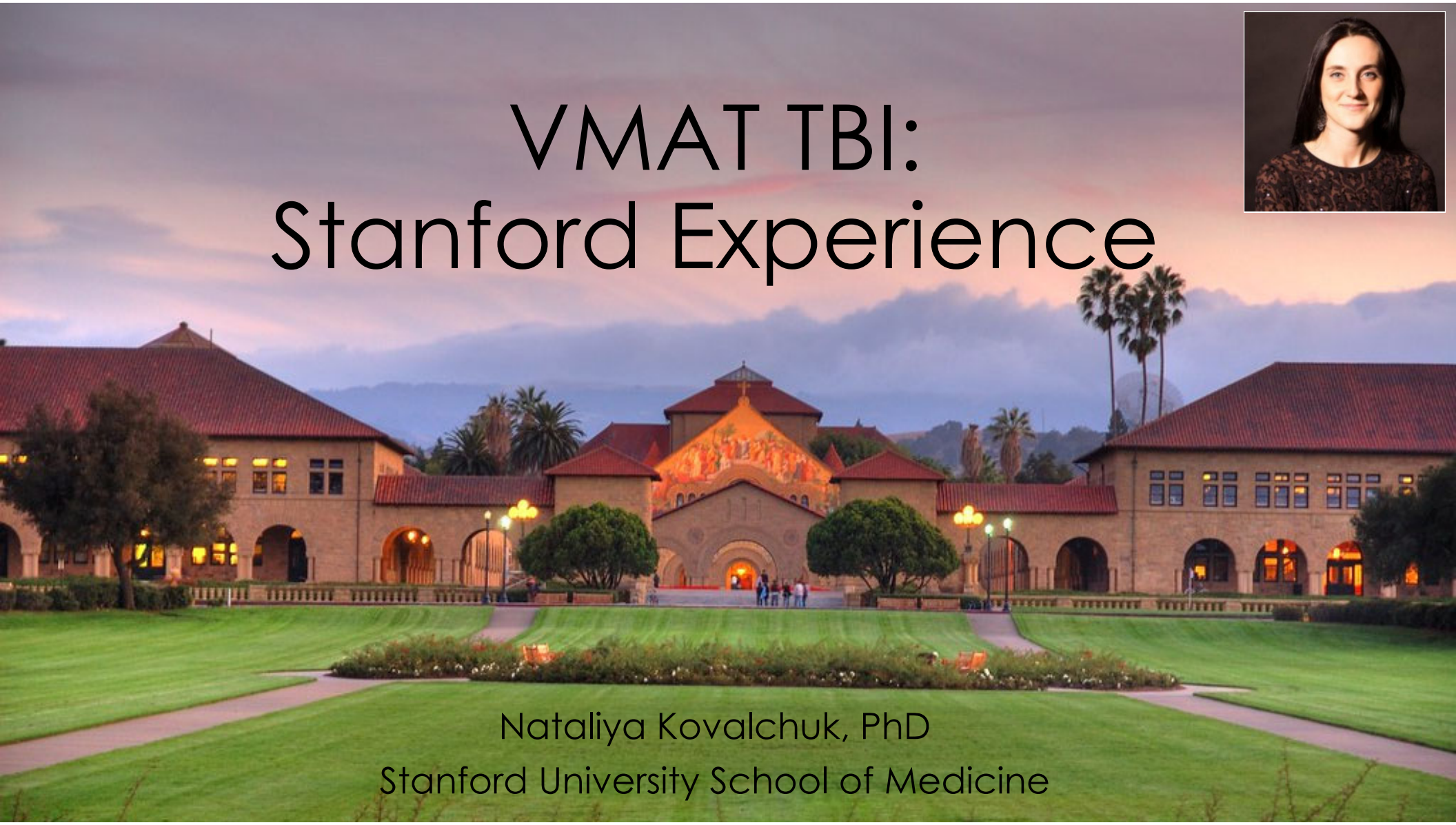


# VMAT TBI: Stanford Experience



Nataliya Kovalchuk, PhD
Stanford University School of Medicine

# Outline

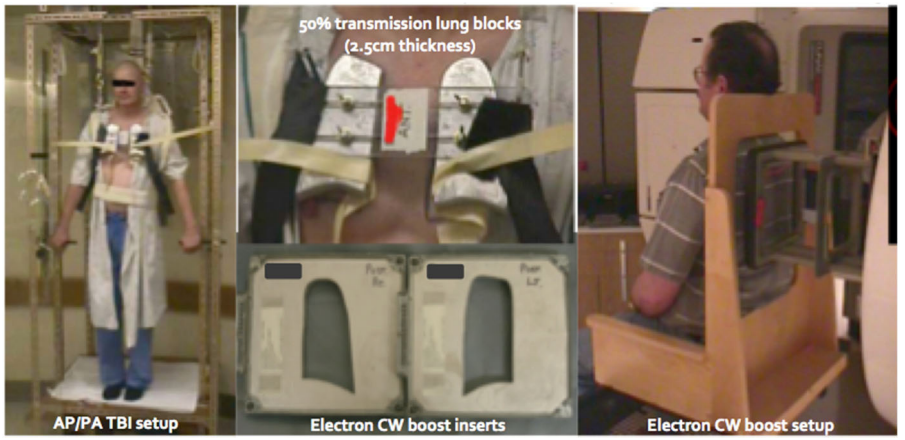
- Stanford TBI patient volume and existing conventional techniques
- Challenges of 2D TBI techniques
- Stanford VMAT TBI Process:
  - Simulation on rotational platform
  - Treatment planning:
    - Dosimetric comparison between VMAT and 2D plans
    - Automation of treatment planning
    - Dosimetric comparison between auto-plans and manual plans
  - Treatment QA and delivery
- Conclusions

# Stanford conventional TBI techniques

- Annual patient volume in 2018:

| | | |
|---|---|---|
| **Total TBI patients** | **163** | |
| Single fx | 67 | 41% |
| >1 fx | 96 | 59% |
| Adult | 127 | 78% |
| Pediatric | 36 | 22% |

- 3 conventional techniques used:
  - AP/PA standing @~5.7m SSD +/- lung blocks and CW boosts
  - RLat/LLat sitting @~5.7m SSD, no lung blocks
  - AP/PA @~2m SSD on the floor for young peds, lung blocks

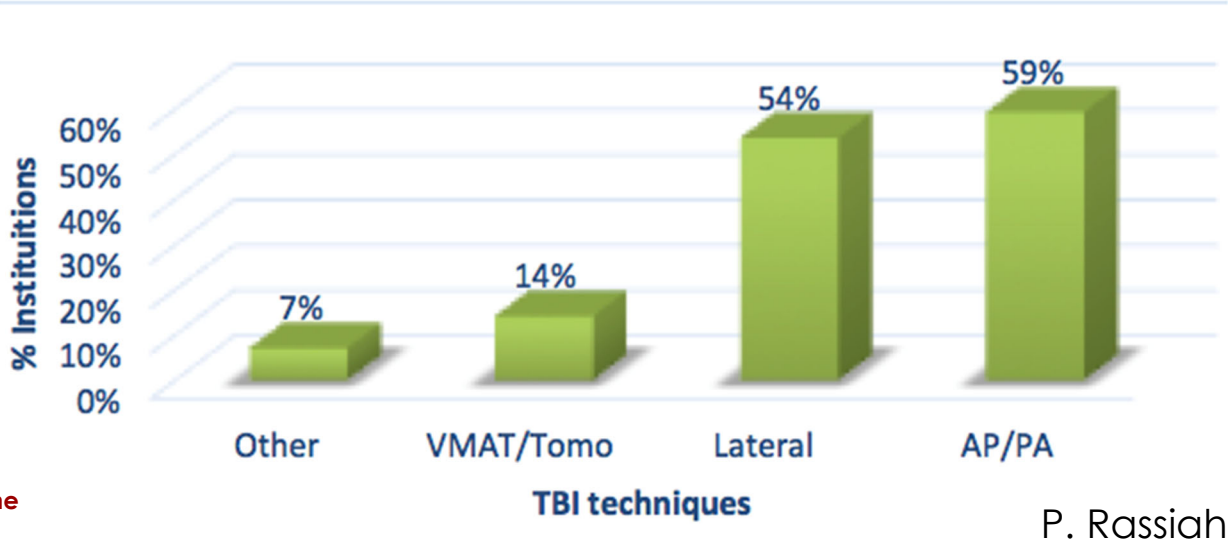



# Challenges with 2D TBI technique

- Uncomfortable for frail patients in standing position
- Unable to treat older children requiring anesthesia
- Extra-large vault is required for 2D technique
- Compensator generation/block cutting required for photon/electron fields
- Tedious simulation and planning requiring caliper measurements and manual entry of planning parameters – highly error-prone process
- Large dosimetric uncertainty

# Children's Oncology Group (COG) survey

- COG TBI workgroup conducted survey in 2020 on TBI techniques for physicists and physicians
- 75% of physicians (n=85) would like to introduce VMAT or Tomo TBI in their clinics
- 100% of physicians would like to reduce the lung dose for myeloablative regimens
- Only 6 US institutions adapted VMAT TBI and 3 institutions adapted Tomo TBI



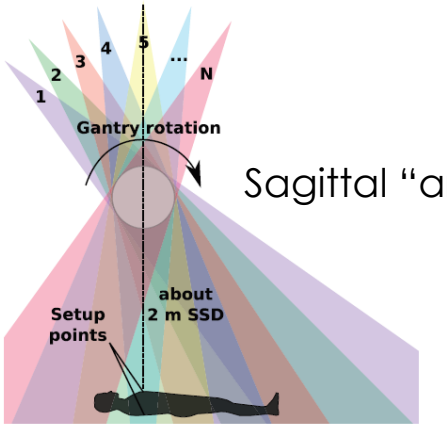



P. Rassiah et al, IJROBP 2020

# Intensity-modulated TBI

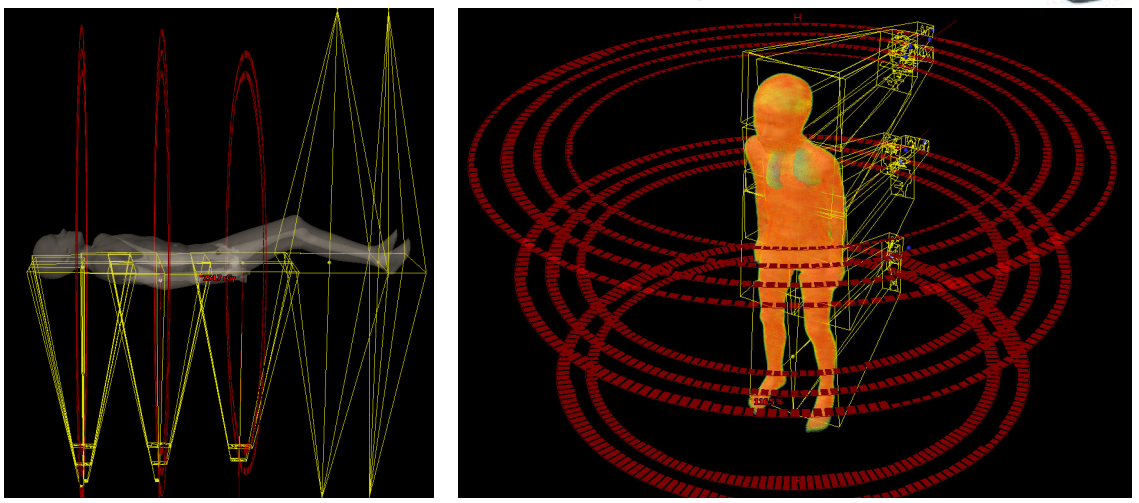
- Modern treatment planning and treatment techniques in TBI
  - Helical Tomotherapy (UW-Madison, City of Hope, U of Arkansas)
  - Single isocenter sagittal arc composed of >20 static beams with patient on the floor (UCSF)
  - Multi-isocenter, axial VMAT-based technique (UTSW, Cleveland Clinic, City of Hope, Ohio State, Toledo, U of Alabama, Stanford)

Tomo




Sagittal "arc" UCSF

FIG. 1. Supine patient setup for modulated-arc total body irradiation with N beams.



Axial VMAT TBI at Stanford

# Patient selection criteria for VMAT TBI at Stanford

- Patients under anesthesia
- All pediatric patients on reduced intensity regimen (gonadal sparing)
- Patients that are unable to stand for prolonged period
- Patients on scleroderma trial
- Patients with prior treatments and need of OAR sparing
- Patients requiring simultaneous boosts

# Stanford VMAT TBI: SIM

- Full body scan in whole body bag on Siemens PET/CT scanner with 4-5 mm slice thickness
- Knee fix, foot fix, arms tight to the body
- Matchline b/w HFS and FFS determined at SIM:
  - Patient height ≤ 115 cm – VMAT only (3 isocenters)
  - Patient height > 115 cm – VMAT (3 isocenters) + AP/PA(1-2 isocenters) on Spinning Manny

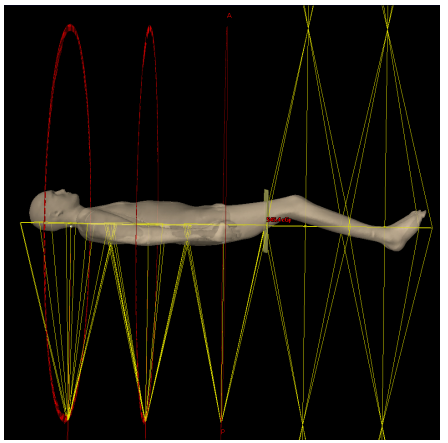



**Figure 1**. In-house developed rotational couch-top enabling patient position transition from HFS to FFS.

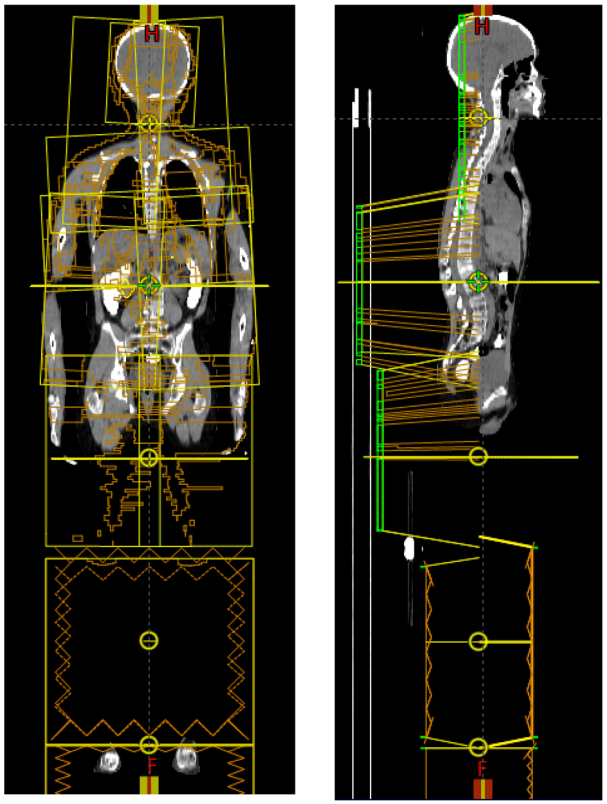
# Stanford VMAT TBI: Contouring

- **Myeloablative regimen:** sparing lungs, kidneys, lenses
- **Reduced Intensity Conditioning:** sparing lungs, kidneys, lenses, brain, thyroid, ovaries/testes
- PTV_Body = (Body-3 mm) – (Lungs+3 mm) – Kidneys – [other OARs]
- 5 mm flash/bolus is added during optimization

| Name of Structure | Description |
|---|---|
| Human_Body | Search BODY in Eclipse |
| Human_Body-0.3cm | 0.3 cm inner margin |
| Lungs | Lungs, remove tiny islands |
| Lungs_Eval | Lungs – 1cm |
| Lungs-2cm | Lungs – 2cm |
| Kidney_R/L, Kidneys | Kidneys, remove tiny islands |
| Kidneys-1cm | Kidneys-1cm |
| Ovary_R/L | Ovaries |
| Scrotum, Testes | Scrotum, Testes |
| Brain | Brain, remove tiny islands |
| Brain-0.5cm | Brain-0.5cm |
| Brain_Eval | Brain-1cm |
| Brain-2cm | Brain-2cm |
| Brain-3cm | Brain-3cm |
| PTV_Body | (Human_Body-0.3cm) – Kidneys– (Lungs+0.3cm) – (Ovaries+1cm include bone) or (Scrotum+2cm) – (Brain-0.5cm) |
| Matchline | Plane at the level of pivot bolt center |
| TS_PTV_VMAT | Cut PTV_Body at matchline, crop 0.5cm from skin |
| Bowel | Bowel bag |
| Lens_R/L | Lenses |
| Skin | 3mm from Human Body |

# Stanford VMAT TBI: Beam Placement

- 3 VMAT isocenters in HFS – 6MV/10MV (head, chest, pelvis)
- 1-2 AP/PA isocenters in FFS – 6MV (upper legs, lower legs)
- Pelvis VMAT iso and Upper Leg AP/PA iso's are equidistant from matchline
- >=2-5 cm overlap in junctions for VMAT
- Head iso (3-4 arcs)
- Chest iso (3-4 arcs)
- Pelvis iso (2-4 arcs)
- Skin match for AP/PA
- AP/PA fields have $90^0$ coll for FiF



# Stanford VMAT TBI: Optimization

- FiF for AP/PA
- Set AP/PA dose as base for VMAT optimization
- Optimizer auto-feathers beam junctions in VMAT
- Dose rate at 100-200 MU/min for Head/Chest iso to keep average dose rate <20 cGy/min for lungs

| Structure | Dosimetric parameter | Limit (2 Gy Rx) | Limit (12 Gy Rx) |
|---|---|---|---|
| PTV_Body | D90%>= | 200 cGy (100%) | 1200 cGy (100%) |
| | Dmax<= | 240 cGy (120%) | 1440 cGy (120%) |
| | V110%<= | 5% | 5% |
| Lungs_Eval (Lungs-1cm) | Dmean<= | 90 cGy (45%) | 540 cGy (45%) |
| Lungs | Dmean<= | 120 cGy (60%) | 720 cGy (60%) |
| Kidneys | Dmax<=<br>Dmean<= | 210 cGy (105%) | 1260 cGy (105%)<br>720 cGy (60%) |
| Bowel | Dmax<= | 210 cGy (105%) | 1260 cGy (105%) |
| Lenses | Dmax<= | 180 cGy (90%) | 1080 cGy (90%) |
| Testes/ovaries | Dmean<=<br>Dmax<= | 50 cGy (25%)<br>ALARA (required <100 cGy) | |
| Brain_Eval (Brain-1cm) | Dmean<= | 150 cGy (75%) | |
| Thyroid | Dmean<= | 150 cGy (75%) | |

# Stanford VMAT TBI: QA and Treatment Delivery

- QA: portal dosimetry Gamma>90% within 3%/2mm; Mobius 3D Gamma>90% within 3%/3mm
- kV/kV match for Chest iso, CBCT
- Fill out final parameters for Couch positions in Shift Spreadsheet
- MV port added to arc after each iso shift for verification
- Treatment time: 35 – 57 min for 25 patients treated since Oct 2019
- Nanodots on matchline

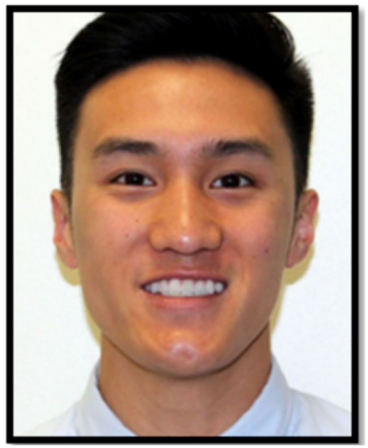
| | Couch Vert | Couch Long | Couch Lat |
|---|---|---|---|
| Chest final (CBCT) | -14.5 | 97.7 | 0.0 |

| Plan | Couch Vert | Couch Long | Couch Lat |
|---|---|---|---|
| Head | -14.5 | 62.7 | 0.0 |
| **Chest** | **-14.5** | **97.7** | **0.0** |
| Pelvis | -14.5 | 133.7 | 0.0 |
| Flip the patient, remember to change Couch LAT to opposite sign | | | |
| Upper Legs | -14.5 | 133.7 | 0.0 |
| Lower Legs | -14.5 | 95.7 | 0.0 |

| | Long Shift from SUP to INF | | Long Shift from CT ref (enter with the sign) | |
|---|---|---|---|---|
| | Shift, cm | direction | Shift, cm | direction |
| shift from CT ref to Head | 47 | SUP | **47** | SUP |
| shift from Head to Chest | 35 | INF | **12** | SUP |
| shift from Chest to Pelvis | 36 | INF | **-24** | INF |
| | | Flip the patient | | |
| stay at same CouchLong as Pelvis | 0 | | **62** | INF |
| shift from Upper Legs to Lower Legs | 38.0 | INF | **100** | INF |

***Bars out***
VMAT TBI setup per procedure. Please ensure the matchline on Spinning Manny and the bag matches
TT=-14.5 for all plans
Dosimetric shifts SUP to INF:
Head iso shift from CT ref 47 cm SUP
Chest iso shift from Head iso 35 cm INF (12 cm SUP from CT ref)
Pelvis iso shift from Chest iso 36 cm INF (24 cm INF from CT ref)
Rotate Spinning Manny, shift to opposite Couch Lat
Upper Leg iso - same Couch Lng as Pelvis iso
Lower Leg iso shift from Upper Leg iso 38 cm INF (100 cm INF from CT ref)

# Comparison between 2D and VMAT TBI

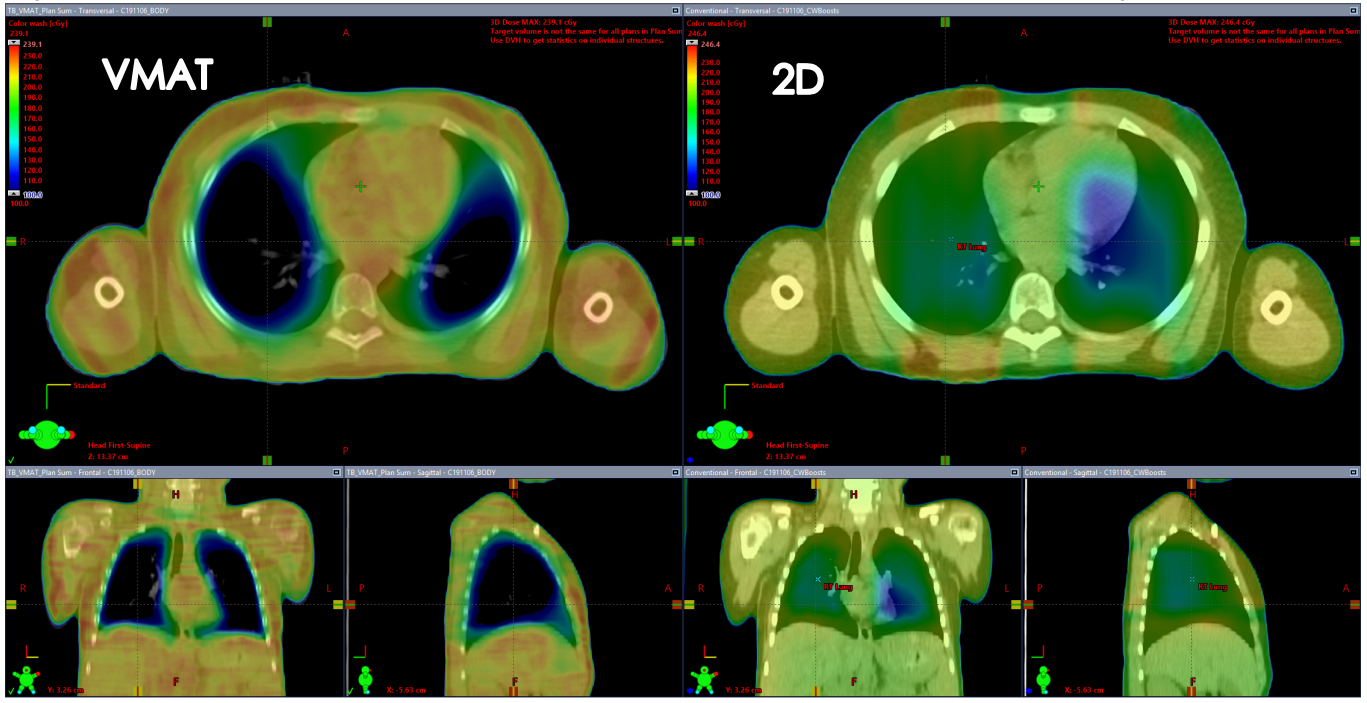


Nic Ngo

Stanford University School of Medicine

# Comparison between 2D and VMAT TBI

- For 10 patients treated with VMAT TBI conventional 2D TBI plans were created






Nic Ngo et al, (submitted to Medical Dosimetry)

# Comparison between 2D and VMAT TBI

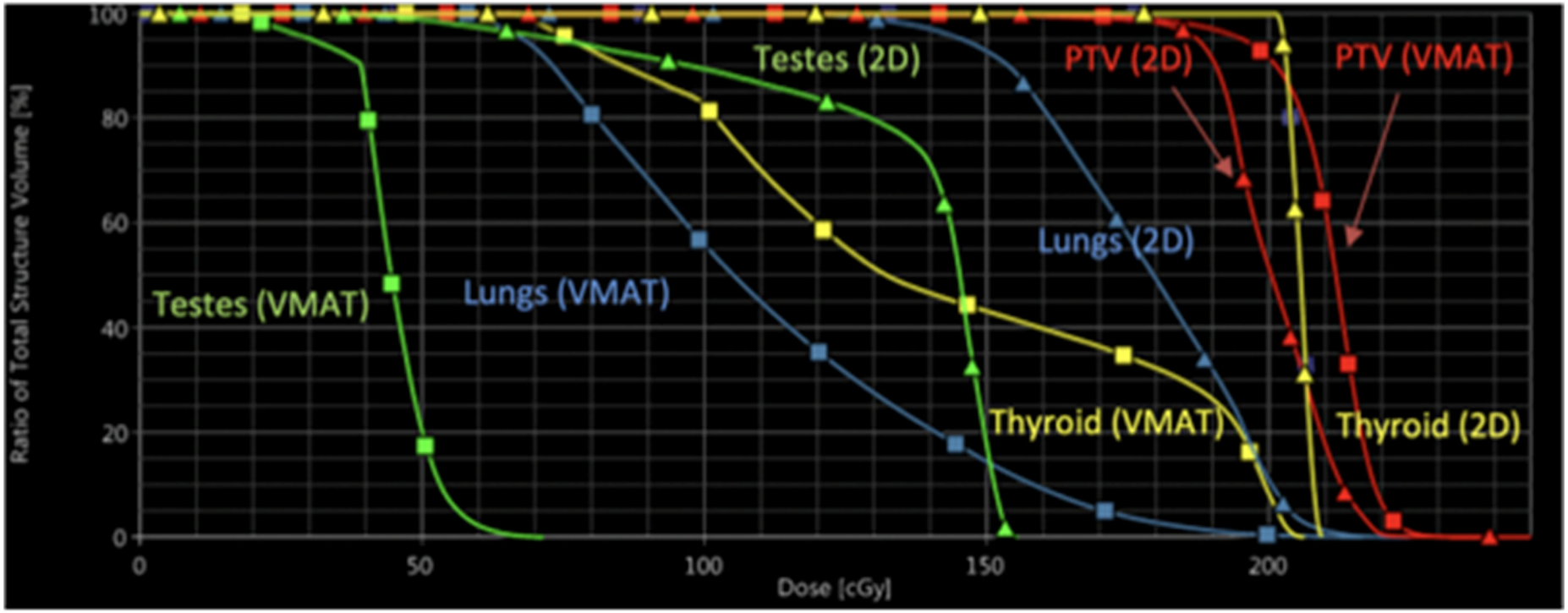
- Overall, the coverage was compromised for 2D plans
- On average, mean lung dose with 2D plans was 25.6%±11.5% higher than that with VMAT TBI plans
- Additionally, VMAT TBI plans spared kidneys, brain, thyroid, testes/ovaries where 2D plans delivered prescription dose

| | VMAT TBI | | | | | 2D TBI | | | | | Difference (VMAT-2D) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PTV D90 | PTV Dmax | PTV V110% | Lungs Dmean,% | Lungs-1cm Dmean, % | PTV D90 | PTV Dmax | PTV V110% | Lungs Dmean,% | Lungs-1cm Dmean, % | PTV D90 | PTV Dmax | PTV V110% | Lungs Dmean,% | Lungs-1cm Dmean, % |
| Patient 1 | 100.0% | 114.6% | 0.1% | 41.8% | 26.6% | 93.8% | 122.0% | 1.4% | 90.0% | 75.9% | 6.2% | -7.4% | -1.3% | -48.2% | -49.3% |
| Patient 2 | 100.0% | 120.5% | 2.2% | 58.3% | 37.3% | 91.3% | 122.5% | 0.7% | 86.7% | 82.1% | 8.8% | -2.0% | 1.5% | -28.4% | -44.8% |
| Patient 3 | 100.0% | 120.3% | 2.9% | 52.5% | 40.3% | 95.3% | 123.2% | 0.5% | 89.0% | 84.0% | 4.7% | -2.9% | 2.4% | -36.5% | -43.7% |
| Patient 4 | 100.0% | 114.7% | 0.3% | 54.4% | 34.1% | 90.0% | 118.5% | 0.4% | 81.9% | 73.0% | 10.0% | -3.8% | -0.1% | -27.5% | -38.9% |
| Patient 5 | 100.0% | 117.5% | 0.5% | 54.6% | 35.8% | 93.4% | 112.8% | 1.9% | 80.8% | 70.4% | 6.6% | 4.8% | -1.4% | -26.2% | -34.6% |
| Patient 6 | 100.0% | 121.0% | 0.9% | 59.4% | 36.5% | 95.8% | 115.6% | 0.2% | 75.4% | 62.6% | 4.3% | 5.4% | 0.7% | -16.0% | -26.1% |
| Patient 7 | 100.0% | 127.3% | 5.3% | 59.8% | 45.7% | 95.0% | 112.9% | 1.8% | 72.0% | 64.1% | 5.0% | 14.5% | 3.5% | -12.2% | -18.4% |
| Patient 8 | 100.0% | 120.4% | 1.6% | 59.9% | 37.5% | 92.6% | 111.0% | 0.0% | 72.0% | 61.2% | 7.4% | 9.4% | 1.6% | -12.1% | -23.7% |
| Patient 9 | 100.0% | 117.2% | 1.8% | 53.4% | 35.8% | 98.5% | 118.2% | 8.6% | 84.2% | 69.4% | 1.5% | -1.0% | -6.8% | -30.8% | -33.6% |
| Patient 10 | 100.0% | 114.2% | 0.1% | 56.4% | 35.3% | 93.4% | 111.2% | 0.0% | 74.3% | 63.4% | 6.6% | 3.1% | 0.1% | -17.8% | -28.1% |
| **Average** | **100.0%** | **118.8%** | **1.6%** | **55.1%** | **36.5%** | **93.9%** | **116.8%** | **1.5%** | **80.6%** | **70.6%** | **6.1%** | **2.0%** | **0.0%** | **-25.6%** | **-34.1%** |
| **Min** | **100.0%** | **114.2%** | **0.1%** | **41.8%** | **26.6%** | **90.0%** | **111.0%** | **0.0%** | **72.0%** | **61.2%** | **1.5%** | **-7.4%** | **-6.8%** | **-48.2%** | **-49.3%** |
| **Max** | **100.0%** | **127.3%** | **5.3%** | **59.9%** | **45.7%** | **98.5%** | **123.2%** | **8.6%** | **90.0%** | **84.0%** | **10.0%** | **14.5%** | **3.5%** | **-12.1%** | **-18.4%** |
| **SD** | **0.0%** | **4.0%** | **1.6%** | **5.4%** | **4.8%** | **2.4%** | **4.8%** | **2.6%** | **6.9%** | **8.1%** | **2.4%** | **6.7%** | **2.9%** | **11.5%** | **10.1%** |
| **p-value** | | | | | | | | | | | 8.115E-06 | 0.226 | 0.444 | 2.965E-05 | 1.024E-06 |



Nic Ngo et al, (submitted to medical dosimetry)

# Comparison between 2D and VMAT TBI

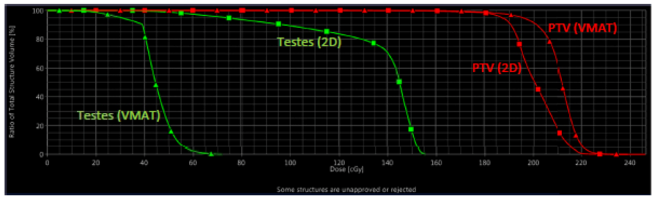





Blomain, Kovalchuk at al, PRO 2020

# Gonadal sparing: 2D vs VMAT

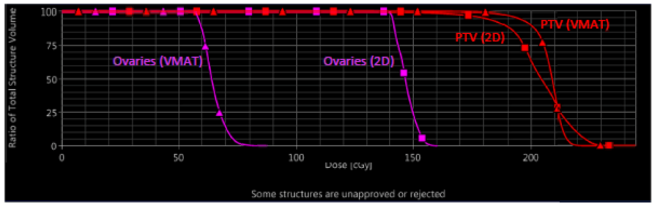
A




B

| Structure | Dosimetric parameter | 2D conventional plan | VMAT plan |
|---|---|---|---|
| PTV_Body | D90%= | 1.9 Gy (95.3%) | 2 Gy (100%) |
| | Dmax= | 2.5 Gy (123.2%) | 2.4 Gy (117.5%) |
| | V110%= | 0.5% | 5% |
| Testes | Dmean=<br>Dmax= | 1.36 Gy (67.8%)<br>1.56 Gy (78%) | 0.44 Gy (22.3%)<br>0.72 Gy (35.9%) |

C




D

| Structure | Dosimetric parameter | 2D conventional plan | VMAT plan |
|---|---|---|---|
| PTV_Body | D90%= | 1.9 Gy (95.3%) | 2 Gy (100%) |
| | Dmax= | 2.33 Gy (116.5%) | 2.4 Gy (117.5%) |
| | V110%= | 9.2% | 0.2% |
| Ovaries | Dmean=<br>Dmax= | 1.47 Gy (73.5%)<br>1.60 Gy (80%) | 0.65 Gy (32.4%)<br>0.88 Gy (43.9%) |

**Figure 2** Dosimetric comparison between 2D and VMAT TBI plans for the boy as shown in dose volume histograms (VMAT plan in *triangles*, 2D plan in *squares*) (**A**) and tabulated form (**B**), and for the girl (**C** and **D**).

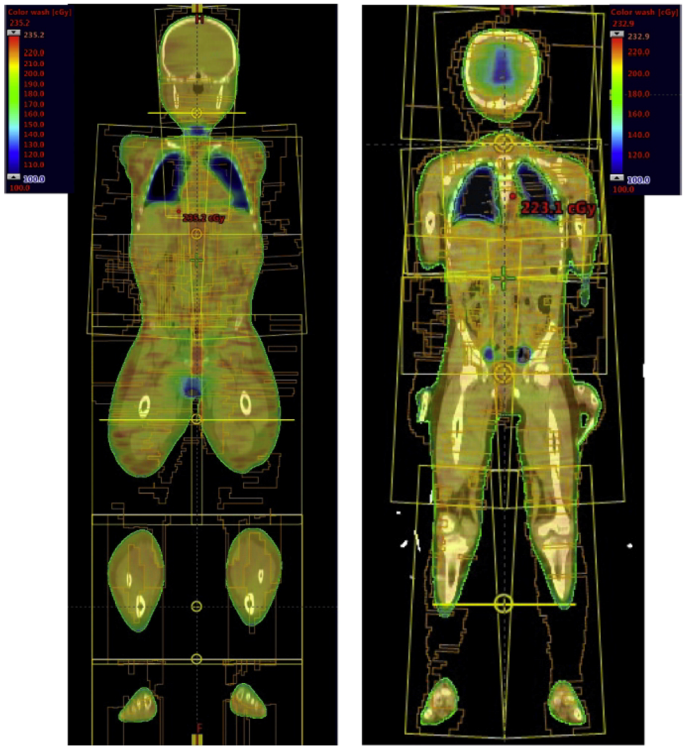



**Figure 1** Volumetric modulated arc therapy (VMAT) total body irradiation (TBI) beam arrangement and dose distribution (color wash) on coronal view for boy (*left*) and girl (*right*).

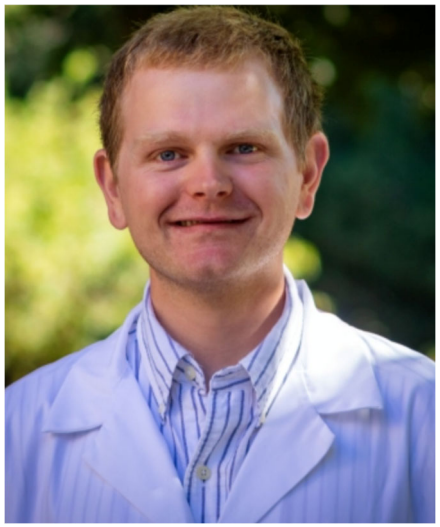
Blomain, Kovalchuk at al, PRO 2020

# Challenges in intensity-modulated TBI

- Equipment limitations
- Special treatment geometry considerations
- Planning time
  - Up to 3 days for VMAT-based TBI

# Automation of the treatment planning process for VMAT TBI using the Eclipse API framework

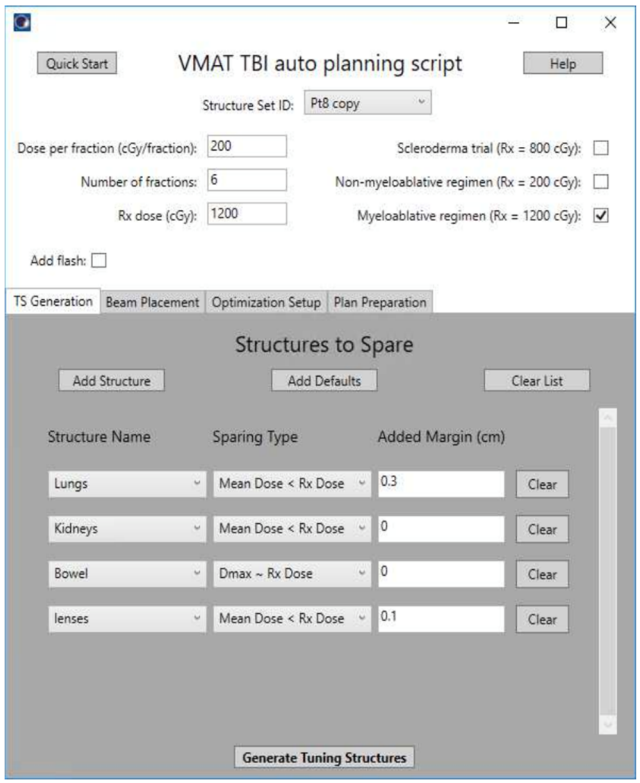
https://github.com/esimiele/VMAT-TBI

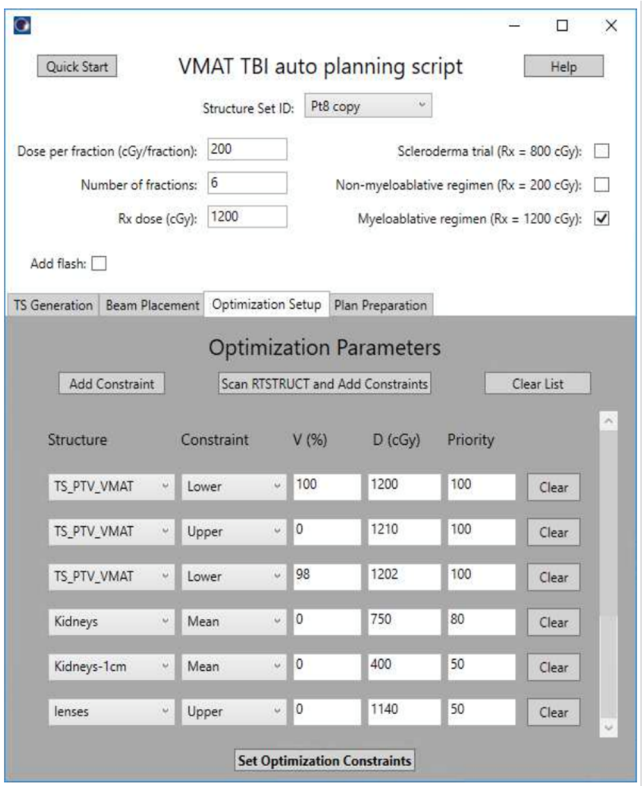


Eric Simiele

Stanford University School of Medicine

# VMAT TBI auto-planning script

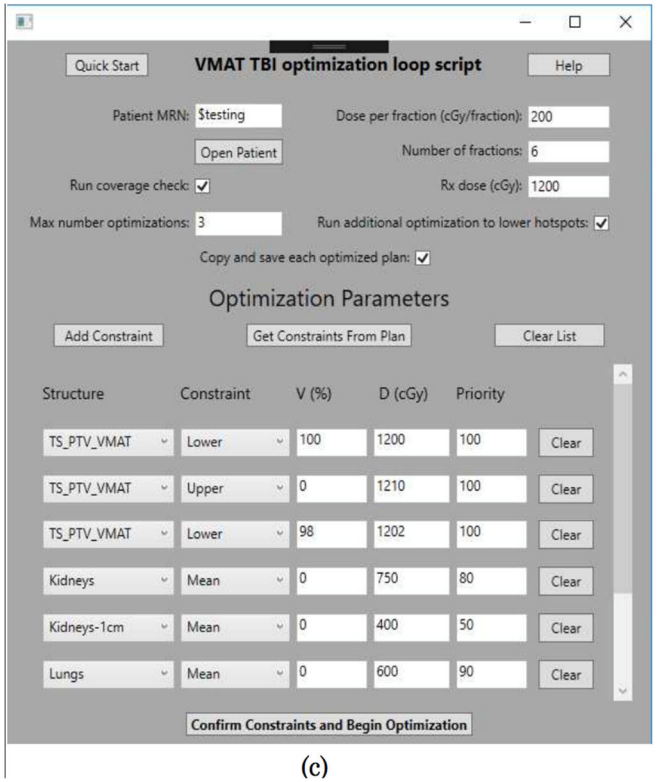


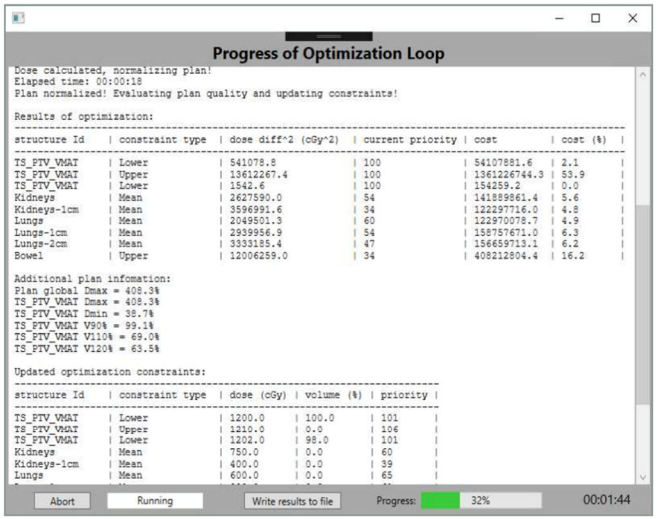

- Binary plug-in to be used within Eclipse
  - Optimization structure generation
  - Plan generation
  - Beam placement
  - Optimization constraint assignment
  - Prepare optimized plan for physician approval and treatment
- Fast
  - Optimization structure generation – optimization constraint assignment → 30s
  - Significant reduction in time required for tedious tasks

Simiele, et al, (PRO, 2021)

# VMAT TBI auto-planning script




(c)




(d)

- Stand-alone executable to be run outside Eclipse
  - Run successive optimizations
  - Update optimization constraints following each optimization
  - Minimal user intervention
    - Picks up where the plug-in script left off
    - Autonomous
    - Multithreaded
      - Provides live updates
    - Time for 3 optimizations ~ 3-5 hours

Simiele, et al, (PRO 2021)

# Results

Plan ten VMAT TBI cases manually and with developed scripts:

- Dosimetric indices:
  - Global $D_{max}$, PTV V110%, lungs and lungs-1cm $D_{mean}$, kidneys $D_{mean}$, and bowel $D_{max}$
  - Paired t-test
- Approximate planning time
- Blinded physician review (60 total responses)

Table 1: Achieved plan quality for each metric considered in this work for the a) manual and b) auto treatment plans. All dose and volume values in a) and b) are expressed as a percentage of the prescription dose and PTV volume, respectively. A plan quality value of N/A indicates that this organ was not considered for sparing in this patient.

(a)

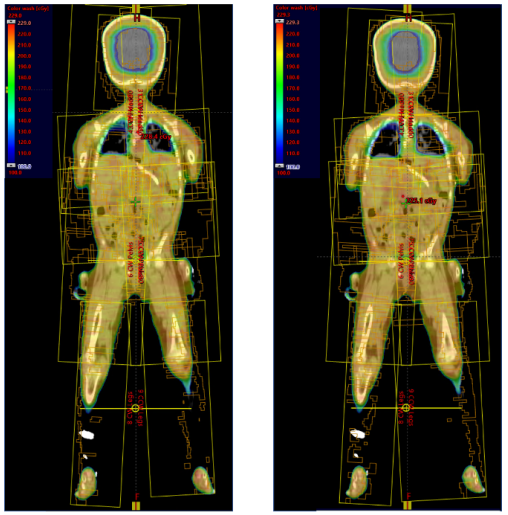
| Manual treatment plans | | | | | | |
|---|---|---|---|---|---|---|
| Patient No. | $D_{max}$ | V110% | Lungs $D_{mean}$ | Lungs-1cm $D_{mean}$ | Kidneys $D_{mean}$ | Bowel $D_{max}$ |
| 1 | 114.5% | 0.2% | 55.7% | 31.8% | 67.6% | 111.9% |
| 2 | 121.0% | 1.4% | 56.7% | 41.2% | 65.0% | 106.1% |
| 3 | 119.5% | 6.2% | 55.0% | 45.7% | N/A | N/A |
| 4 | 116.5% | 0.1% | 60.0% | 44.6% | N/A | 110.3% |
| 5 | 114.0% | 0.0% | 75.0% | 60.6% | N/A | 108.1% |
| 6 | 122.5% | 2.5% | 65.0% | 42.8% | 60.0% | 111.5% |
| 7 | 128.5% | 4.5% | 60.4% | 45.4% | 66.3% | 116.0% |
| 8 | 121.5% | 1.6% | 62.5% | 40.0% | 72.5% | 111.2% |
| 9 | 116.0% | 0.6% | 65.0% | 47.0% | 70.0% | 112.8% |
| 10 | 113.9% | 0.0% | 58.3% | 36.5% | 65.0% | 110.0% |

(b)

| Auto treatment plans | | | | | | |
|---|---|---|---|---|---|---|
| Patient No. | $D_{max}$ | V110% | Lungs $D_{mean}$ | Lungs-1cm $D_{mean}$ | Kidneys $D_{mean}$ | Bowel $D_{max}$ |
| 1 | 114.6% | 0.1% | 41.8% | 26.6% | 64.1% | 110.0% |
| 2 | 120.5% | 2.2% | 58.3% | 37.3% | 64.2% | 111.2% |
| 3 | 120.3% | 2.9% | 52.5% | 40.3% | N/A | N/A |
| 4 | 114.7% | 0.3% | 54.4% | 34.1% | N/A | 102.5% |
| 5 | 117.5% | 0.5% | 54.6% | 35.8% | N/A | 112.4% |
| 6 | 121.0% | 0.9% | 59.4% | 36.5% | 65.3% | 111.6% |
| 7 | 127.3% | 5.3% | 59.8% | 45.7% | 73.3% | 114.2% |
| 8 | 120.4% | 1.6% | 59.9% | 37.5% | 72.6% | 115.0% |
| 9 | 117.2% | 1.8% | 53.4% | 35.8% | 64.9% | 112.3% |
| 10 | 114.2% | 0.1% | 56.4% | 35.3% | 68.4% | 103.3% |

Table 2: Mean and standard deviation, $\sigma$, of the difference in percent between the auto and manual treatment plans. In addition, the calculated p-value from a one-sided t-test is shown for each evaluated metric. A p-value $< 0.05$ was considered to be statistically significant in this study.

| | $D_{max}$ | V110% | Lungs $D_{mean}$ | Lungs-1cm $D_{mean}$ | Kidneys $D_{mean}$ | Bowel $D_{max}$ |
|---|---|---|---|---|---|---|
| Mean | 0.0% | -0.1% | -6.3% | -7.1% | 0.6% | -0.5% |
| $\sigma$ | 1.6% | 1.3% | 6.9% | 7.2% | 3.7% | 4.3% |
| p-value | 0.969 | 0.750 | 0.018 | 0.013 | 0.598 | 0.703 |



(a) (b)

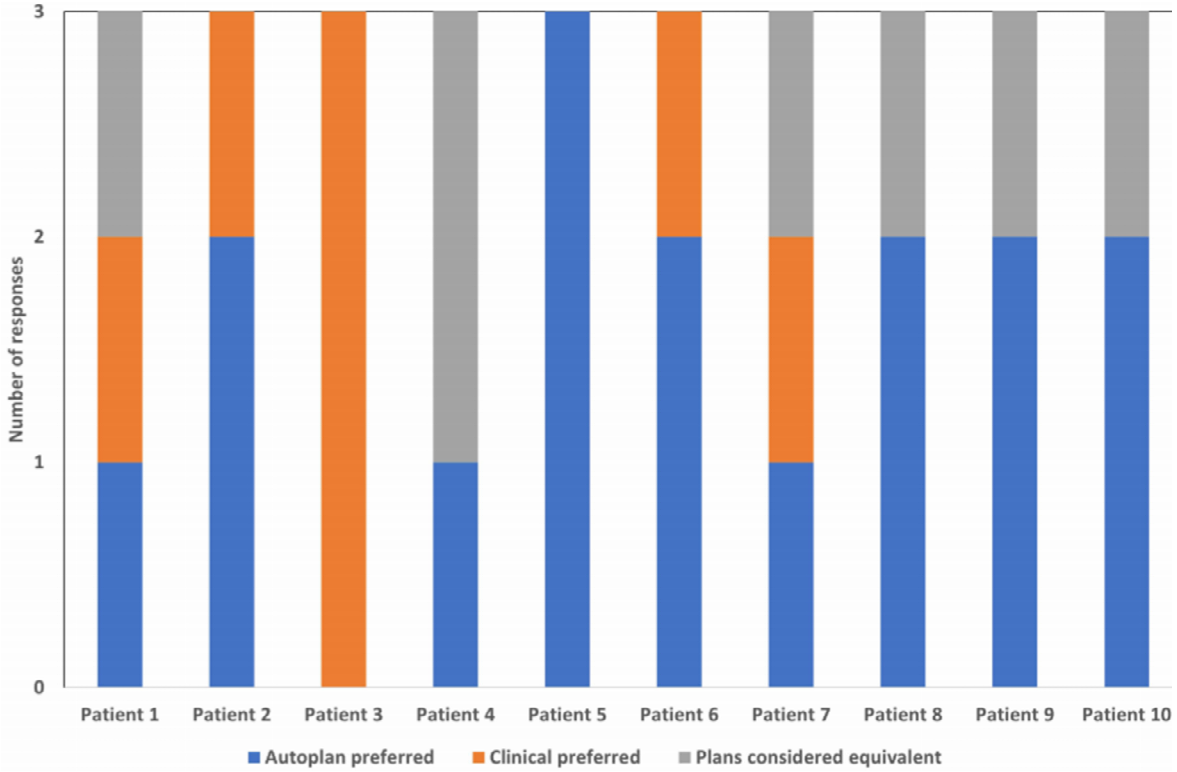
Figure 3: Resulting coronal dose distributions for patient 1 for the a) manual plan and b) autoplan. The prescription for this patient was 2 Gy in one fraction where lungs, kidneys, bowel, gonads, brain, and lenses were selected for sparing.



Simiele, et al, (PRO 2021)

# Results

- 20 plans for 10 patients were reviewed by 3 physicians
- Overall, the autoplans were marked as equivalent or superior to the manual plans 77% of the time




Simiele, et al, (PRO 2021)

# Plan preparation

- Plan preparation module of auto-planning script:
  - Separates plans into separate isocenters
  - Removes optimization structures
  - Generates shift note
- Another script – Automated Plan Checker – automates the physics plan check by inspecting >150 plan elements and outputs the DVH constraints metrics

| | Couch Vert | Couch Long | Couch Lat |
|---|---|---|---|
| Chest final (CBCT) | -14.5 | 97.7 | 0.0 |

| Plan | Couch Vert | Couch Long | Couch Lat |
|---|---|---|---|
| Head | -14.5 | 62.7 | 0.0 |
| **Chest** | **-14.5** | **97.7** | **0.0** |
| Pelvis | -14.5 | 133.7 | 0.0 |
| Flip the patient, remember to change Couch LAT to opposite sign | | | |
| Upper Legs | -14.5 | 133.7 | 0.0 |
| Lower Legs | -14.5 | 95.7 | 0.0 |

| | Long Shift from SUP to INF | | Long Shift from CT ref (enter with the sign) | |
|---|---|---|---|---|
| | Shift, cm | direction | Shift, cm | direction |
| shift from CT ref to Head | 47 | SUP | **47** | SUP |
| shift from Head to Chest | 35 | INF | **12** | SUP |
| shift from Chest to Pelvis | 36 | INF | **-24** | INF |
| | | Flip the patient | | |
| stay at same CouchLong as Pelvis | 0 | | **62** | INF |
| shift from Upper Legs to Lower Legs | 38.0 | INF | **100** | INF |

***Bars out***
VMAT TBI setup per procedure. Please ensure the matchline on Spinning Manny and the bag matches
TT=-14.5 for all plans
Dosimetric shifts SUP to INF:
Head iso shift from CT ref 47 cm SUP
Chest iso shift from Head iso 35 cm INF (12 cm SUP from CT ref)
Pelvis iso shift from Chest iso 36 cm INF (24 cm INF from CT ref)
Rotate Spinning Manny, shift to opposite Couch Lat
Upper Leg iso - same Couch Lng as Pelvis iso
Lower Leg iso shift from Upper Leg iso 38 cm INF (100 cm INF from CT ref)

# Conclusions

- VMAT TBI is a modern alternative to conventional 2D TBI treatment
- It offers:
  - possibility of organ sparing (lungs, kidneys, gonads, brain, thyroid, lenses) and SIB boosts
  - accurate dose calculation and image-guided delivery
  - more comfortable patient positioning
  - ability to treat TBI patient is small size vaults
- VMAT auto-planning script is loved in the clinic. It reduces treatment planning time to a few hours instead of days
- Stanford treated 25 patients with VMAT TBI since it's initiation in October 2019

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  - Jonathan Lewis, CMD
  - Nicole Howell, CMD
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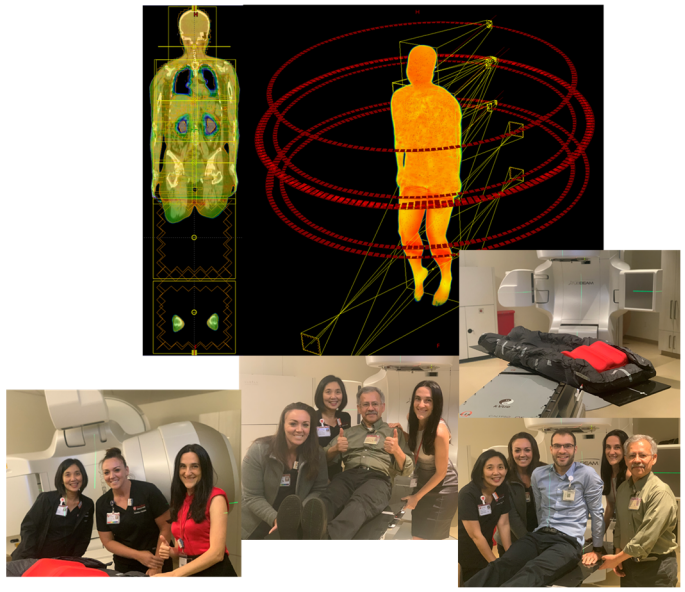
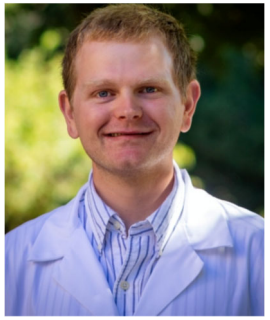
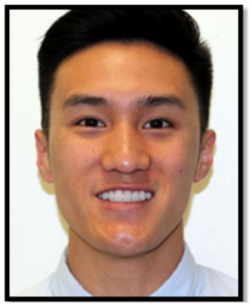
  - Manny Villegas
- **All Stanford RTTs**



Eric Simiele



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