Structure Relationships

Introduction

The Structure Relationships package is used to generate an interactive and customizable diagram on the geometrical relationships between radiation therapy structures. It is primarily intended as a quality assurance tool to assist with the treatment plan checking process.

The Structure Relationships package provides a quick, easy-to-read diagram of the geometrical relationships between structures. For example, PTV *contains* CTV; If the CTV was modified to add a suspicious node, but the PTV expansion was not re-generated, the relationship would change to PTV *overlaps* CTV. If there are multiple target volumes, the diagram will allow the physicist to quickly verify that each of the target CTV and PTV expansions are correctly labeled to match each other and their corresponding GTVs.

The Structure Relationships package also provides appropriate metrics for the relationships. For example, with PTV *contains* CTV, the metrics would be the margins between the PTV and CTV in the 6 orthogonal directions, as well as the maximum, minimum and mean margins. Similarly, with PTV *overlaps* Parotid RT the metrics would be the volume percentage of the overlap between the PTV and Parotid RT structures.

There are many redundant (logical) relationships between structures, such as: “PTV *contains* CTV, and CTV *contains* GTV, therefore PTV *contains* GTV”. To reduce the clutter in the diagram, these redundant relationships are hidden by default, so that the important relationships are highlighted.

The Structure Relationships diagram and accompanying report simplify the process of verifying the appropriateness of the structures used in the planning process.

Simple workflow example

The following is a typical workflow example.

1. The Plan and Structures are exported as DICOM RT files.
2. The DICOM structure file is selected and loaded.
3. The program automatically extracts the information for each of the structures found in the file.
4. Certain structures are automatically dropped from further processing based on their name or structure type.
5. Geometrical data for all remaining structures is analyzed to identify the relationships between each structure and all other structures.
6. Appropriate metrics are calculated based on the relationships identified.
7. A diagram is generated, with each structure as a labeled geometric shape, based on its structure type, and with its color matching the structure’s color in the plan. Lines of different styles are used to indicate the type of relationship between two structures.
8. Hovering the mouse over a structure in the diagram gives a popup with details about the structure, such as its volume, and any assigned Hounsfield Units.
9. Hovering the mouse over a relationship line in the diagram gives a popup with the calculated metrics for that relationship.
10. Right clicking on a structure brings up a menu with options to hide the structure, restore a hidden relationship line, or insert a note into the structure’s label.
11. Right clicking on a relationship line brings up a menu with options to hide the line, select which metrics to display, or add a note beside the line.
12. At completion, a PDF document is generated that includes the final version of the diagram along with a table of all structures and relationships visible in the diagram.

Example simple breast contours.

Diagram illustrates:

**Targets**

* CTV *Contained In* PTV
* eval\_PTV *Part Of* PTV

**OARs**

* Lung\_L *Part Of* Lung\_B
* Lung\_R *Part Of* Lung\_B

**OARs with targets**

* Body *Overlaps* PTV
* Body *Contains* eval\_PTV

Relationship values in table

* Mean (selected) margin between CTV and PTV
* Volume (in %) of PTV within eval\_PTV
* Volume (in %) of Lung\_B not contained in Lung\_L + Lung\_R
* Minimum (selected) Margin between eval\_PTV and Body

Design Details

Available Structure information

Identification

* Structure Id
* Structure Category:
* Target
* Organ
* External
* Planning
* Dose
* Other
* Structure Type (from DICOM Standard)
* Structure Code (Eclipse)
* Code Meaning (Eclipse)
* Structure Code Scheme (Eclipse)
* Color

Structure Geometry

* Volume
* Surface Area
* Thickness (for wall structures)
* Length (with SUP and INF extent)
* Sphericity (Metric of how close to a spherical shape.
* Geometrical Center coordinates
* Contour Resolution (Eclipse)

Types of Shapes

The following shape approximate a 2D region. A region consists of one or more contour. When the region contains multiple contours, the contours must not overlap. In the example below (Multi), one contour is embedded within the hole of another contour, but the two contours do not overlap because the hole is not part of the contour.

Each contour has two components: An *external* and a list of *holes*. In addition, the *convex hull* of a contour allows for the identification of relationships between crescent shapes contours and contours partially surrounded by the crescent.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| **Simple** | **Cove** | **Hollow** | **Archipelago** |
|  |  |  |  |
| **External** | **External** | **External** | **External** |
|  |  |  |  |
| **Convex Hull** | **Convex Hull** | **Convex Hull** | **Convex Hull** |
|  |  |  |  |
|  |  | **Hole** | **Hole** |
|  |  |  |  |
|  |  |  | **Island** |

Islands can be treated as separate contours for determining relationships

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | = |  | + |  |

2D Relationship Matrix (DE-9IM)

DE-9IM is used to describe the spatial relations between two geometries in two-dimensions. The DE-9IM model is based on a 3×3 intersection matrix with the form below, where ***dim*** is the dimension of the intersection of the interior (***I***), boundary (***B***), and exterior (***E***) of geometries a and b:

![A table with different colored shapes

Description automatically generated]()

Some examples of defined relationships are:

|  |  |  |
| --- | --- | --- |
| **Name** | **DE-9IM** | **Meaning and definition** |
| **Disjoint** |  | *a* and *b* have no points in common. |
| **Overlaps** |  | *a* overlaps *b*: they have some but not all points in common. |
| **Within** |  | *a* lies in the interior of *b*. |

Note:

* All mask string codes end with \*. This is because EE is trivially true, and thus provides no useful information.
* The relationships between external contours of (*a* and *b* with their holes filled) or convex hulls are only specified where necessary to distinguish relationships.
* The geometrical relations between 3D structures must be inferred by combining the relationships for the contours on each slice.

Relationship Types and Definitions

***region a***

***region b***

***intersection of a & b***

Disjoint Relations

Surrounds/ Embeds Transitive

***a*** and ***b*** have no interior points in common, and with holes filled ***b*** lies in the interior of ***a***.

|  |  |  |
| --- | --- | --- |
| A blue and white circle with a green center  Description automatically generatedA blue and green circle  Description automatically generated | **Region** | **Exterior** |
|  | |  |  | | --- | --- | | Surrounds | Embeds | |  |  | |

Metrics

Distances between the surrounded and surrounding shape.

Shelters / Sheltered Transitive

***a*** and ***b*** have no points in common, but the *Convex Hull* of ***a*** contains ***b***.

|  |  |  |
| --- | --- | --- |
| A blue and green object  Description automatically generated | **Region** | **Hull** |
|  | |  |  | | --- | --- | | Shelters | Sheltered | |  |  | |

Metrics

Distances between the sheltered island and surrounding shape.

Fully Disjoint Symmetric

***a*** and ***b*** have no points in common.

|  |  |  |
| --- | --- | --- |
|  | **Region** | **Hull** |
|  |  |

Metrics

None

Borders

The exterior boundaries of ***a*** and ***b*** have more than one point in common, but their interiors do not intersect.

|  |  |  |
| --- | --- | --- |
| A blue and green object  Description automatically generated | **Region** | **Exterior** |
|  |  |

Metrics

Ratio of the length of overlaping exterior borders to the average length of the two exterior perimeters:

Where:

is the length of the perimeter that and have in comon.

is the exterior perimeter of *a.*

Confines / Exsects

The interior boundary of one shape ***a*** and the exterior boundary of another shape ***b*** have more than one point in common, but their interiors do not intersect.

|  |  |  |
| --- | --- | --- |
|  | **Matrix** | **Exterior** |
|  | |  |  | | --- | --- | | Confines | Exsects | |  |  | |

Metrics

Ratio of the length of overlaping interior border to the average length of the relevant perimeter (exterior or hole):

Where:

is the perimeter of the relevant hole in *a*

is the exterior perimeter of *b*

is the length of the perimeter that and have in comon.

Overlaps *Symmetric*

***a*** overlaps ***b***: both have some but not all points in common.

|  |  |
| --- | --- |
| A colorful drawing of a yellow blue and green object  Description automatically generated with medium confidenceA cartoon of a hat  Description automatically generatedA colorful circle with a yellow and blue circle  Description automatically generatedA blue yellow and green circle  Description automatically generatedA blue green yellow and orange circle  Description automatically generated | **Region** |
|  |

Metrics

Ratio of the area of overlap to area of both:

Partitions / Incorporates *Transitive*

All points of ***a*** lie in the interior of ***b***, no points of ***a*** lie in the exterior of ***b***, some points in ***b*** are exterior to ***a***, and the boundaries of ***a*** and ***b*** have more than one point in common.

|  |  |
| --- | --- |
| A blue and yellow object  Description automatically generatedA blue and white circle with yellow center  Description automatically generatedA blue and yellow circle  Description automatically generated | **Region Test** |
| |  |  | | --- | --- | | Partitions | Incorporates | |  |  | |

Metrics

Ratio of the area of overlap to area of the larger shape:

Within / Contains *Transitive*

All points of ***a*** lie in the interior of ***b***, no points of ***a*** lie in the exterior of ***b***, some points in ***b*** are *exterior to* ***a****, and the boundaries of* ***a*** *and* ***b*** *do not intersect.*

|  |  |
| --- | --- |
| A blue and yellow egg  Description automatically generatedA cartoon of a fried egg  Description automatically generated | **Region** |
| |  |  | | --- | --- | | Within | Contains | |  |  | |

Metrics

Distances between the exterior of ***a*** and the boundary of ***b***. (For Within, ***a*** & ***b*** reversed for Contains).

Equals Symmetric, Transitive

The interiors of ***a*** and ***b*** intersect and no part of the interior of one geometry intersects the exterior of the other.

|  |  |
| --- | --- |
| A yellow circle with black outline  Description automatically generated | **Region** |
|  |

Metrics

None

Summary

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Relationship** | **Region** | | **Exterior** | | **Hull** | |
| Surrounds |  | FF\*FF\*\*\*\* |  | T\*\*\*F\*FF\* |  |  |
| Embeds |  | FF\*FF\*\*\*\* |  | T\*F\*FF\*\*\* |  |  |
| Shelters |  | FF\*FF\*\*\*\* |  |  |  | T\*\*\*F\*F\*\* |
| Sheltered |  | FF\*FF\*\*\*\* |  |  |  | T\*F\*F\*\*\*\* |
| Disjoint |  | FF\*FF\*\*\*\* |  |  |  | FF\*FF\*\*\*\* |
| Borders |  | FF\*FT\*\*\*\* |  | FF\*FT\*\*\*\* |  |  |
| Confines |  | FF\*FT\*\*\*\* |  | T\*T\*F\*FF\* |  |  |
| Exsects |  | FF\*FT\*\*\*\* |  | T\*F\*FFTFF |  |  |
| Overlaps |  | TTTT\*TTT\* |  |  |  |  |
| Partitions |  | T\*F\*TFT\*\* |  |  |  |  |
| Incorporates |  | T\*T\*T\*FF\* |  |  |  |  |
| Within |  | T\*F\*FFT\*\* |  |  |  |  |
| Contains |  | T\*T\*F\*FF\* |  |  |  |  |
| Equals |  | T\*F\*\*FFF\* |  |  |  |  |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Relationship** | **Region Test** | **Exterior Test** | **Hull Test** | **Complement** |
| Disjoint | FF\*FF\*\*\*\* | FF\*FF\*\*\*\* | FF\*FF\*\*\*\* | Disjoint |
| Shelters | FF\*FF\*\*\*\* | FF\*FF\*\*\*\* | T\*\*\*F\*F\*\* | Sheltered |
| Sheltered | FF\*FF\*\*\*\* | FF\*FF\*\*\*\* | T\*F\*F\*\*\*\* | Shelters |
| Surrounds | FF\*FF\*\*\*\* | T\*\*\*F\*FF\* |  | Embeds |
| Embeds | FF\*FF\*\*\*\* | T\*F\*FF\*\*\* |  | Surrounds |
| Borders | FF\*FT\*\*\*\* | FF\*FT\*\*\*\* |  | Borders |
| Confines | FF\*FT\*\*\*\* | T\*T\*F\*FF\* |  | Exsects |
| Exsects | FF\*FT\*\*\*\* | T\*F\*FFTFF |  | Confines |
| Partitions | T\*F\*TFT\*\* |  |  | Incorporates |
| Incorporates | T\*T\*T\*FF\* |  |  | Partitions |
| Within | T\*F\*FFT\*\* |  |  | Contains |
| Contains | T\*T\*F\*FF\* |  |  | Within |
| Overlaps | TTTT\*TTT\* |  |  | Overlaps |
| Equals | T\*F\*\*FFF\* |  |  | Equals |

Convert each test string into two binary number:

1. An ignore mask (0 indicates ignored):
   1. Replace ‘\*’ with ‘0’
   2. Replace ‘F’ and ‘T’ with ‘1’
   3. Convert string to a binary integer int(string, 2)
2. A value (Binary number)
   1. Replace ‘\*’ with ‘0’
   2. Replace ‘F’ with ‘0’
   3. Replace ‘T’ with ‘1’
   4. Convert string to a binary integer int(string, 2)

|  |  |  |
| --- | --- | --- |
| **Relationship** | **Masks and Values** | |
| Disjoint | *Mask* | (110110000, 110110000, 110110000) |
| *Value* | (000000000, 000000000, 000000000) |
| Shelters | *Mask* | (110110000, 110110000, 100010100) |
| *Value* | (000000000, 000000000, 100000000) |
| Sheltered | *Mask* | (110110000, 110110000, 101010000) |
| *Value* | (000000000, 000000000, 100000000) |
| Surrounds | *Mask* | (110110000, 100010110, 0) |
| *Value* | (000000000, 100000000, 0) |
| Embeds | *Mask* | (110110000, 101011000, 0) |
| *Value* | (000000000, 100000000, 0) |
| Borders | *Mask* | (110110000, 110110000, 0) |
| *Value* | (000010000, 000010000, 0) |
| Confines | *Mask* | (110110000, 101010110, 0) |
| *Value* | (000010000, 101000000, 0) |
| Exsects | *Mask* | (110110000, 101011111, 0) |
| *Value* | (000010000, 100000100, 0) |
| Partitions | *Mask* | (101011100, 0, 0) |
| *Value* | (100010100, 0, 0) |
| Incorporates | *Mask* | (101010110, 0, 0) |
| *Value* | (101010000, 0, 0) |
| Within | *Mask* | (101011100, 0, 0) |
| *Value* | (100000100, 0, 0) |
| Contains | *Mask* | (101010110, 0, 0) |
| *Value* | (101000000, 0, 0) |
| Overlaps | *Mask* | (111101110, 0, 0) |
| *Value* | (111101110, 0, 0) |

Properties

The spatial predicates have the following properties of binary relations:

**symmetric**

Equals, Overlaps, Disjoint, Borders

A relation is **symmetric** if for all a and b. For example, if ***a*** *Equals* ***b*** then ***b*** *Equals* ***a***.

**transitive**

Equals, Contains, Within, Shelters, Sheltered, Surrounds, Embeds.

A relation is **transitive** if whenever, and then . For example, if ***a*** *Contains* ***b*** and ***b*** *Contains* ***c*** relation, then ***a*** *Contains* ***c***.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Relationship** | **Symmetric** | **Transitive** | **Complement** | **Link Name** |
| *Disjoint* | *Yes* | *No* | *Disjoint* | *NA* |
| Shelters | No | Yes | Sheltered | Shelter |
| Sheltered | No | Yes | Shelters | Shelter |
| Surrounds | No | Yes | Embeds | Island |
| Embeds | No | Yes | Surrounds | Island |
| Borders | Yes | No | Borders | Borders |
| Confines | No | No | Exsects | Cut-out |
| Exsects | No | No | Confines | Cut-out |
| Partitions | No | No | Incorporates | Group |
| Incorporates | No | No | Partitions | Group |
| Within | No | Yes | Contains | Expansions |
| Contains | No | Yes | Within | Expansions |
| Overlaps | Yes | No | Overlaps | Overlaps |
| Equals | Yes | Yes | Equals | Equals |

|  |  |  |
| --- | --- | --- |
| **Relationship** | **Metrics** | |
| Surrounds | Distances between the surrounded and surrounding shape. | |
| Embeds |
| Shelters | Distances between the sheltered island and surrounding shape. | |
| Sheltered |
| Disjoint | *N/A* | |
| Exterior Borders | Ratio of the length of overlap to the length of the exterior perimeter. | Where:  is the perimeter of *a*  is the exterior perimeter of *a*  is the perimeter of the relevant hole in *a*  is the length of the perimeter of *a* |
| Interior Borders | Ratio of the length of overlap to the length of the relevant hole perimeter. |
| Overlaps | Ratio of the area of overlap to area of both: | |
| Partitions | Ratio of the area of overlap to area of the larger shape: | |
| Incorporates |
| Contains | Distances between the exterior of ***a*** and the boundary of ***b***. (For Within, ***a*** & ***b*** reversed for Contains). | |
| Within |
| Equals | *N/A* | |

Diagram

Default Structure Properties

|  |  |
| --- | --- |
| **Property** | **Value** |
| fixedsize | shape |
| width | 1 |
| height | 0.6 |
| fontname | Helvetica-Bold |
| fontsize | 12 |
| labelloc | c |
| penwidth | 3 |
| style | filled |
| fontcolor | black |

Structure Shape and Style

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **DicomType** | **shape** | **style** | **penwidth** | **fillcolor** | **subgraph** |
| GTV | pentagon | "filled" | 3 |  | Targets |
| CTV | hexagon | "filled" | 3 |  | Targets |
| PTV | octagon | "filled" | 3 |  | Targets |
| EXTERNAL | doublecircle | "filled" | 2 | white | External |
| ORGAN | rectangle | "rounded, filled" | 3 |  | OAR |
| NONE | trapezium | "rounded, filled" | 3 |  | OAR |
| AVOIDANCE | house | "rounded, filled" | 3 |  | Planning |
| CONTROL | invhouse | "rounded, filled" | 3 |  | Planning |
| TREATED\_VOLUME | parallelogram | "rounded, filled" | 3 |  | Planning |
| IRRAD\_VOLUME | parallelogram | "rounded, filled" | 3 |  | Planning |
| DOSE\_REGION | diamond | "rounded, filled" | 3 |  | Dose |
| CONTRAST\_AGENT | square | "rounded, filled" | 3 |  | Other |
| CAVITY | square | "rounded, filled" | 3 |  | Other |
| SUPPORT | triangle | "rounded, bold" | 3 |  | External |
| BOLUS | oval | "bold" | 3 |  | External |
| FIXATION | diamond | "bold" | 3 |  | External |

Default Relationship Line Properties

|  |  |
| --- | --- |
| **Property** | **Value** |
| arrowhead | none |
| arrowtail | none |
| penwidth | 3 |
| style | "solid" |
| labelfloat | "false" |
| labelfontname | "Times" |
| fontcolor | "#55AAFF" |
| fontsize | 10 |
| color | #e27dd6ff" |

Relationship Line Properties

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Relationship** | **Symmetric** | **Transitive** | **Complement** | **Link Name** | **style** | **dir** | **penwidth** | **color** |
| Disjoint | Yes | No | Disjoint | NA | "invis" |  |  |  |
| Logical | No | No | NA | Logical | "dotted" |  | 1 |  |
| Shelters | No | Yes | Sheltered | Shelter | "tapered" | "forward" | 3 | "blue" |
| Sheltered | No | Yes | Shelters | Shelter | "tapered" | "back" | 3 | "blue" |
| Surrounds | No | Yes | Embeds | Island | "tapered" | "forward" | 3 | "blue" |
| Embeds | No | Yes | Surrounds | Island | "tapered" | "back" | 3 | "blue" |
| Borders | Yes | No | Borders | Borders | "dashed" | "both" | 3 | "green" |
| Confines | No | No | Exsects | Cut-out | "tapered" | "forward" | 3 | "magenta" |
| Exsects | No | No | Confines | Cut-out | "tapered" | "back" | 3 | "magenta" |
| Partitions | No | No | Incorporates | Group | "tapered" | "back" | 6 | "white" |
| Incorporates | No | No | Partitions | Group | "tapered" | "forward" | 6 | "white" |
| Within | No | Yes | Contains | Expansions | "tapered" | "back" | 6 | "cyan" |
| Contains | No | Yes | Within | Expansions | "tapered" | "forward" | 6 | "cyan" |
| Overlaps | Yes | No | Overlaps | Overlaps | "tapered" | "both" | 6 | "green" |
| Equals | Yes | Yes | Equals | Equals | "bold" |  | 5 | "red" |

A diagram of different colored circles

Description automatically generated

Definitions

Structure file: An RS\_DICOM file contining all data used by the program.

* The file must follow the NEMA DICOM StructureSet format (Modality=RS) . ([RT Structure Set CIOD – DICOM Standard Browser (innolitics.com)](https://dicom.innolitics.com/ciods/rt-structure-set))

ROI number: A Region-Of-Interest index number.

* The ROI number provides a reference for a 3D space, kown as a "Structure", which is used for treatment planning.

Slice: An axial plane at a set location and with a specified thickness.

* The location is specified as an offset in the SUP/INF (Z) direction from the DICOM origin.
* Thickness is defined as the sum of half the distance to its two neighbouring slices.
* For end slices (without a neighbour in one direction) Thickness is the distance to the existing neighbour and are assumed to extend a half slice distance beyond the end location.
* Thicknesses are calculated using all slice locations referenced in the structure file.

Contour: A regular closed line defining a polygon.

* The line must define a single area (i.e the line segments do not cross).
* The coordinates of the line points are in 3 dimensions (i.e. have X, Y, and Z coordinates).
* The Z coordinate is expected to be the same for all points in the contour (i.e. limited to an axial plane).
* Each contour has an associated slice (based on its Z coordinate) and an ROI number.

Hole: A contour that defines an area within the external bounds of a larger area, that should be excluded from that larger area.

* A hole contour is always linked to another contour that it is to be subtracted from.

Island: A contour that defines an area within a hole, that should be excluded from hole.

* This concept allows for doughnut shaped holes to exist.
* An island contour is always linked to the same contour that its corresponding hole is linked to.

External Contour: A contour with a given ROI number and slice index, which is not contained within any other contours with the same ROI number and slice index.

* An external contour may be linked with other other contours that are entirely contained within it (Holes and Islands).
* An external contour must not overlap with any other contours with the same ROI number and slice index except its holes and islands.

Convex Hull: A bounding contour generated from an external contour.

* A convex hull can be pictures as an elastic band stretched around the external contour.

Region: A defined area on a given slice.

* A region consists of:
  1. An external contour.
  2. A convex hull contour (generated).
  3. All hole and island contours belonging to the external contour.
* A region is formed by combining a contour with all other ***overlapping*** contours on the same axial plane having the same ROI number.
* The convex hull contour is generated from the region's external contour.

Volume: A collection of regions that define a single 3D surface.

* A volume is formed from all contours with the same ROI number which can be combined to form a single 3D surface.
* A given volume may contain more than one contour per slice.

Structure: A collection of all volumes with the same ROI number in the structure file.

* Structure properties include information regarding the labeling and use of the structure.

StructureSet: A collection of all structures from one RS\_DICOM file.

* StructureSet propertines include information about the associated image set

Relationship: A description of the geometric interaction between two stuctures

* A relationship has a type and metrics
* The type describes how the structures interact
* The metrics quantifty the interactions
* Different metrics are used depending on the type

Maximum Gap: The largest allowable distance (in cm) between neighbouring slices where the contours can still be considered as matched.

This is to help idenify structures with distinct volumes that are SUP / INF of each other.

The gap may be derived from the slice spacing and a maximum number of skipped slices.

Minimum Overlap: The smallest percent overlap between two contours where the contours can still be considered as matched.

Precision: The grid size (in cm) to use for the contours.

* Contour coordinates will be snaped to this grid size.
* It is used to avoid floating point errors when calculating relationships.
* Distance metrics will be rounded to the is precision.