Decision support for adaptive radiotherapy:
in Vivo Dosimetry

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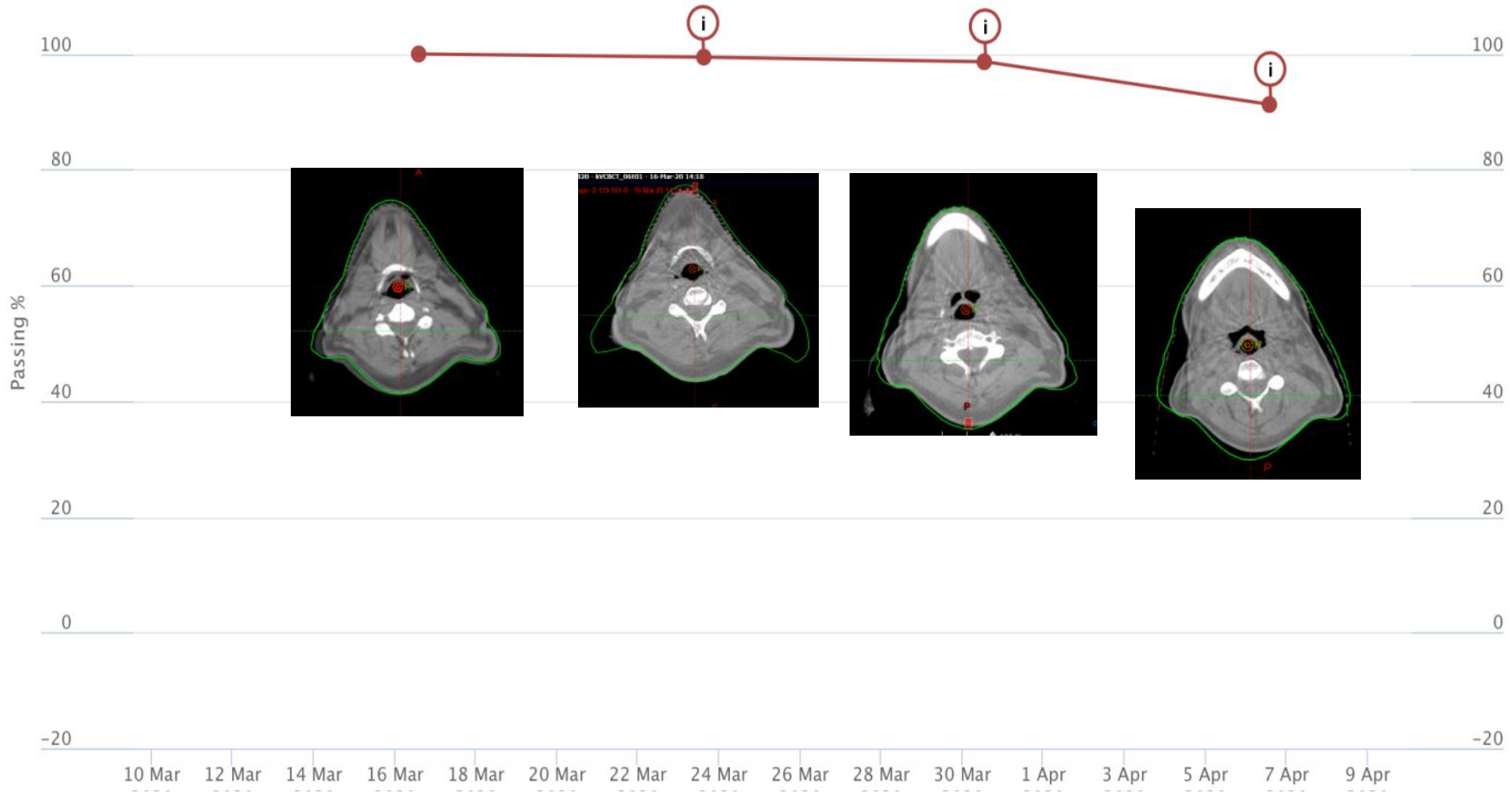
Patient may change during the treatment course

2D analysis trending



At what point should we adapt

- What is understood as ”adaptation”?
- When should the treatment be ”replaned”?

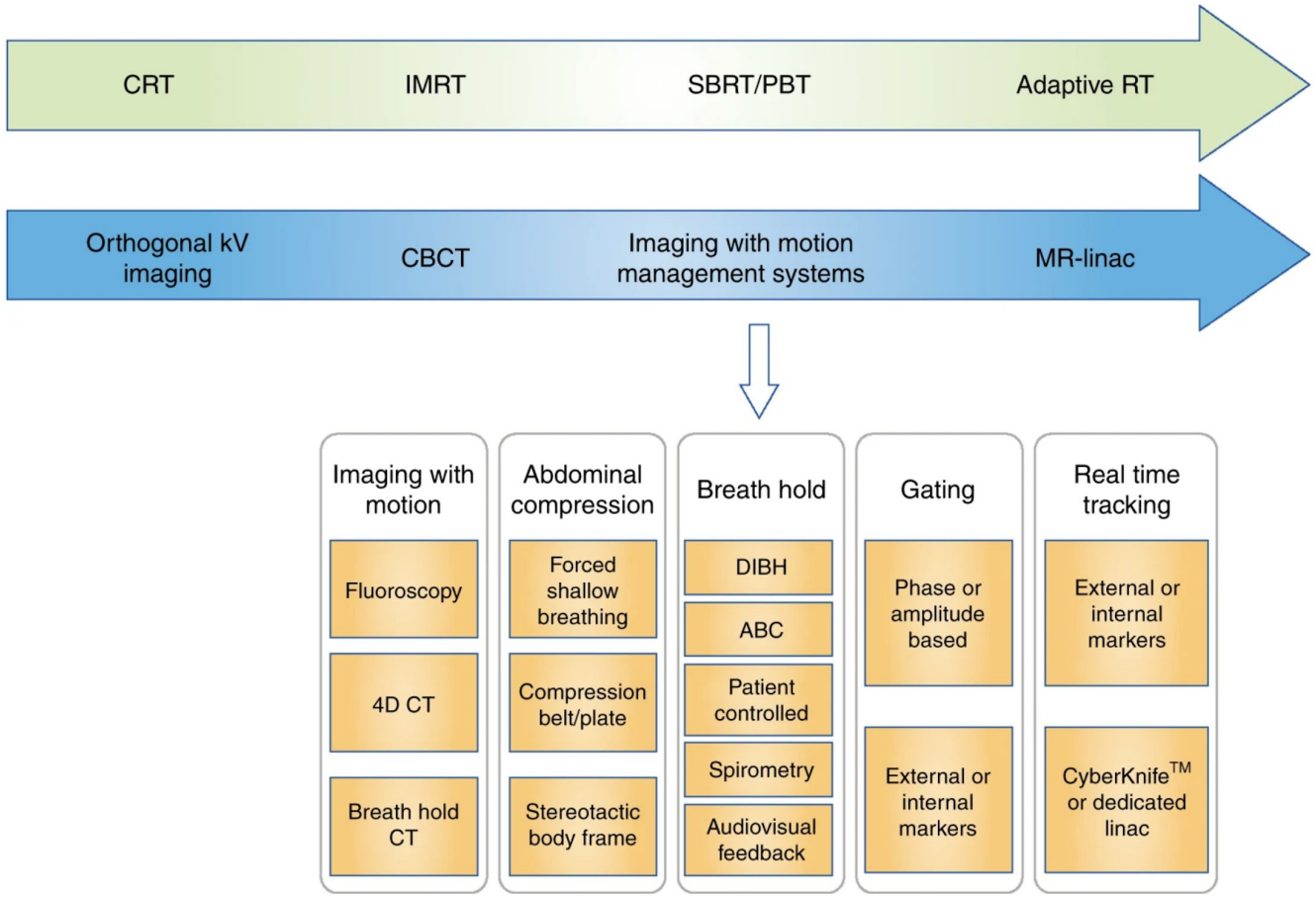
At what point should we adapt

- **What is understood as ”adaptation”?**
  - Any change made during the delivery so that the patient conforms to our patient model used for treatment planning.
  - Can it be adapting the position, can be adapting to motion (breath hold/gatting)
- **When should the treatment be ”replaned”?**
  - When the differences cannot be compenasted by repositionning/table shifts and rotations, motion control strategies
  - When the immobilisation devices do not fit to the patient and lose their purpose
  - When the there can be ”relevant” differences in the resulting dose distribution

Some points to consider

- Imaging can be used for real time treatment monitoring:
    - Patient position and tumor/organ motion.
- Adaptive radiotherapy: Adapting to tumor size and position.

Advances in dose delivery need more accurate patient positioning and monitoring



Beaton, L., Bandula, S., Gaze, M.N. *et al.* How rapid advances in imaging are defining the future of precision radiation oncology. *Br J Cancer* **120**, 779–790 (2019).

We are already adapting to changes with IGRT

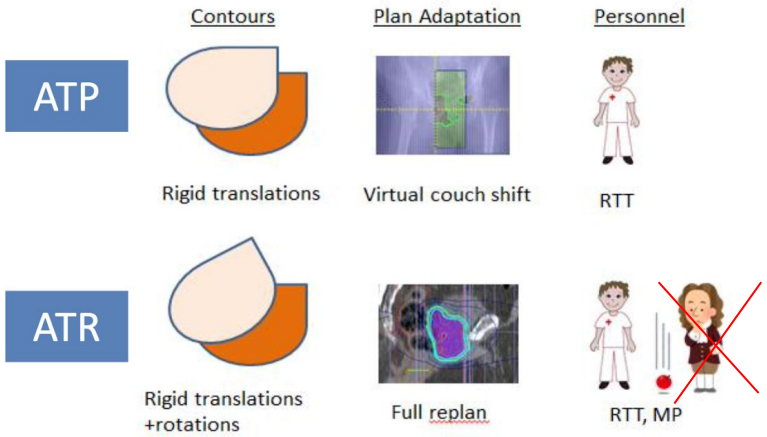
Different approaches to on-line adaptation

ATP: “Adapt to Position”

(virtual) couch shift

ATR: “Adapt to Rotation”

Shift and rotate targets rigidly ~~and replan~~
no re-contouring



Dose distribution invariant when we adapt to position and rotations

Static dose cloud approximation

We are already adapting to changes with IGRT

Different approaches to on-line adaptation

ATP: “Adapt to Position”

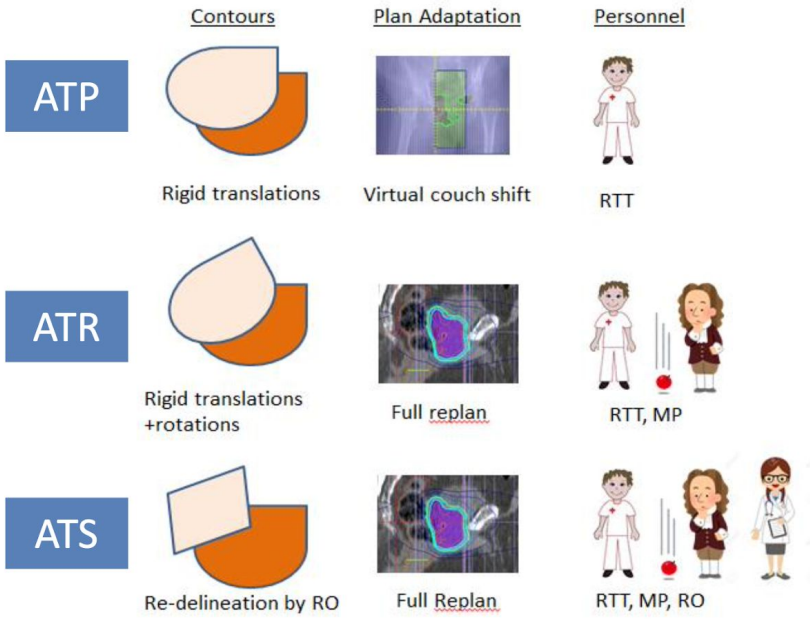
(virtual) couch shift

ATR: “Adapt to Rotation”

Shift and rotate targets rigidly and replan
no re-contouring

ATS: “Adapt to Shape”

Full adaptation



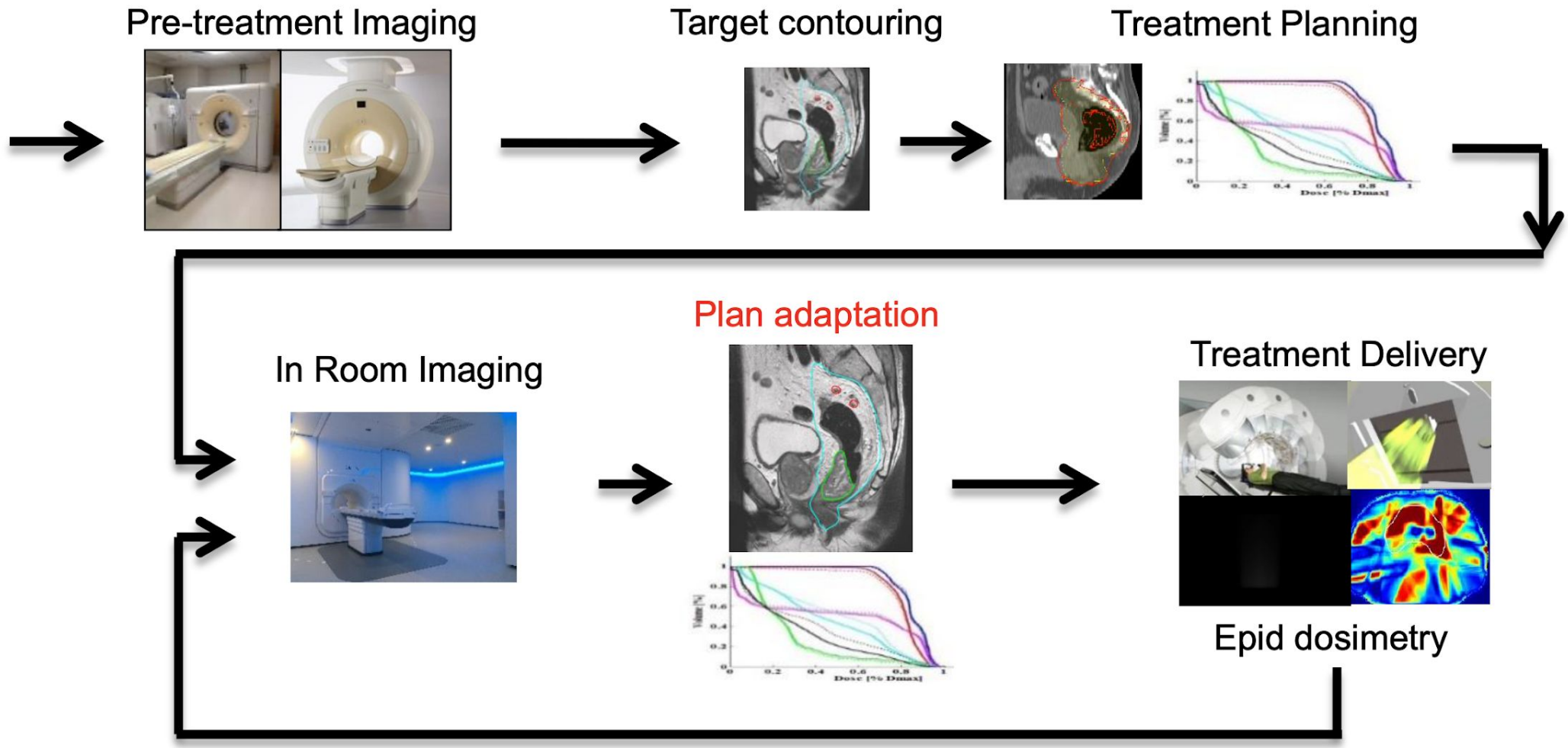
NETHERLANDS CANCER INSTITUTE
ANTONI VAN LEEUWENHOEK

But we know that the dose distribution changesv…

Static dose cloud approximation

FALSE

Adapt each fraction to the changing shape of the tumor



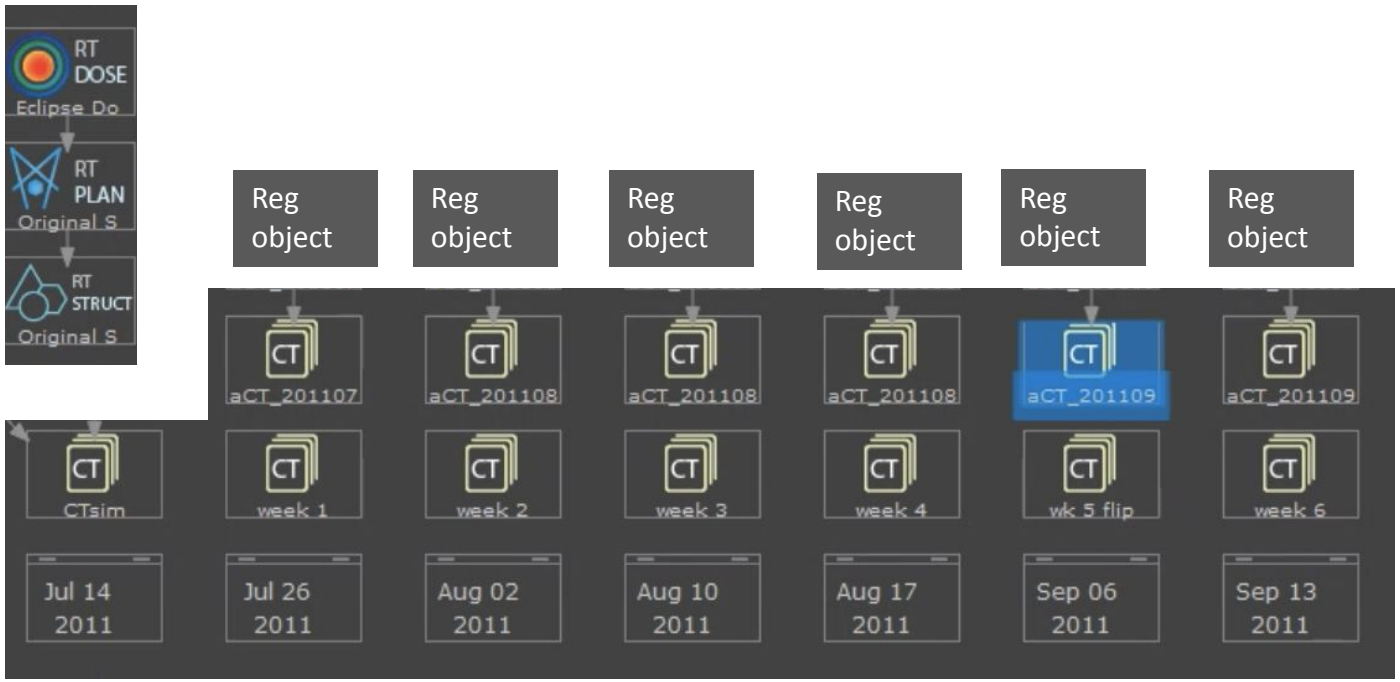
From Uulke van der Heide EMA 2024

How can we know that the difference is significant?

Available data

How can we know that the difference is significant?

Syntetic CT from CBCT

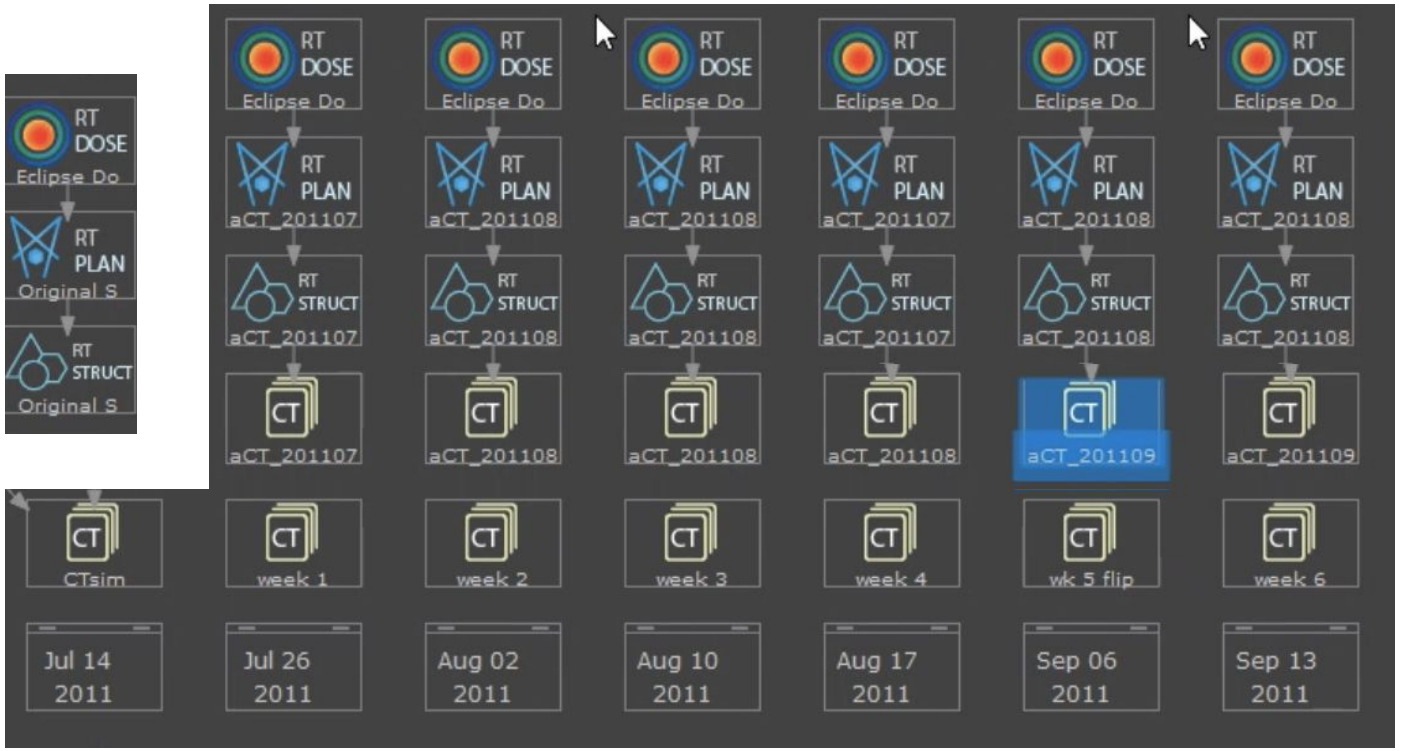


How can we know that the difference is significant?

Deformable registration + structure set in the CBCT

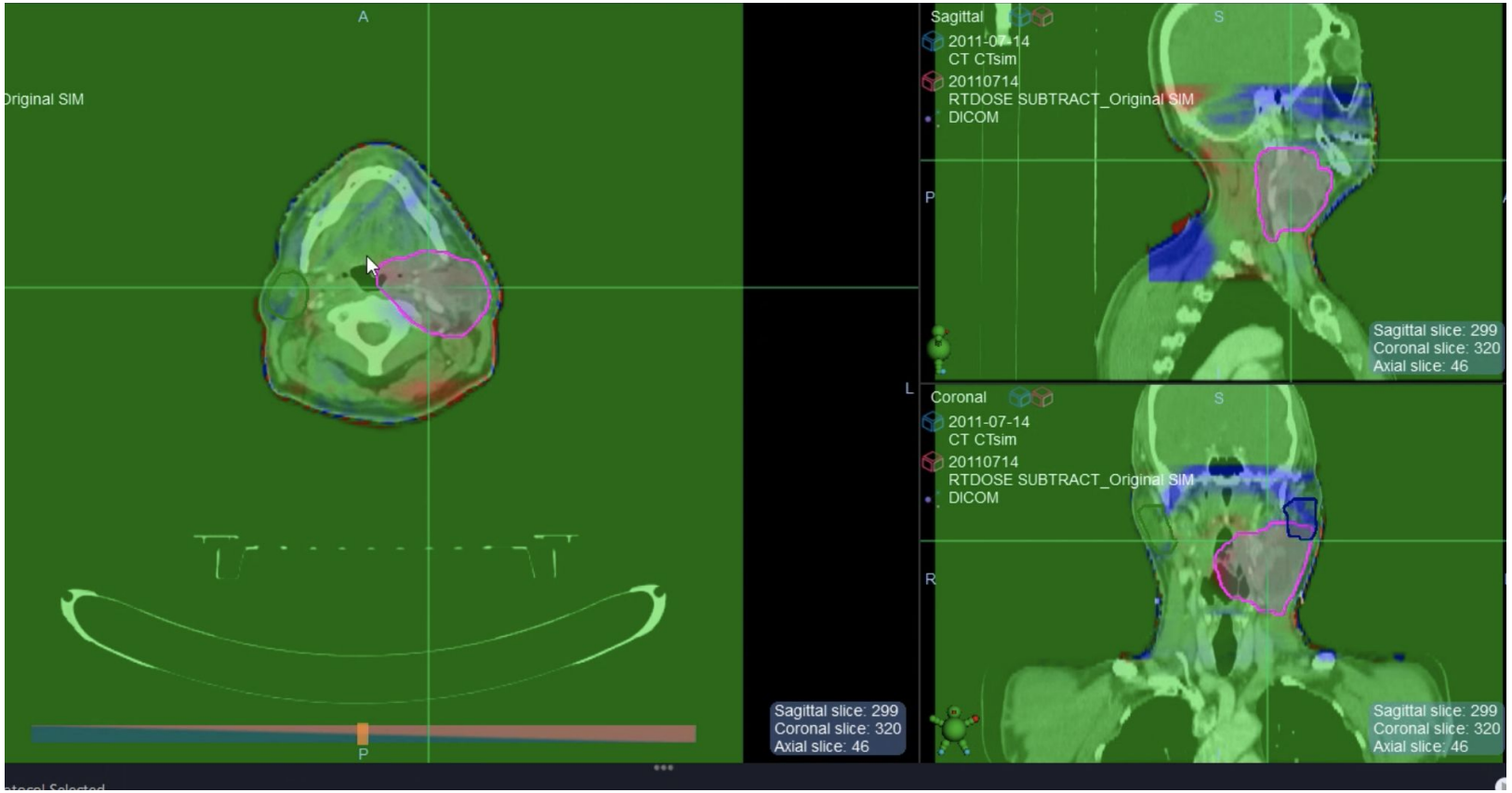
How can we know that the difference is significant?

Dose recalculation (original RT plan)



How can we know that the difference is significant?

Comparison of actual delivered dose with the planned dose



Discussion with RO

There exist some commercial solutions

In vivo dosimetry as a suport tool for adaptive RT

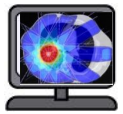
Sant Pau Hospital

4 linacs

1 x Clinac 2100

3 x Truebeam

iVD for every patient: 1800 patients/year



TPS: Eclipse

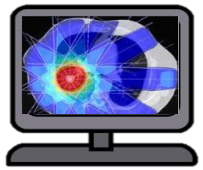
IOS: ARIA

Platform

Secondary calculation and transit In-Vivo dosimetry:
PerFraction (Sun Nuclear)

Transit in-Vivo Dosimetry: Clinical Use

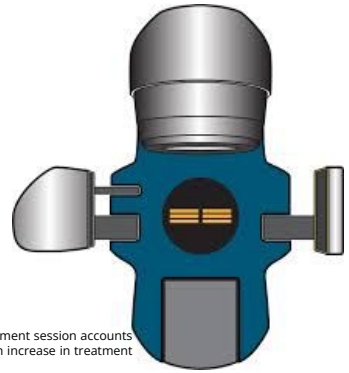
Patient-specific quality assurance



Conclusion

Real-time monitoring of patient surface and beam control during the whole treatment session accounts for higher in-vivo dosimetry gamma rates obtained using SGRT. This highlights an increase in treatment accuracy.

Treatment Planing System



Linac

Patient

Plan TPS

Secondary calculation
Dose distribution

Plan checked
Constrains
Data transfering

Pre-treatment verification
Linac performance

IGRT

In-Vivo Dosimetry (iVD)

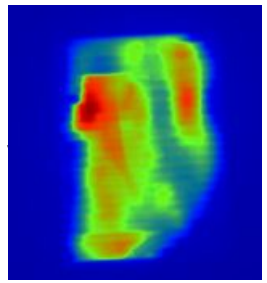
IVD experience at Sant Pau Hospital

1997

In-Vivo Dosimetry with diodes

✓ 3DCRT, IMRT,

✗ Electrons



2019

Clinical use of Transit iVD

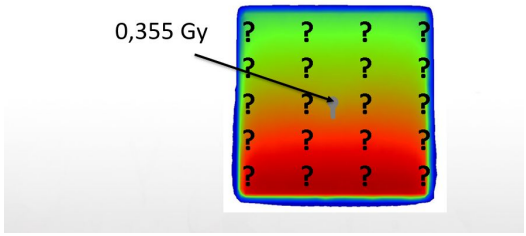
2021

Use of database

✓ 3DCRT (homogeneous fluence at beam entrance)

✗ IMRT

These readings confirm point doses



2017

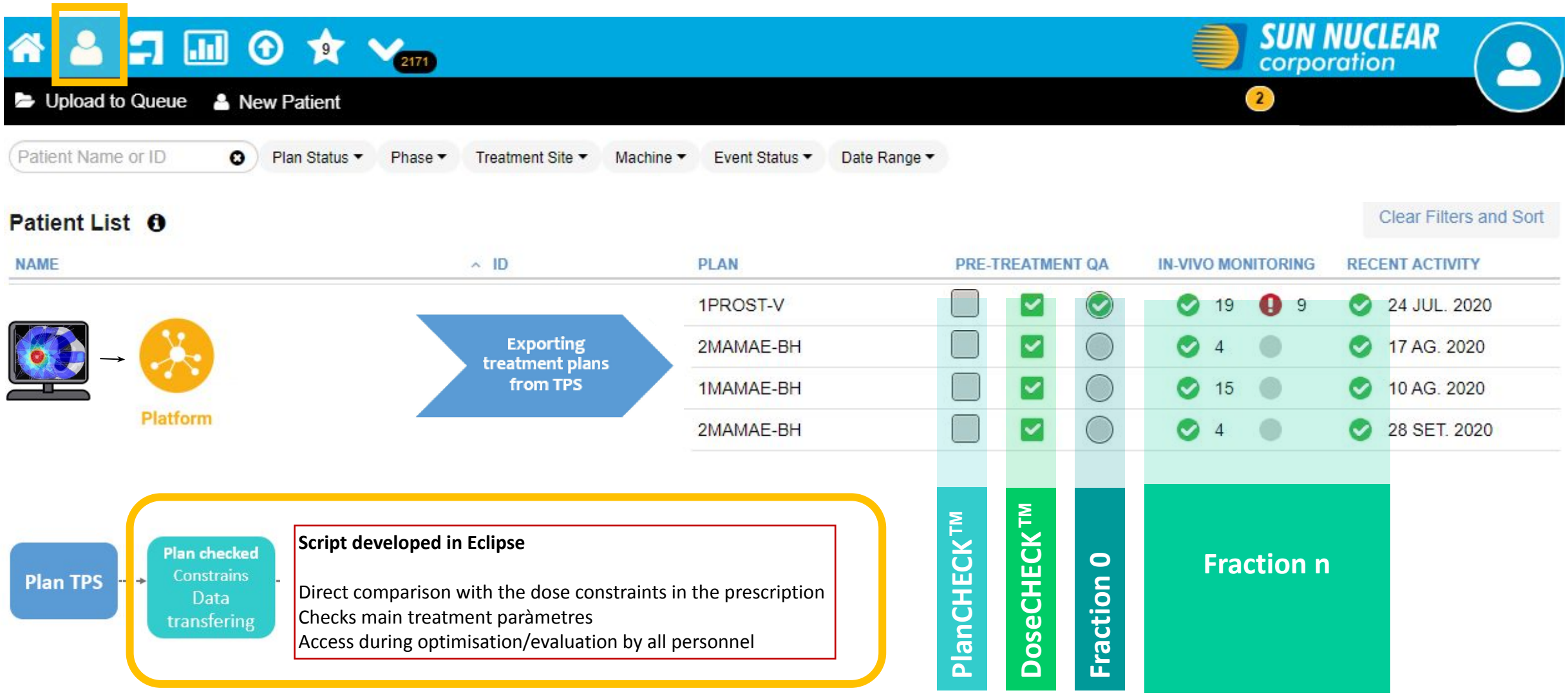
SunCHECK installation

Secondary dose distribution calculation clinical use

2020

Analysis of results and tolerances adjustment

Patient platform

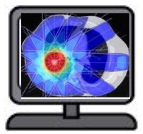


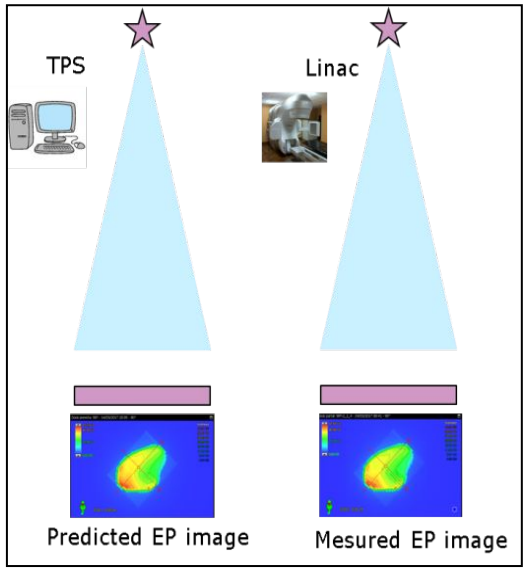
Patient-specific quality assurance

❶ First level:

F0: pre-treatment verification

→ EPID based **image**

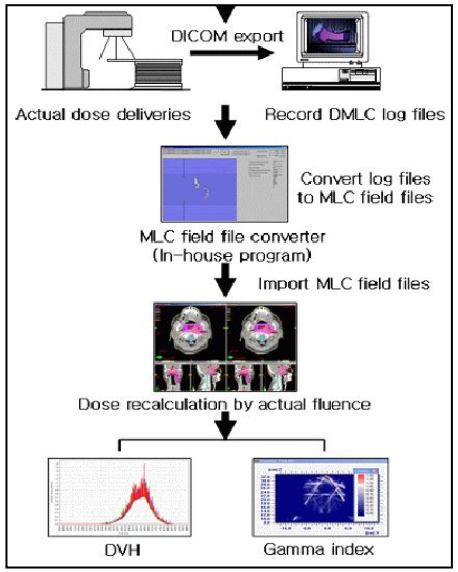




❷ Second level:

Fn: **online verification**

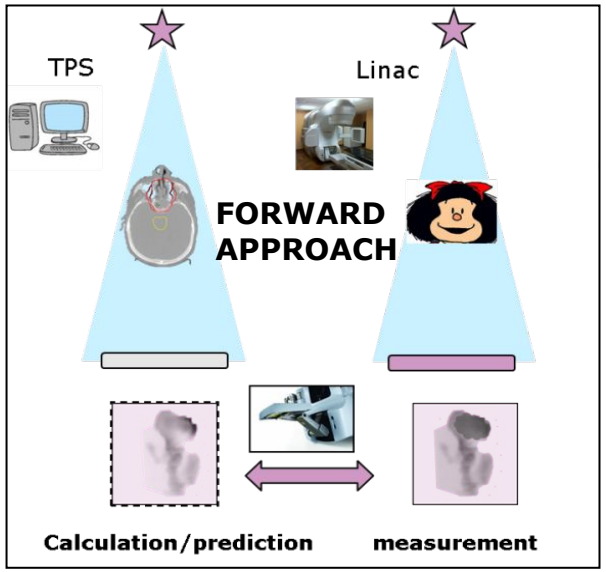
→ **log-files based calculation**



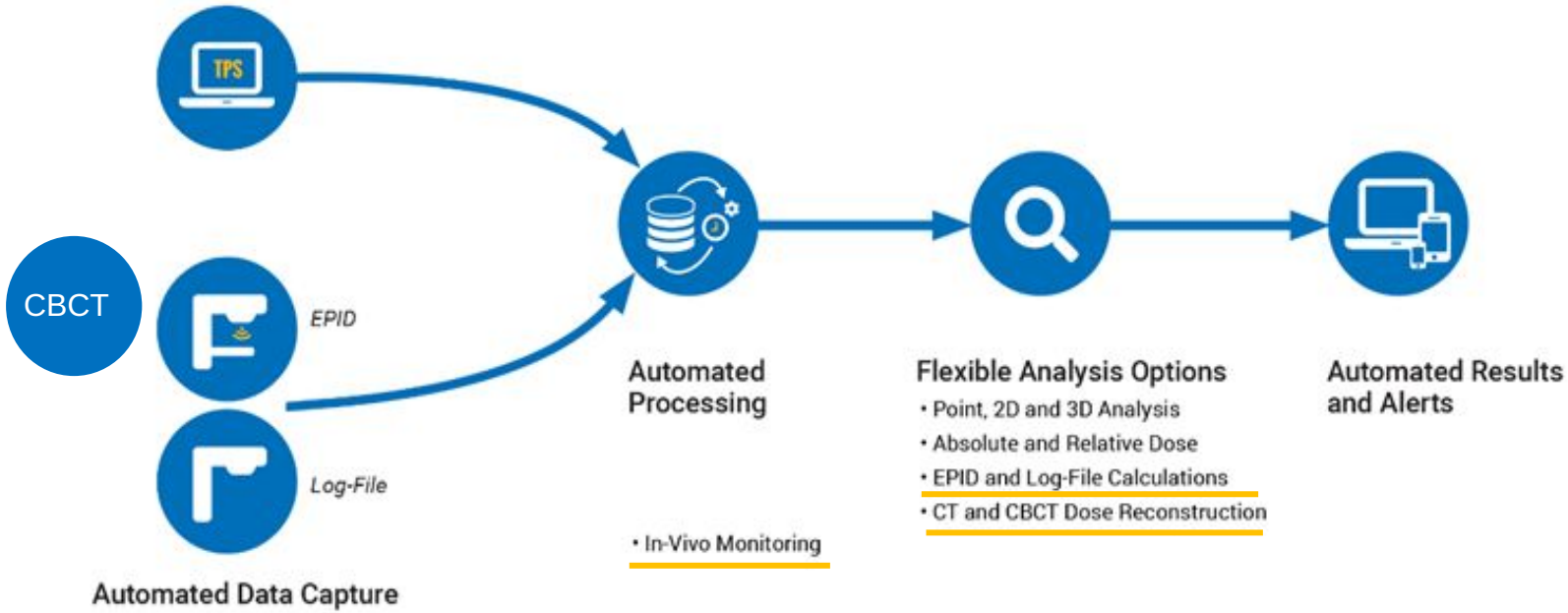
❸ Third level:

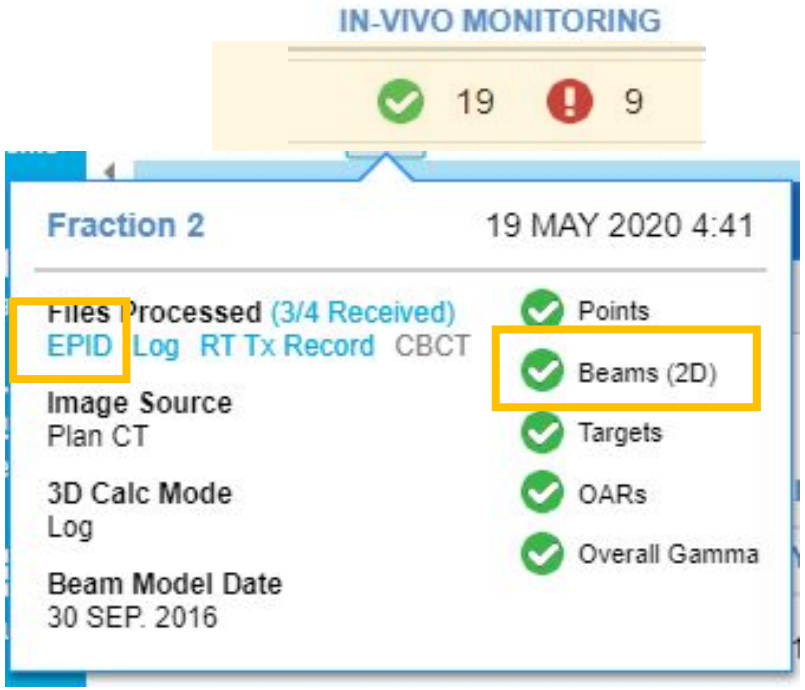
Fn: **in-Vivo verification** **(iVD)**

→ **EPID transit image**

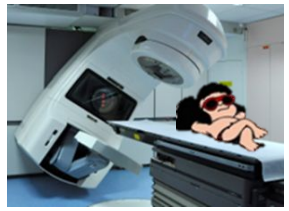


PerFRACTION™ platform





Workflow



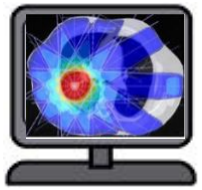
Treatment plan exporting from TPS

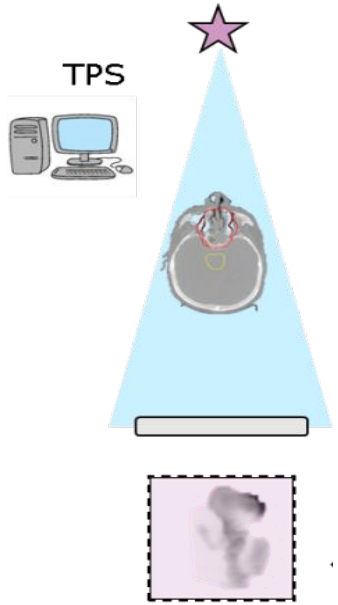
Action levels template assigning

Predicted image calculation at the EPID level

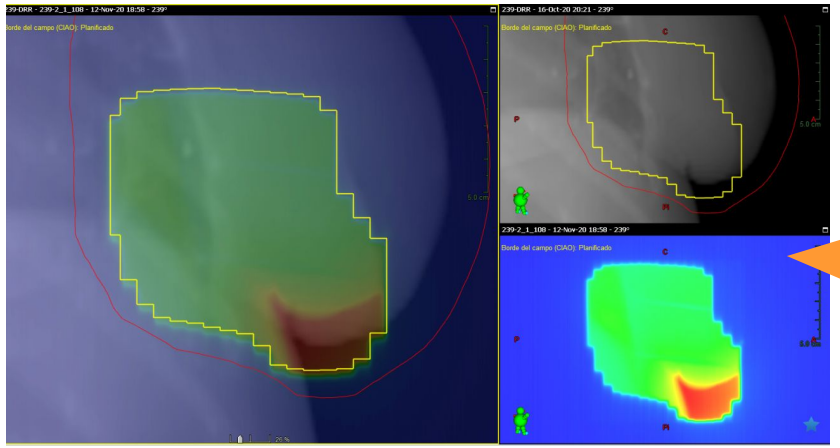
Automatic retrieve of the EPID integrated image

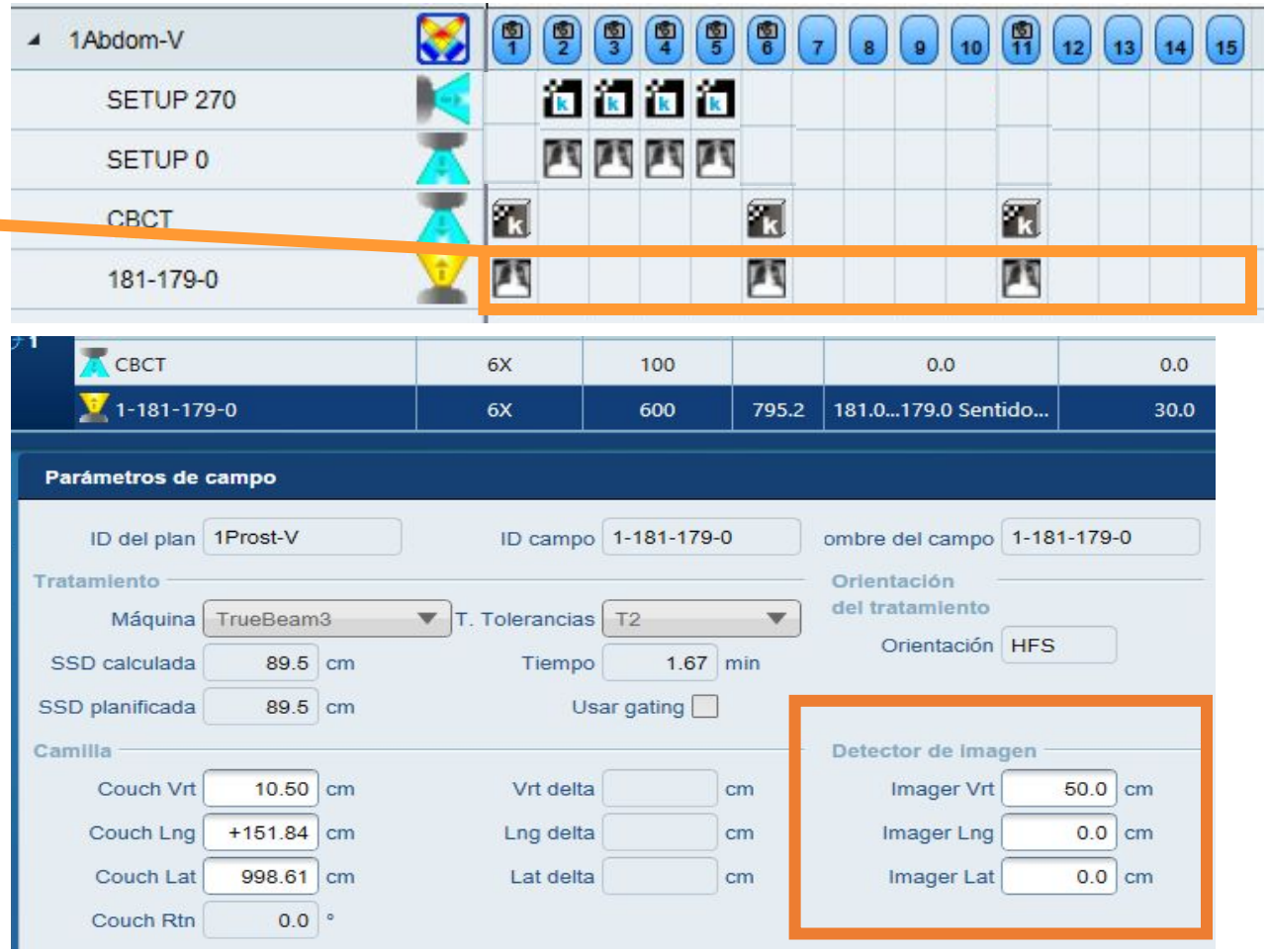
Automatic calculation of Gamma analysis





EPID-based transit IVD





Limitations of EPID-based transit iVD:

- **Large fields** (size of EPID)
- **Lateral fields** (collision risk)
- **Fields with couch rotation** (collision risk)

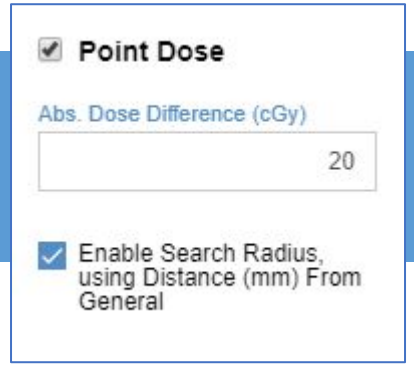
checking the field size to avoid irradiating EPID electronics!!

Analysis

Analysis 1D

Points

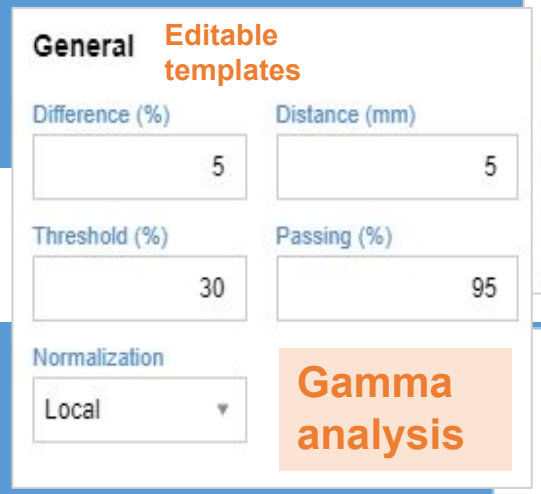
RT TX record , logfiles in all sessions

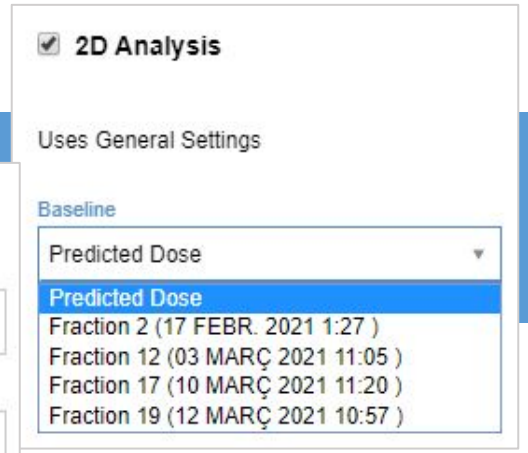


Analysis 2D

Beams (2D)

EPID integrated images

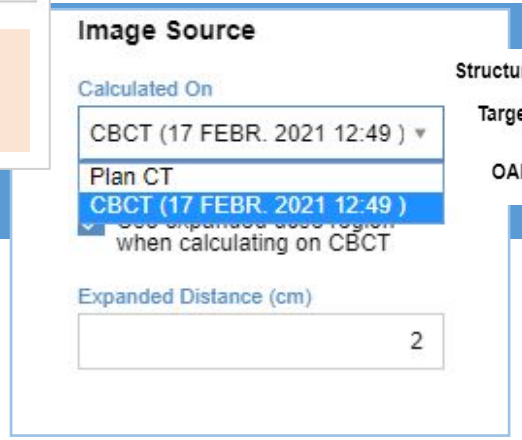


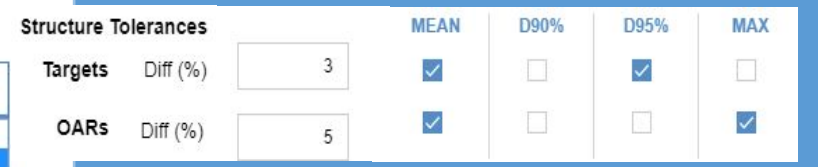


Analysis 3D

Targets OARs

RT TX record Logfiles CBCT





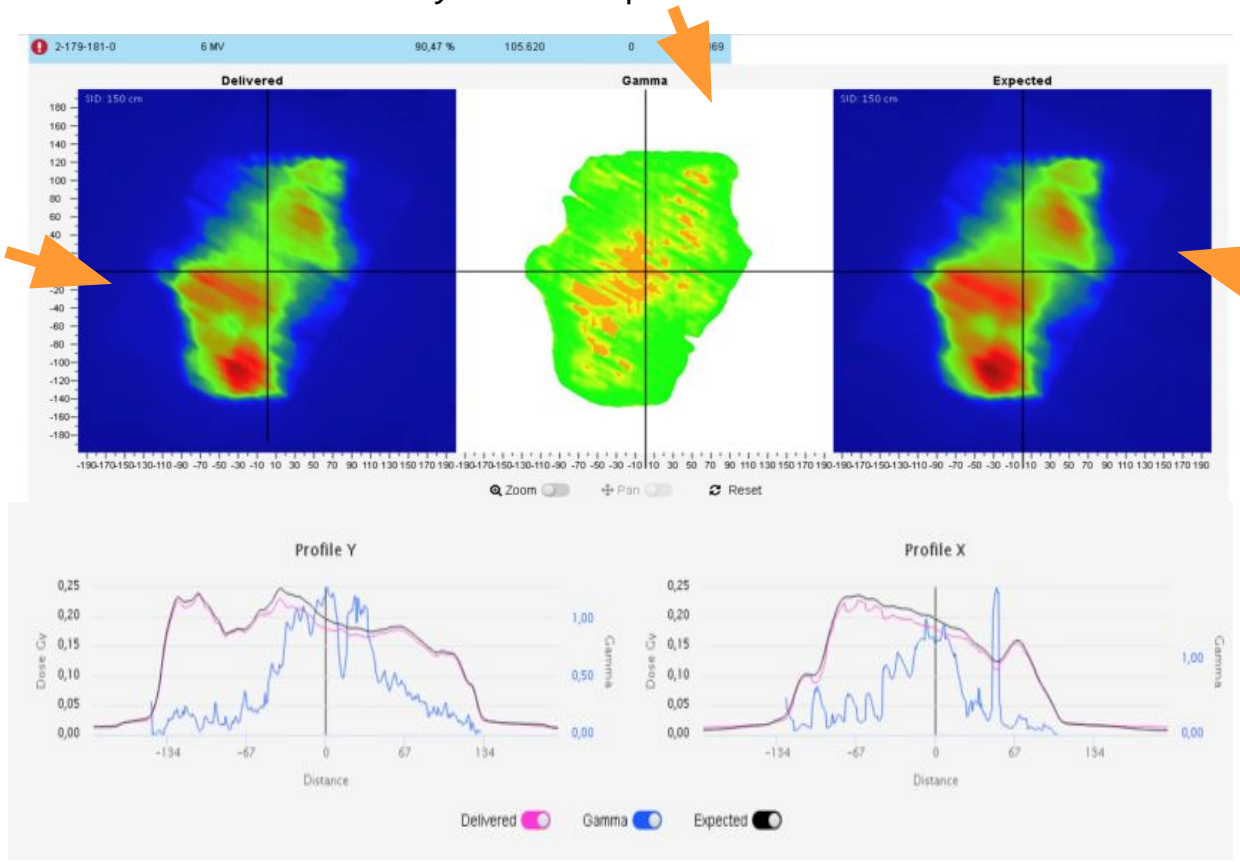
2D analysis: transit IVD

2D image analysis: integrated image

Beams (2D)

Comparison:
Gamma analysis (user-predefined and automatic calculation)

Delivered image:
Integrated image per beam



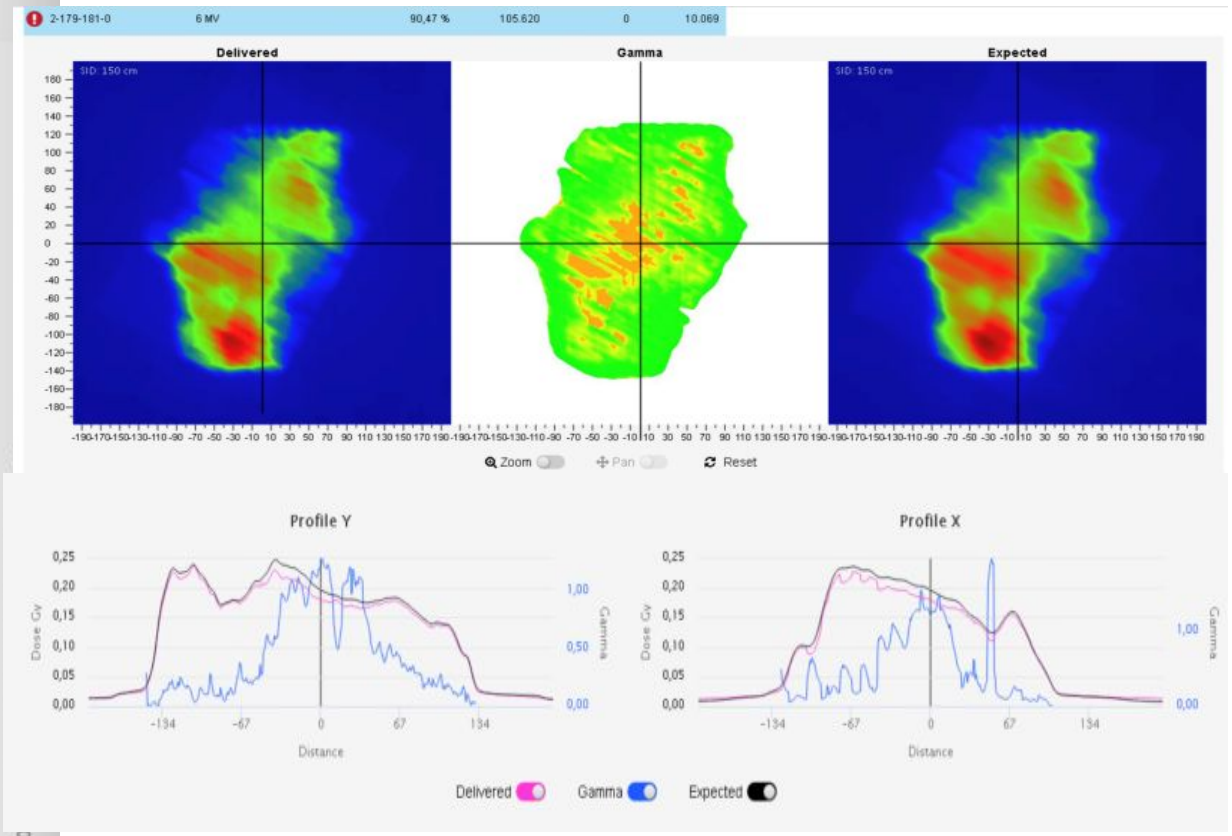
Expected image:

- Relative: 1st fraction EPID image
- **Absolute**: predicted dose by the platform using RT plan and CT simulation

2D analysis: transit IVD

2D image analysis: integrated image

Beams (2D)



Gamma analysis

Difference (%)	Distance (mm)
5	5
Threshold (%)	**Passing (%)**
30	95

Normalization: Local

editable templates

Template	Localitzacions	Criteris gamma DIV
abdomen-chest	Abdomen and Thorax	Local **5%,5mm** Th: 30% Tolerancia **95%**
head and neck	H&N and brain	Local **3%,3mm** Th: 30% Tolerancia **95%**
Breast or palliative	Breast, extremities, palliatives	Local **5%,7mm** Th: 30% Tolerancia **90%**

3D analysis

3D image analysis: log-files + CBCT

Targets OARs

Image Source

Calculated On

CBCT (17 FEBR. 2021 12:49)

Plan CT

CBCT (17 FEBR. 2021 12:49)

Images

Delivered

Gamma

Planned

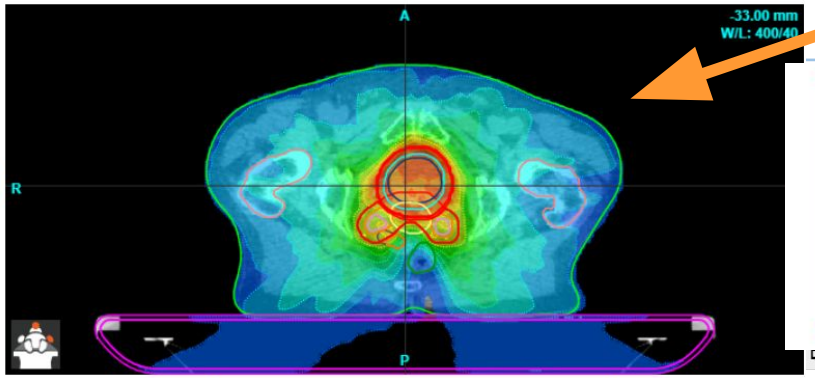
Dose Opacity

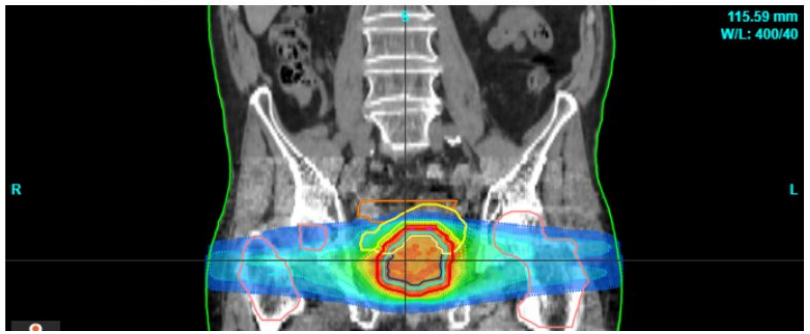
100%

Profile Tool

Dose Scale

> 2,71
2,46
2,22
1,97
1,73
1,49
1,24
1,00
0,76
0,51
0,27





CTV_5280 86,56 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,91	1,87	-1,82
D95	1,60	1,51	-5,55

CTV_5940 99,90 % Gamma

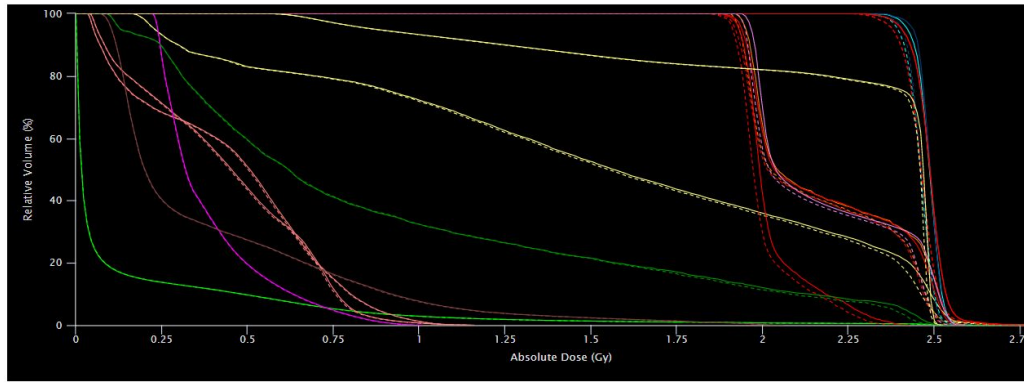
METRIC	TPS	QA	Δ%
Mean	2,04	2,01	-1,27
D95	1,80	1,77	-1,61

CTV_6996 99,91 % Gamma

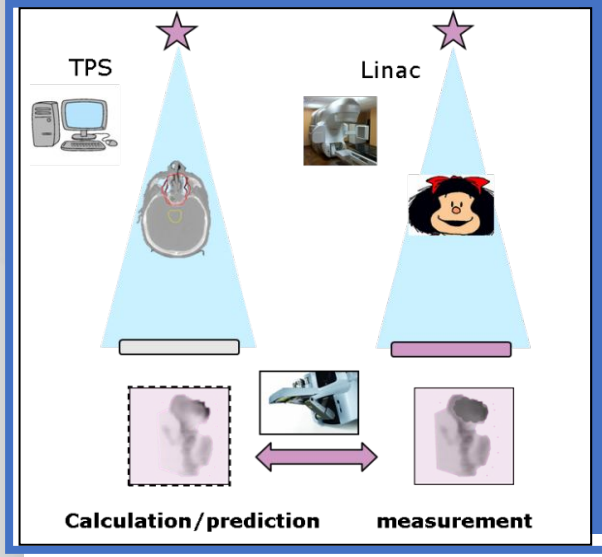
METRIC	TPS	QA	Δ%
Mean	2,13	2,11	-1,12
D95	2,08	2,06	-1,00

DVH

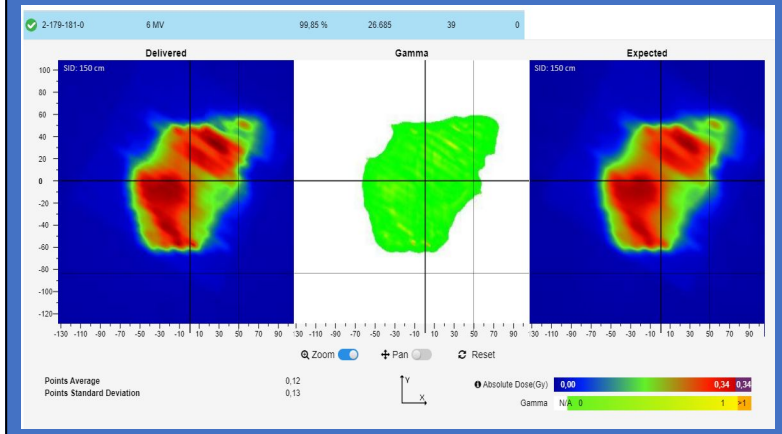
STRUCTURE NAME	MIN	MAX	MEAN
Bladder	0,16 Gy	2,77 Gy	1,51 Gy
BODY	0,00 Gy	2,77 Gy	0,13 Gy
CTVp_5600	1,90 Gy	2,56 Gy	2,16 Gy
CTVp_7000	2,27 Gy	2,58 Gy	2,46 Gy
Femur_L	0,03 Gy	1,14 Gy	0,45 Gy
Femur_R	0,04 Gy	1,15 Gy	0,44 Gy
PenileBulb	0,22 Gy	1,00 Gy	0,38 Gy
Prostate	2,30 Gy	2,56 Gy	2,46 Gy
PTVp_5600	1,77 Gy	2,56 Gy	2,15 Gy
PTVp_5600HDV	1,77 Gy	2,37 Gy	2,00 Gy
PTVp_7000	2,20 Gy	2,77 Gy	2,46 Gy



In-Vivo and log-files based analysis



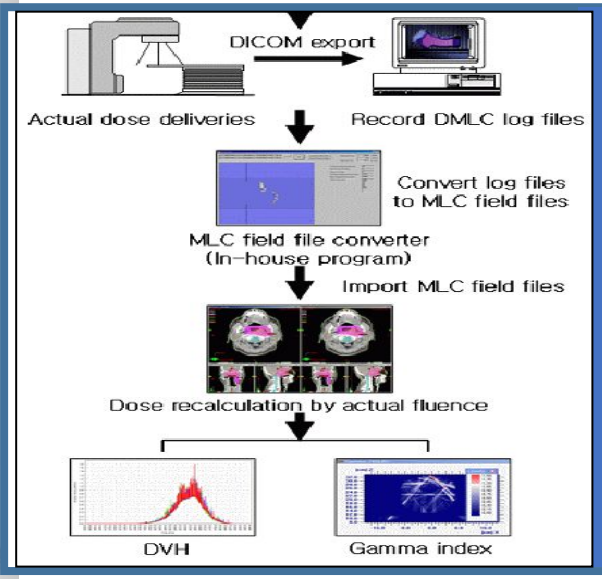
Analysis 2D



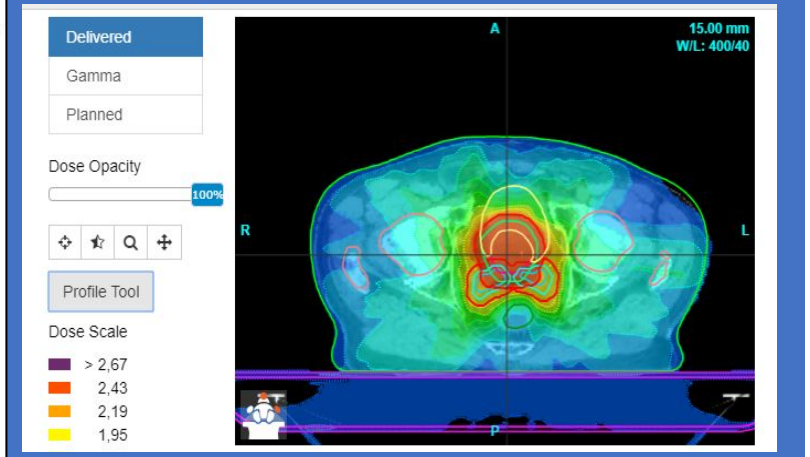
in-Vivo verifications

EPID images for detecting transit dose

- ✔ Treatment delivery as expected?
- ✔ Verification of patient position during treatment



Analysis 3D



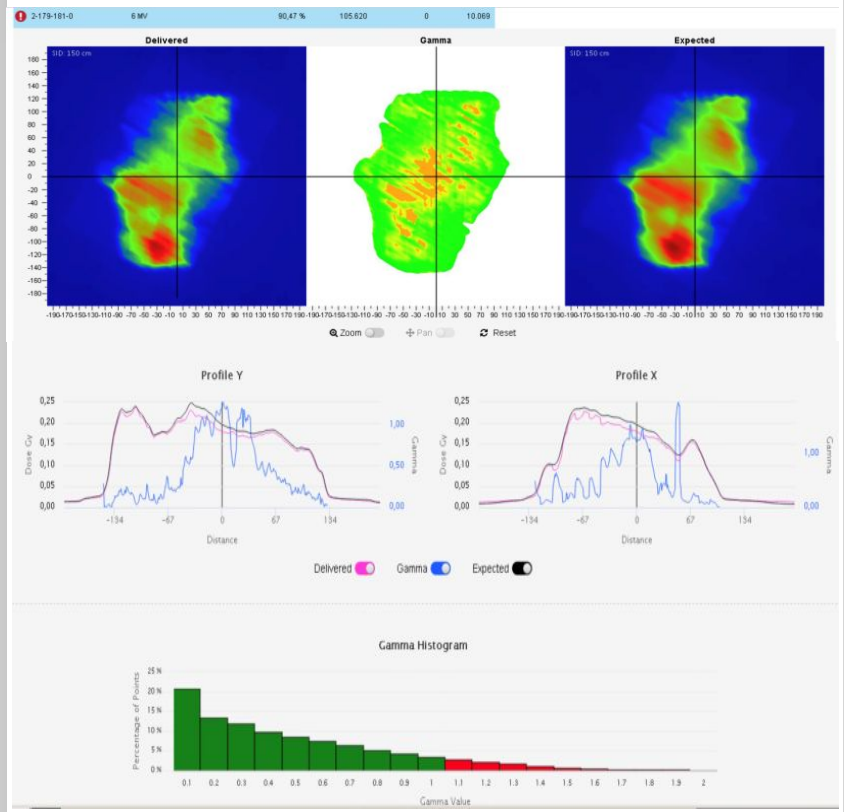
Offline verifications

Logfiles + CBCT

- ✔ Evaluating the causes of the deviation
- ✔ Dosimetric impact assessing→ supporting replanning decision by RO

Flag alerts assesing

Out of tolerance → Alert assessment → Actions to be taken →



EPID results

- (•) FAIL
- ( ) PASS
- ( ) NO RESULTS

External Data Base

REDCap santpau

EPID_Reasons for failure

- [ ] Patient position
- [ ] Anatomical changes body co
- [ ] Anatomical changes internal
- [ ] Intrafraction motion
- [ ] Positioning devices
- [ ] EPID adcquisition
- [ ] Preditcted dose calculation
- [ ] MLC motion/position
- [ ] Beam stability
- [ ] Beam interrupted
- [ ] Unknown
- [ ] Other

CBCT recalculation results

- (•) FAIL
- ( ) PASS
- ( ) NO RESULTS

CBCT_Reasons for failure

- [ ] Patient position
- [ ] Anatomical changes body contour
- [ ] Anatomical changes internal structures/tumor
- [ ] Intrafraction motion
- [ ] Positioning devices
- [ ] CBCT artifacts
- [ ] Preditcted dose calculation
- [ ] Partial logs
- [ ] No new information apart from logs

Actions

- [ ] Repetir 2D
- [ ] Repetir CBCT
- [ ] Fer CBCT
- [ ] Perfraction diari
- [ ] Valorar replanificació
- [ ] Indicacions a maquina posicionament/preparacio
- [ ] Observacio properes fraccions
- [ ] tractament finalizat
- [ ] Per comentar amb sunnuclear
- [ ] Per comentar en reunio servei
- [ ] N/A

Saved for training/session

Results

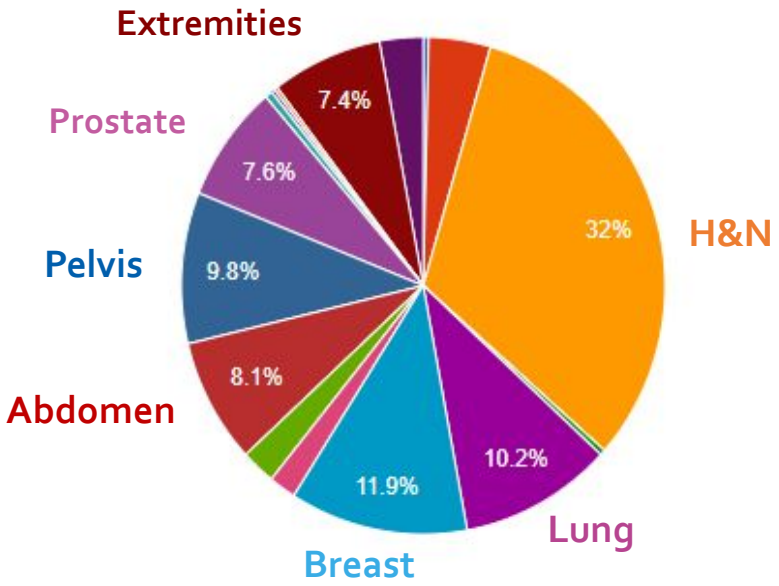
Results: failed fractions

10% of daily sessions flag alerts

EPID-based iVD analysis

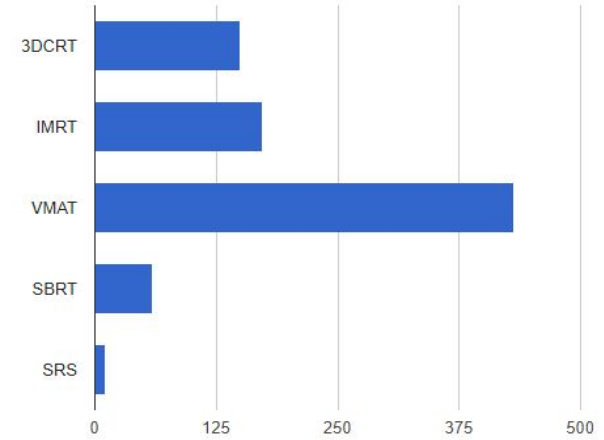
By location

Counts/frequency: General unespecified (3, 0.4%), Brain (34, 4.1%), Head and Neck (264, 32.0%), Esophagus (3, 0.4%), Lung (84, 10.2%), Breast (98, 11.9%), Mediastinum (15, 1.8%), Gastrointestinal (19, 2.3%), Abdomen (67, 8.1%), Pelvis (81, 9.8%), Prostate (63, 7.6%), Genitourinary (4, 0.5%), GYN (0, 0.0%), Colorectal (2, 0.2%), Kidney (2, 0.2%), Extremities (61, 7.4%), Bone (24, 2.9%)



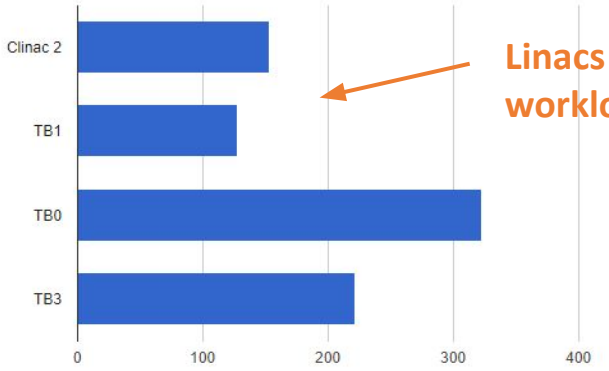
By technique

Counts/frequency: 3DCRT (150, 18.2%), IMRT (173, 21.0%), VMAT (431, 52.3%), SBRT (59, 7.2%), SRS (11, 1.3%)



By treatment unit

ounts/frequency: Clinac 2 (153, 18.6%), TB1 (128, 15.5%), TB0 (322, 39.1%), TB3 (221, 26.8%)



Linacs with half of the workload

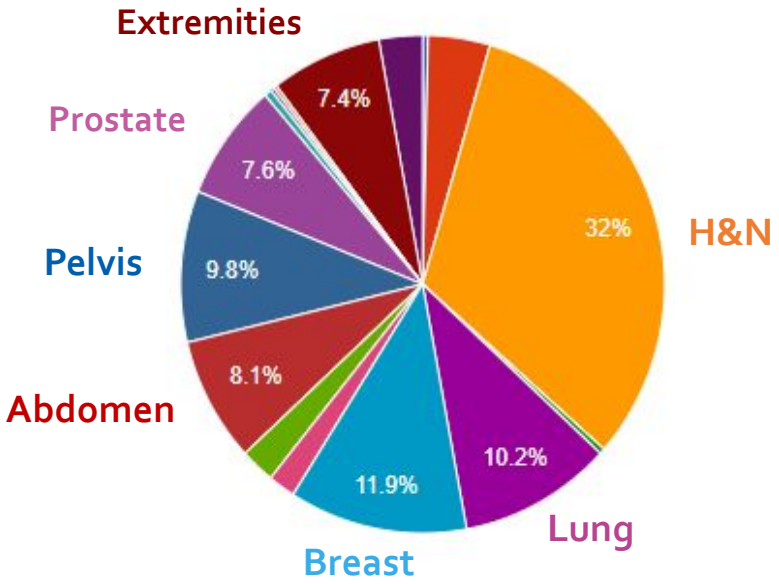
Results: failed fractions

EPID-based iVD analysis

10% of daily sessions flag alerts

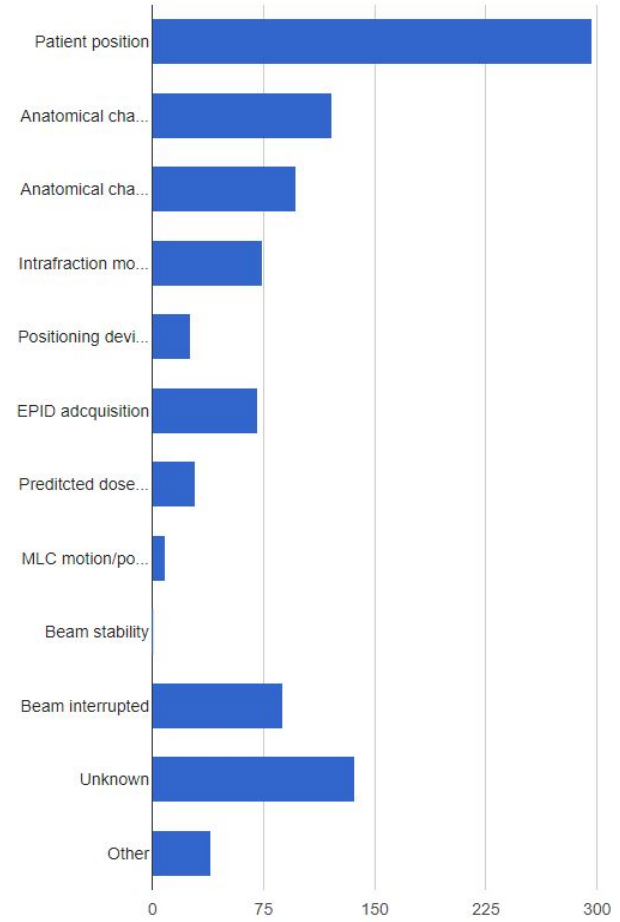
By location

Counts/frequency: General unespecified (3, 0.4%), Brain (34, 4.1%), Head and Neck (264, 32.0%), Esophagus (3, 0.4%), Lung (84, 10.2%), Breast (98, 11.9%), Mediastinum (15, 1.8%), Gastrointestinal (19, 2.3%), Abdomen (67, 8.1%), Pelvis (81, 9.8%), Prostate (63, 7.6%), Genitourinary (4, 0.5%), GYN (0, 0.0%), Colorectal (2, 0.2%), Kidney (2, 0.2%), Extremities (61, 7.4%), Bone (24, 2.9%)



Cause of alerts

Counts/frequency: Patient position (297, 36.0%), Anatomical changes body contour (121, 14.7%), Anatomical changes internal structures/tumor (97, 11.8%), Intrafraction motion (74, 9.0%), Positioning devices (26, 3.2%), EPID adcquisition (71, 8.6%), Preditcted dose calculation (29, 3.5%), MLC motion/position (9, 1.1%), Beam stability (1, 0.1%), Beam interrupted (88, 10.7%), Unknown (137, 16.6%), Other (40, 4.8%)



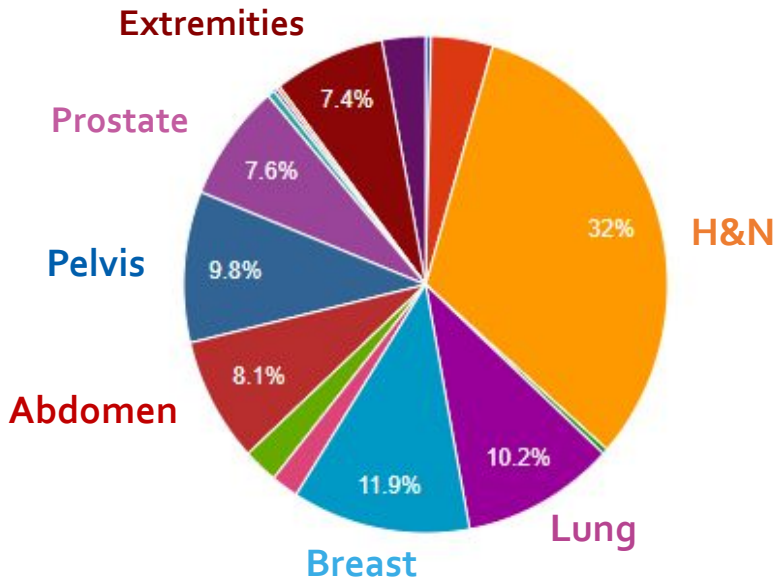
Results: failed fractions

10% of daily sessions flag alerts

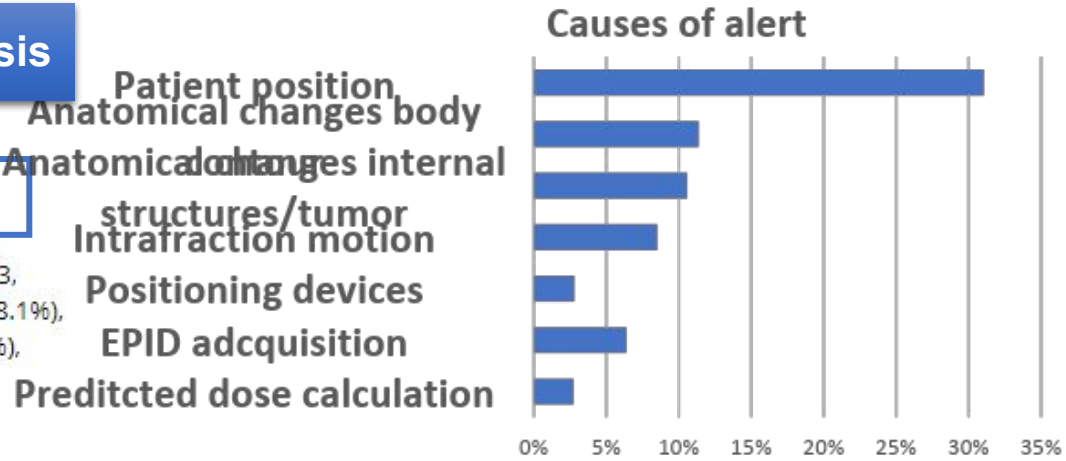
EPID-based IVD analysis

By location

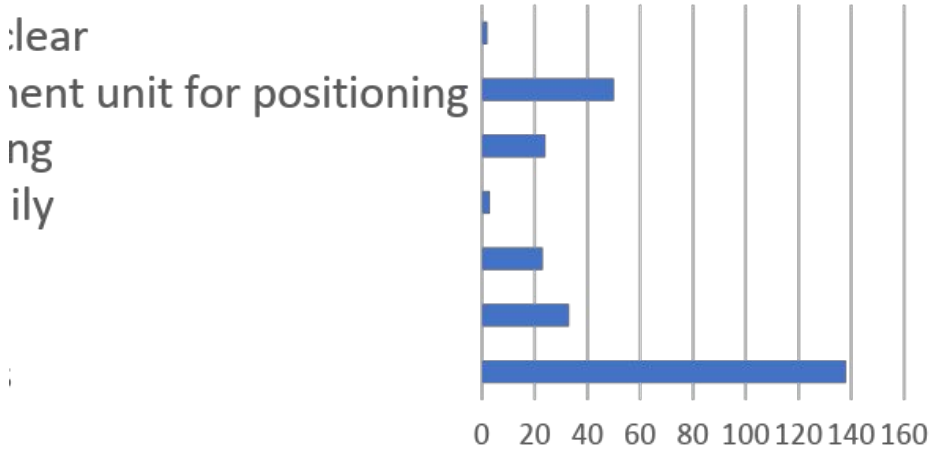
Counts/frequency: General unespecified (3, 0.4%), Brain (34, 4.1%), Head and Neck (264, 32.0%), Esophagus (3, 0.4%), Lung (84, 10.2%), Breast (98, 11.9%), Mediastinum (15, 1.8%), Gastrointestinal (19, 2.3%), Abdomen (67, 8.1%), Pelvis (81, 9.8%), Prostate (63, 7.6%), Genitourinary (4, 0.5%), GYN (0, 0.0%), Colorectal (2, 0.2%), Kidney (2, 0.2%), Extremities (61, 7.4%), Bone (24, 2.9%)



Download image



Actions

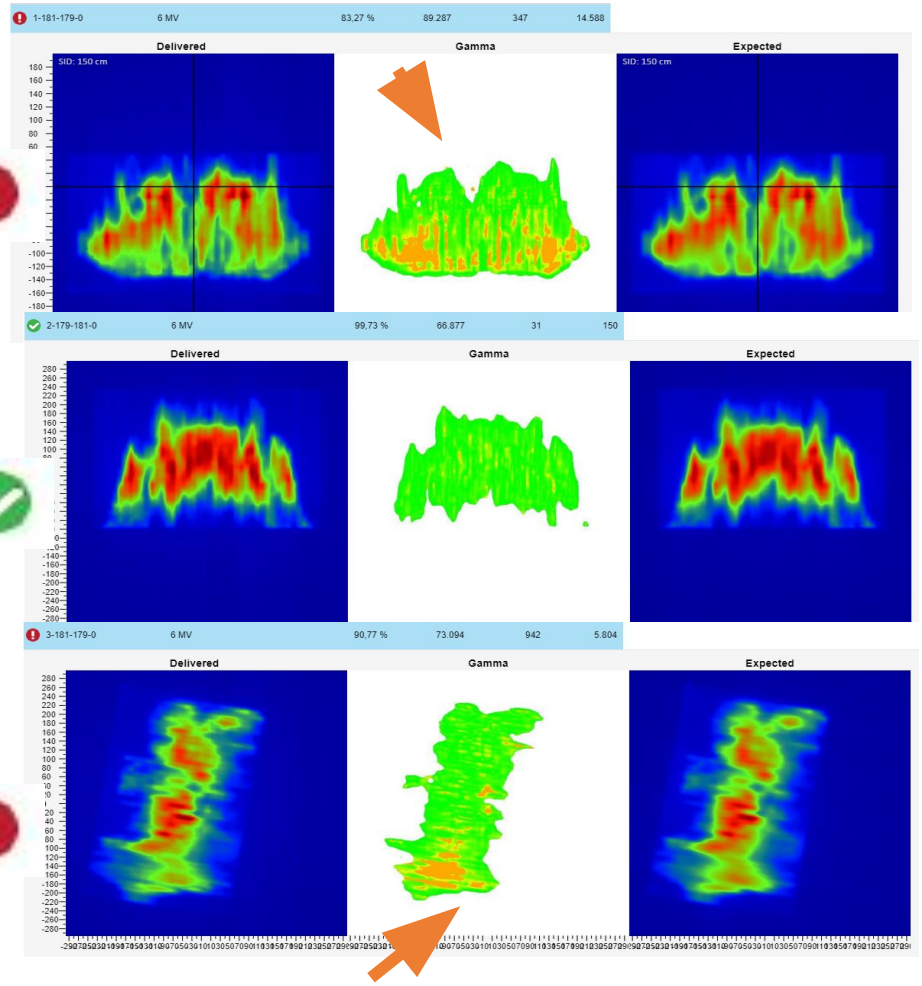


Clinical examples

Ex 1: Patient position

H&N

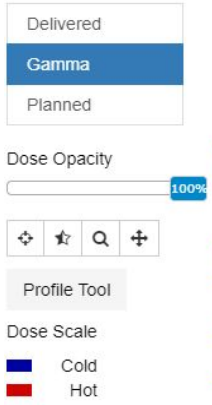
Delivered	Gamma analysis	Expected

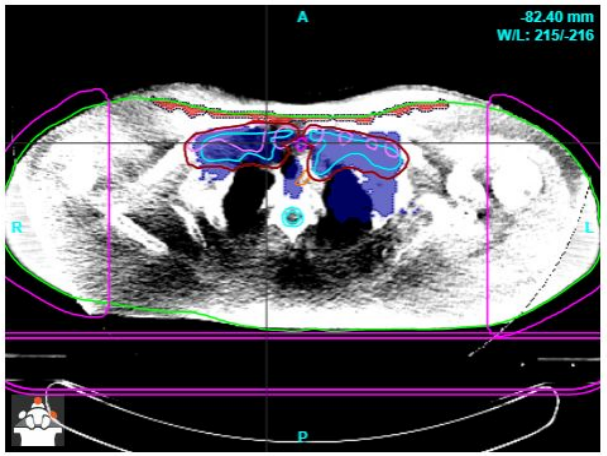


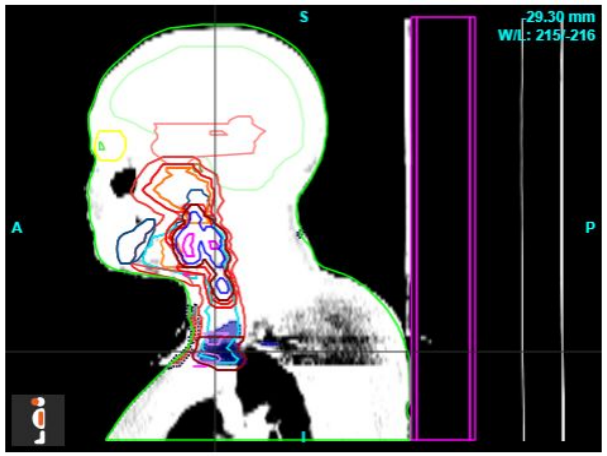
CTV_5280			
86,56 % Gamma			
METRIC	TPS	QA	Δ%
Mean	1,91	**1,87**	-1,82
D95	1,60	**1,51**	**-5,55**

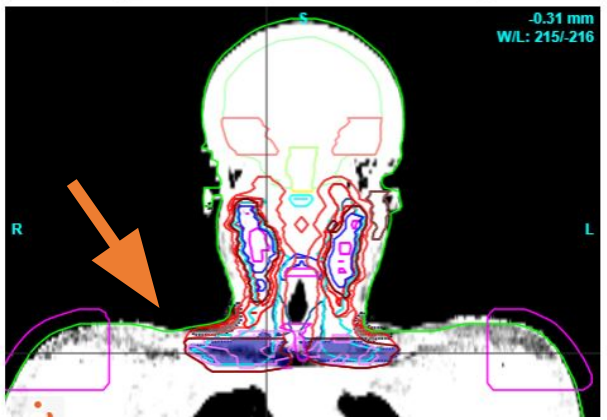
CTV_5940			
99,90 % Gamma			
METRIC	TPS	QA	Δ%
Mean	2,04	**2,01**	-1,27
D95	1,80	**1,77**	-1,61

CTV_6996			
99,91 % Gamma			
METRIC	TPS	QA	Δ%
Mean	2,13	**2,11**	-1,12
D95	2,08	**2,06**	-1,00





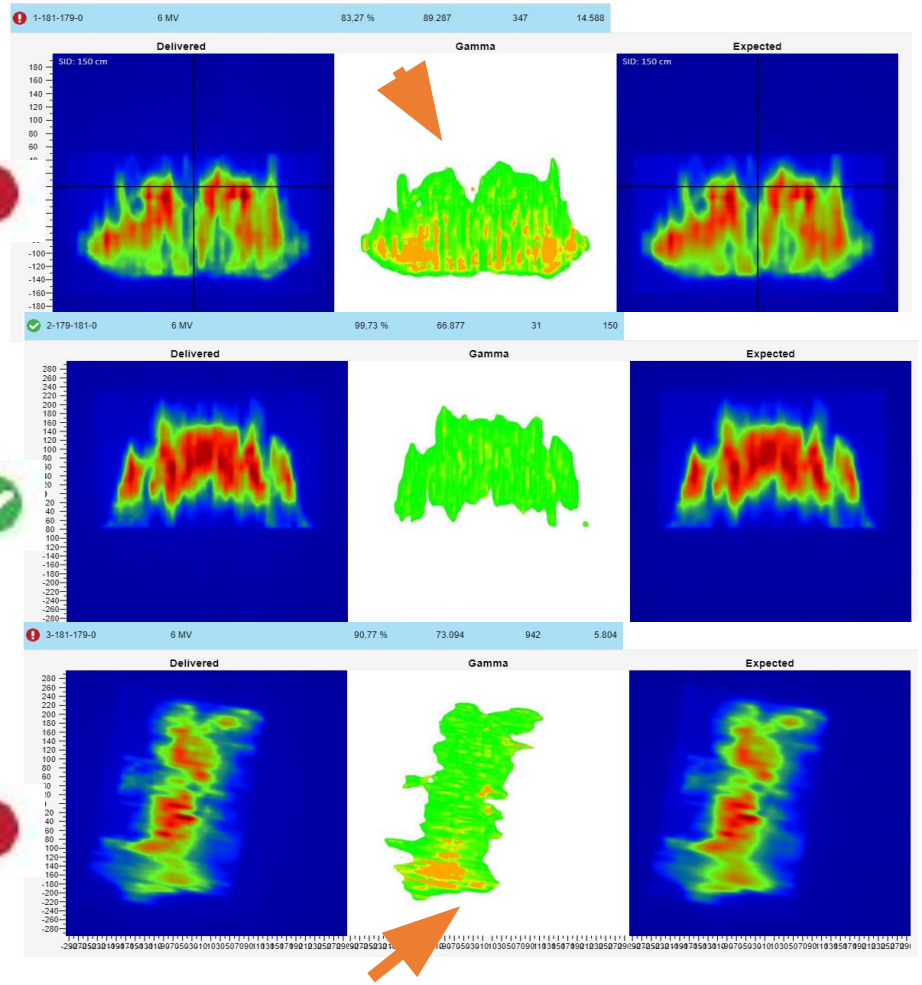


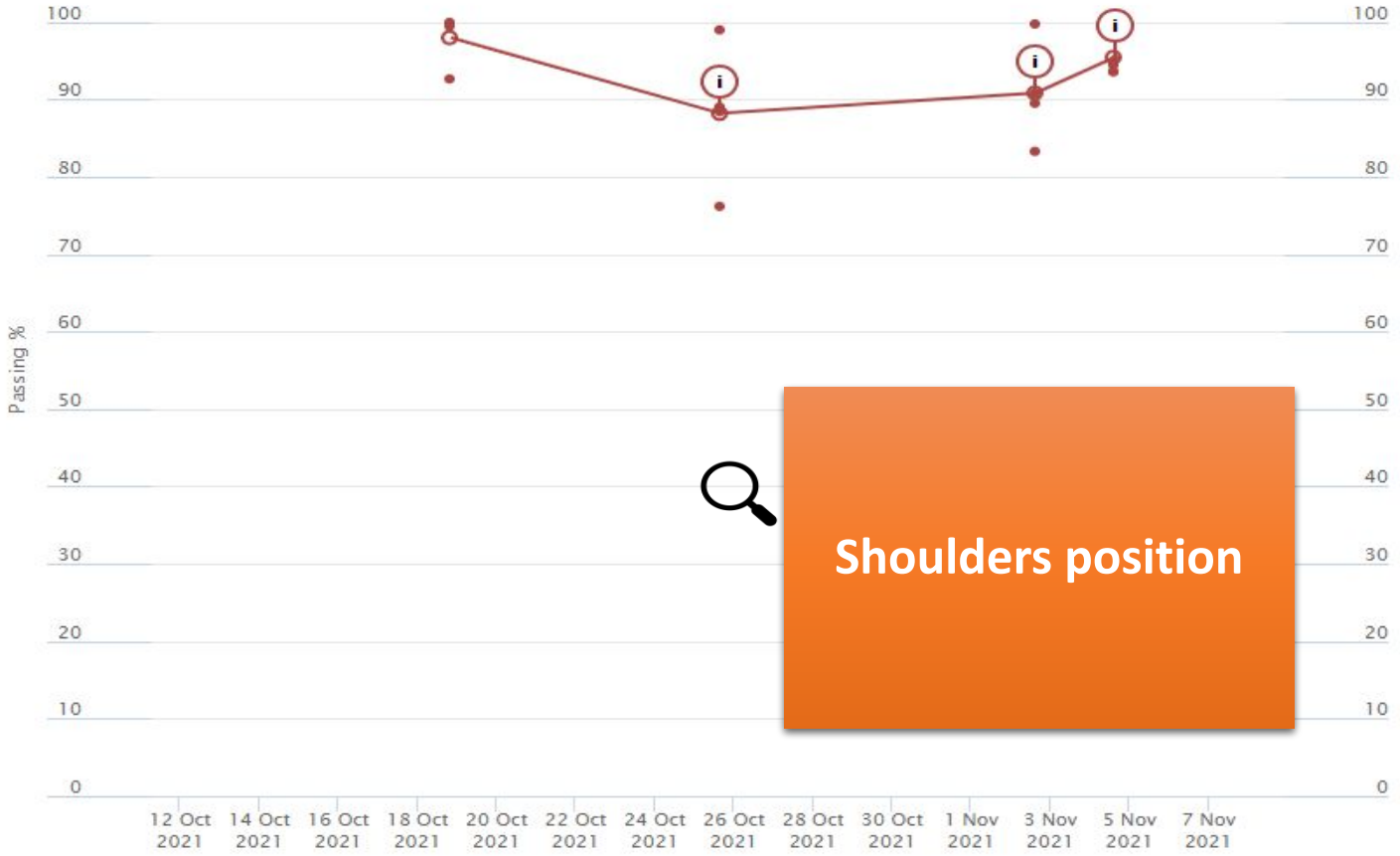


Shoulders position

Ex 1: Patient position

H&N





Shoulders position

Ex 1: Patient position: change of practice

Patient long mask

Planning CT

Take out the mask

Place IV

Reposition patient Mask

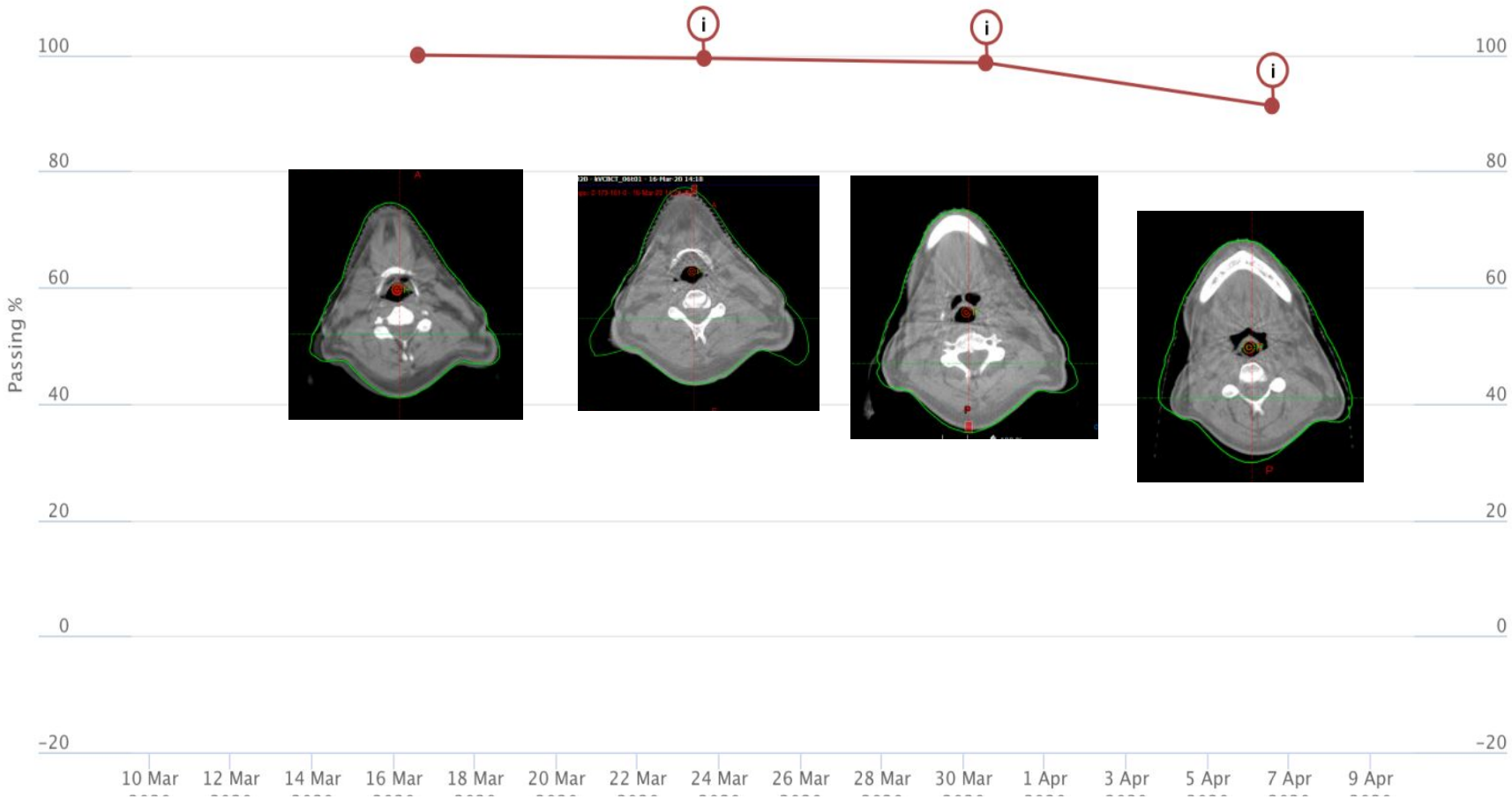
Contrast CT

Ex 2: Patient anatomy

H&N

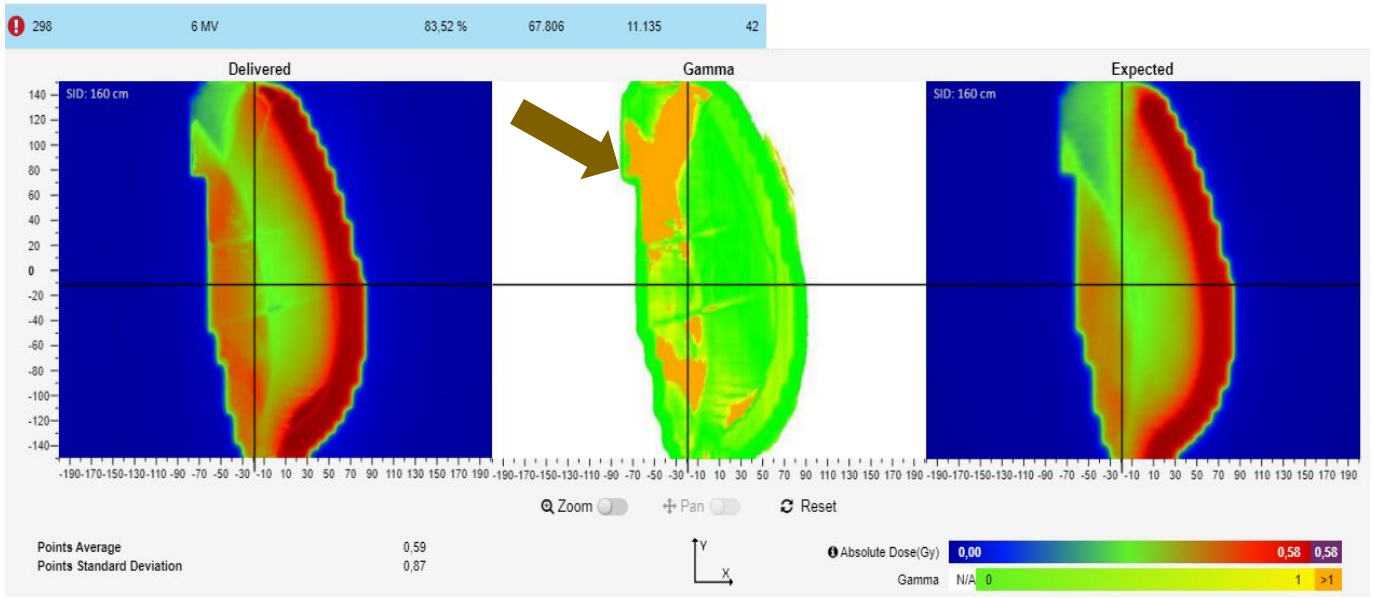
2D analysis trending

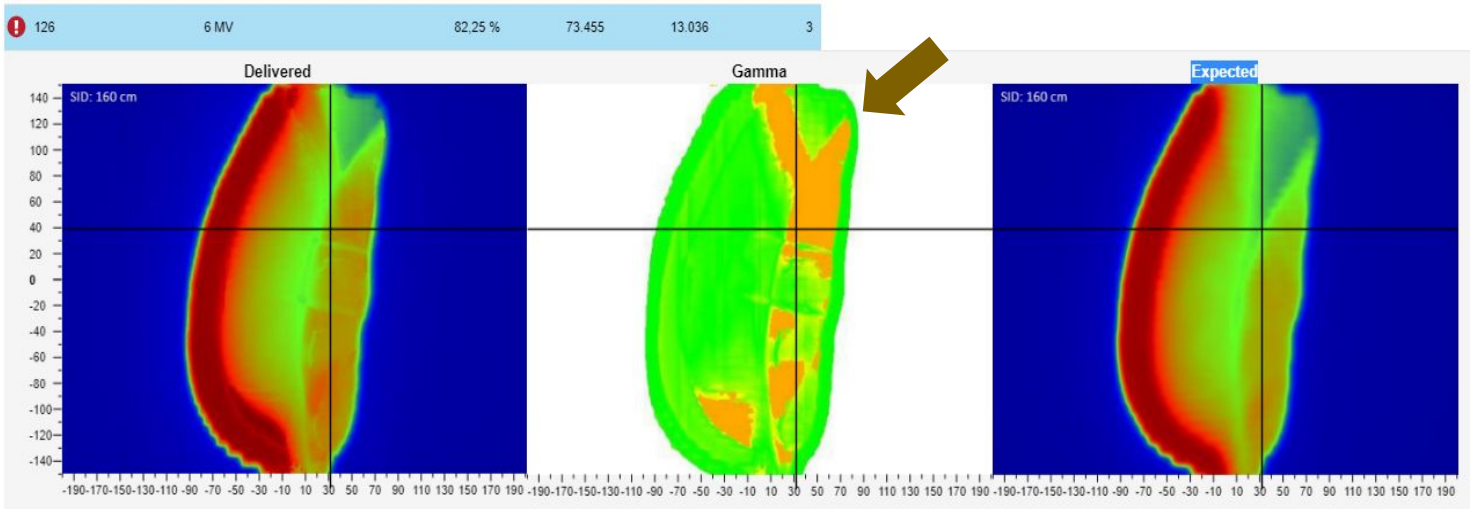
Weight loss



Off line adaptive Replanning

Ex 3: Patient position





Breast

Arm position

Ex 3: Patient position change of practice

On line adaptive ??

IMPLEMENTATION OF IGRT

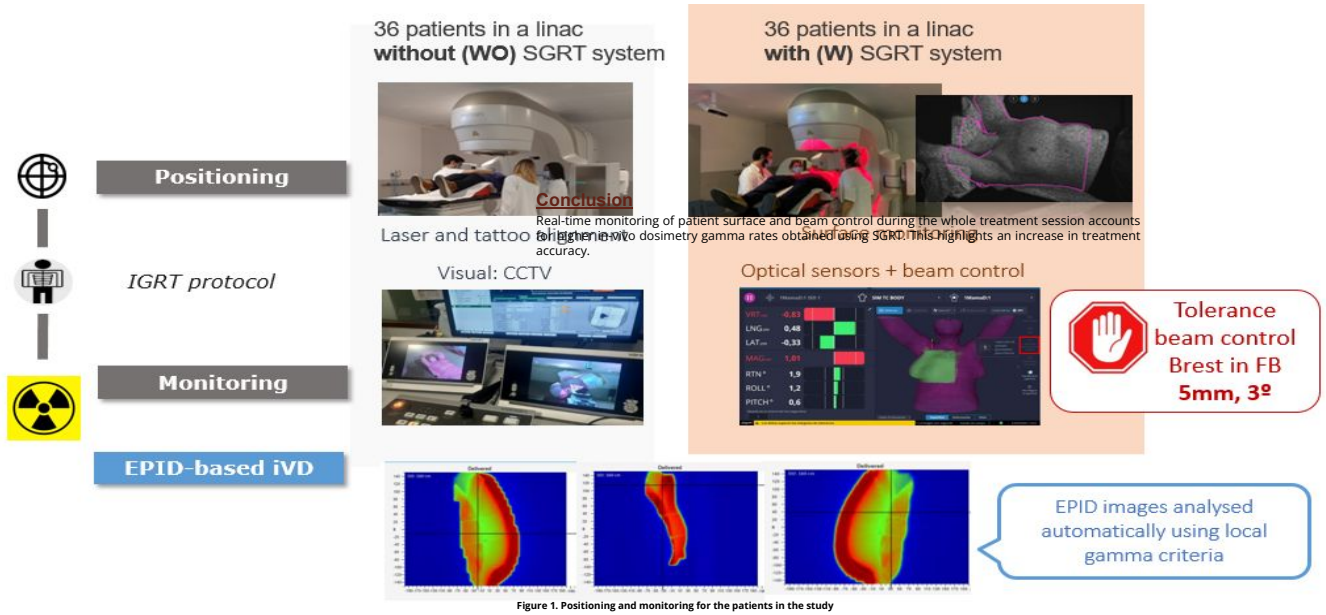
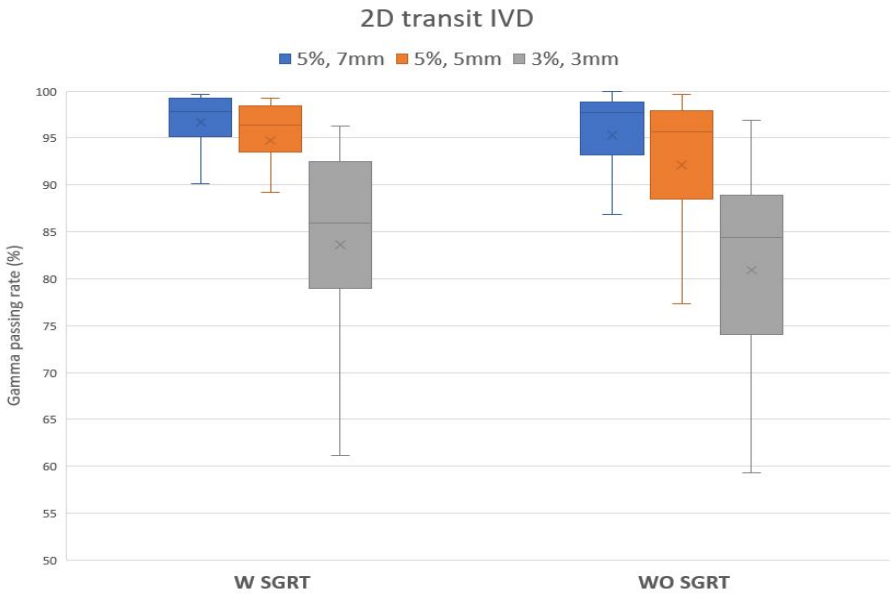


Figure 1. Positioning and monitoring for the patients in the study

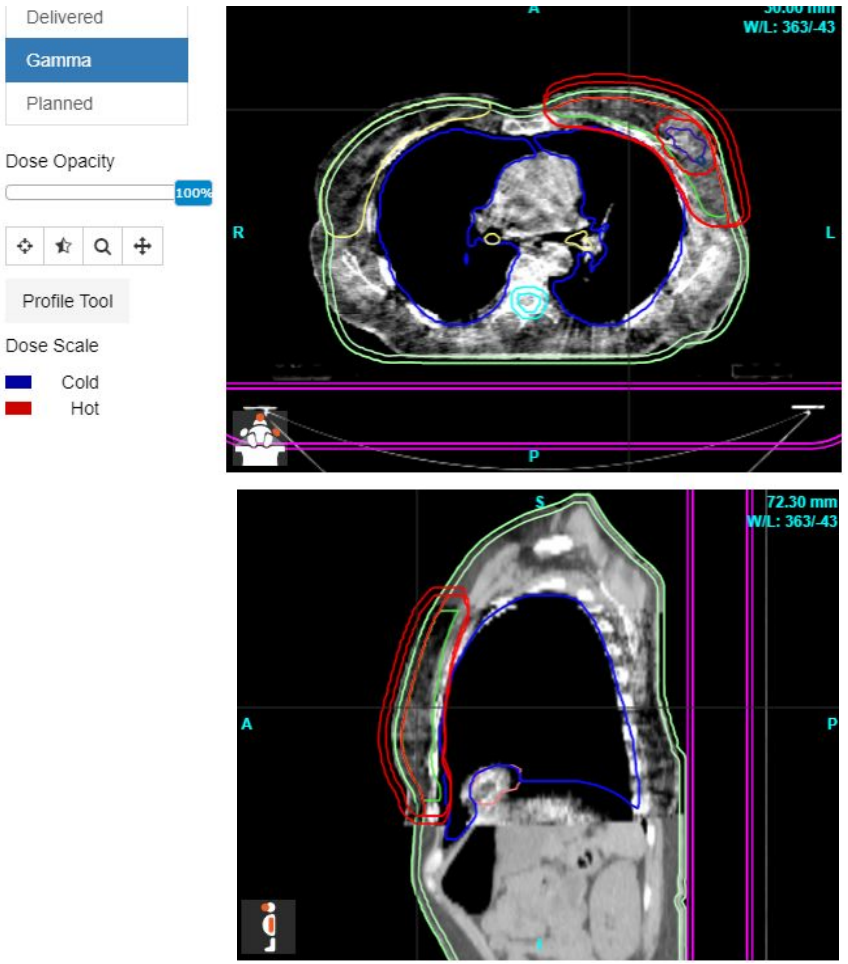


Conclusion

Real-time monitoring of patient surface and beam control during the whole treatment session accounts for higher in-vivo dosimetry gamma rates obtained using SGRT. This highlights an increase in treatment accuracy.

Ex 4: Intrafraction motion

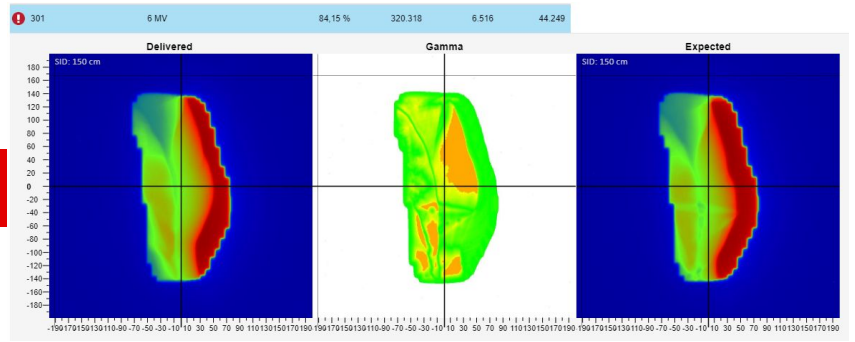
IGRT image shows good agreement with CT simulation



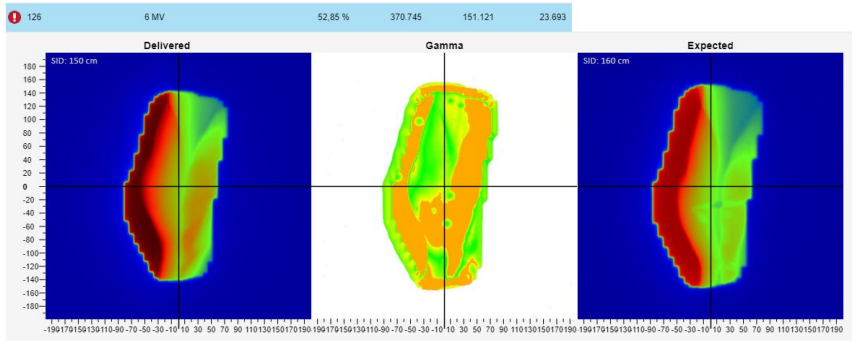
Breast

iVD shows poorer and poorer agreement within the session

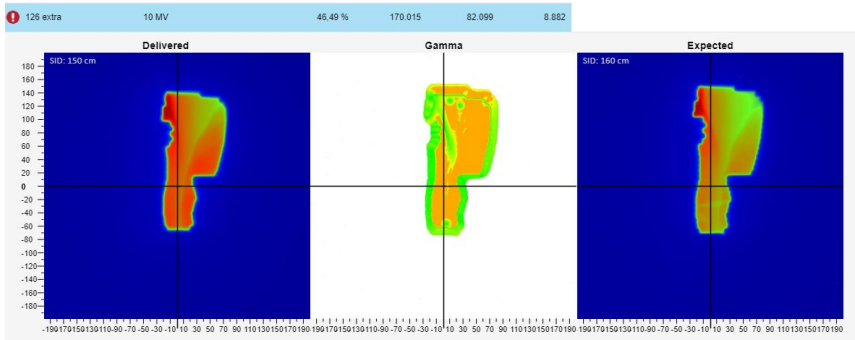
GPR = 84%



GPR = 52%



GPR = 46%



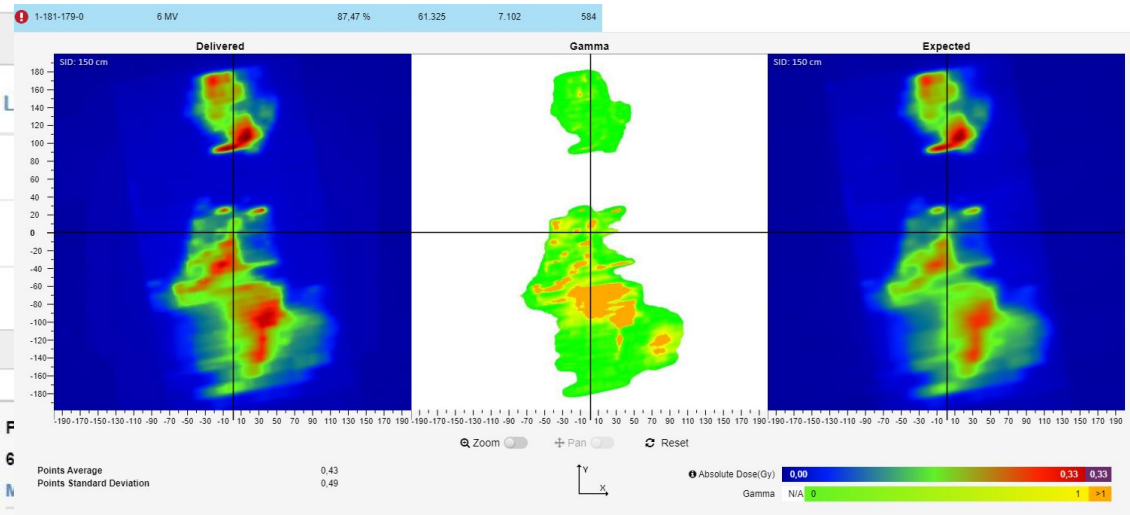
Ex 5: Respiratory movement

Fraction 1 | Approve | intrafraction motion: breath motion

Action : transit iVD next

Beams (2D)

BEAM NAME	ENERGY	PERCENT	POINTS	FAILED HIGH	FAILED L
2-179-181-0	6 MV	89,09 %	68.082	7.428	
1-181-179-0	6 MV	87,47 %	61.325	7.102	



Targets

CTV_5040 ✓
61,59 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,98	**2,07**	4,47
D95	1,95	**1,95**	-0,10

CTV_4500 ✓
71,31 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,94	**2,01**	3,33
D95	1,79	**1,78**	-0,50

CTVp_4500 ✓
70,67 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,94	**2,00**	3,50
D95	1,78	**1,77**	-0,55

CTVn_4500 ✓
67,25 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,98	**2,06**	4,12
D95	1,94	**1,94**	0,00

Mean	1,98	**2,06**	4,18
D95	1,92	**1,92**	-0,05

Mean	1,90	**1,96**	3,09
D95	1,76	**1,75**	-0,28

OARs

SpinalCord ✓
100,00 % Gamma

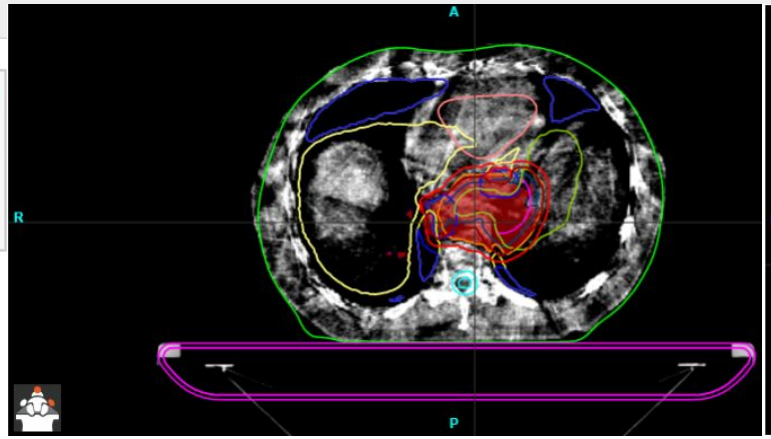
METRIC	TPS	QA	Δ%
Max	0,60	**0,59**	-1,48

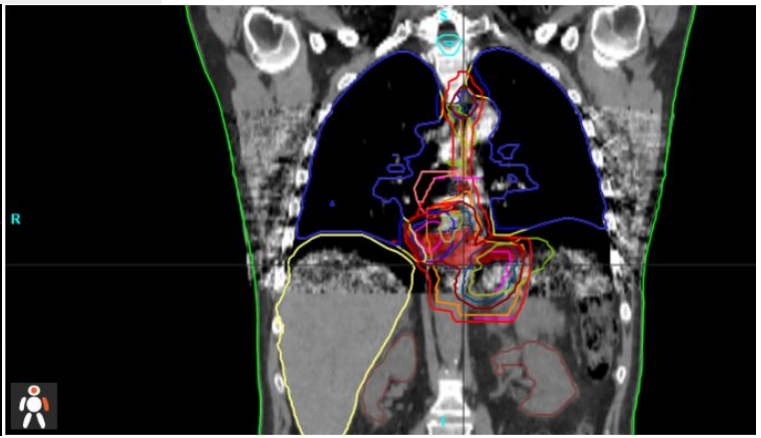
Lungs ✓
99,23 % Gamma

METRIC	TPS	QA	Δ%
Max	2,06	**2,24**	8,70

Liver ✓
99,89 % Gamma

METRIC	TPS	QA	Δ%
Max	1,98	**2,08**	5,03

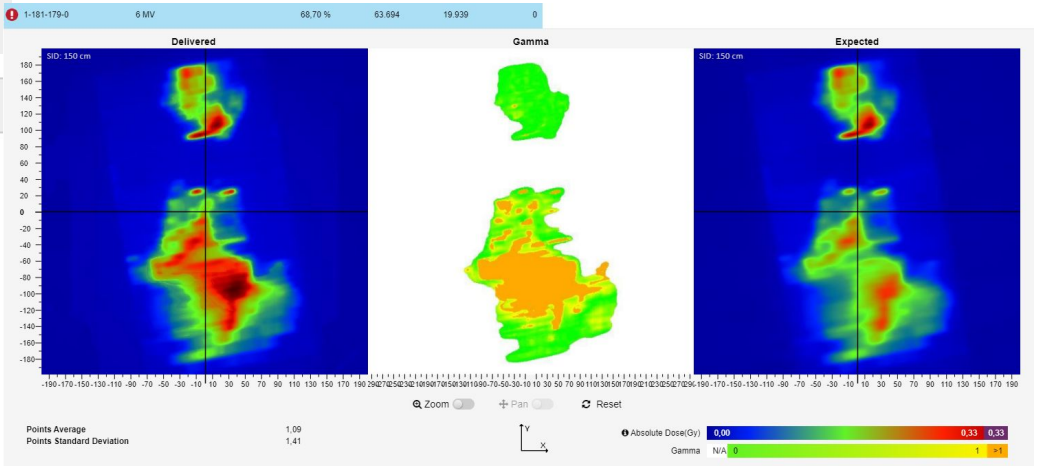




Ex 5: Respiratory movement

Fraction 8 | Approve | respiratory motion. Demanat repetir en expiració forçada.

Action : plan with breath control



Beams (2D)

BEAM NAME	ENERGY	PERCENT	POINTS	FAILED HIGH	FAILED LOW
1-181-179-0	6 MV	68,70 %	63.694	19.939	0
2-179-181-0	6 MV	71,90 %	69.161	19.436	0

Targets

CTV_5040 — **19,50** % Gamma

METRIC	TPS	QA	Δ%
Mean	1,98	2,25	13,17
D95	1,95	2,01	3,12

CTV_4500 — **35,97** % Gamma

METRIC	TPS	QA	Δ%
Mean	1,94	2,16	11,04
D95	1,79	1,84	2,79

CTVp_4500 — **32,93** % Gamma

METRIC	TPS	QA	Δ%
Mean	1,94	2,16	11,74
D95	1,78	1,83	2,63

CTVn_4500 — **34,96** % Gamma

METRIC	TPS	QA	Δ%
Mean	1,98	2,19	10,26
D95	1,94	1,94	0,15

PTV_5040 — **28,61** % Gamma

METRIC	TPS	QA	Δ%
Mean	1,98	2,21	11,85
D95	1,92	1,96	1,91

PTV_4500 — **45,74** % Gamma

METRIC	TPS	QA	Δ%
Mean	1,90	2,08	9,48
D95	1,76	1,79	1,70

OARs

Lungs — **98,42** % Gamma

METRIC	TPS	QA	Δ%
Max	2,06	2,36	14,56

Liver — **79,60** % Gamma

METRIC	TPS	QA	Δ%
Max	1,98	2,35	18,69

Heart — **90,16** % Gamma

METRIC	TPS	QA	Δ%
Max	2,04	2,38	16,99

SpinalCord — **100,00** % Gamma

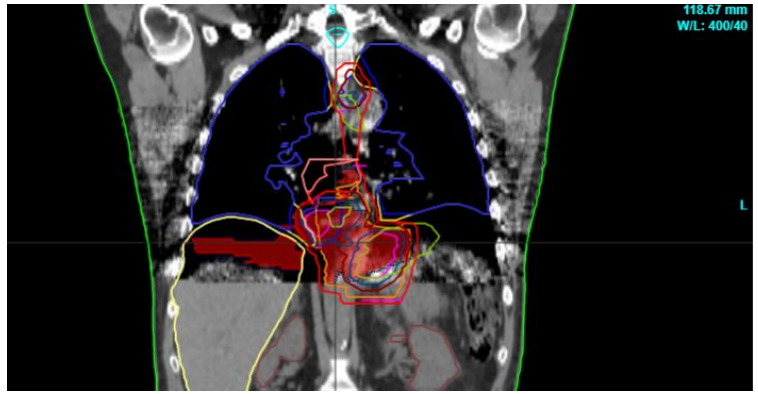
METRIC	TPS	QA	Δ%
Max	0,60	0,60	-0,16

Kidney_R

METRIC	TPS	QA	Δ%
Max	0,36	0,34	-3,86

Kidney_L — **100,00** % Gamma

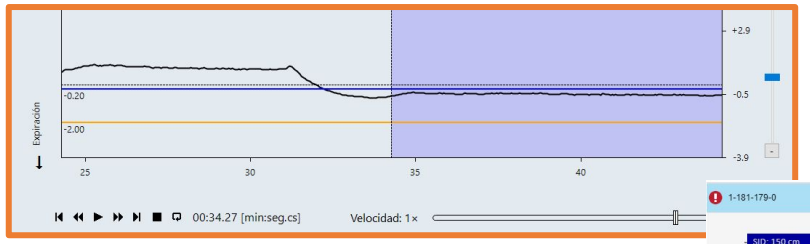
METRIC	TPS	QA	Δ%
Max	1,42	1,42	-0,07

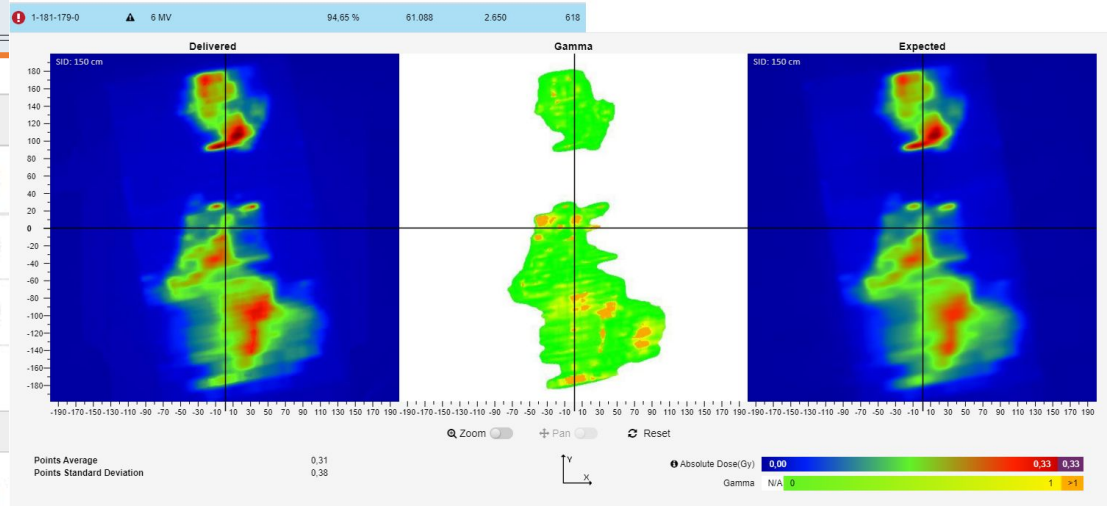


Ex 5: Respiratory movement

Following fractions...

Plan with breath control





Beams (2D)

BEAM NAME	ENERGY	PERCENT	POINTS	FAILED HIGH	FAILED LOW
1-181-179-0	6 MV	94,65 %	61.088	2.650	618
2-179-181-0	6 MV	97,76 %	67.612	1.515	0

Targets

CTV_5040
99,06 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,98	**2,02**	1,60
D95	1,95	**1,96**	0,30

CTV_4500
99,43 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,94	**1,97**	1,18
D95	1,79	**1,79**	0,16

CTVp_4500
99,42 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,94	**1,96**	1,33
D95	1,78	**1,78**	0,11

CTVn_4500
98,92 % Gamma

METRIC	TPS	QA	Δ%
Mean	1,98	**2,00**	1,10
D95	1,94	**1,93**	-0,56

OARs

BODY
99,80 % Gamma

METRIC	TPS	QA	Δ%
Mean	0,28	**0,28**	0,35
Max	2,07	**2,10**	1,15

SpinalCord
100,00 % Gamma

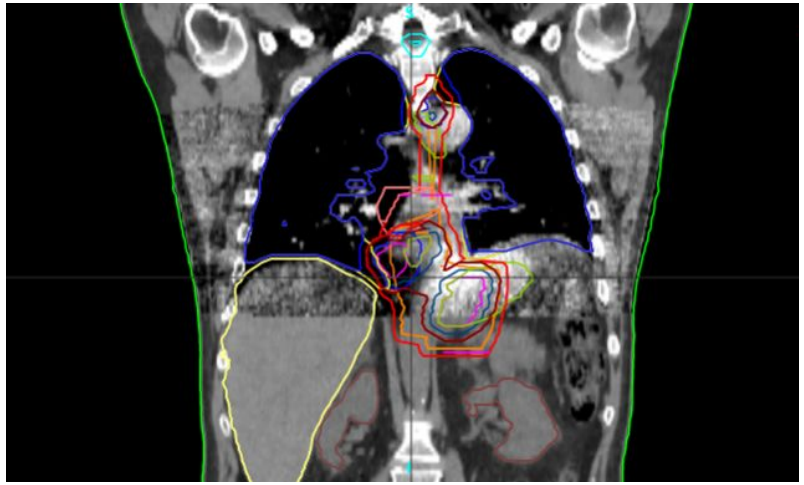
METRIC	TPS	QA	Δ%
Mean	0,37	**0,37**	-0,52
Max	0,60	**0,60**	-0,65

Lungs
99,63 % Gamma

METRIC	TPS	QA	Δ%
Mean	0,47	**0,47**	0,00
Max	2,06	**2,05**	-0,67

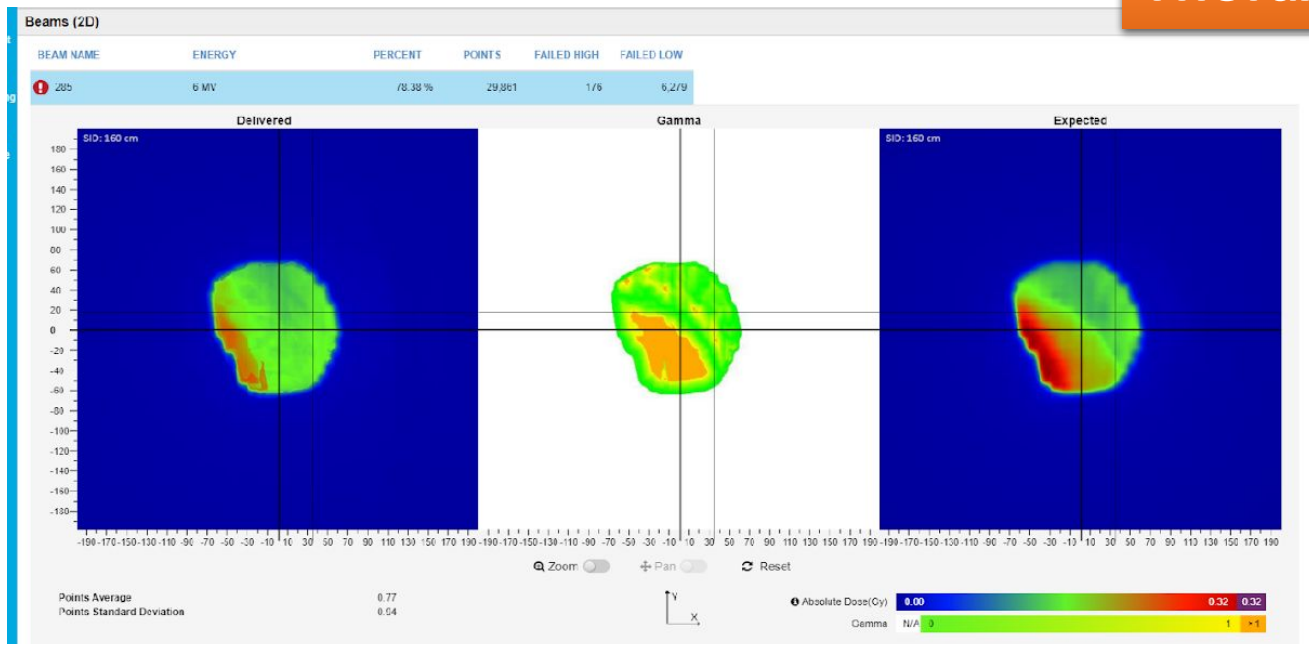
Liver
99,94 % Gamma

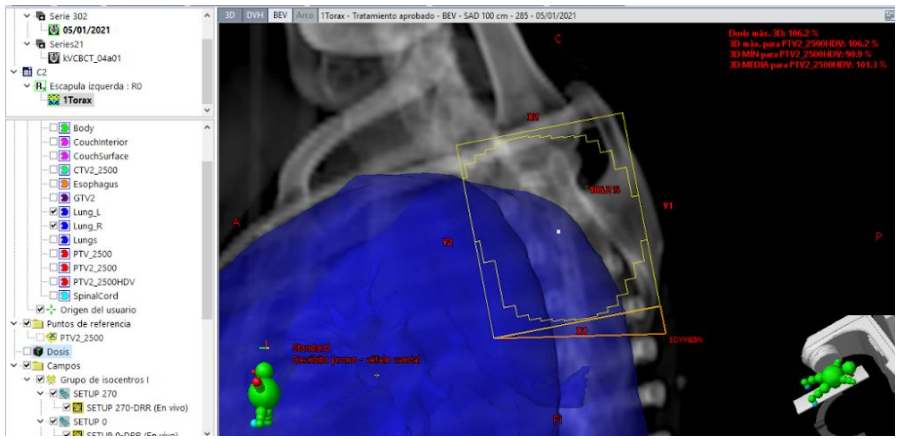
METRIC	TPS	QA	Δ%
Mean	0,47	**0,48**	1,04
Max	1,98	**2,05**	3,37



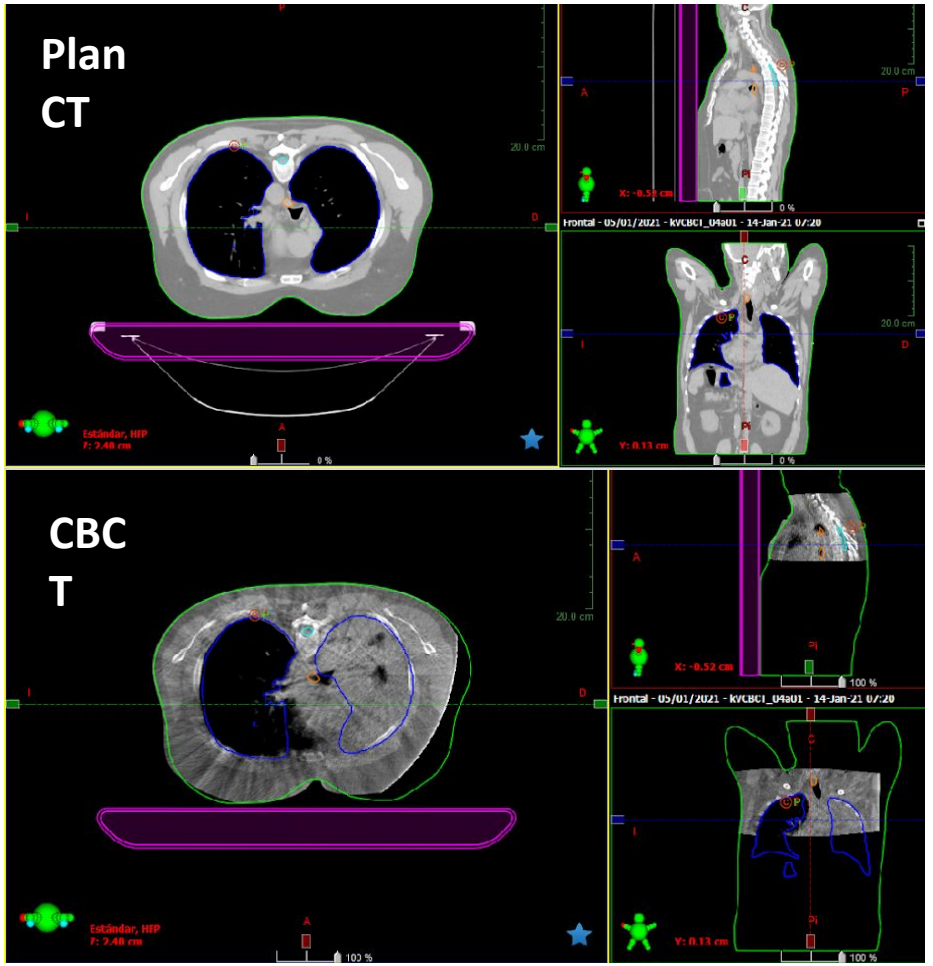
Ex 6: Patient anatomy

Thorax





Atelectasis



Conclusions

Take-home messages

We have the data to assess whether a patient would benefit from replanning/adapting

BUT, the information has to be processed to be appropiate for those assessments (deformable registration / structure deformation/ syntetic CT generator/ Dose calculation/ Dose accumulation)

Automation is needed to be able to detect patients that would benefit from replanning/adapting.

Take-home messages

In vivo dosimetry allows to flag treatments that could benefit from an adaptive strategy without adding any extra-dose due to CBCT

Our in vivo procedures are a safety network as we detect patient variations before the RO goes through off line review.

Experience with EPID-based in vivo verification of advanced treatments shows that medical physicists are much more involved in assuring the quality of the actual patient treatment than when only performing a pre-treatment dose verification measurement

In Memoria to Ben Mijnheer

He had a pivotal role in medical physics in Europe and a true pioneer in in vivo dosimetry and EPID-based IVD in particular