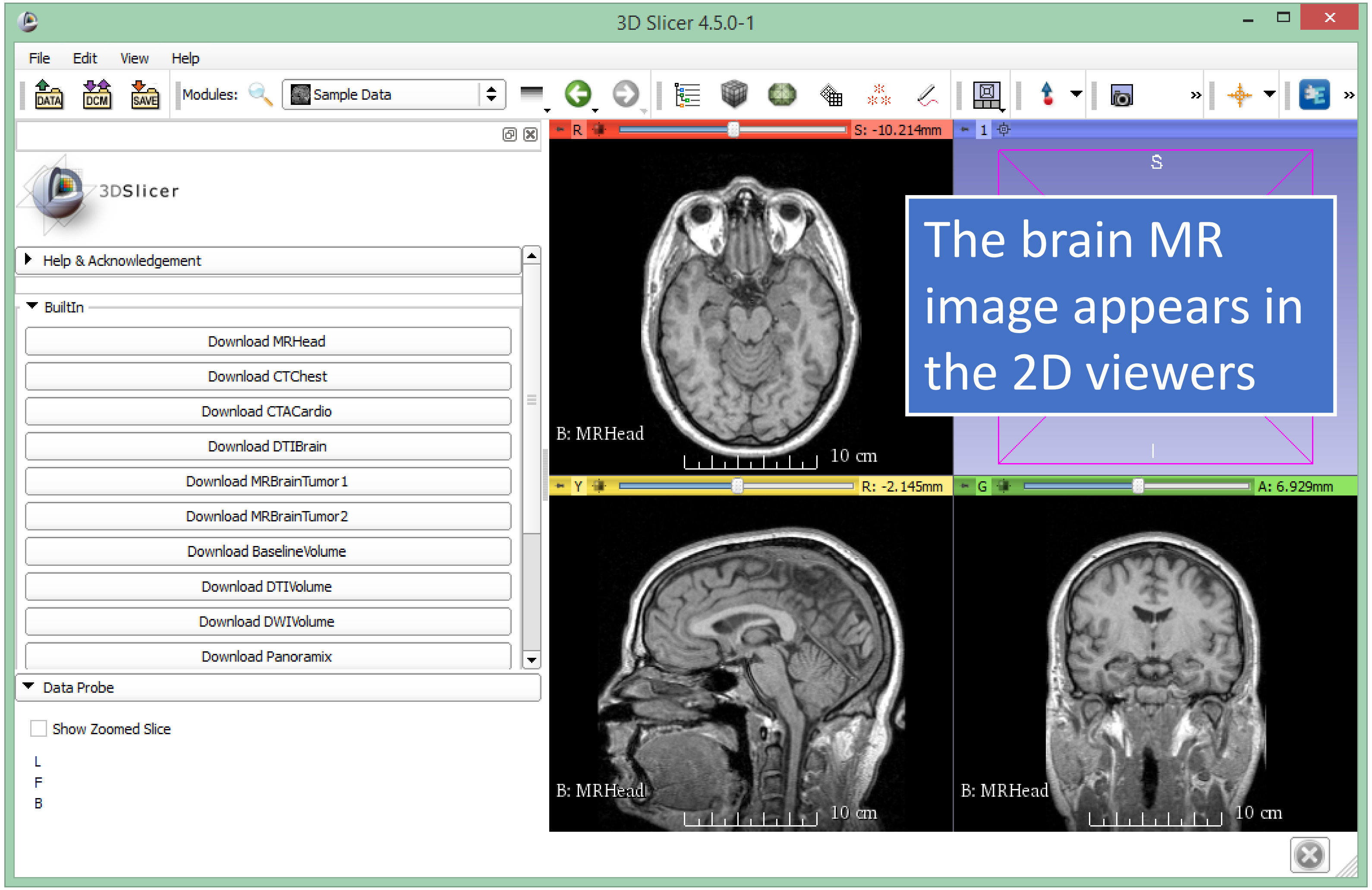


- Brain MRI
- Chest CT
- Cardiac CT
- Diffusion Tensor Imaging
- Brain MRI (tumor patient)

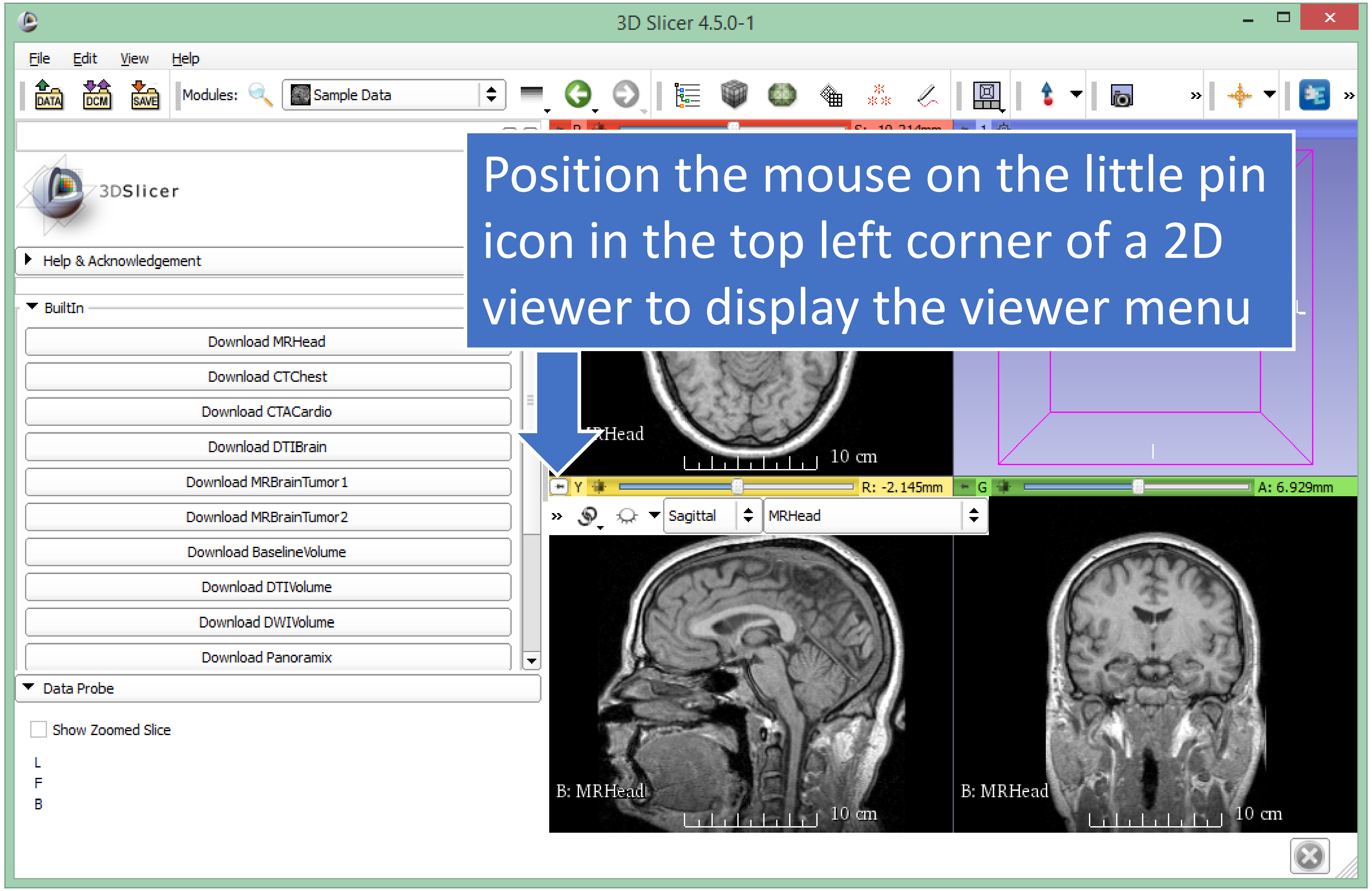
Sample Data


3D Slicer 4.5.0-1
File
Edit
View
Help
Modules:
Sample Data
3DSlicer
Help & Acknowledgement
BuiltIn
Download MRHead
Download CTChest
Download CTACardio
Download DTIBrain
Download MRBrainTumor1
Download MRBrainTumor2
Download BaselineVolume
Download DTIVolume
Download DWIVolume
Download Panoramix
Data Probe
Show Zoomed Slice
S: 0.000mm
A: 0.000mm
10 cm
10 cm
Click on **Download MRHead** to download the dataset in Slicer

Sample Data

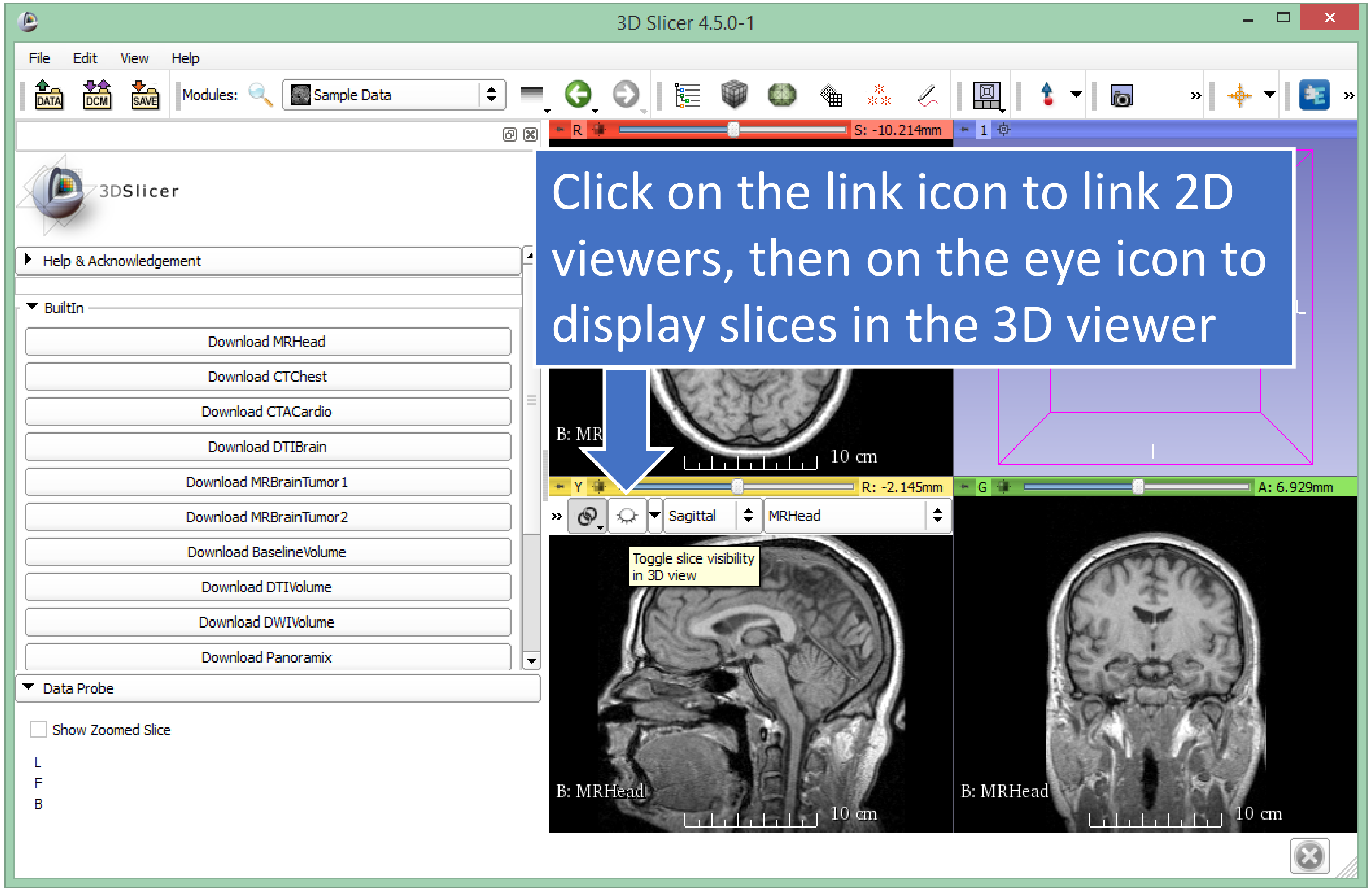

3D Slicer 4.5.0-1
File
Edit
View
Help
Modules:
Sample Data
3DSlicer
Help & Acknowledgement
BuiltIn
Download MRHead
Download CTChest
Download CTACardio
Download DTIBrain
Download MRBrainTumor1
Download MRBrainTumor2
Download BaselineVolume
Download DTIVolume
Download DWIVolume
Download Panoramix
Data Probe
Show Zoomed Slice
S: -10.214mm
R: -2.145mm
A: 6.929mm
B: MRHead
10 cm
The brain MR image appears in the 2D viewers

MR Brain Sample Dataset

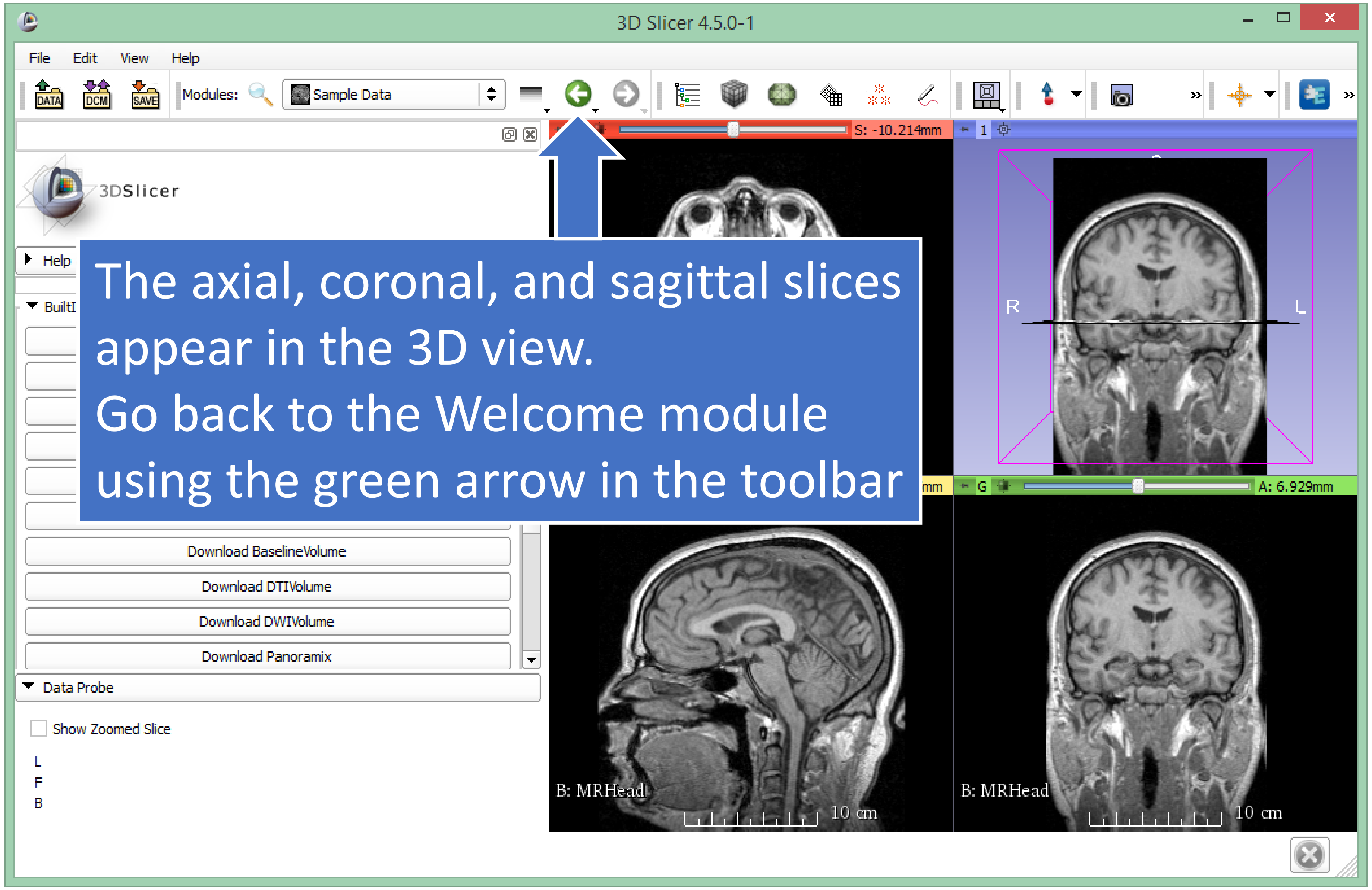


Position the mouse on the little pin icon in the top left corner of a 2D viewer to display the viewer menu

MR Brain Sample Dataset

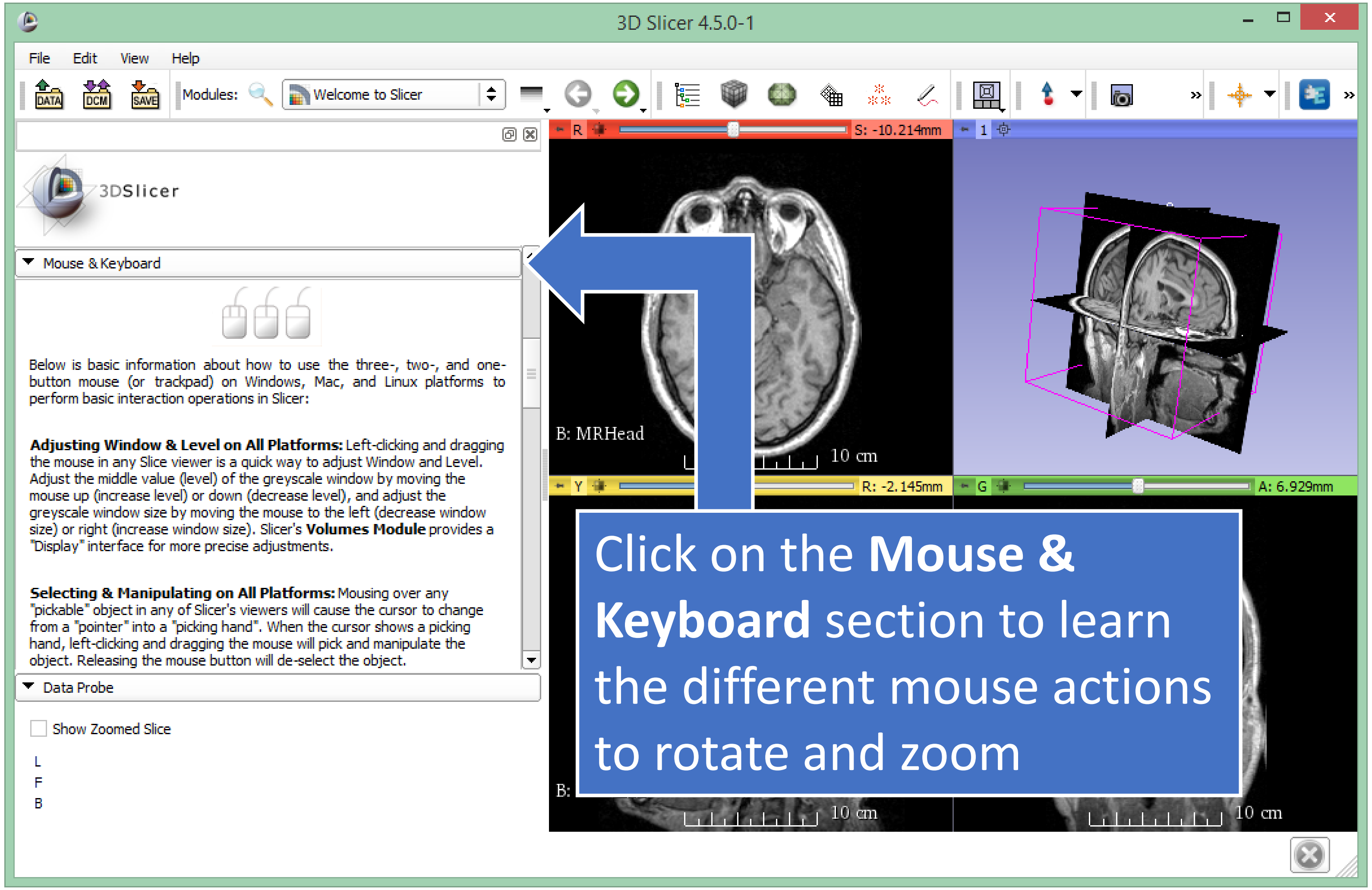


MR Brain Sample Dataset



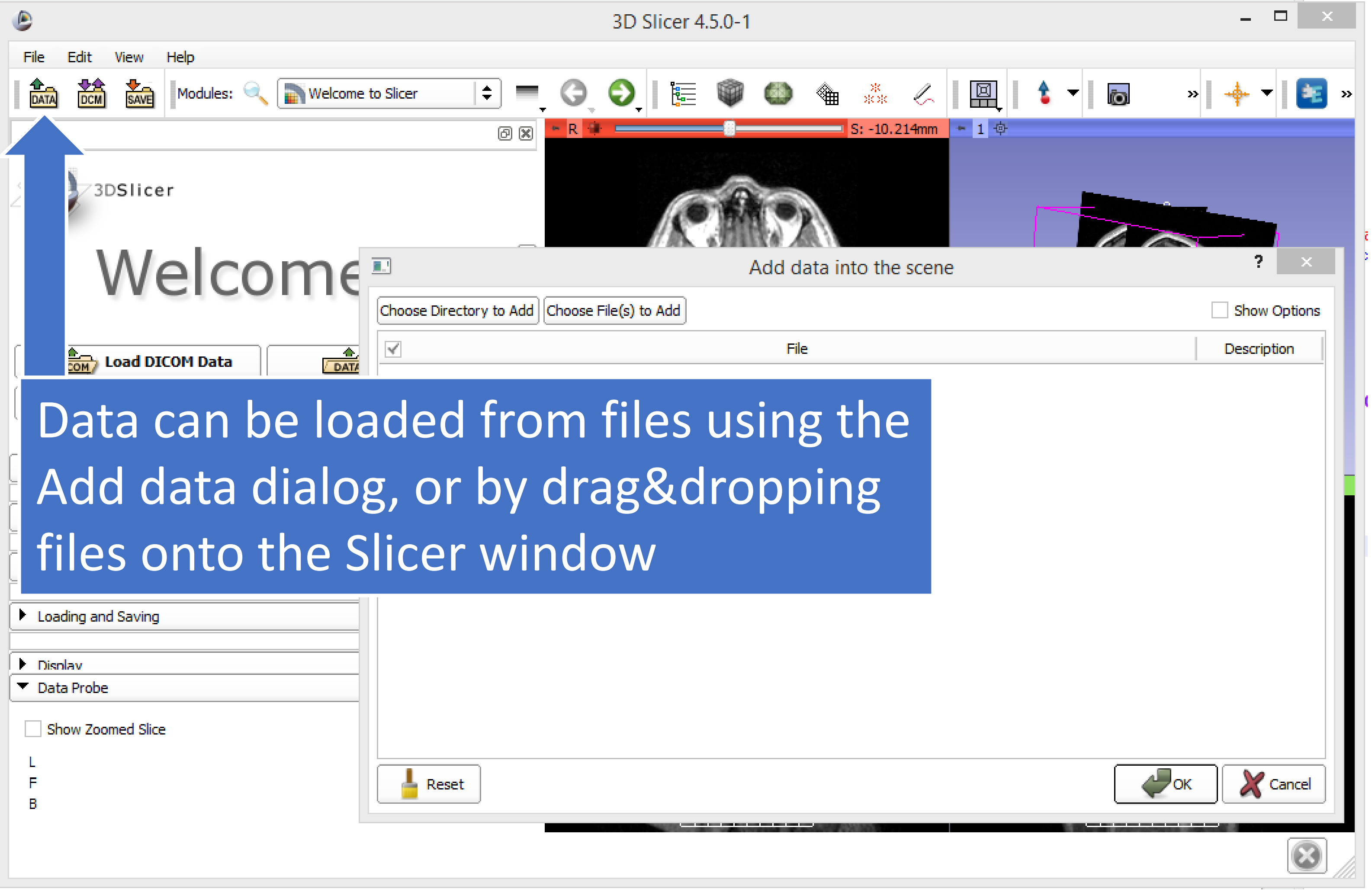
The axial, coronal, and sagittal slices appear in the 3D view.
Go back to the Welcome module using the green arrow in the toolbar

MR Brain Sample Dataset



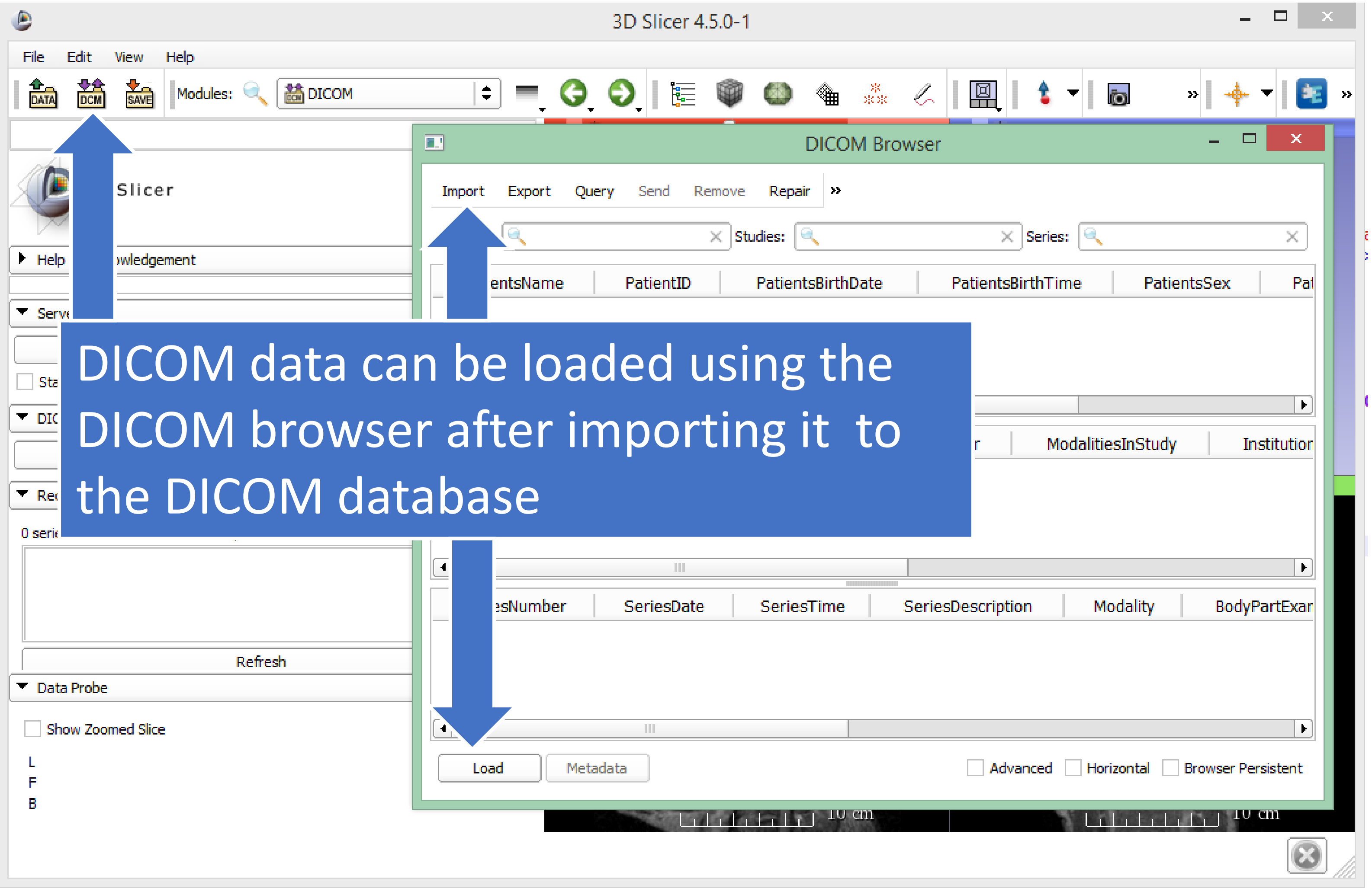
Click on the **Mouse & Keyboard** section to learn the different mouse actions to rotate and zoom

Load data from file



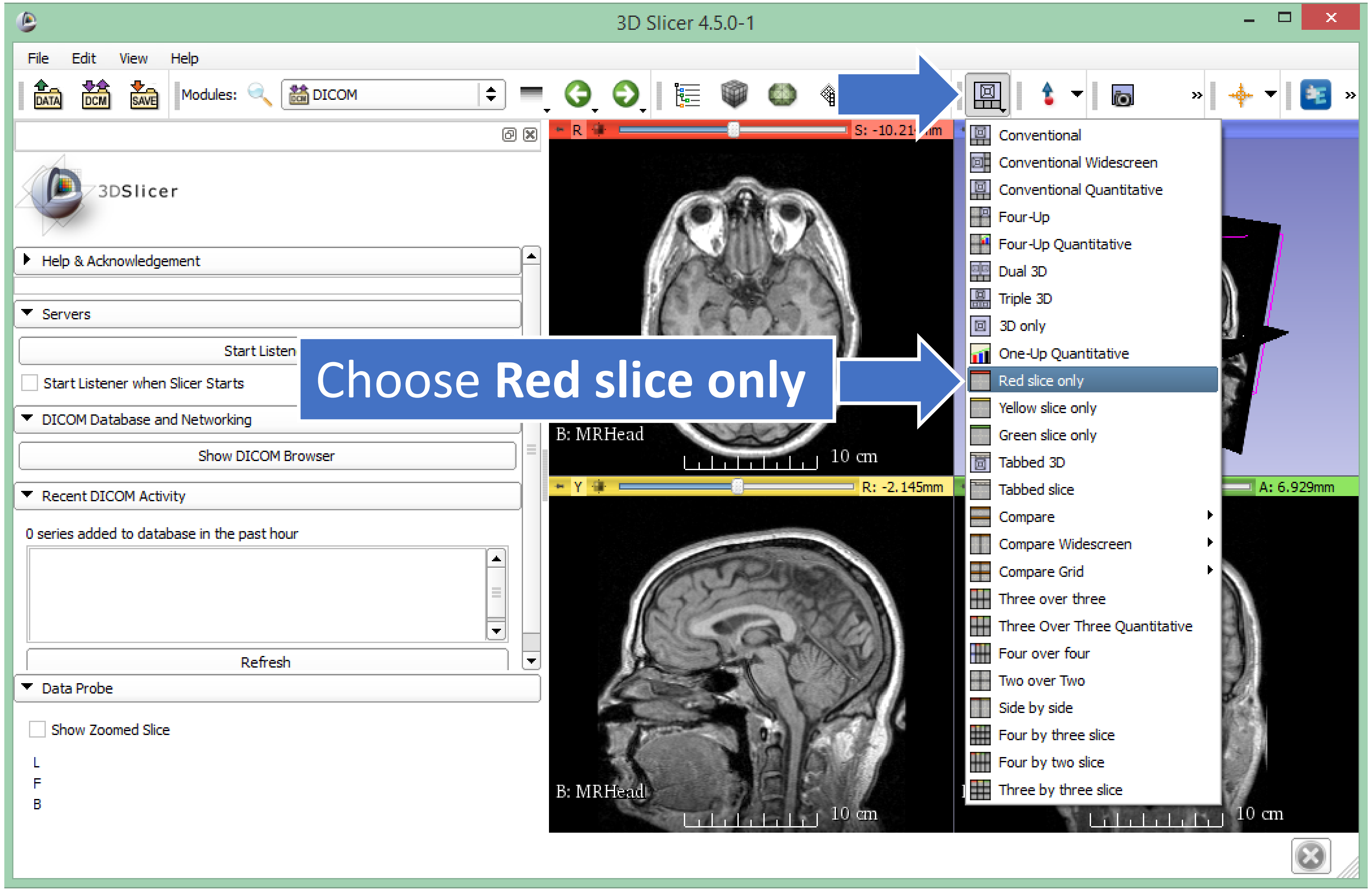
Data can be loaded from files using the Add data dialog, or by drag&dropping files onto the Slicer window

Load DICOM data

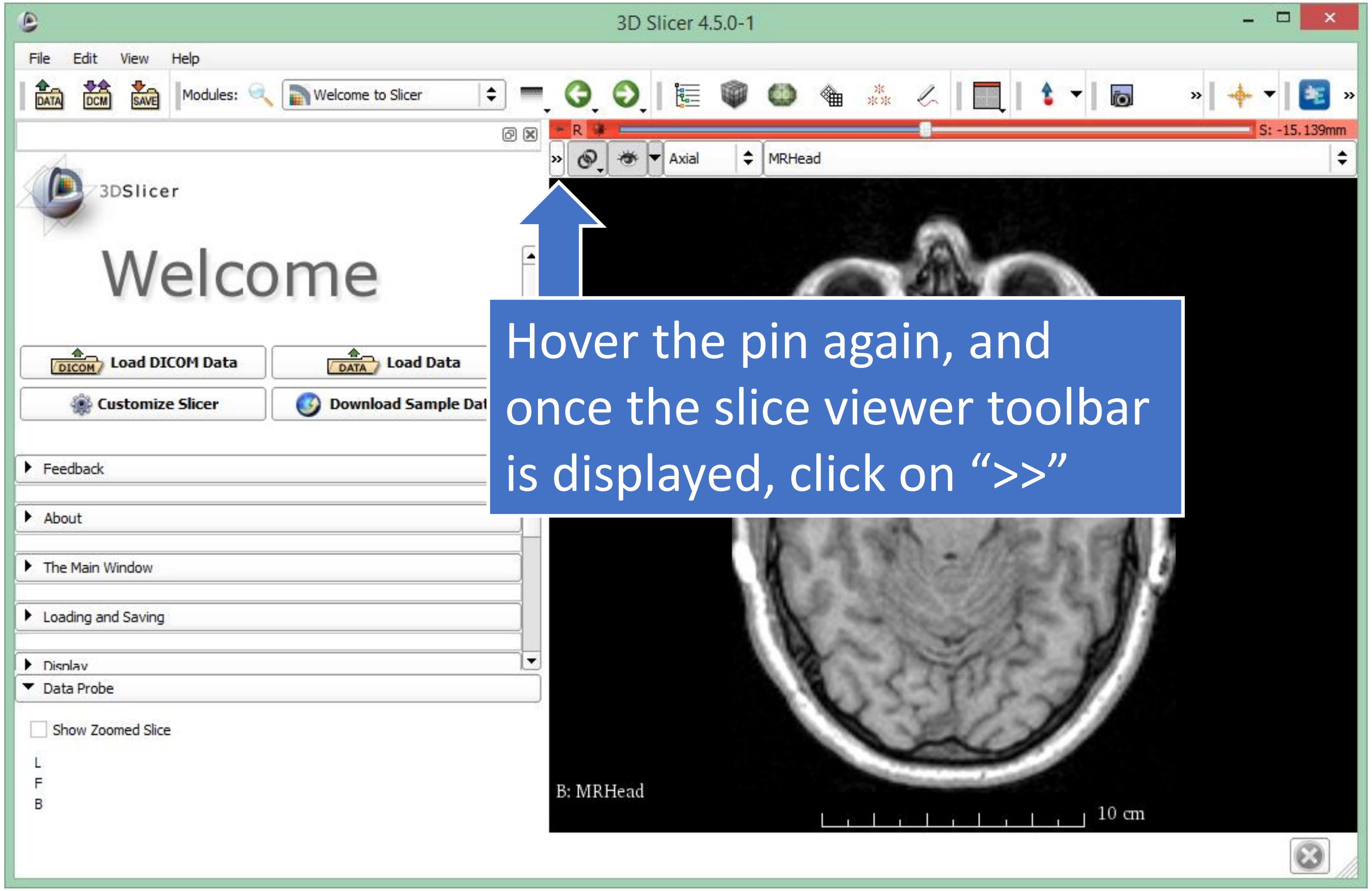


DICOM data can be loaded using the DICOM browser after importing it to the DICOM database

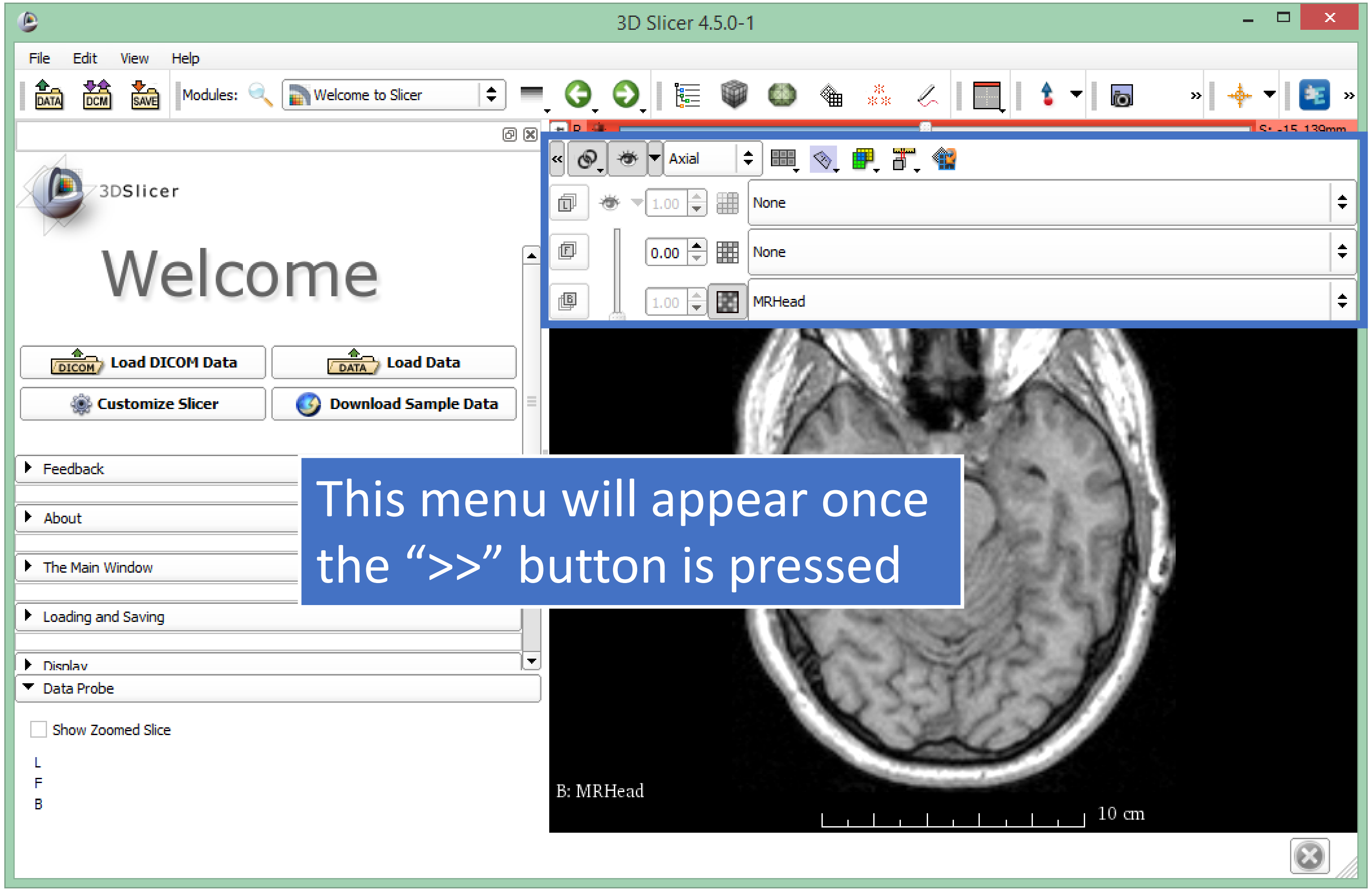
Changing layout



Slice viewer toolbar cont'd

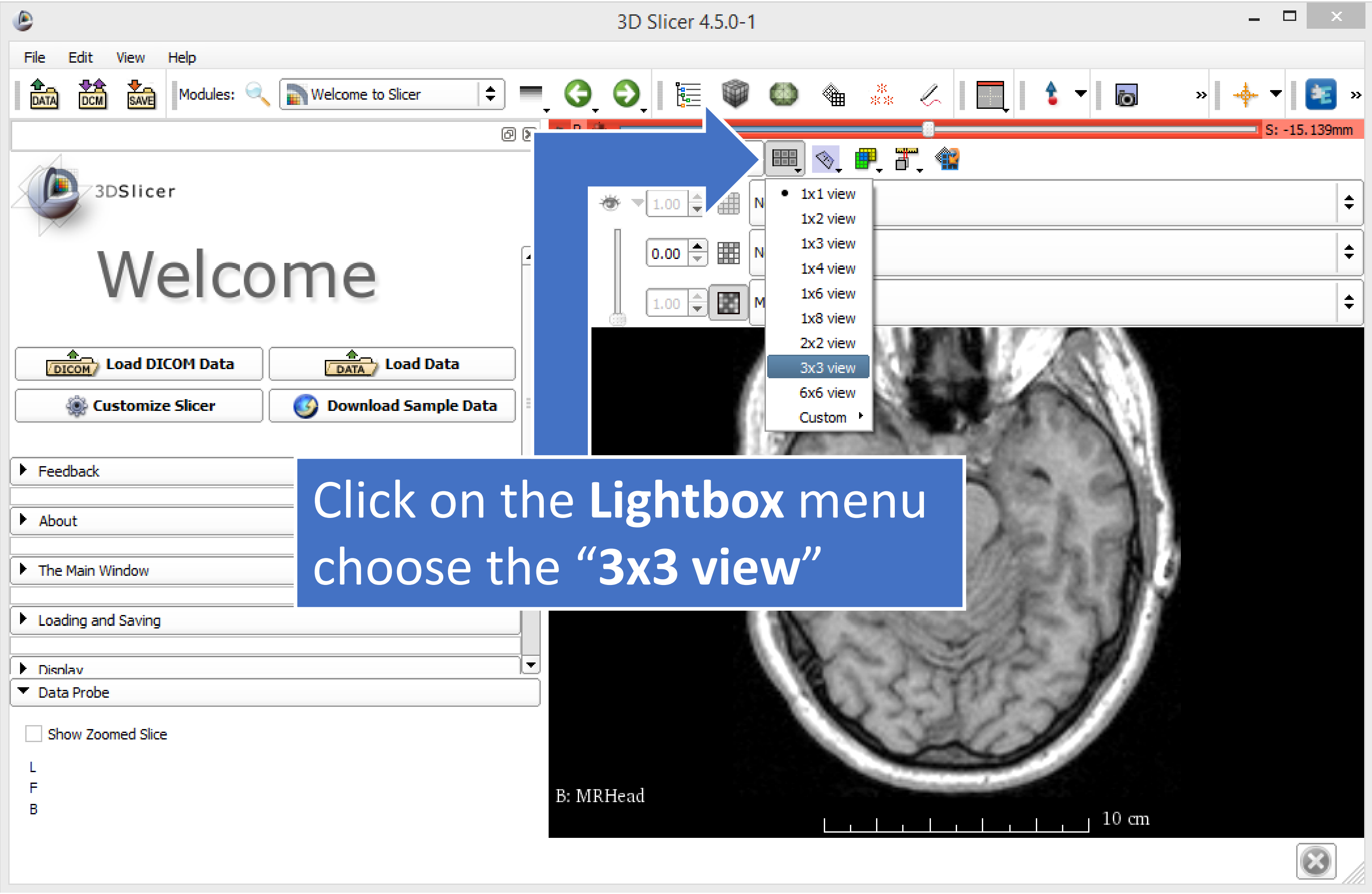


Slice viewer toolbar cont'd

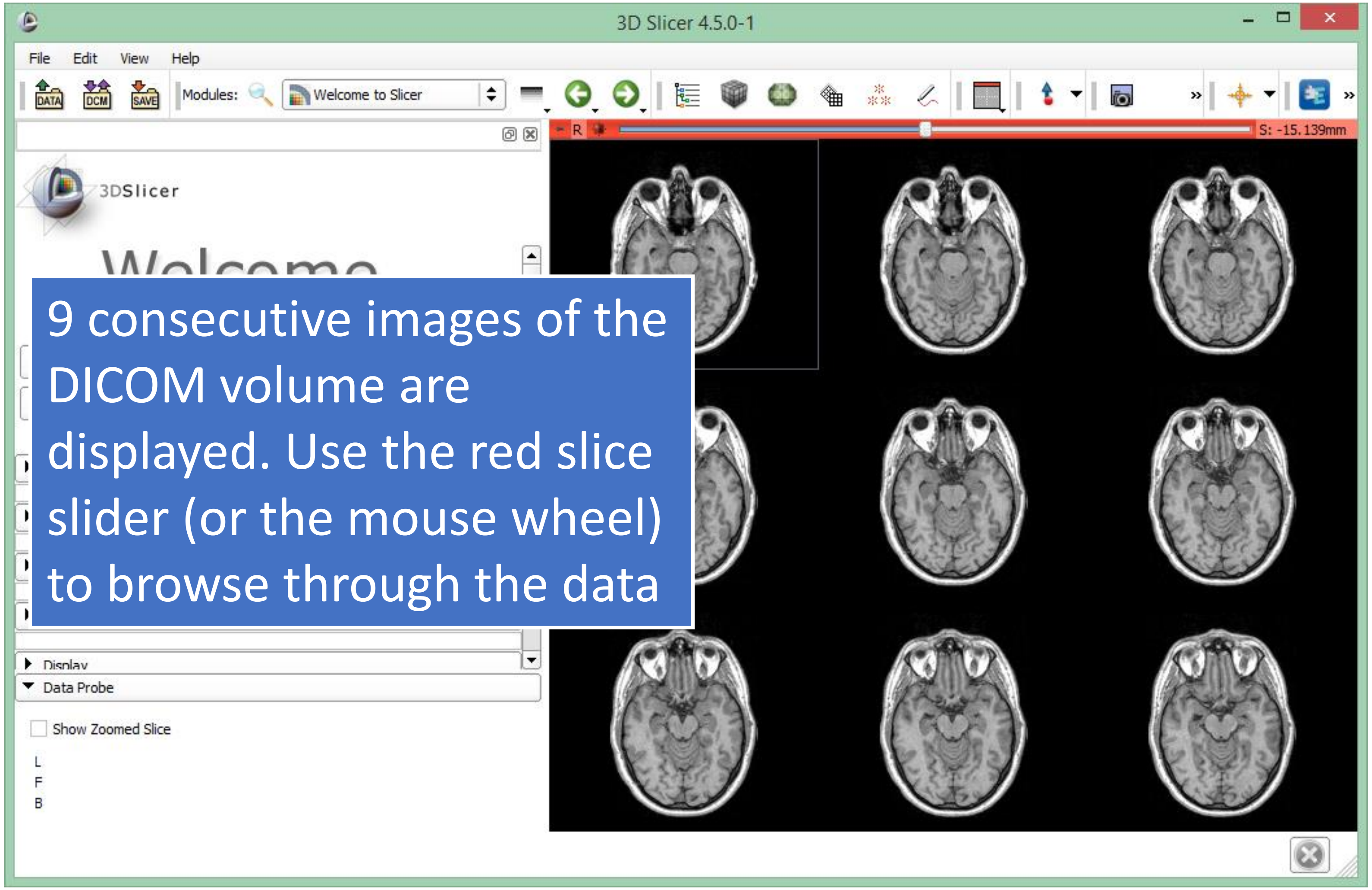


This menu will appear once the "»" button is pressed

Lightbox view

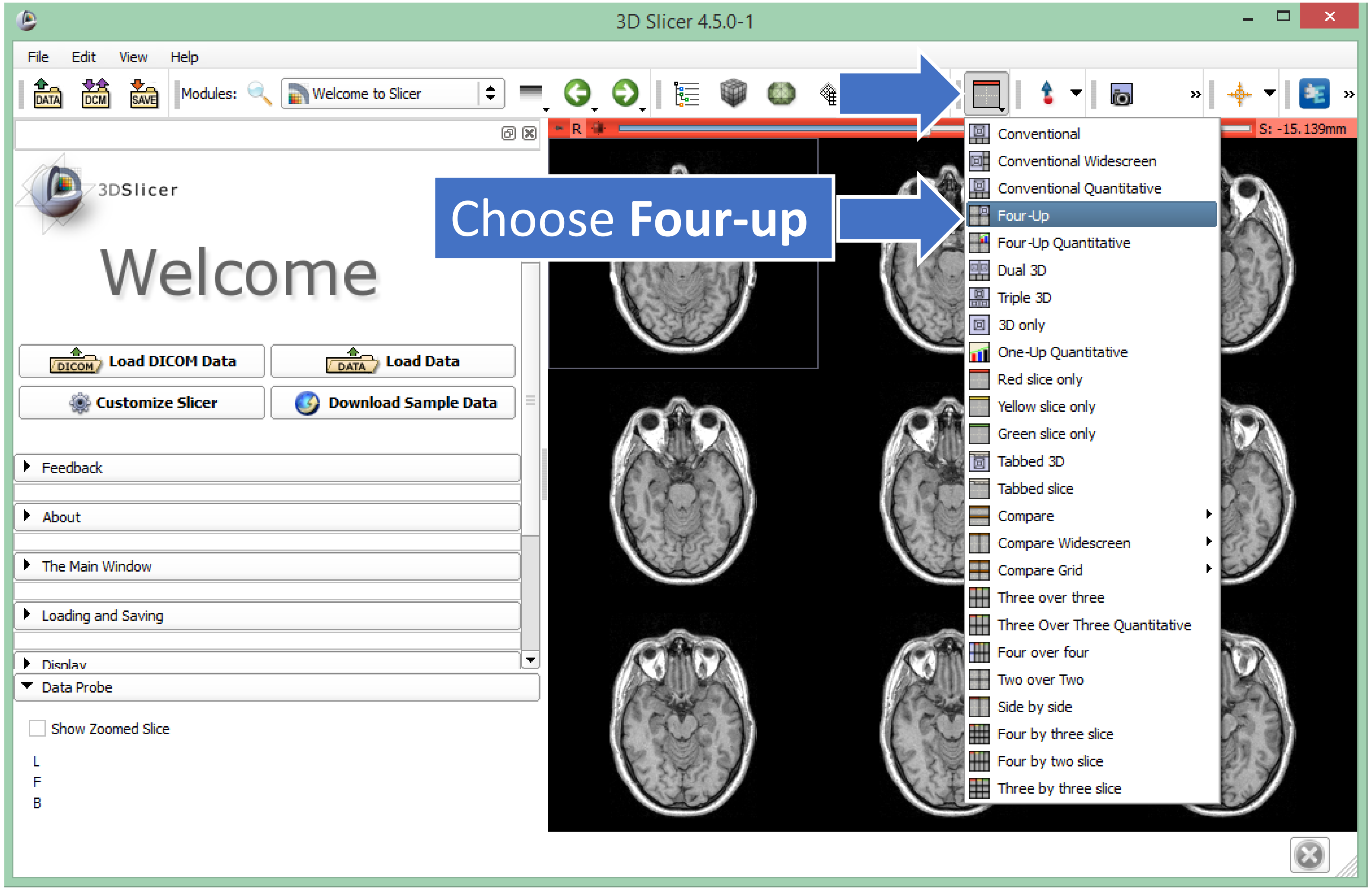


Lightbox view

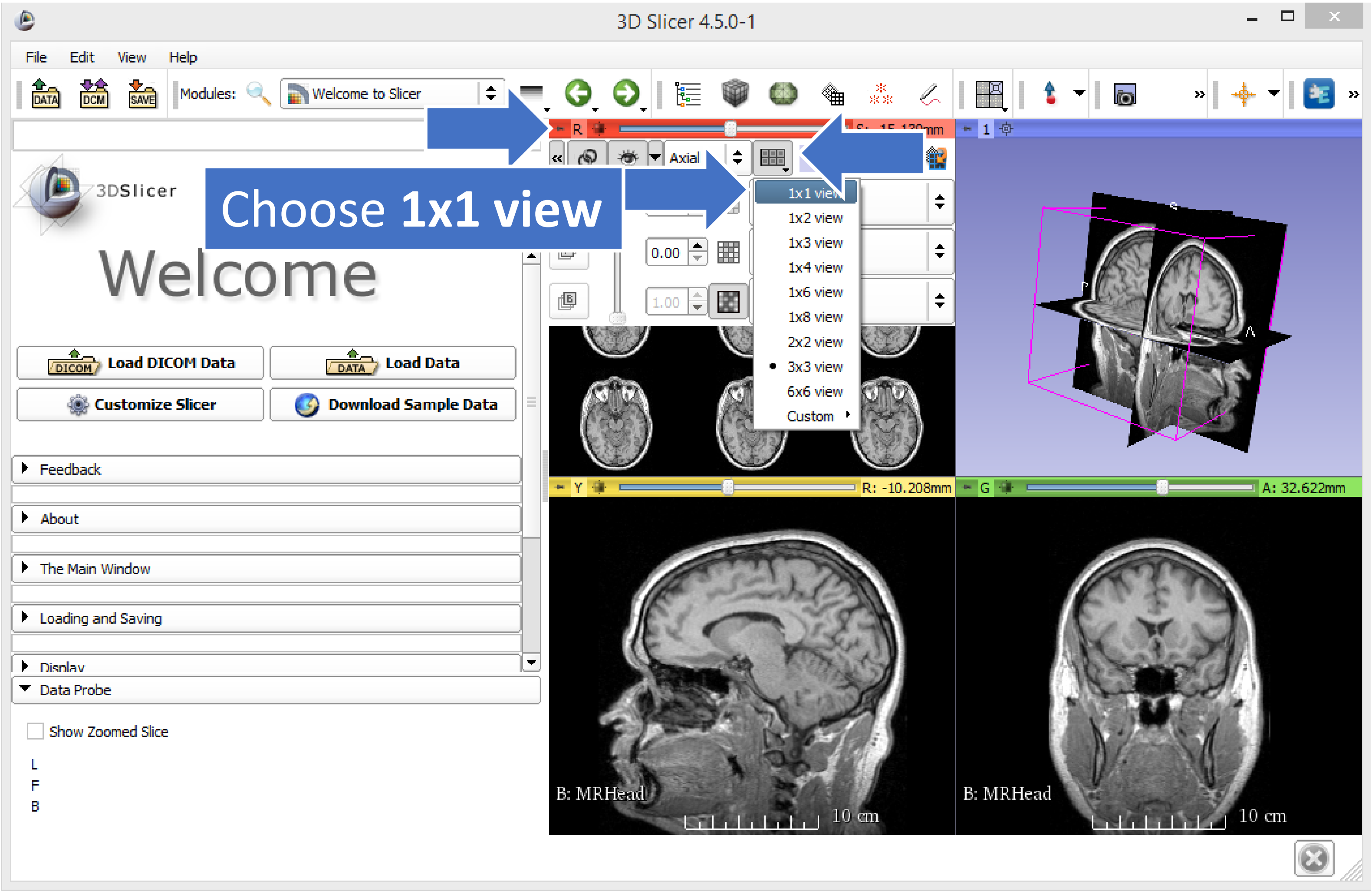


9 consecutive images of the DICOM volume are displayed. Use the red slice slider (or the mouse wheel) to browse through the data

Switch back the layout



Turn off lightbox view



Close Slicer scene