<u>Gamma Knife System for CISC 330</u>

Nick Cheney

SN 20063624

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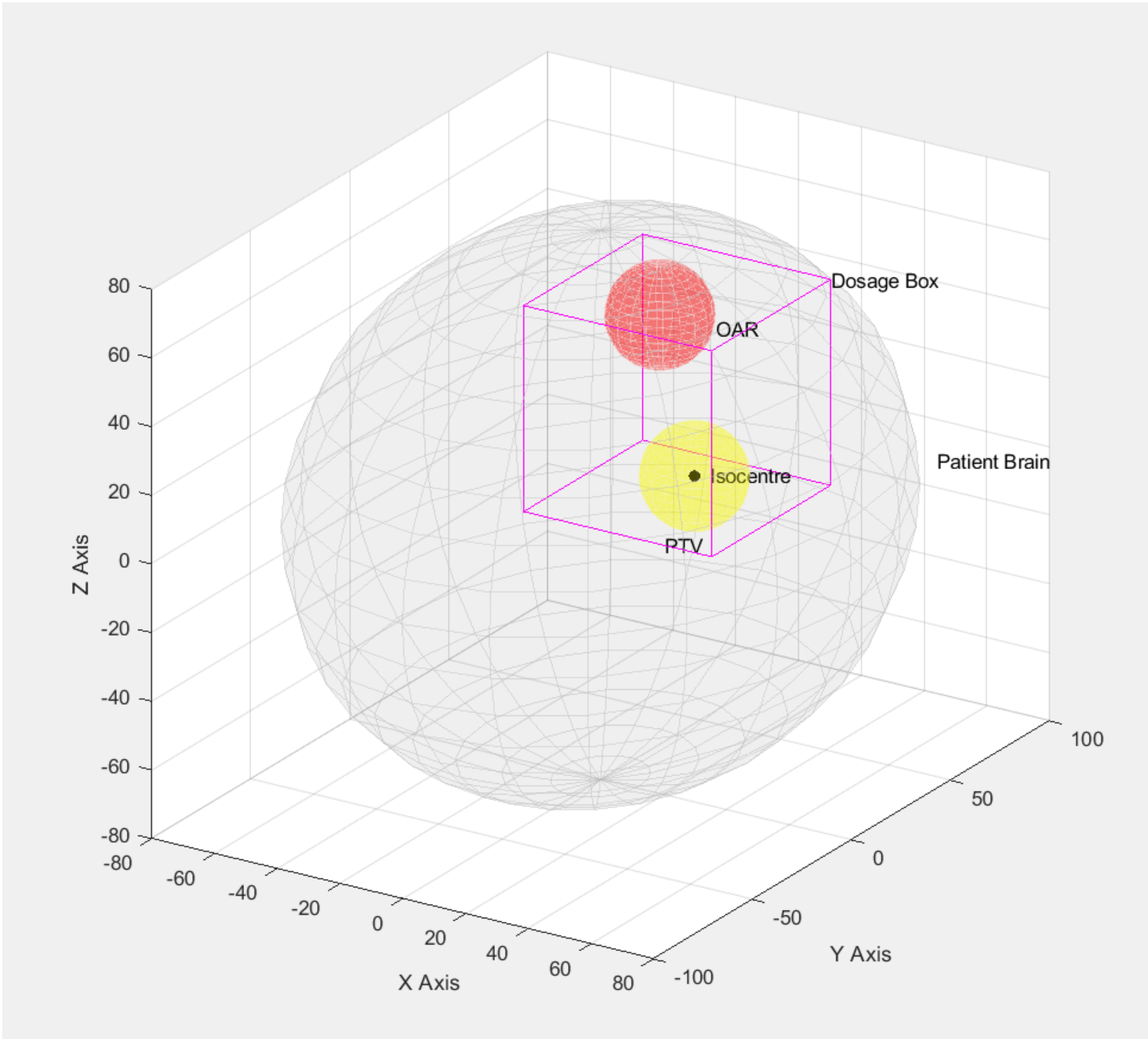
1) Comparing Radiosurgery Modalities

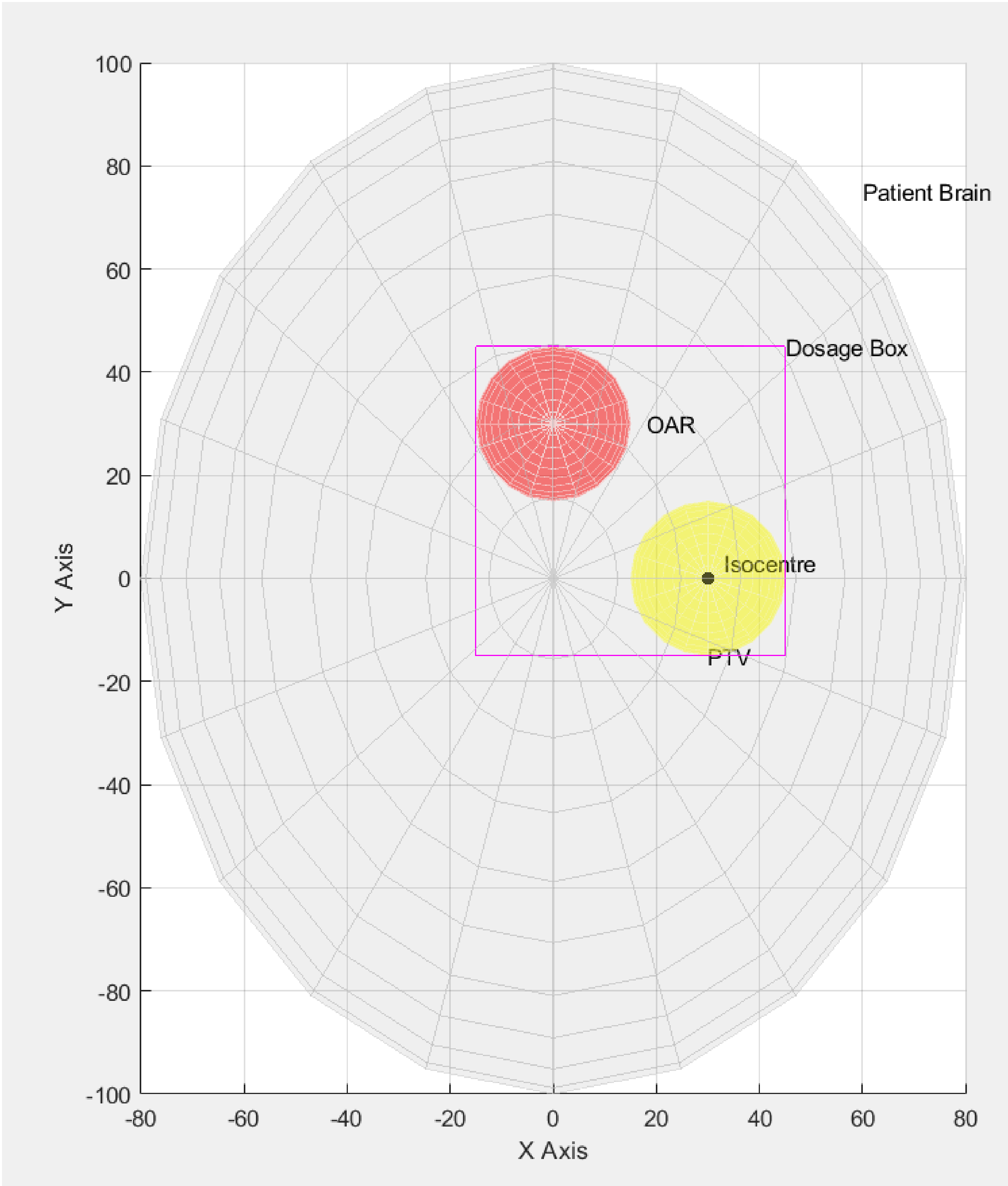
In class, three modalities of radiosurgery were studied: the gamma knife system, standard isocentric LINAC and the Cyber Knife LINAC system. The second two are quite different than the gamma knife, as they rely on high-energy X-Rays, produced by accelerating a beam of electrons then colliding them into a metal foil screen to produce an electron beam, rather than relying on Gamma Rays from Cobalt-60 sources. In isocentric LINAC, there is one high powered (25 million volts) X-Ray source, which is quite powerful and can be seen as a pro or a con. In this treatment, the machine must be placed in a lead bunker to protect staff against straying radiation, and it requires an expensive liquid cooling and shielding system. Also, since there is only one source which rotates along a single axis, a complex mechatronic system is required to help orient the patient in a sufficient number of poses. Also, like the gamma knife, a head frame is required to hold the patient in place for imaging and calibration, and during the procedure. Because the X-Ray source is quite powerful, the treatment is usually done in a single shot and not fractioned. The cyber knife operates on a similar principle, again using X-Rays from a linear accelerator system, but this time having two point sources with weaker strengths each (6 million volts apiece vs 25 million earlier). In some cases, unlike the gamma knife and standard LINAC, a head frame is not required as the patient is more lightly immobilized with a thermoplastic face mask, and a optical tracker can keep an eye on patient movements. In terms of accuracy, the gamma knife is still the most precise as it’s calibration systems are usually fixed in place due to the mechanical setup, whereas the cyber knife’s calibration is more relative and involves more computations. Thus, the gamma knife is accurate to 0.15 mm while the cyber knife is only precise to 1.10 mm. Also, the cyber knife is decades newer than the gamma knife, and thus there is less clinical data available on the system. But, an advantage over the gamma knife is that it is designed for surgeries over the whole body, while the gamma knife is specialized for small brain tumours only.

3) Draw 3D Scene

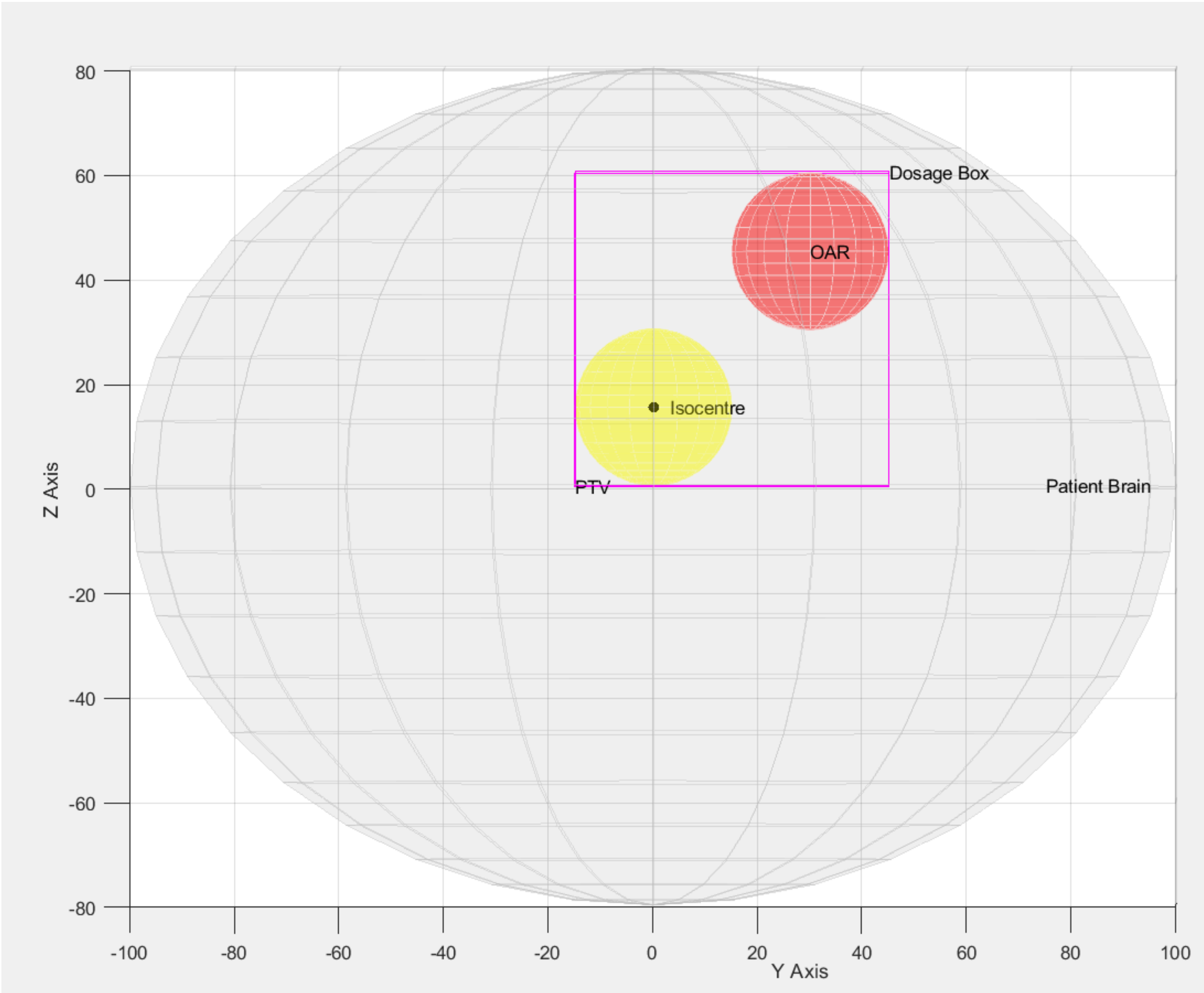
As shown in the views of the scene below, the dosage box was properly computed and tightly wraps the OAR and PTV

.


Dosage Box
OAR
Isocentre
PTV
Patient Brain
Z Axis
X Axis
Y Axis
80
60
40
20
0
-20
-40
-60
-80
-80
-60
-40
-20
0
20
40
60
80
100
50
0
-50
-100



Patient Brain
Dosage Box
OAR
Isocentre
PTV
Y Axis
X Axis
100
80
60
40
20
0
-20
-40
-60
-80
-100
-80
-60
-40
-20
0
20
40
60
80



4) Estimate Dose

Dose Estimation

To estimate the dose to the OAR and isocenter (aka centre of PTV), we first need to consider the geometry of the helmet as a hemisphere:

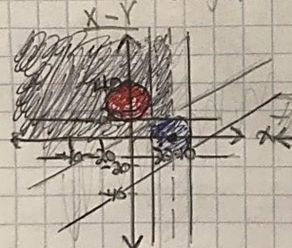
To place beam point sources, add lines of latitude and longitude at every 30° like so and add points at the crosshairs:

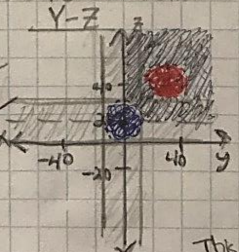
Thus, in total there would be $N = 12 \times 3 + 1 = 37$ beam sources to consider.

From the 3-D plot from question 3 above, we can see the isocenter is positioned at the centre of the PTV, and since all beams will focus on it, the isocentre dosage can be approximated by:

$\#$ of non-plugged beams $\times D_0 \times DAF(d_{av})$ where d is the average isocentric beam depth beneath the skin.

Since we don't want any beams to pass directly through the OAR, we can approximate the space to be plugged on the helmet through the following views (note beam radius = PTV radius)

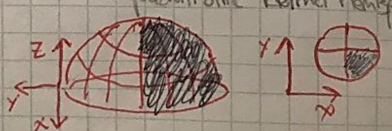




and a similar for X-Z.

The shaded regions are where beam central lines cannot be placed to avoid contact with the OAR.
beam

This ends becoming approximately a quadrant of the helmet hemisphere:



But note all beams originating in the X-Y quadrant are safe!
Thus, we can approximate the number of plugged holes as $\frac{(37-12)}{4} = 6.25$

to get average beam depth to isocentre, we can crudely estimate by averaging the X and Y half-axis values of the head with the Z half-axis value − Z component of isocentre coordinate (since only the top hemisphere of the brain is contained within the helmet). Thus,

$$d_{av} = \frac{80mm + 100mm + (80mm - 15mm)}{3} = 81.7mm$$

We can now estimate the dose at the isocentre:

47/,=4

$$D_i(81.7, 0) = (37 - 6.25)(1)(DAF(81.7))$$
$$= 21.279$$

Next, we need to estimate the maximum dosage in the OAR. This is most likely to be on the closest OAR point to the isocentre due to radial dose leakage. Find this point using a direction vector between the isocenter and the OAR center and the OAR radius:

$$v = \frac{\text{isocenter} - \text{OAR centre}}{|\text{isocentre} - \text{OAR centre}|} = \frac{(30, 0, 15) - (0, 30, 45)}{\sqrt{30^2 + (-30)^2 + (15-45)^2}} = \frac{(30, -30, -30)}{51.962}$$

$$v' = R_{OAR} * v$$

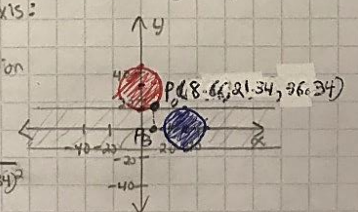
$$v' = 15 * \frac{(30, -30, -30)}{51.962} = (8.66, -8.66, -8.66)$$

Adding this to centre of OAR we get: (8.66, 21.34, 36.34)

We can estimate a single beam dose hitting this point via a beam that runs along the x-axis:

By inspection, the closest point on the beam is (8.66, 0, 15), and the distance between the two is $|P_0 - P_B|$

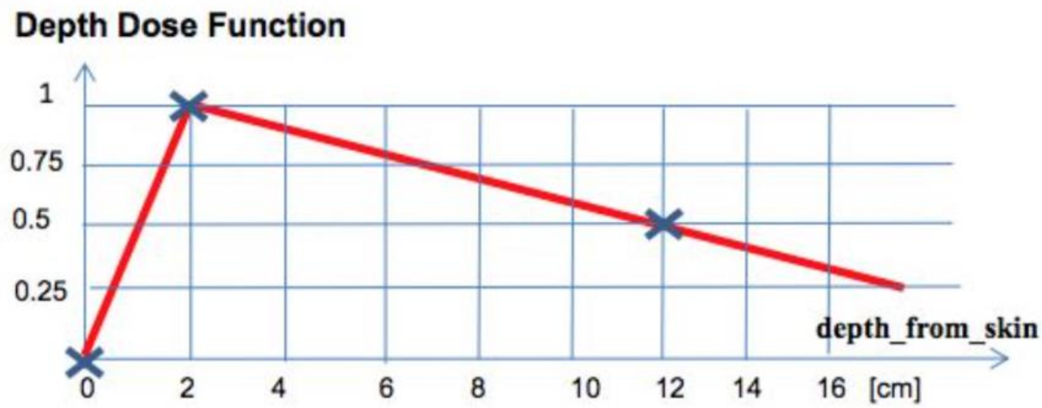
$$= \sqrt{0 + (21.34)^2 + (21.34)^2}$$
$$= 30.18$$



By the radial dose function, at this radius no dose would enter the OAV point. Thus, the maximum dose at any point in the OAV should be close to zero. This OAV dose is much less than the D_{OARM} of 10, and the earlier isocentre dose of 21.271 was over the D_{100} of 20, so the treatment plan looks to realistically achieve it's goals, ensuring in the actual calculations that beams touching the OAV sphere are plugged.

5) Compute Dose Absorption Function Table

Using the linear function for dose absorption per depth in the assignment, we can see from d = 0 to d = 20mm the dosage increases at 0.025 units per mm, starting at 0.5 units, and then decreases at 0.005 units per mm:



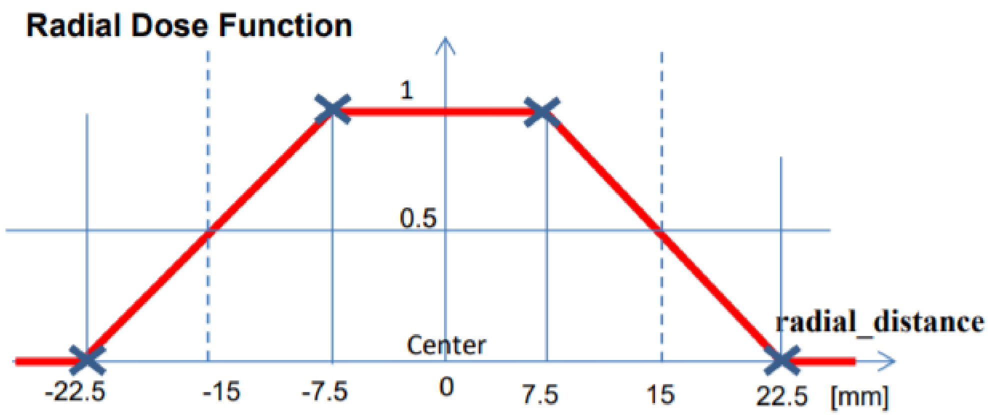
The computed table matched this function:

0	0.5000
1.0000	0.5250
2.0000	0.5500
3.0000	0.5750
4.0000	0.6000
5.0000	0.6250
6.0000	0.6500
7.0000	0.6750
8.0000	0.7000
9.0000	0.7250
10.0000	0.7500
11.0000	0.7750
12.0000	0.8000
13.0000	0.8250
14.0000	0.8500
15.0000	0.8750
16.0000	0.9000
17.0000	0.9250
18.0000	0.9500
19.0000	0.9750
20.0000	1.0000
21.0000	0.9950
22.0000	0.9900
23.0000	0.9850
24.0000	0.9800
25.0000	0.9750
26.0000	0.9700
27.0000	0.9650
28.0000	0.9600

etc…

6) Compute Radial Dose Function Table

Using the radial dose function from the notes, we can see below r = -22.5 the function is zero, from -22.5 to -7.5 the function increases by 1/15 unit per mm, from -7.5 to 7.5 the function result remains 1, from 7.5 to 22.5 the function decreases from 1 by 1/15 unit per mm, and above 22.5 it is zero again:



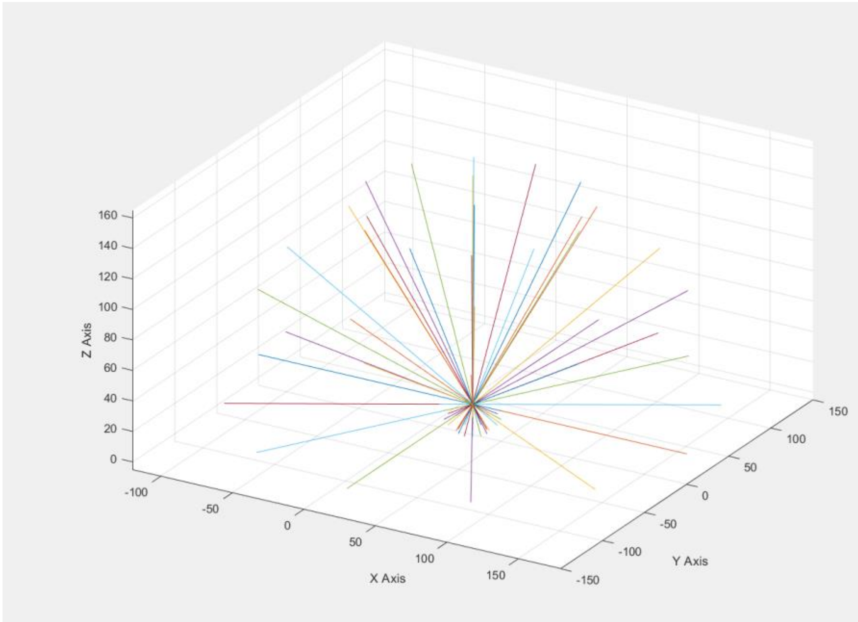
The computed table matched this function:

-23.0000	0
-22.0000	0.0333
-21.0000	0.1000
-20.0000	0.1667
-19.0000	0.2333
-18.0000	0.3000
-17.0000	0.3667
-16.0000	0.4333
-15.0000	0.5000
-14.0000	0.5667
-13.0000	0.6333
-12.0000	0.7000
-11.0000	0.7667
-10.0000	0.8333
-9.0000	0.9000
-8.0000	0.9667
-7.0000	1.0000
-6.0000	1.0000
-5.0000	1.0000
-4.0000	1.0000
-3.0000	1.0000
-2.0000	1.0000
-1.0000	1.0000
0	1.0000
1.0000	1.0000
2.0000	1.0000
3.0000	1.0000
4.0000	1.0000
5.0000	1.0000
6.0000	1.0000
7.0000	1.0000
8.0000	0.9667

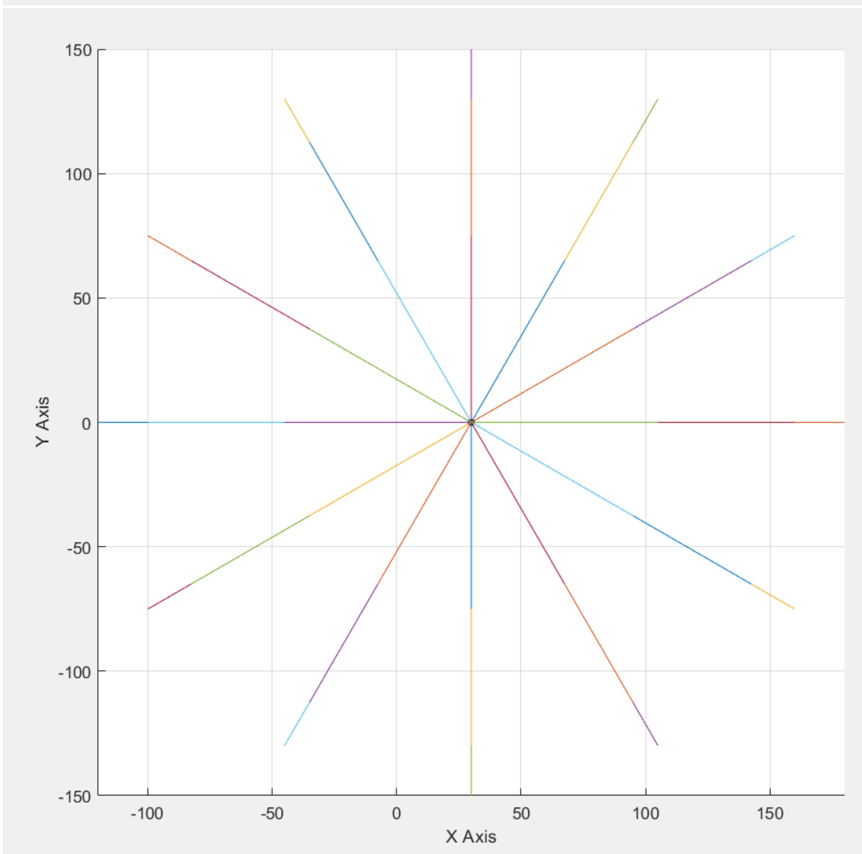
9.0000	0.9000
10.0000	0.8333
11.0000	0.7667
12.0000	0.7000
13.0000	0.6333
14.0000	0.5667
15.0000	0.5000
16.0000	0.4333
17.0000	0.3667
18.0000	0.3000
19.0000	0.2333
20.0000	0.1667
21.0000	0.1000
22.0000	0.0333
23.0000	0

7) Compute Beam Directions

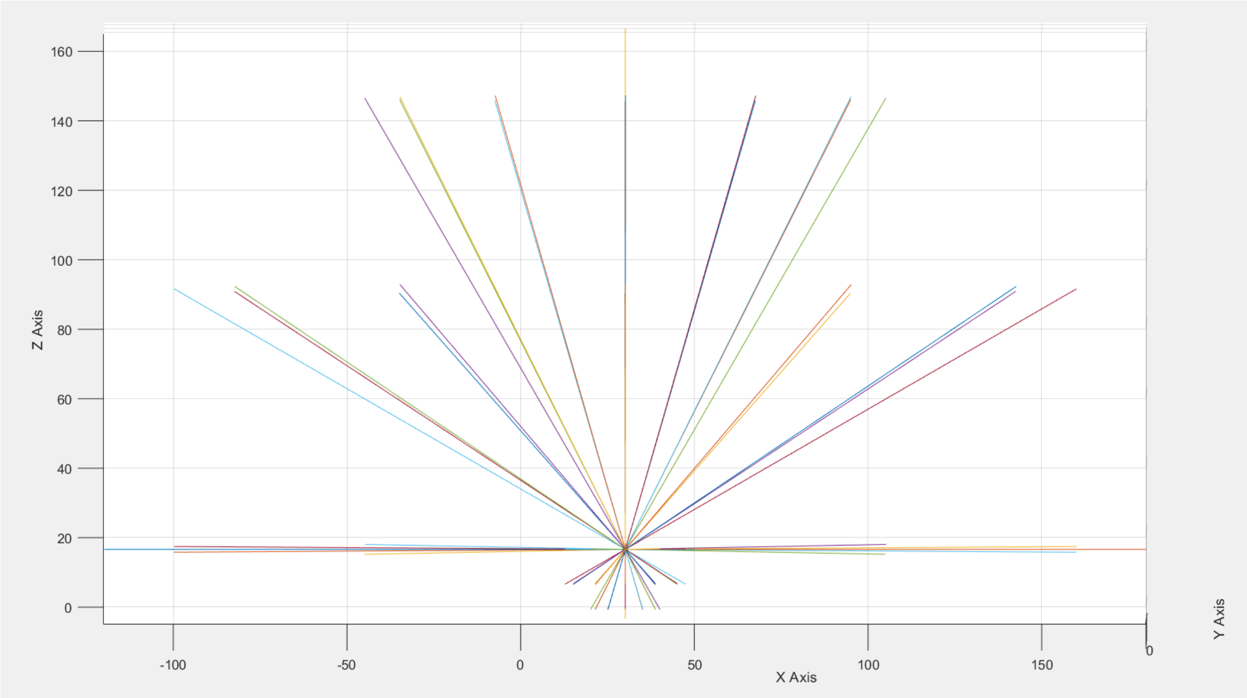
Produced 3-D scene shows that beams are initialized as expected, with a separation of 30° between both polar coordinates:



Z Axis
X Axis
Y Axis

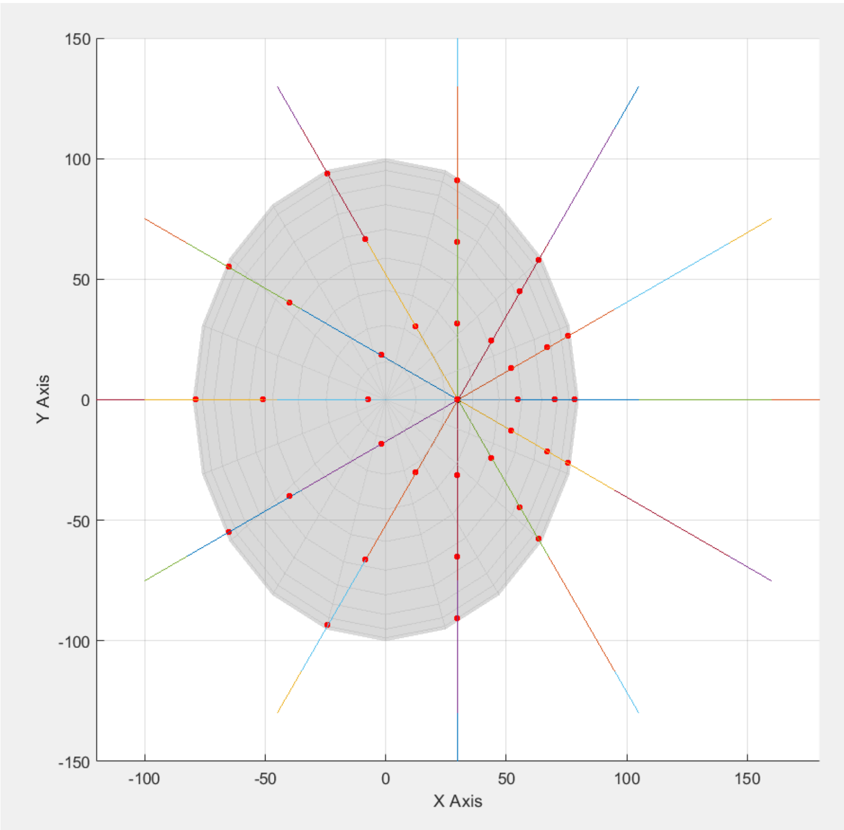


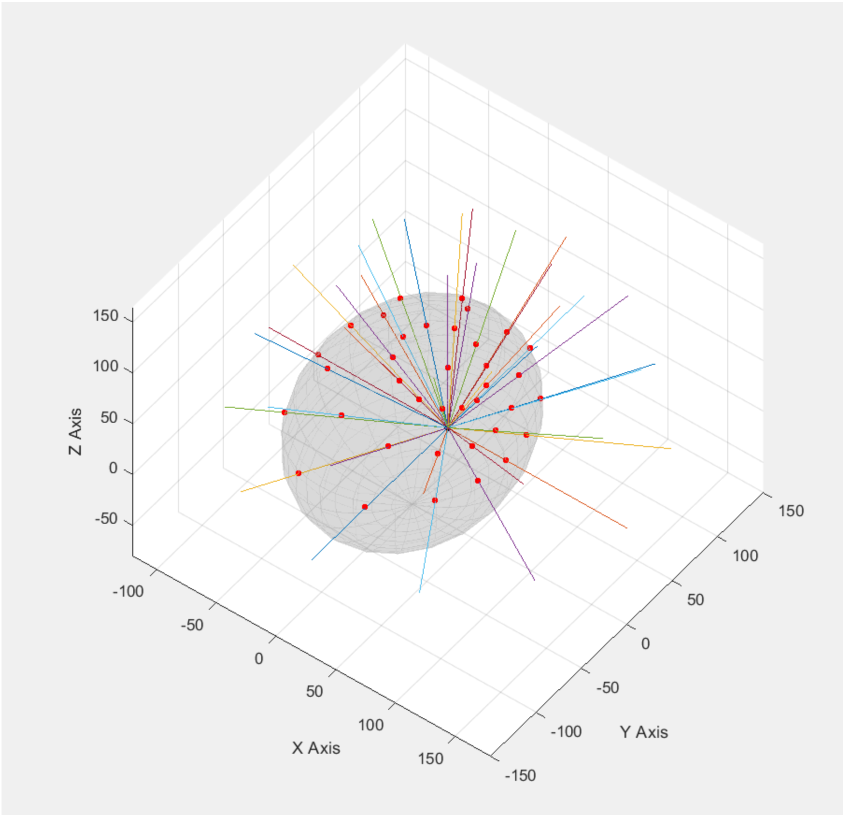
Y Axis
X Axis



8) Compute Skin Entry Points

The beam safety flags were successfully computed at the correct intersections of the head and each beam, as can be verified through the following views:



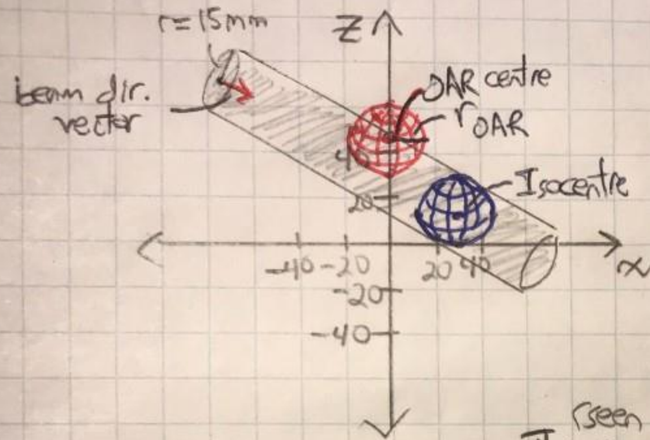


9) Compute Beam Safety Flags

My approach for this question is shown below:

Compute Beam Safety Flag

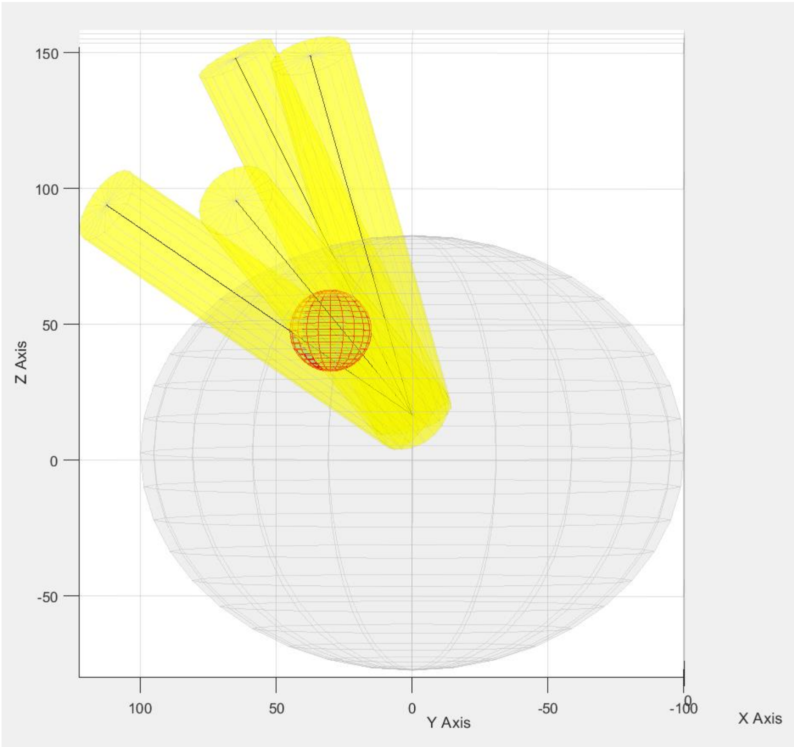
A "hit" on the OAR is registered when a beam (represented as a cylinder) overlaps part of the OAR sphere, like so:

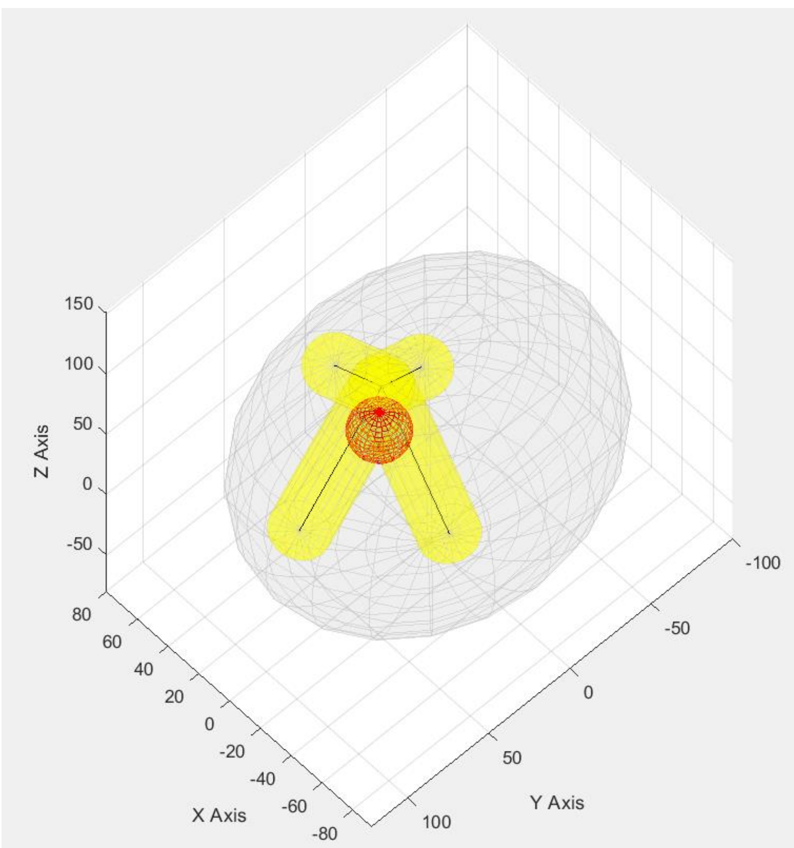


(seen from perspective of y-axis)

This can be determined using the Intersect Sphere-and-Cylinder() function from assignment 1, with the OAR centre and radius, PTV centre/isocentre, beam radius (beam diameter/2), and beam direction vector.

The unsafe beams, overlapping the OAR, were successfully flagged, as verified by the view below:





10) Compute Radial Distance

The ground truth test using the beam with 90° latitude was passed:

```
-------------Running Compute_Radial_Distance Script---------------
Radial distance (should be 15): 15
```

11) Compute Depth from Skin

The ground truth test using the beam with 90° latitude was passed:

```
-------------Running Compute_Depth_from_Skin Script---------------
Point depth from skin (should be 59.162): 59.162
```

12) Compute Point Dose from Beam

Program produces expected output, ascertaining correctness:

```
------Running Compute_Point_Dose_from_Beam_Testing Script-------
Point dose value is the same as DAF at isocentre for all beams
```

See testing script for more details.

13) Compute Point Dose from All Beams

Program produces expected output, ascertaining correctness:

```
----Running Compute_Point_Dose_from_All_Beams_Testing Script----
Computed Net Point Dose equals sum of beam-point DAFs at isocentre
```

See testing script for more details.

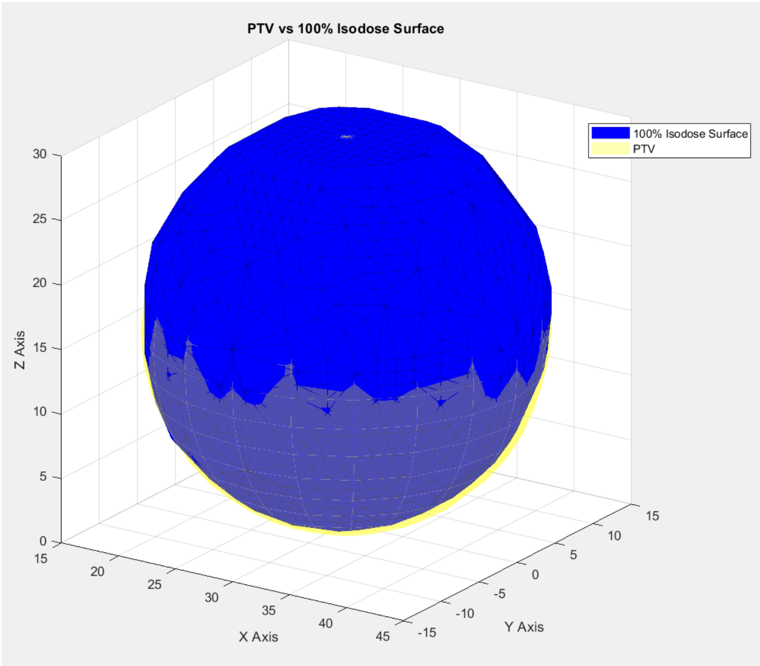
14) Compute Dose

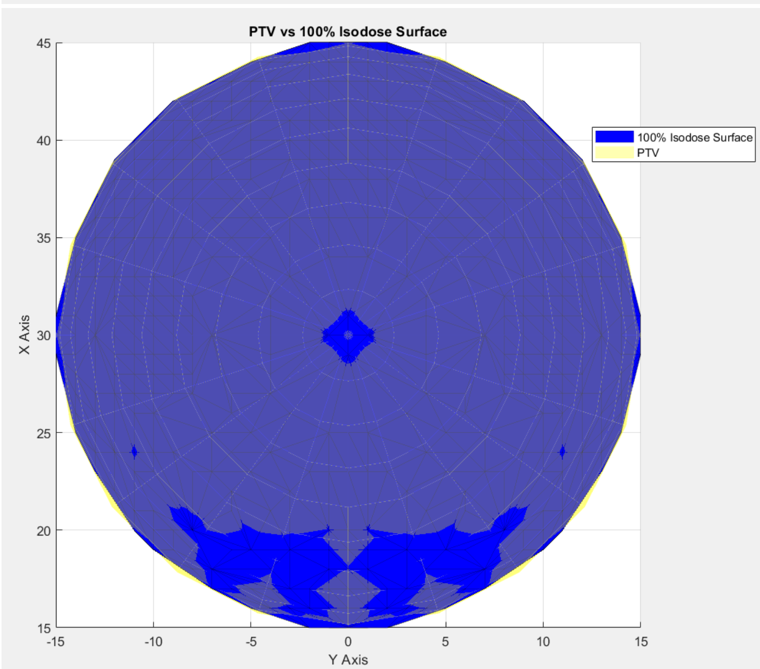
Computation of the Dose Box was performed separately for the OAR and PTV, and the overall function took 1:24 min to run.

15) Dosimetry Analysis

<u>100% Isodose Surface vs Tumor</u>

Below are plots of the 100% isodose surface and the tumor (margin = 1 mm, can be set higher to save time)

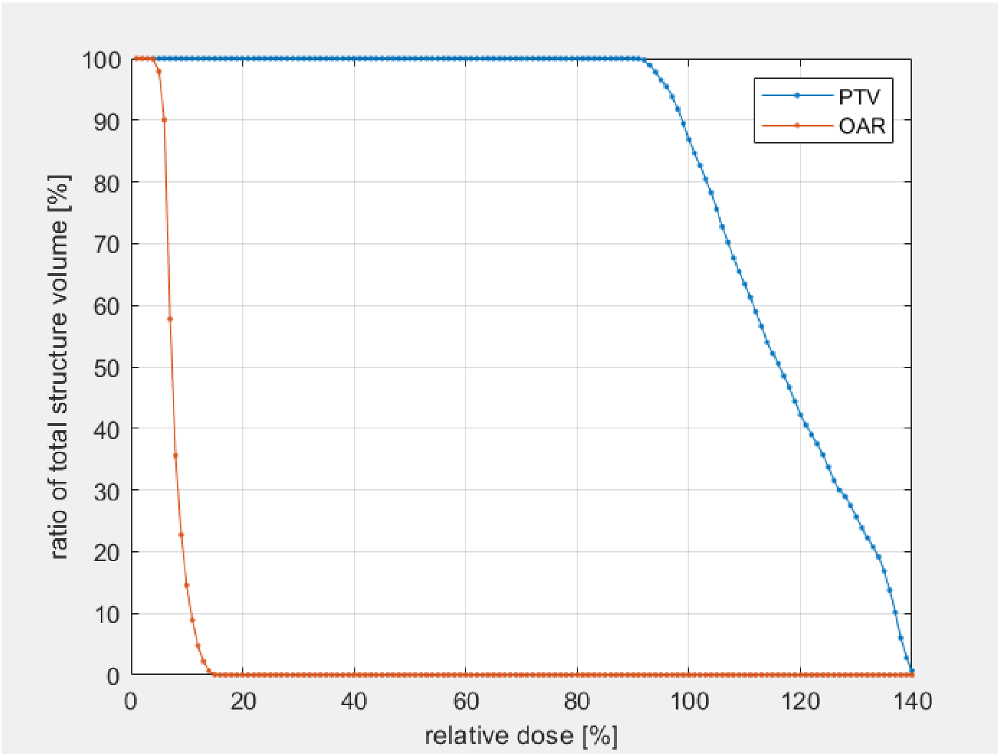




As can be seen above, the isodose surface is roughly 40% beneath the tumor exterior, meaning not 100% of the tumor is provided with the goal dosage of 20 units.

Dose Volume Histograms

Next, the dose volume histograms were plotted for the PTV and OAR:



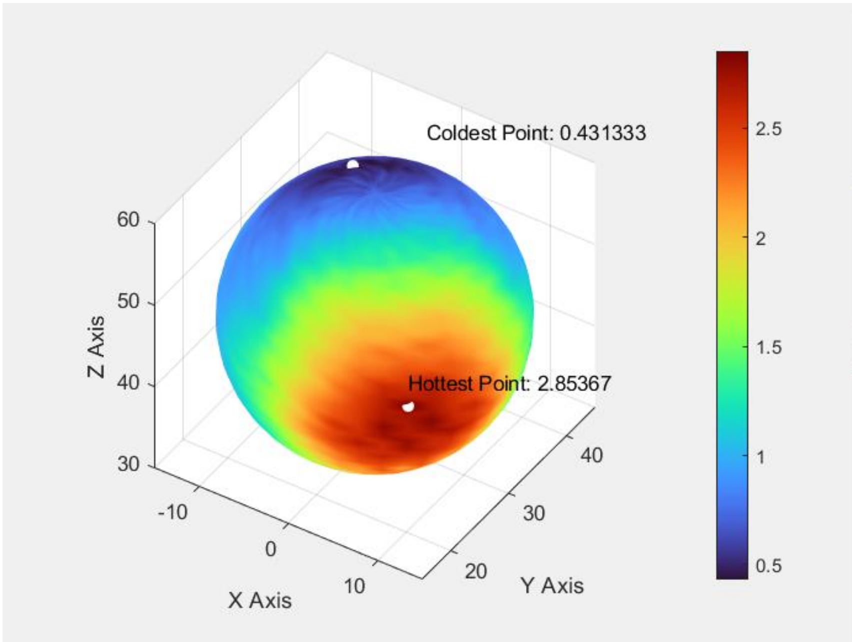
Optimizing Treatment Plan

Analysing the above DVHs, it appears that for the PTV, at least 90% of the tumor is completely provided with the prescribed dose, albeit with about 87% of the tumor receiving an excessive amount of radiation. On the other hand, the OAR completely receives safe levels of radiation, with no part of it exceeding 15% of the relative dose, in this case 30% of the maximum safe dosage for it. Thus, to optimize the treatment plan we can unplug some of the 4 beams plugged, allowing some direct contact with the OAR. This would still allow the OAR to be under its safe limit of 10 units, even with all four beams unplugged (as the current OAR maximum is 3-4 units), and simultaneously allow the ~10% of the PTV not receiving the full dosage to receive more radiation and meet the requirement.

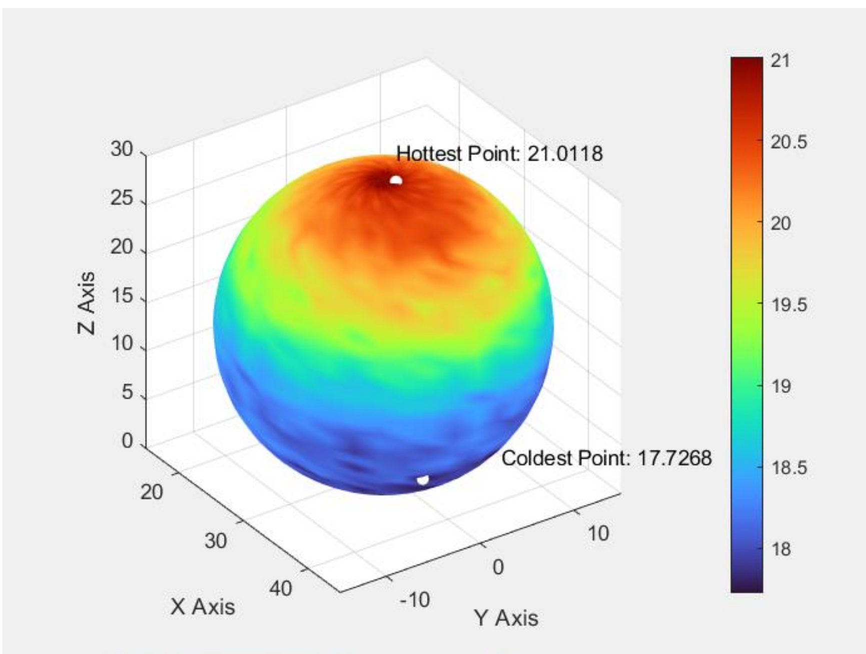
16) Compute Surface Dose

The hottest and coldest points on the OAR and PTV were successfully computed and plotted as shown below:

OAR



PTV



The point locations and values were also printed to the console:

```
--------------Running Compute_Surface_Dose Function--------------
Hottest point on PTV: (30.95, 0.69, 29.95)   Dosage: 21.01
Coldest point on PTV: (41.54, -3.75, 6.18)   Dosage: 17.73

Hottest point on OAR: (10.57, 19.43, 46.18)  Dosage: 2.85
Coldest point on OAR: (-4.64, 33.37, 58.86)  Dosage: 0.43
```