Democratizing real-time image guidance and verification: Approaches implemented on conventional linacs

DANISH CENTRE FOR PARTICLE THERAPY

Per Poulsen, Aarhus University Hospital, Denmark

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Agenda

- Introduction and scope
- Real-time IGRT methods
- Real-time dose reconstruction
- Conclusion

Stereotactic Body Radiation Therapy

SBRT:

- Involves high fraction doses with steep dose gradients
- Requires high accuracy at each fraction
- Challenged by intra-fraction motion

Stereotactic Body Radiation Therapy

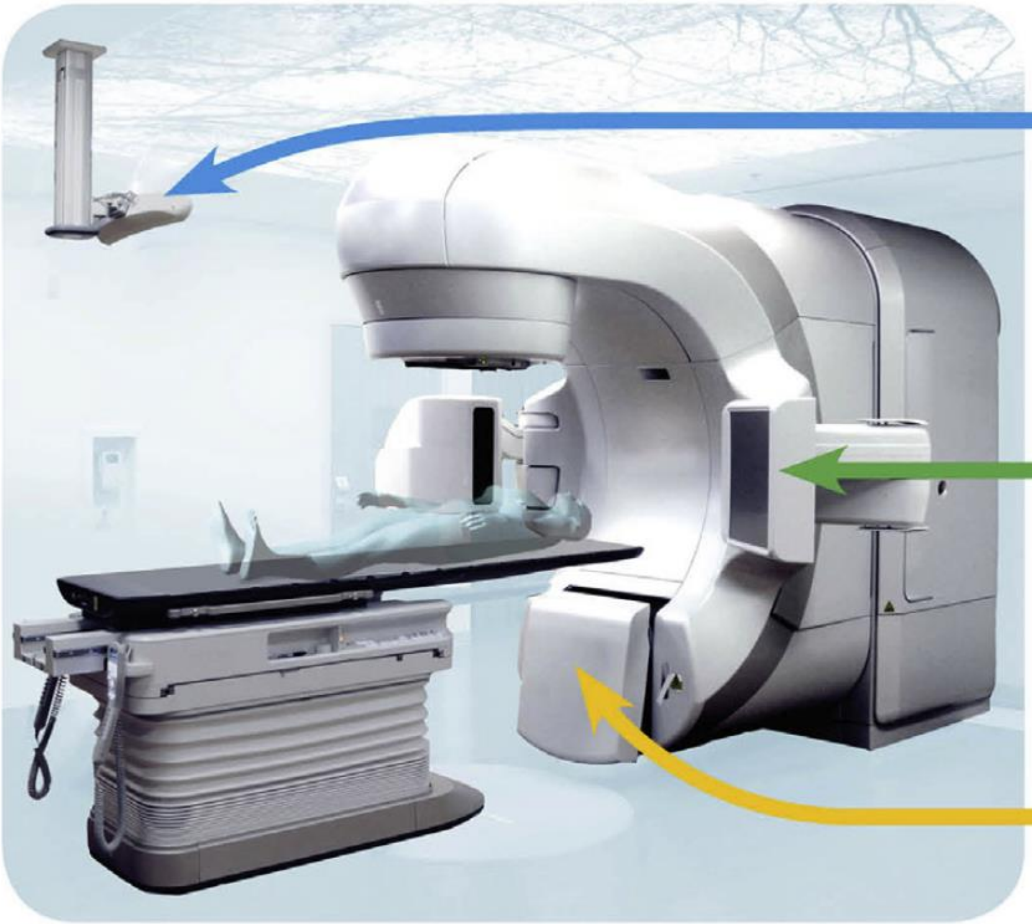
SBRT:

- Involves high fraction doses with steep dose gradients
- Requires high accuracy at each fraction
- Challenged by intra-fraction motion

Real-time motion adaptation:

- Could ensure high accuracy at each fraction
- Requires real-time motion monitoring

Real-time signals available on conventional linacs

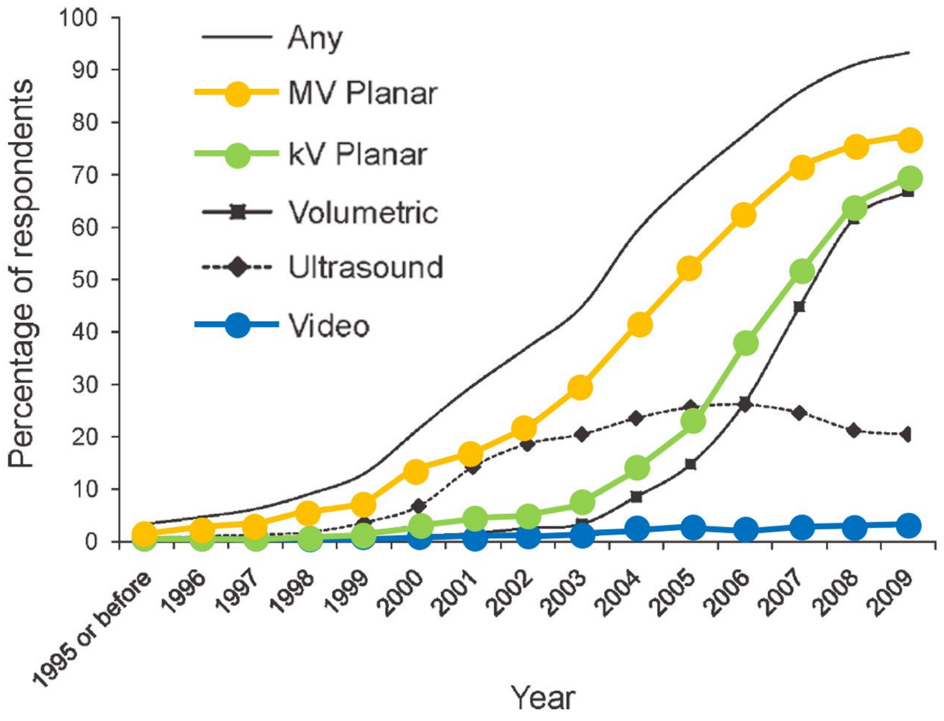


Adopted from Keall et al. IJROBP 2018: 102: 922-31

Surveys: Use of in-room imaging

Simpson *et al*. Cancer 2010

Survey scope: 385 MDs in US



MV imaging

kV imaging

Respiratory signal

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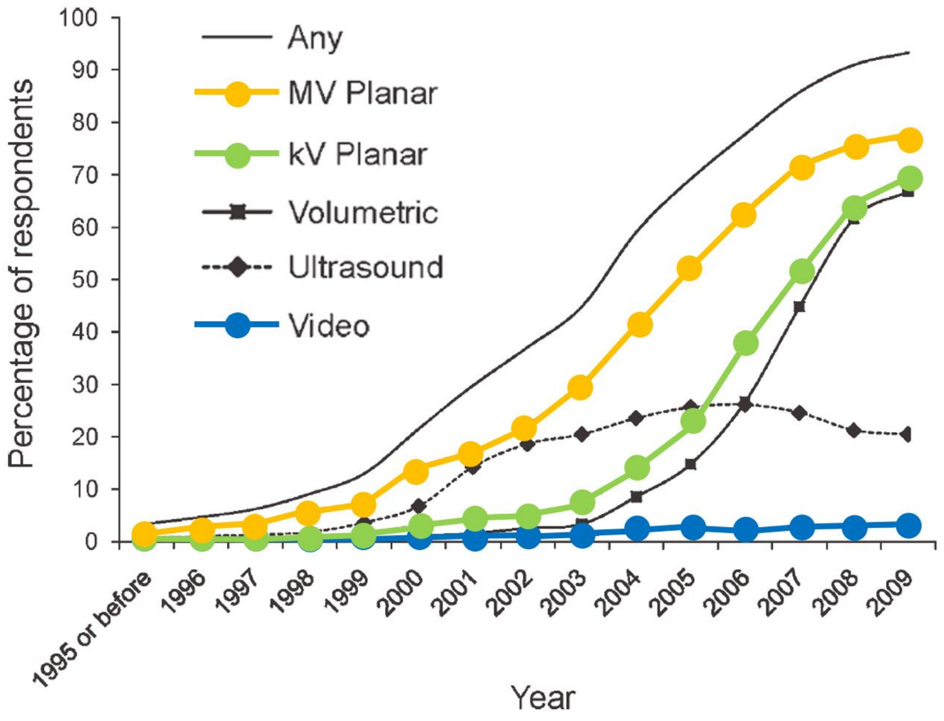
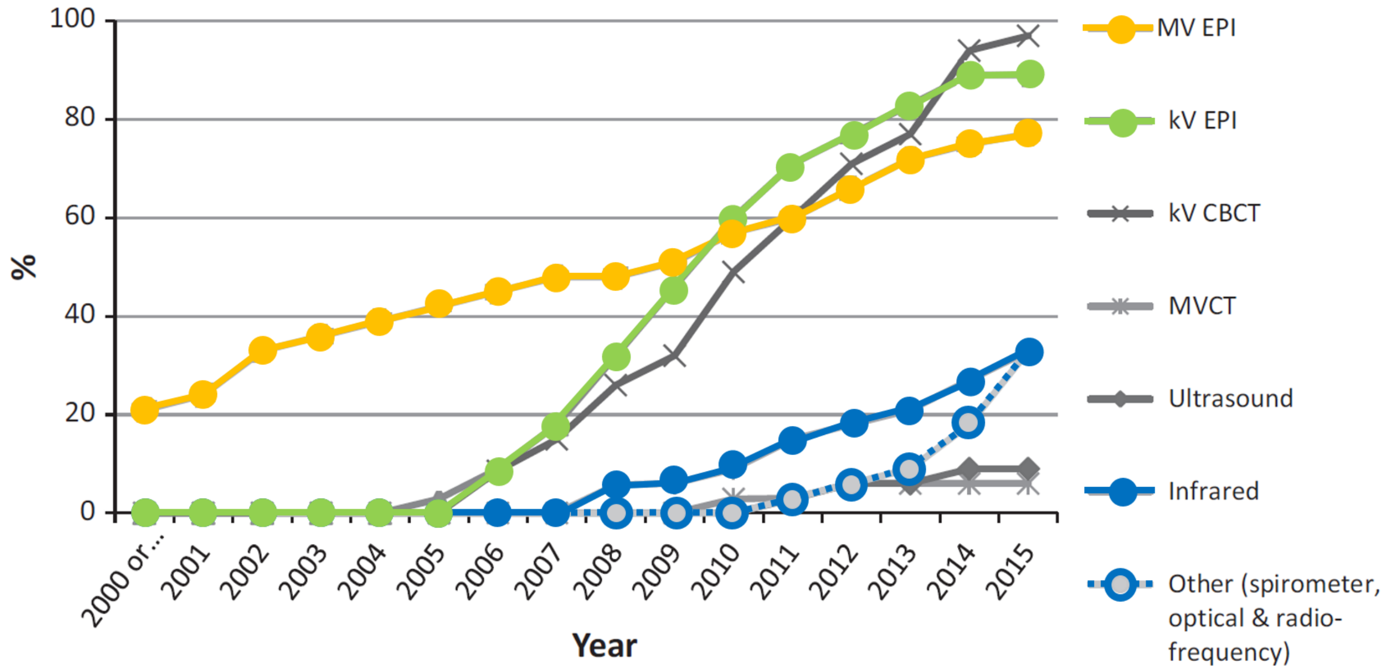


Batumalai *et al*. J Med Im Rad Onc 2017

Survey scope: 132 linacs in Australia



MV imaging

kV imaging

Respiratory signal

Real-time signals available on conventional linacs

MV imaging

- Beam's eye view
- Relatively poor contrast
- Field-of-view and time-of-view dictated by treatment plan

kV imaging

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kV imaging

- Decoupled from treatment plan
- Gives imaging dose to patient
- Perpendicular to treatment field

Respiratory signal

Real-time signals available on conventional linacs

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- Beam's eye view
- Relatively poor contrast
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kV imaging

- Decoupled from treatment plan
- Gives imaging dose to patient
- Perpendicular to treatment field

Respiratory signal

- Higher frequency, lower latency
- Compatible with couch rotations
- Only external monitoring

Scope

Real-time 3D image-guidance methods:

- Based on kV, MV and respiratory signals
- Used clinically during treatment delivery with conventional linacs

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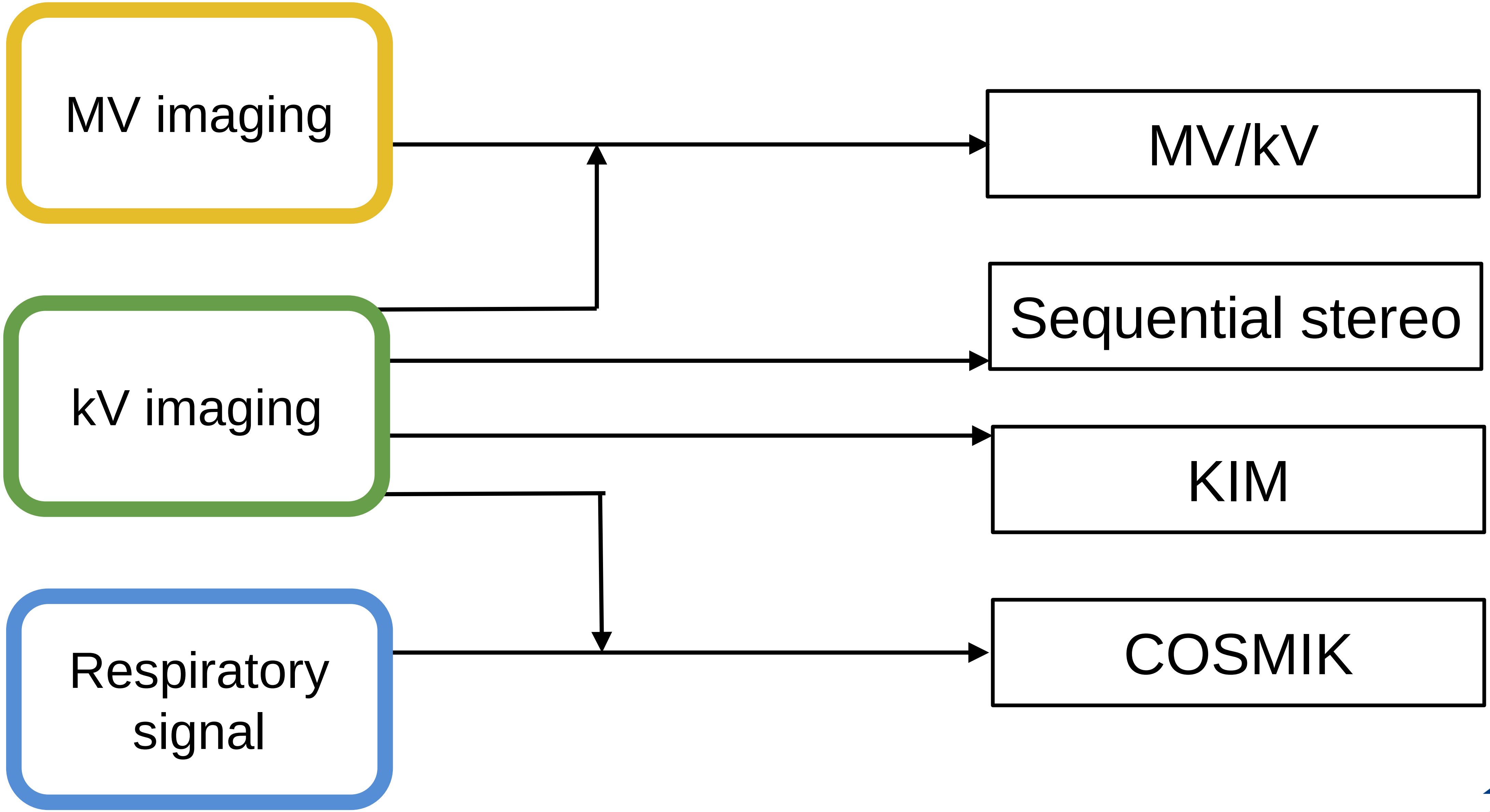
Four real-time IGRT methods implemented on conventional linacs



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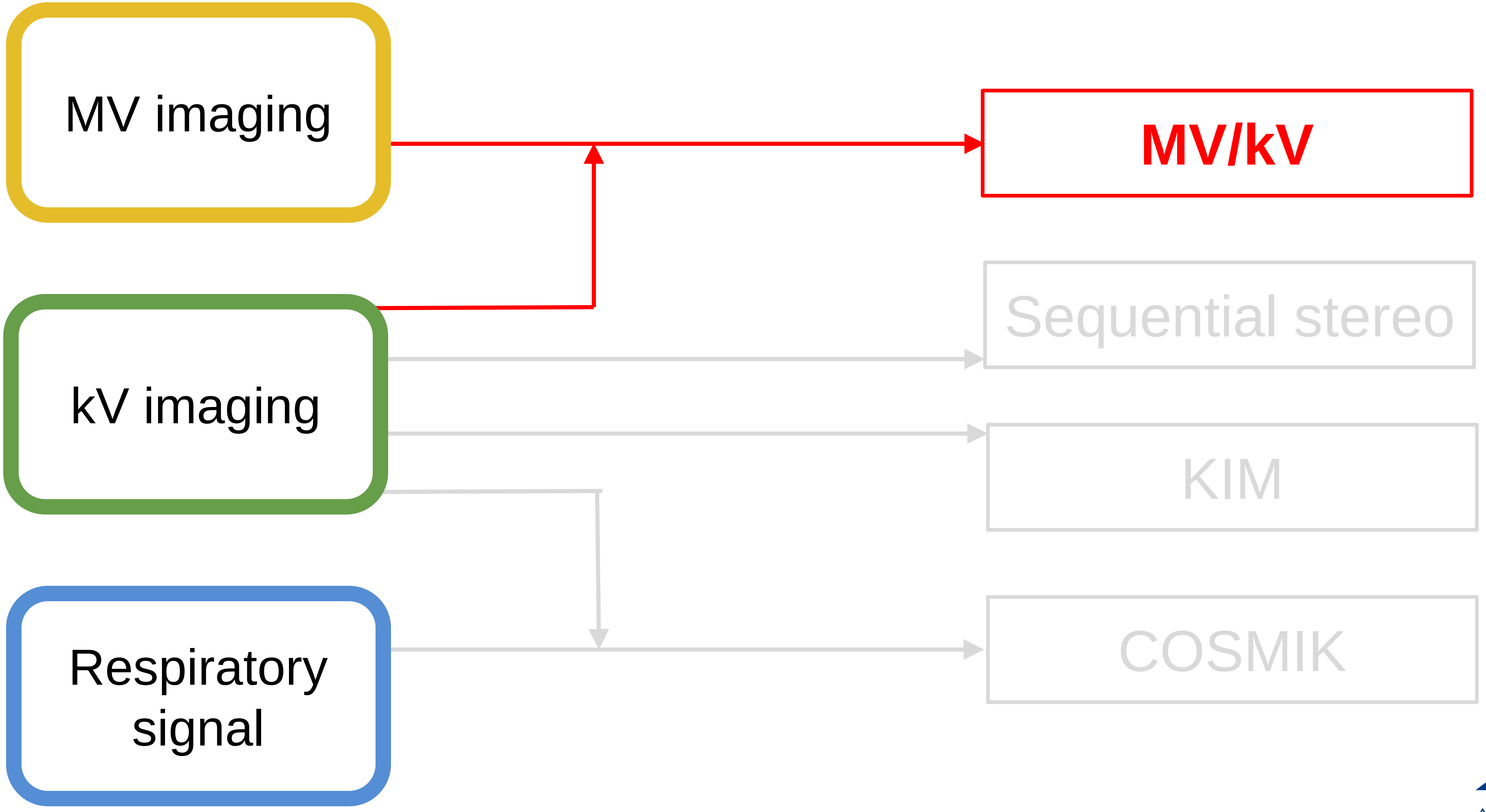
Four real-time IGRT methods implemented on conventional linacs



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MV/kV imaging

VMAT prostate SBRT with implanted markers:

- Memorial Sloan Kettering Cancer Center

Hunt et al, J Appl Clin Med Phys 17; 473-86 (2016)

MV/kV imaging

<u>VMAT prostate SBRT with implanted markers:</u>

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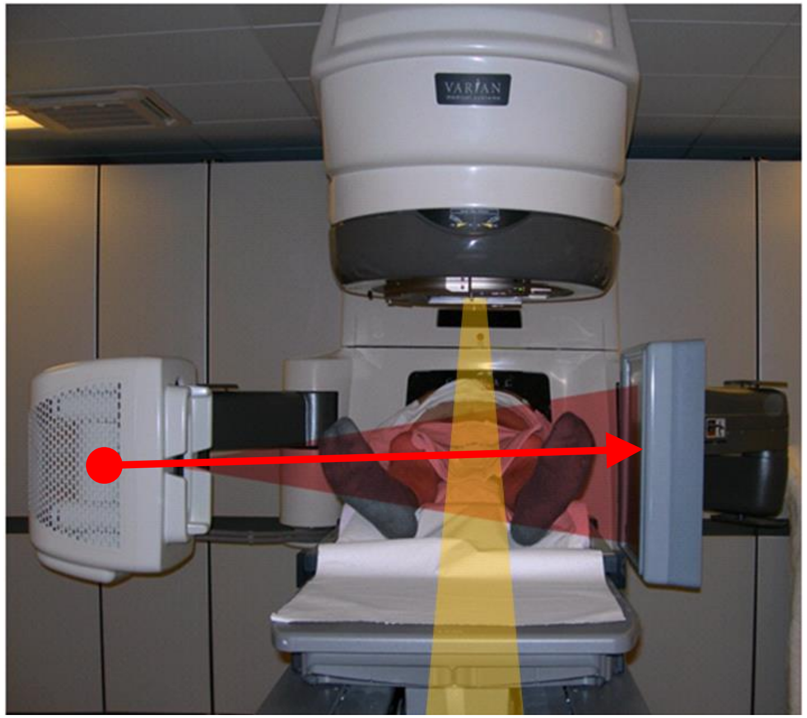
- kV images triggered every 20° gantry angle



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MV/kV imaging

VMAT prostate SBRT with implanted markers:

- Memorial Sloan Kettering Cancer Center
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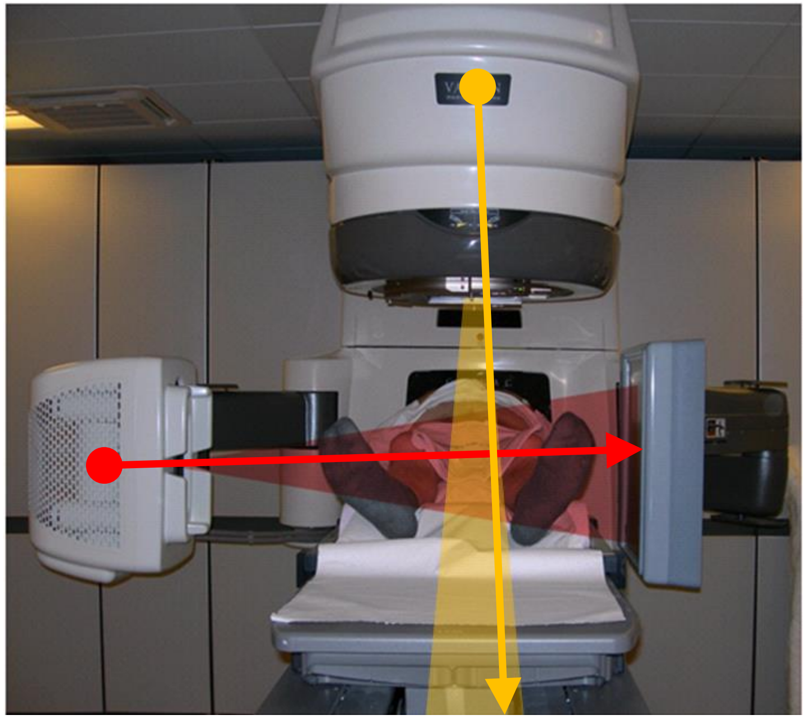
- Cine MV acquired continuously (9.5 Hz)
- Short-arc MV DTS (digital tomosynthesis, 3°) image reconstructed at kV image angles



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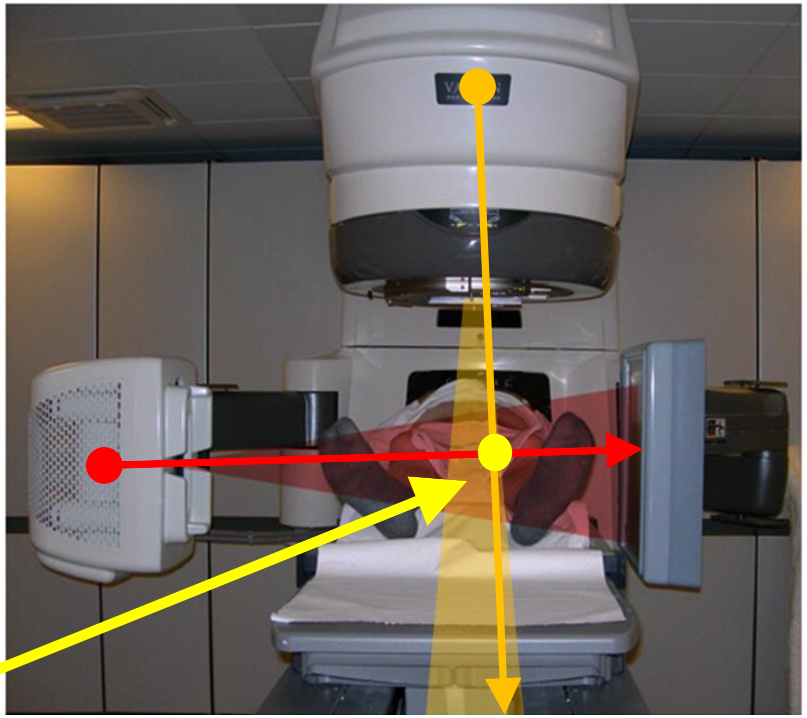
- 3D localization by MV-kV triangulation



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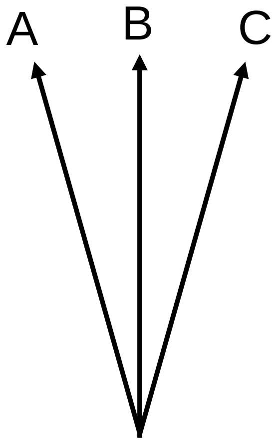
Marker visibility in MV DTS

- The markers are blocked by the MLC 60-80% of the time[(*)]
- TPS script used for automatic VMAT plan manipulation
- Ensures visibility of at least one marker during the MV DTS
- Minimal degradation of plan quality

[(*)] Happersett et al, J Appl Clin Med Phys 20; 120-24 (2019)

Ensuring marker visibility during MV short-arc DTS



Original control
points around
DTS position

Happersett et al, J Appl Clin Med Phys 20; 120-24 (2019)

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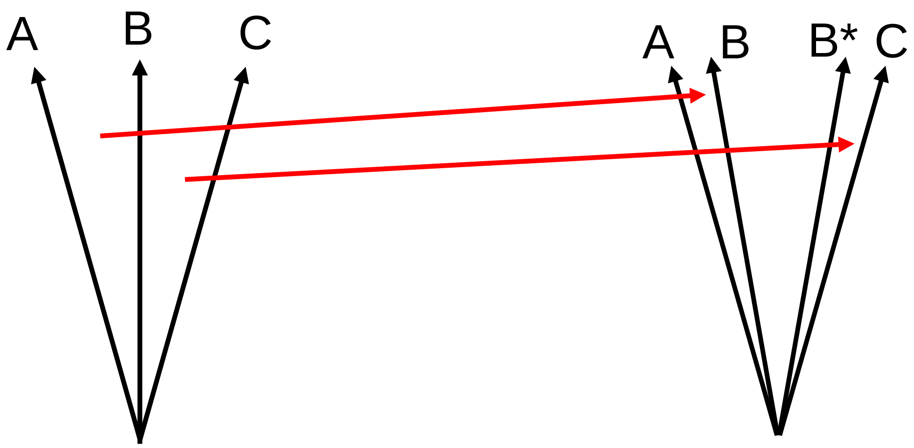

Original control points around DTS position

Squeeze MU delivery to smaller angular span

Happersett et al, J Appl Clin Med Phys 20; 120-24 (2019)

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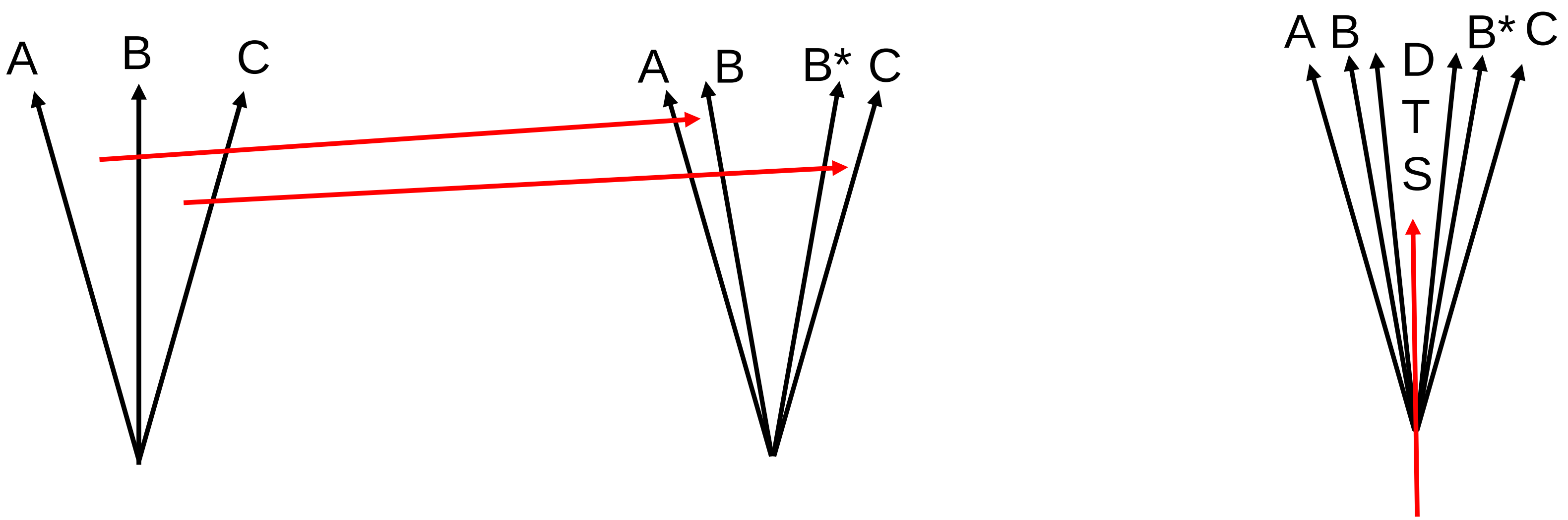

Original control points around DTS position

Squeeze MU delivery to smaller angular span

Insert DTS arc with MLC opened around at least one marker.

MU_{DTS} = 1.5–2 MU

Happersett et al, J Appl Clin Med Phys 20; 120-24 (2019)

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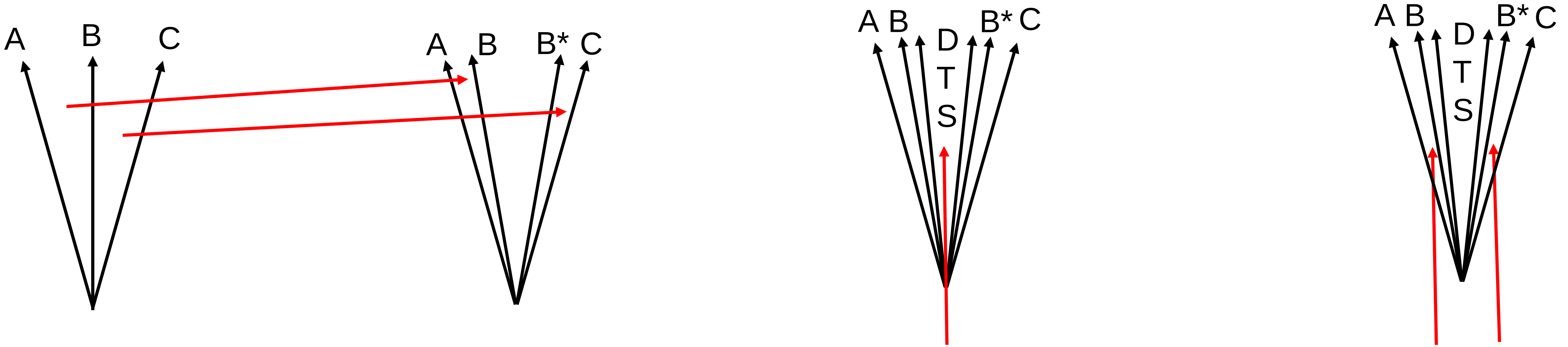
Ensuring marker visibility during MV short-arc DTS



Original control points around DTS position

Squeeze MU delivery to smaller angular span

Insert DTS arc with MLC opened around at least one marker.

MU_{DTS} = 1.5–2 MU

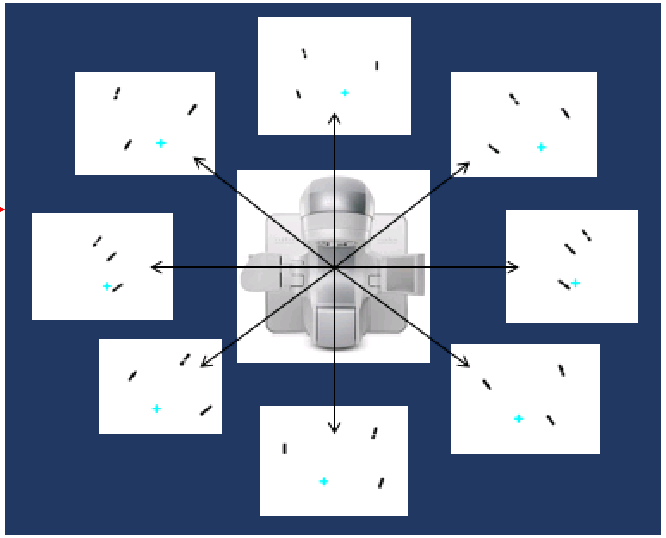
Adjust MU for MU_{DTS}

Happersett et al, J Appl Clin Med Phys 20; 120-24 (2019)

MV/kV imaging at Memorial Sloan Kettering Cancer Center

VMAT prostate SBRT implementation:

- Tracking templates created at 1° intervals



Thank you: Laura Happerset, Pengpeng Zhang, Margie Hunt, Ping Wang, Hai Pham

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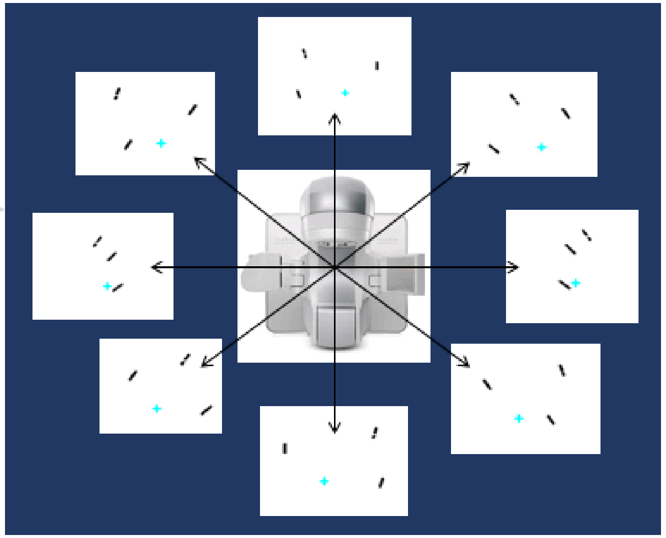
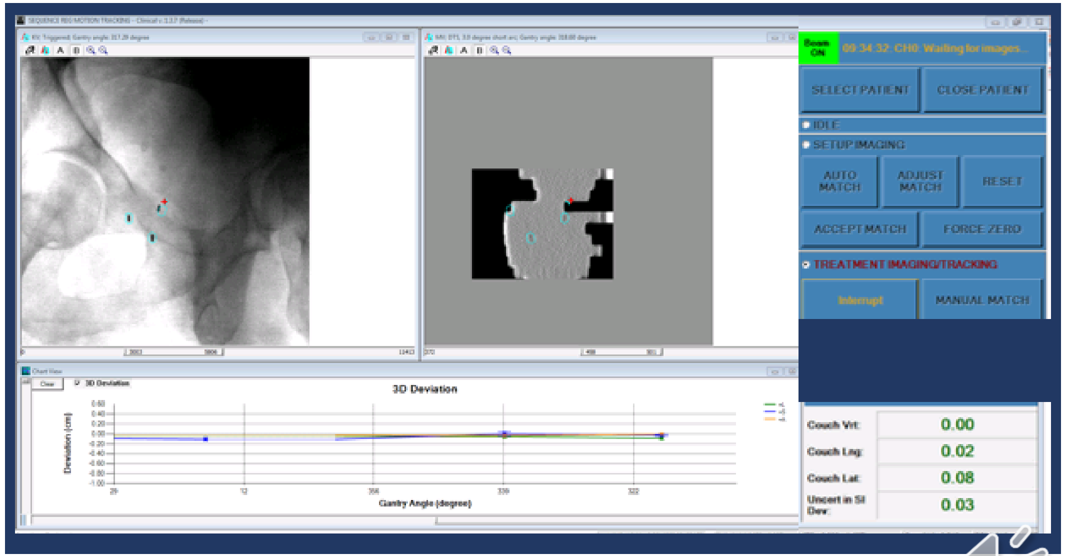


- Registered with MV DTS and kV images by Sequence Reg software during treatment delivery
- Gate-off manually and correct if >1.5mm error in two consecutive images



Thank you: Laura Happerset, Pengpeng Zhang, Margie Hunt, Ping Wang, Hai Pham

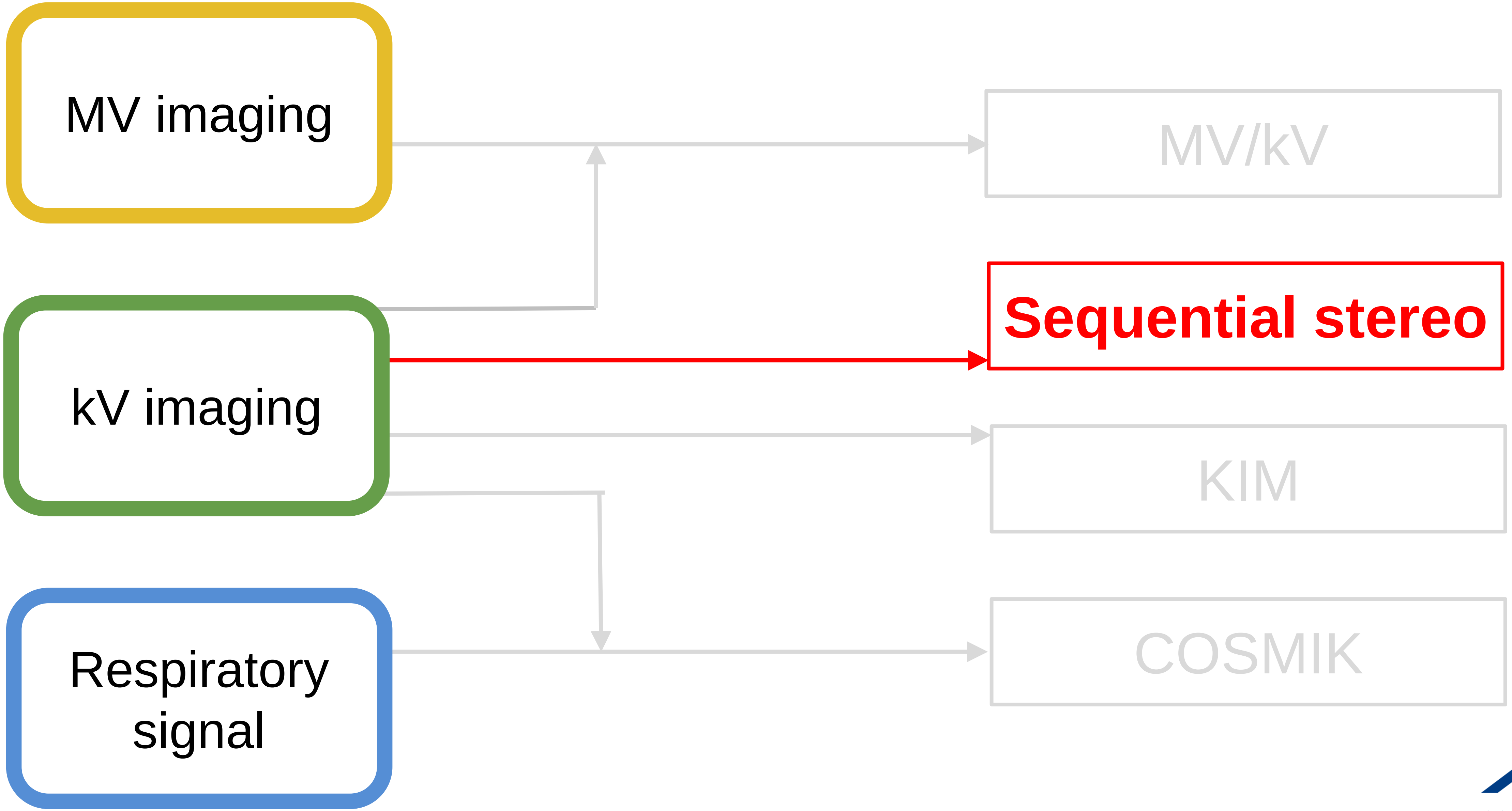
MV/kV imaging at Memorial Sloan Kettering Cancer Center

VMAT prostate SBRT application:

- 594 5-fraction prostate cancer patients treated 2016-2020
- On average 1.2 interruptions per fraction
- Prostate motion >5 mm for 10% of patients
- Median treatment time 9 minutes (measured for subset of patients)

Thank you: Laura Happerset, Pengpeng Zhang, Margie Hunt, Ping Wang, Hai Pham

Four real-time IGRT methods implemented on conventional linacs



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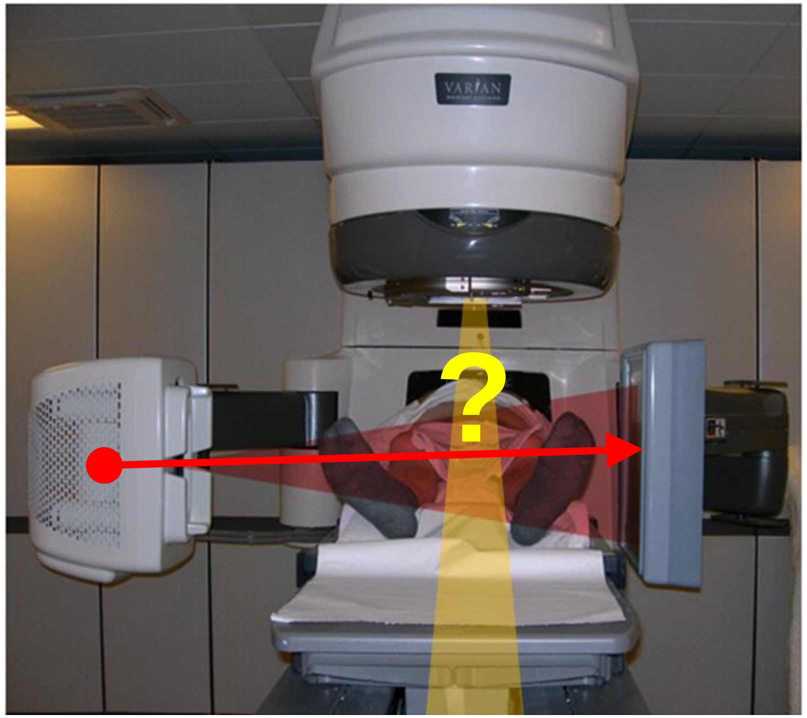
Sequential stereo

<u>VMAT spine SBRT:</u>

- VU University Medical Center, Amsterdam
- Continuous kV imaging (7 Hz)
- Match on spine with DRRs from planning CT

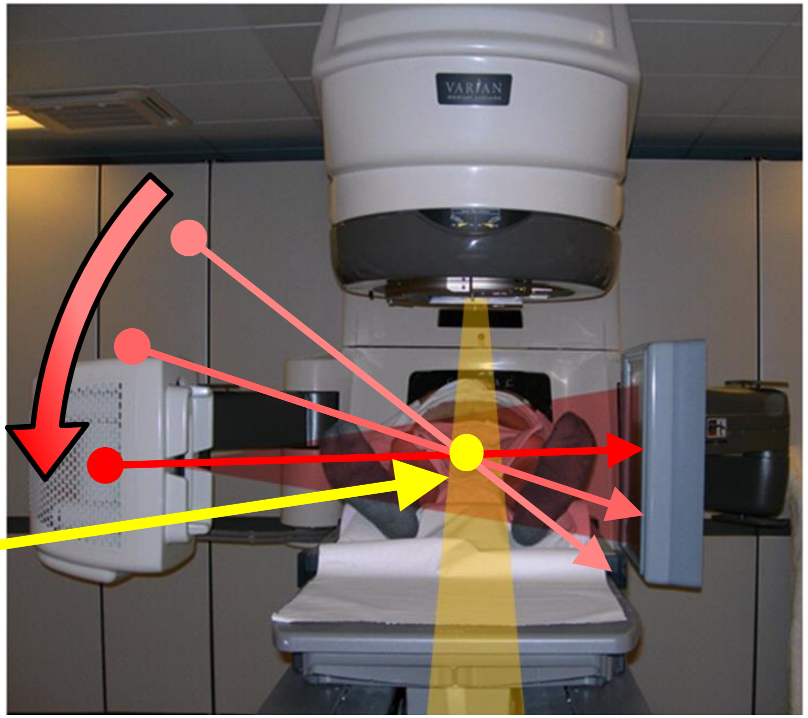


Hazelaar et al, IJROBP 2018

Sequential stereo

VMAT spine SBRT:

- VU University Medical Center, Amsterdam
- Continuous kV imaging (7 Hz)
- Match on spine with DRRs from planning CT
- Triangulation with 2-8 previous kV images
- Assume no motion along current ray line since the previous images

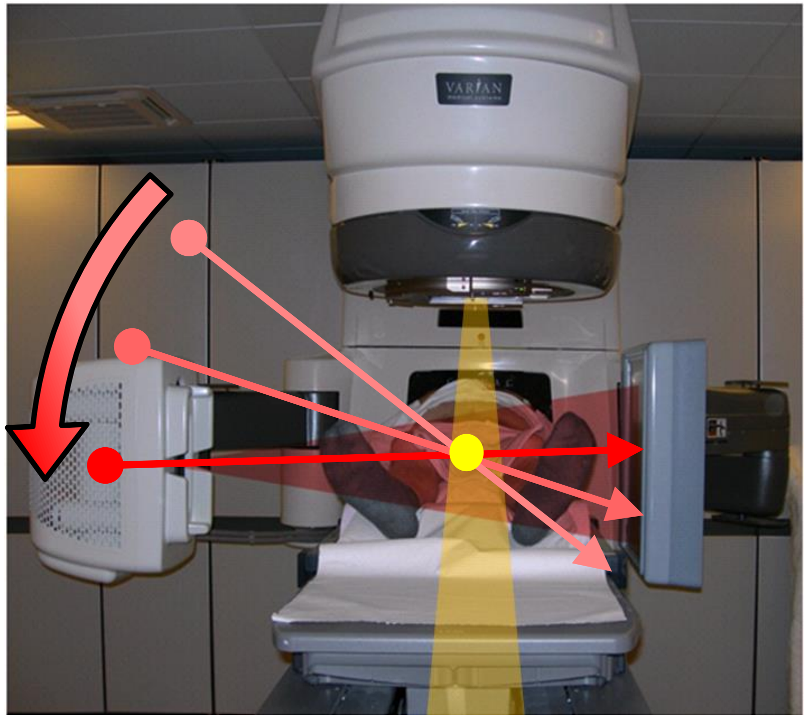


Hazelaar et al, IJROBP 2018

Sequential stereo

<u>Selection of previous kV images for triangulation:</u>

- acquired 14-72° prior to current image
- ray line <1mm from current ray line
- all 2-8 selected ray lines intersect in a small volume close to current ray line



Hazelaar et al, IJROBP 2018

Sequential stereo at VU University Medical Center, Amsterdam

VMAT spine SBRT implementation:

- Tracking templates (DRRs) created at 1° intervals
- Registered with streamed kV images during treatment delivery
- Gate-off manually and correct (by CBCT) if >1mm error in any direction

Hazelaar et al, IJROBP 2018

Sequential stereo at VU University Medical Center, Amsterdam

First clinical online real-time experiences(*):

- 10 spine SBRT fractions of 3 patients:
- Images analyzed at ~1Hz (limited by computing speed)
- 2 beam interruptions in total due to >1mm errors

(*) Hazelaar et al, IJROBP 2018

Sequential stereo at VU University Medical Center, Amsterdam

First clinical online real-time experiences(*):

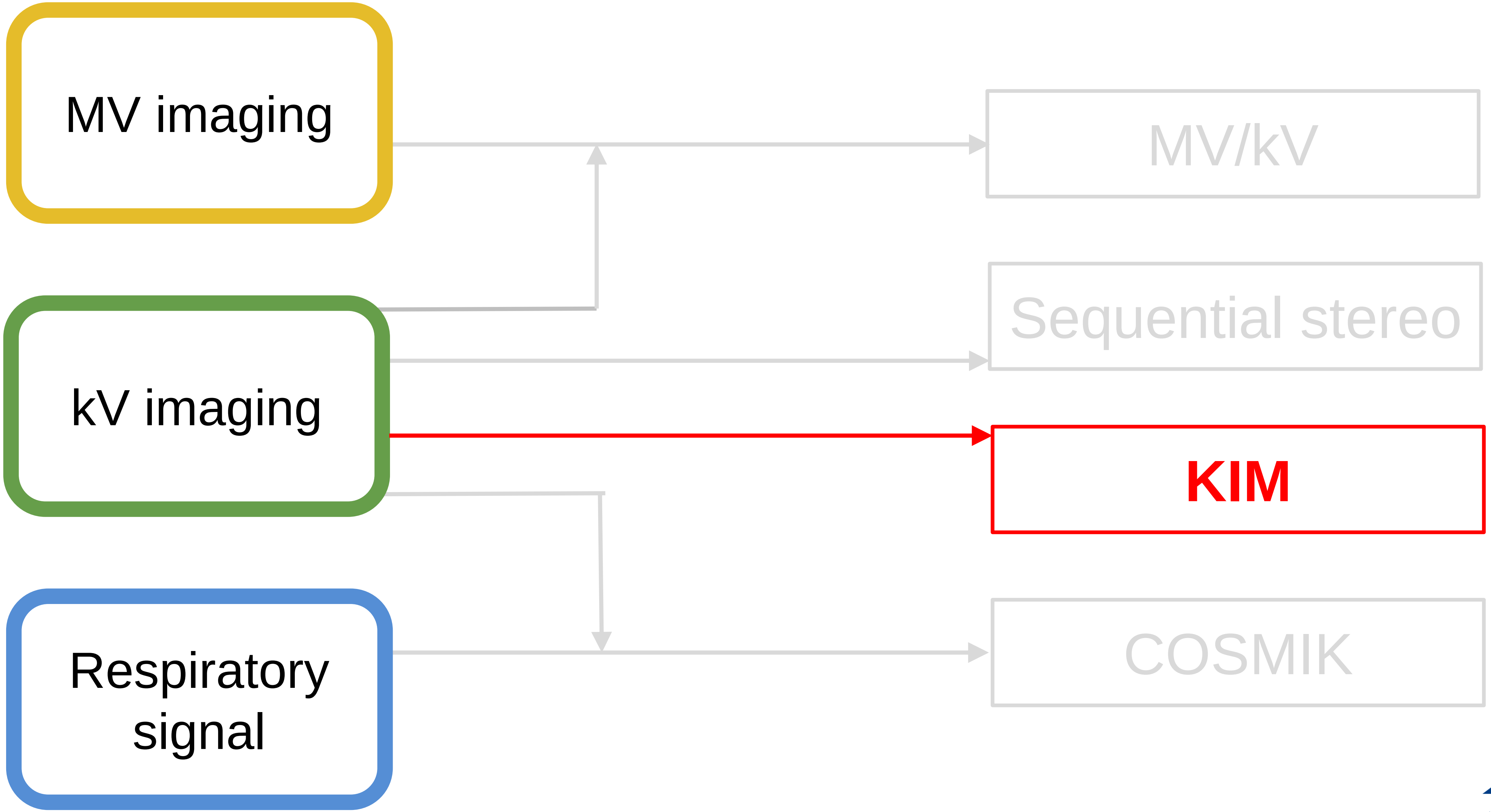
- 10 spine SBRT fractions of 3 patients:
- Images analyzed at ~1Hz (limited by computing speed)
- 2 beam interruptions in total due to >1mm errors

Further clinical experiences with real-time sequential stereo(**):

- ~40 spine SBRT
- DIBH lung SBRT
- Airway tracking (proximal bronchial tree) for central lung SBRT

(*) Hazelaar et al, IJROBP 2018 (**) W Verbakel, private communication

Four real-time IGRT methods implemented on conventional linacs



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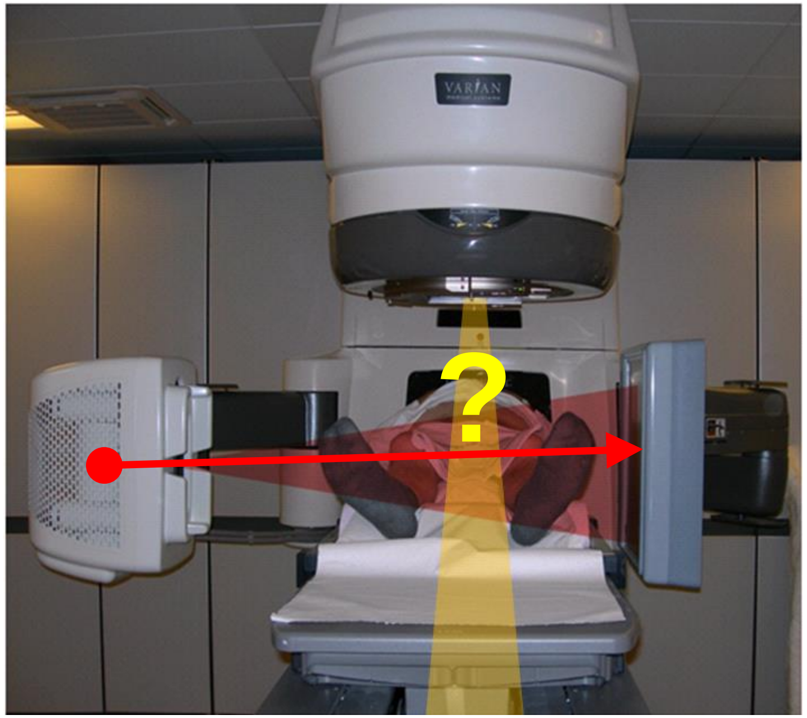
KIM (Kilovoltage Intrafraction Monitoring)

KIM:

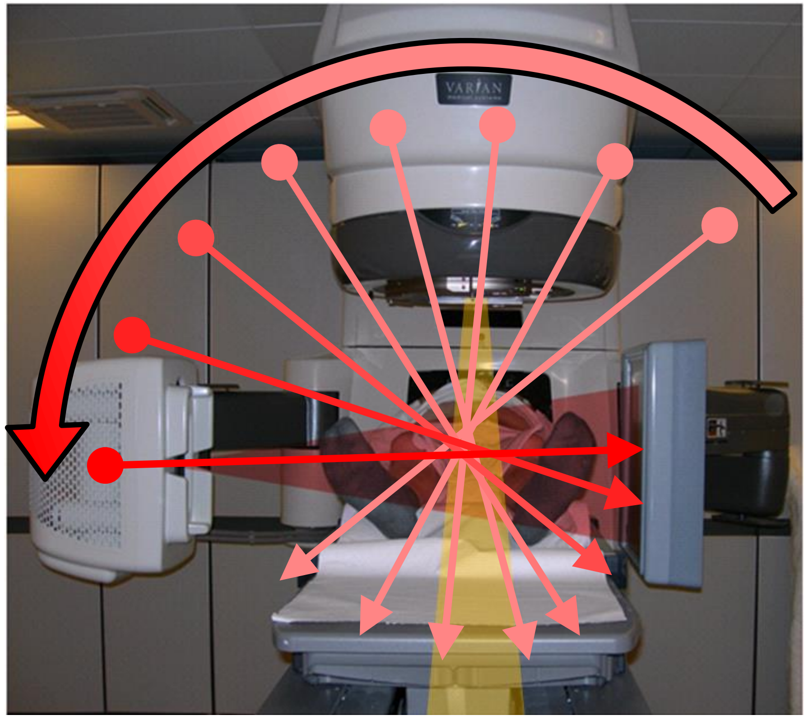
- Continuous kV imaging (5-11 Hz)



KIM (Kilovoltage Intrafraction Monitoring)

KIM:

- Continuous kV imaging (5-11 Hz)
- Use all previous images in >120° angular span



Poulsen et al, IJROBP 2008, PMB 2008, 2009

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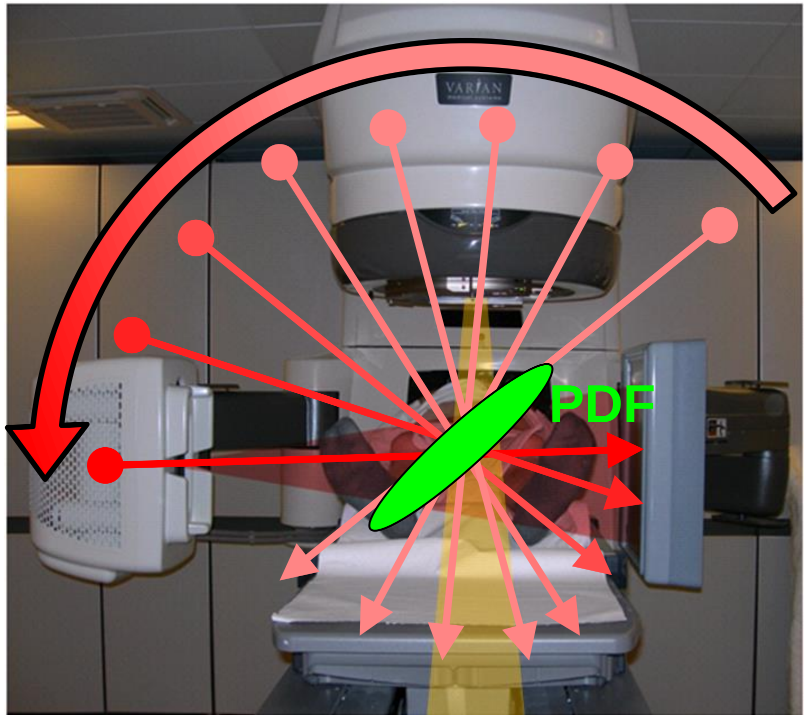
- Find the 3D Gaussian Probability Density Function (PDF) that best describes the target motion (by maximum likelihood estimation)



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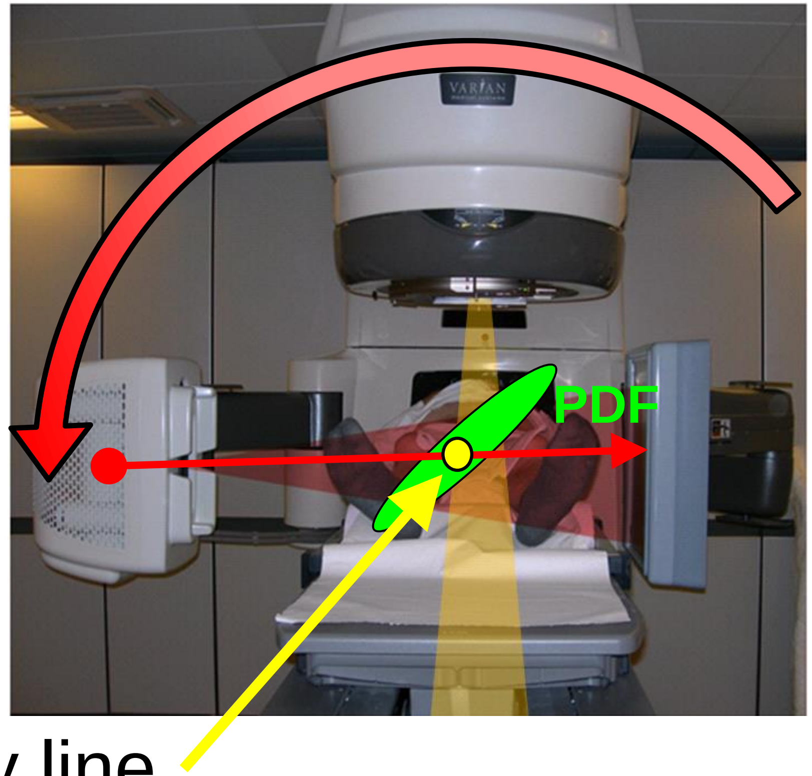


KIM:

- Continuous kV imaging (5-11 Hz)
- Use all previous images in >120° angular span
- Find the 3D Gaussian Probability Density Function (PDF) that best describes the target motion (by maximum likelihood estimation)
- Find the most likely target position along the ray line

Poulsen et al, IJROBP 2008, PMB 2008, 2009

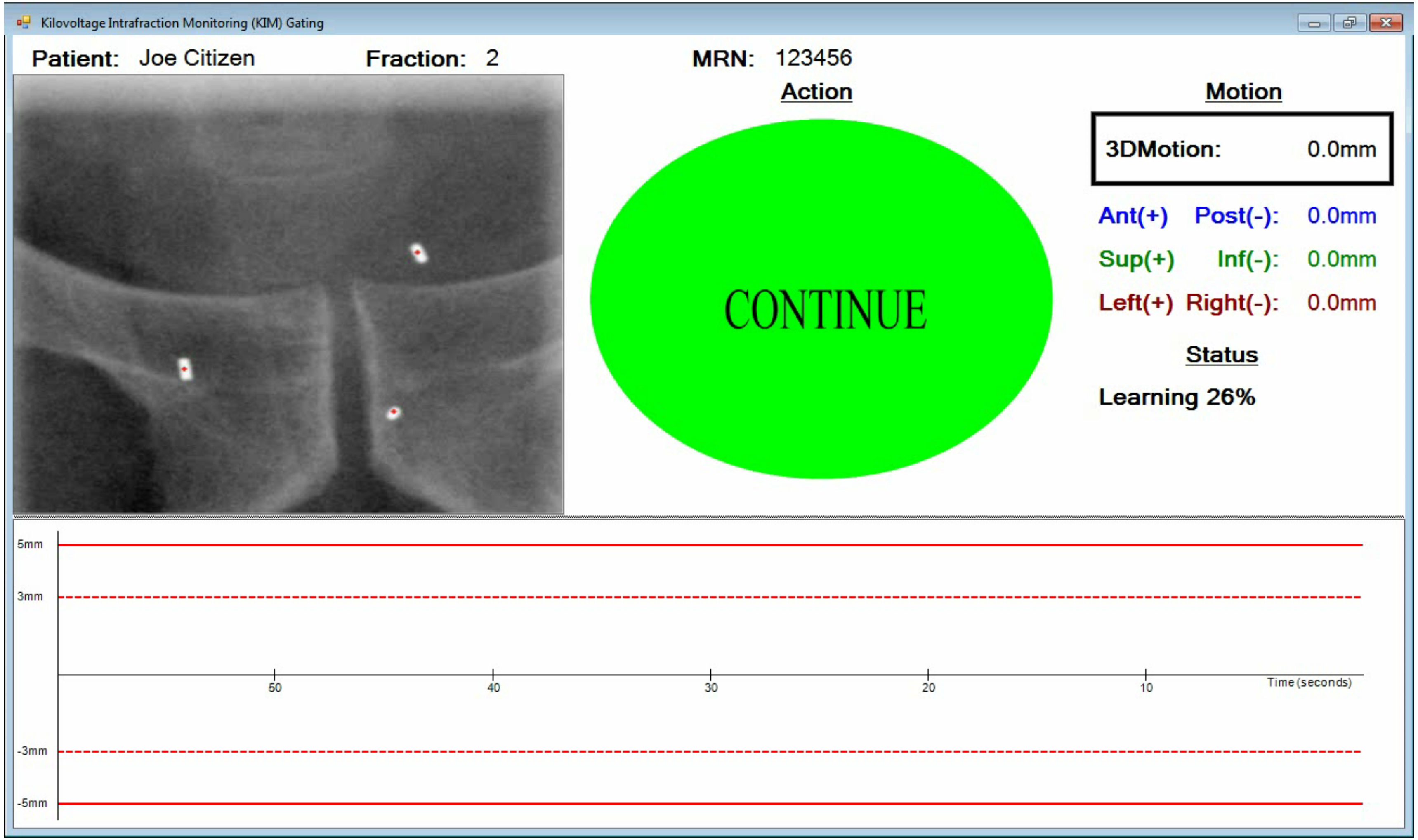
Online real-time KIM

Online real-time application:

- Northern Sydney Cancer Center and four other Australian clinics
- Implemented on Varian Clinac, Varian TrueBeam, Elekta Synergy linacs
- 120 prostate cancer patients:
    - Gate-off and correct couch if >3mm error in >5s (~2000 fractions)
    - MLC tracking (49 fractions)
- 2 liver SBRT patients treated in breath-hold (7 fractions)

Keall *et al*, Med Phys 2015, IJROBP 2016, 2020. Hewson *et al,* Med Phys 2019

Prostate KIM at Northern Sydney Cancer Center



Video from Paul Keall, Doan Trang Nguyen, Jeremy Booth

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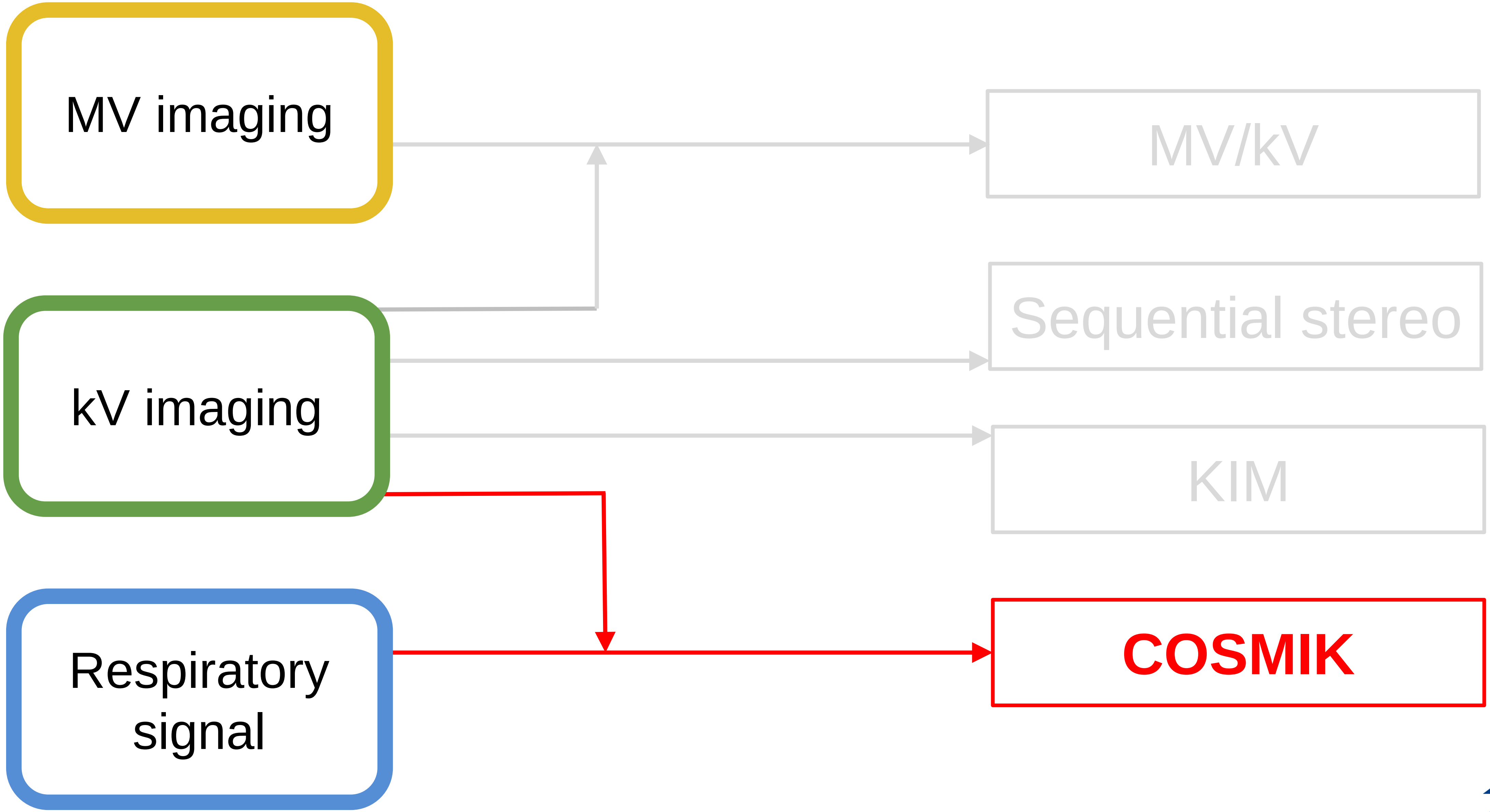
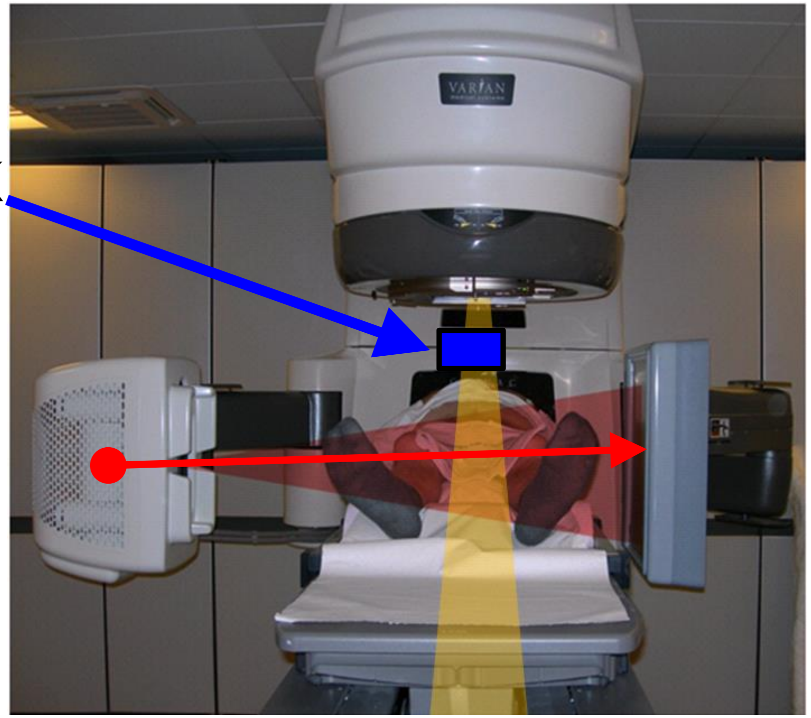
Four real-time IGRT methods implemented on conventional linacs



COSMIK (Combined Optical and Sparse Monoscopic Imaging with KV x-rays)

COSMIK:

- Continuous monitoring of external marker block
- Sparse kV imaging of implanted markers (every 3 sec)
- Only for respiratory motion



Bertholet *et al*, PMB 2018

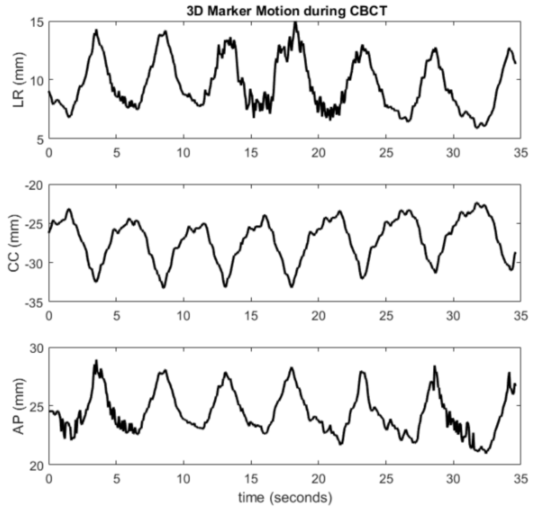
COSMIK workflow (liver SBRT)

<u>Pre-treatment setup CBCT:</u>

1. Extract internal 3D marker trajectory using KIM
2. Establish correlation model between external and internal motion

CBCT projections (liver SBRT)

KIM →



3D marker motion

→

External motion

↓

External-internal motion correlation model

COSMIK workflow (liver SBRT)

Pre-treatment setup CBCT:

1. Extract internal 3D marker trajectory using KIM
2. Establish correlation model between external and internal motion

During treatment delivery:

- Continuous external optical monitoring (20 Hz):
  - 3D internal marker motion estimated from correlation model
- Sparse kV imaging (0.33 Hz):
  - 3D internal marker position estimated with KIM
  - Update correlation model to account for tumor drift

Bertholet *et al*, PMB 2018

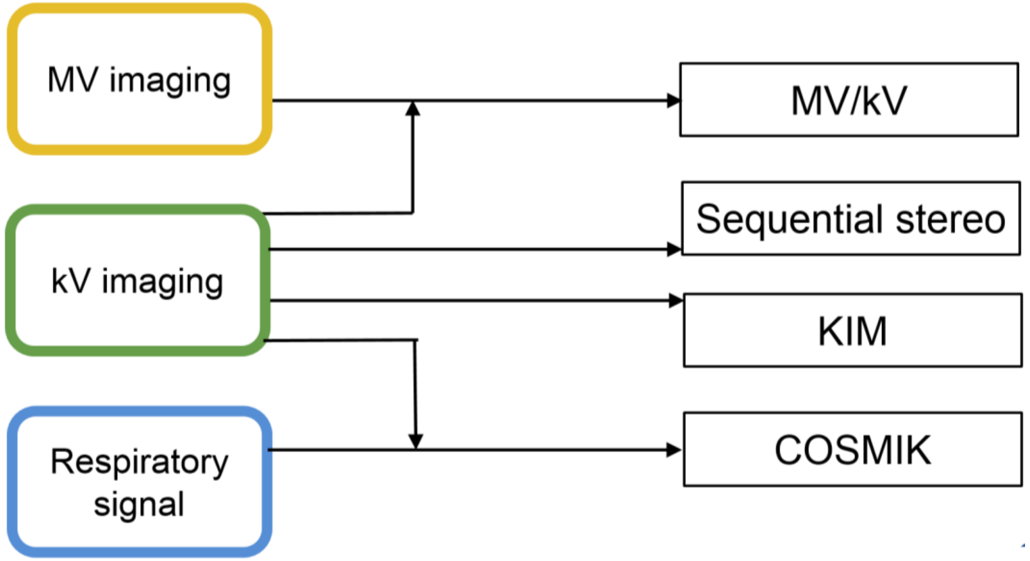
COSMIK at Aarhus University Hospital

Online real-time application:

- ~20 liver SBRT patients
- 1 lung cancer patient (markers in mediastinal lymph nodes)

- Real-time motion-including tumor dose reconstruction

Common characteristics of all four real-time IGRT methods



- Implemented clinically on conventional linacs
- Research software, not commercially available
- (Sub)-millimeter accuracy
- 3 of 4 methods currently rely on implanted markers

Summary of clinically implemented 3D real-time IGRT methods

	MV/kV	Sequential stereo	KIM	COSMIK
Principle	MV short-arc DTS Triangulation	Triangulation	Monoscopic imaging	Monoscopic imaging Breathing correlation
Tumor sites	Prostate	Spine	Prostate, liver	Liver, mediastinal LN
Treatment adaptation	Gate-off and adjust couch	Gate-off and adjust couch	Gate-off and adjust couch. MLC tracking	None (only real-time dose reconstruction)
Markers	Yes	No	Yes	Yes
Non-coplanar	No	No	No	Yes
Frequency	0.1-0.2 Hz (every 20°)	1 Hz (7Hz imaging)	5-11 Hz	20 Hz
Motion type	Small	Small (or periodic)	Any	Respiratory motion
Comments	• Low kV dose • Prior imaging not needed • Requires marker in MLC aperture	• Requires prior images with same target position	• Requires learning • Requires stable motion PDF	• Requires learning • Low kV dose • Continuous monitoring at Fx • Low latency

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Real-time motion-including dose reconstruction

Motivation:

- Dose errors from motion >> Dose errors from machine QA

Dose reconstruction during treatment delivery:

- Enabled by real-time IGRT
- Important tool for real-time verification

Real-time motion-including dose reconstruction

DoseTracker in-house software:

- Very simple dose calculation
    - Water density
    - Flat patient surface
    - Same phantom scatter in all depths

Ravkilde *et al*, PMB 2014, Med Phys 2018

Real-time motion-including dose reconstruction

DoseTracker in-house software:

- Very simple dose calculation
    - Water density
    - Flat patient surface
    - Same phantom scatter in all depths
- ….but flexible and fast
    - Any set of calculation points
    - ~100ms for 20,000 calculation points in a tumor
    - **Includes motion**

Ravkilde *et al*, PMB 2014, Med Phys 2018

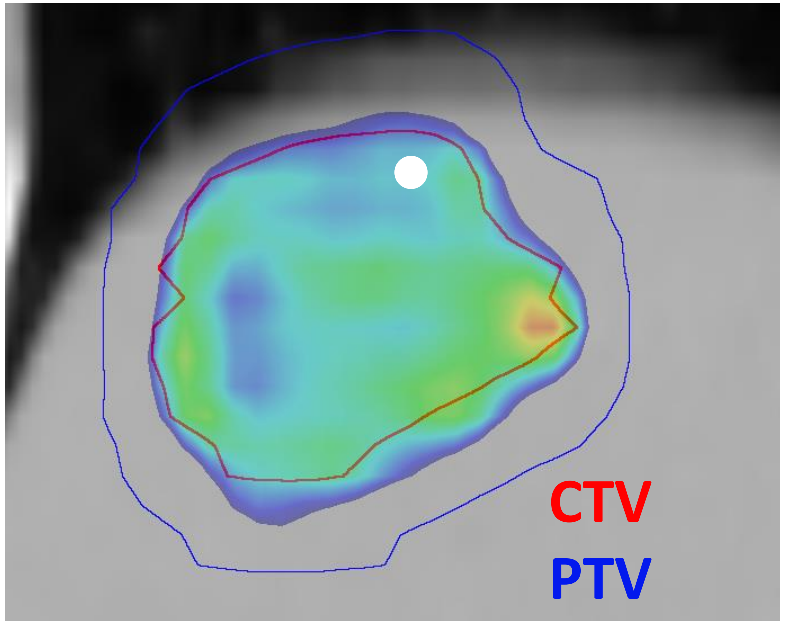
Real-time dose reconstruction

First online application:

- Aarhus University Hospital
- 7 VMAT liver SBRT patients (10 fractions)
- Tumor position (COSMIK) and linac parameters streamed to DoseTracker
- Dose reconstructed in the PTV (1700-4500 calculation points, ~9 Hz)

Skouboe *et al*, Radiother Oncol 2019

Example: Dose reconstruction in a single point



Planned dose to liver tumor
(95-107% shown)

Skouboe *et al*, Radiother Oncol 2019

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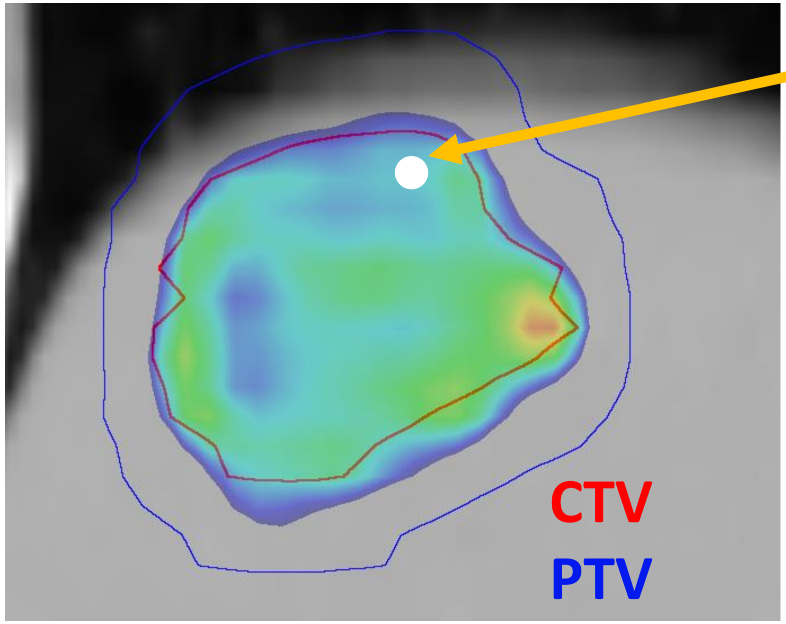

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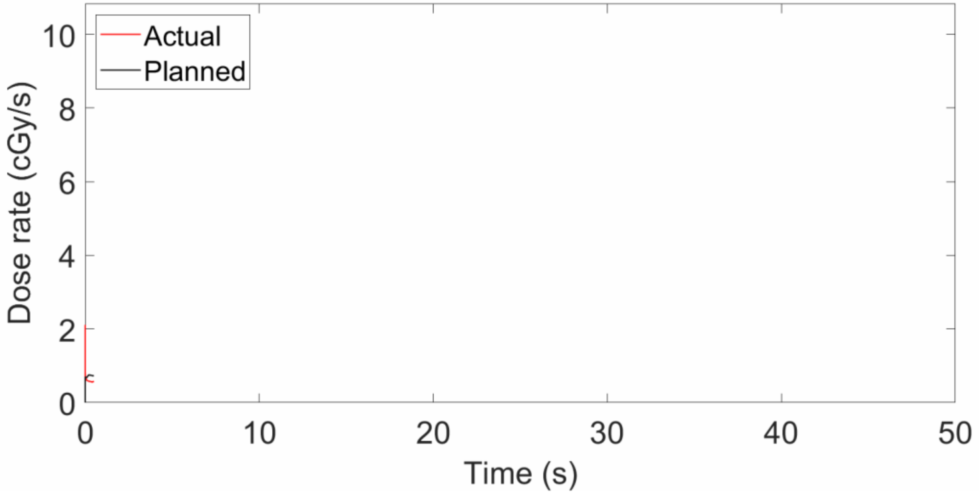
DoseTracker (during treatment)



Skouboe *et al*, Radiother Oncol 2019

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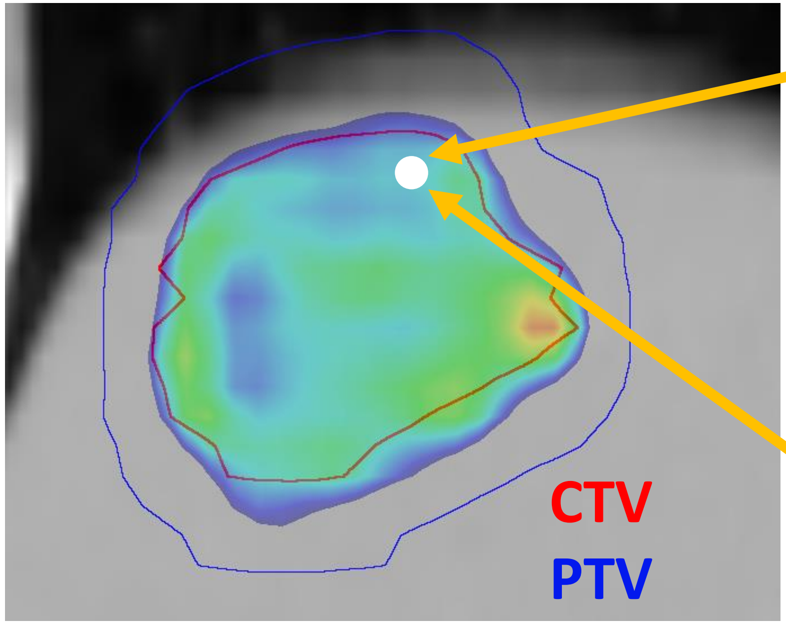

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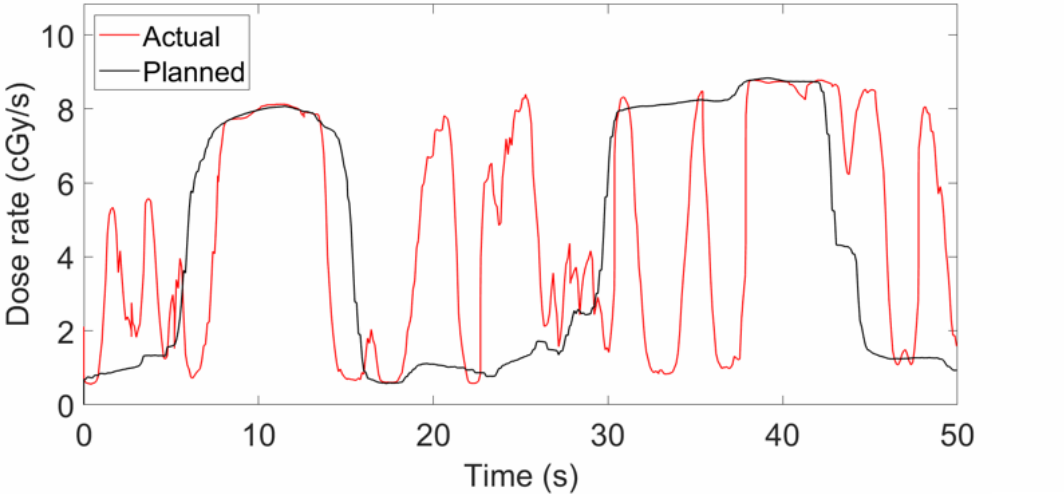
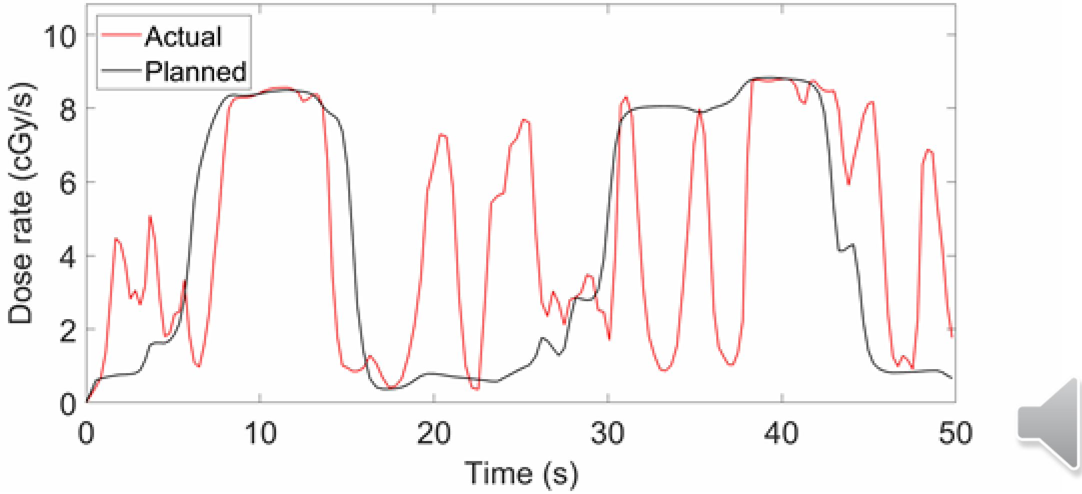
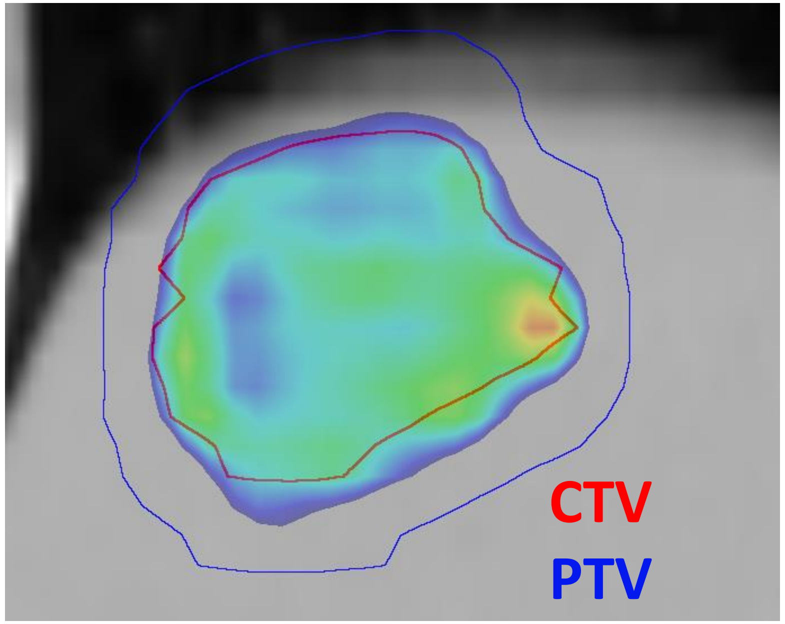


TPS, isocenter shift (post-treatment)



Skouboe *et al*, Radiother Oncol 2019

Planned and delivered dose distribution



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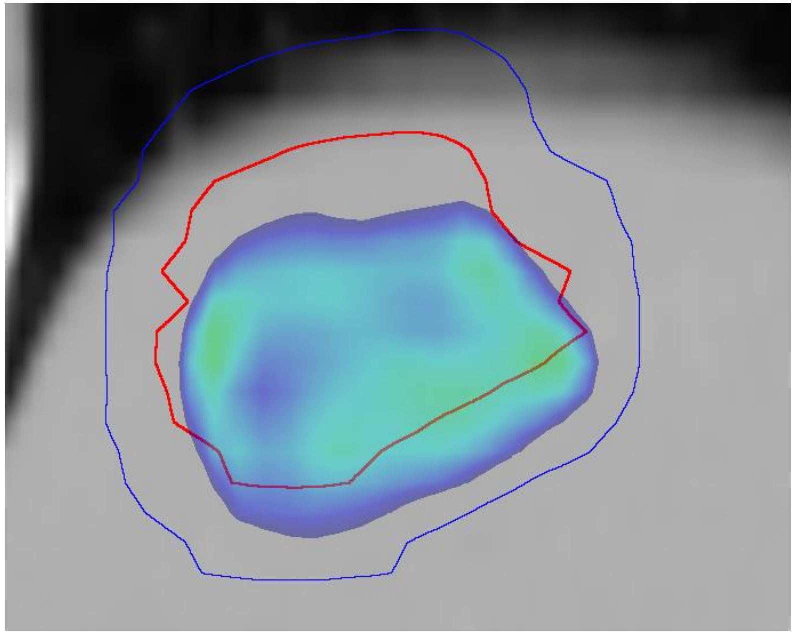
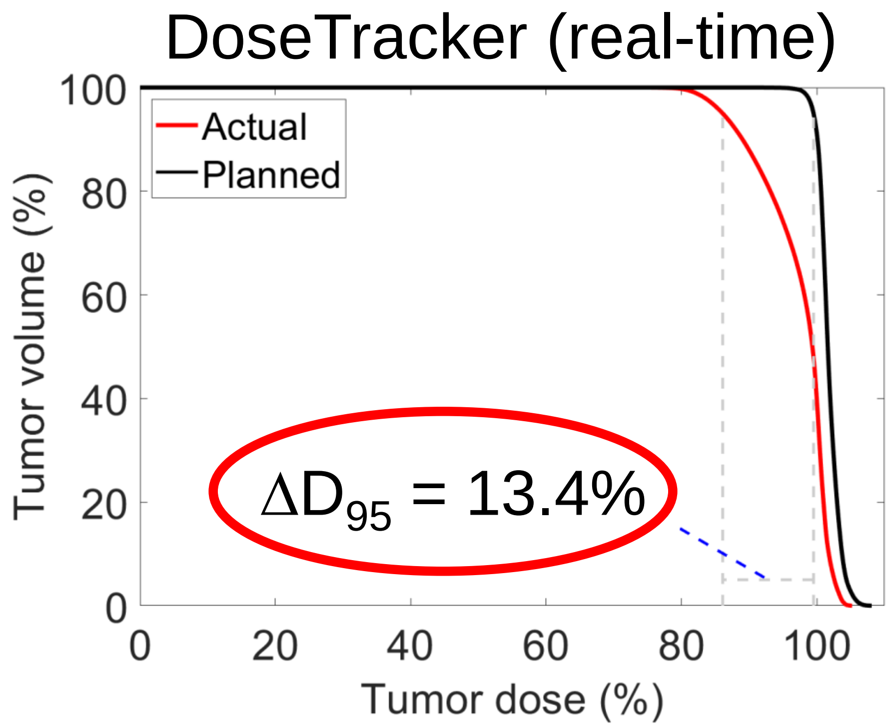
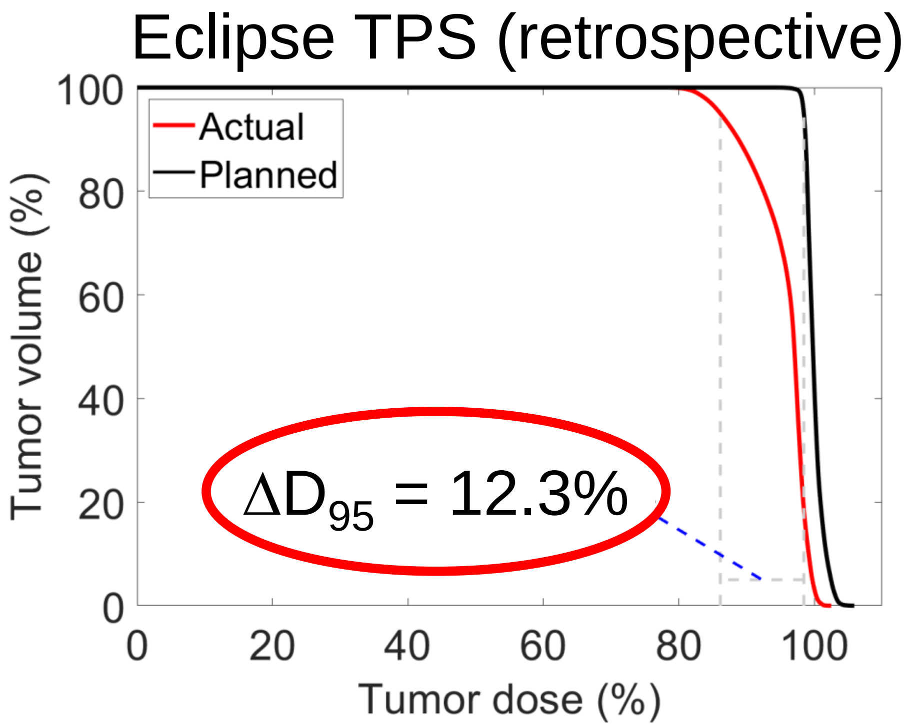


Delivered dose
(95-107% shown)

Skouboe *et al*, Radiother Oncol 2019

Motion-induced reduction in CTV D_{95}





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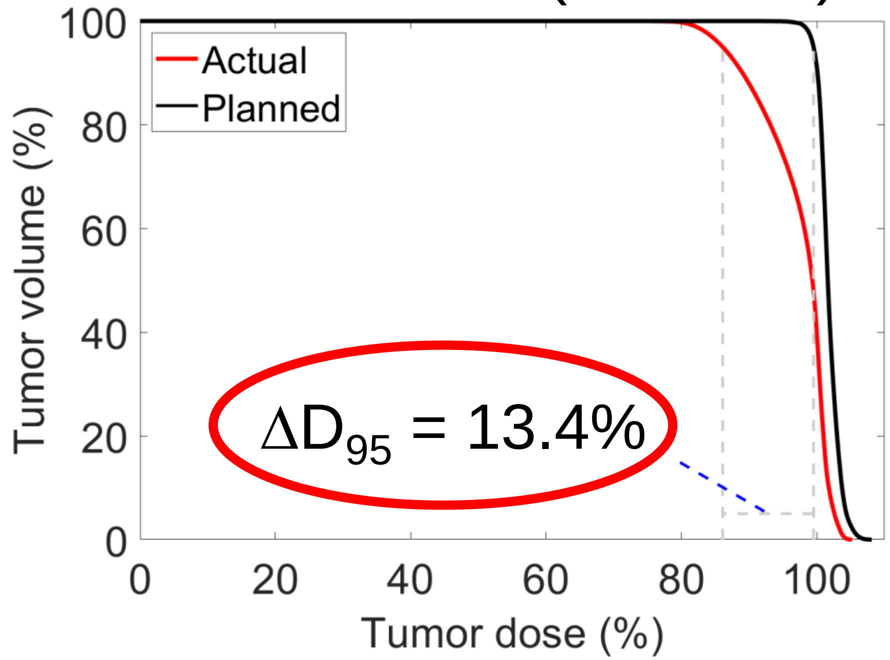
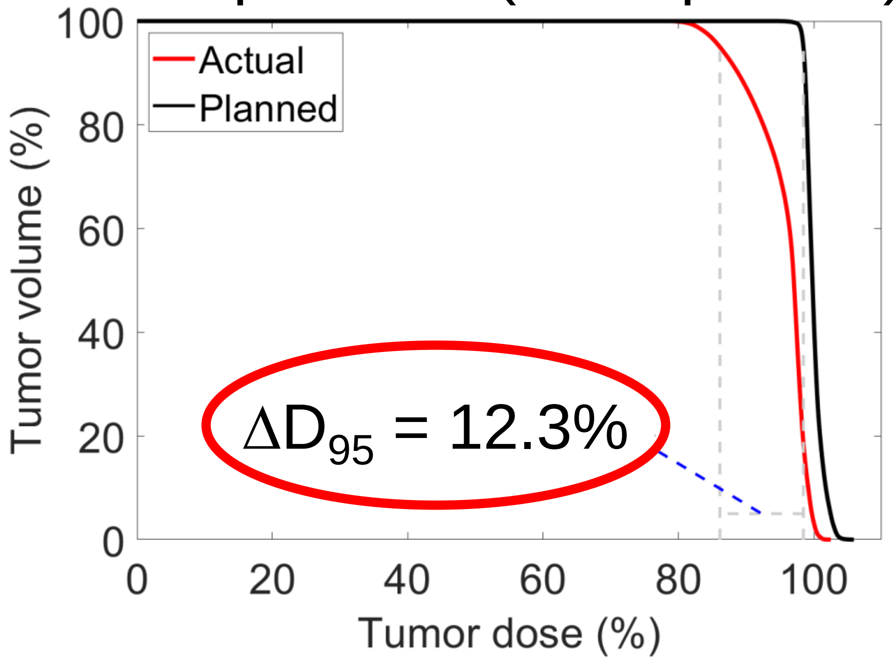
Motion-induced reduction in CTV D_{95}

DoseTracker (real-time)



Eclipse TPS (retrospective)



RMS error in real-time calculated ΔD_{95} for all 10 fractions: <u>1.3%-points</u>

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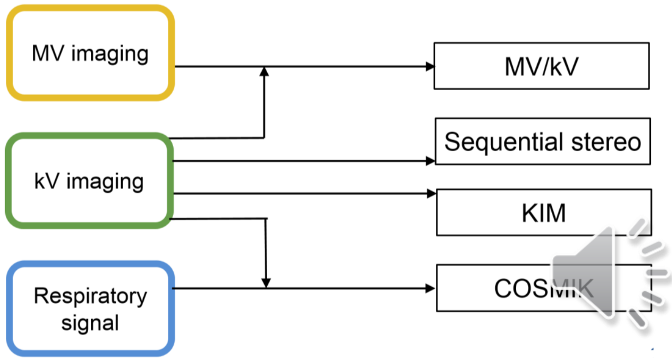
Agenda

- Introduction
- Real-time IGRT methods
- Real-time dose reconstruction
- Conclusion

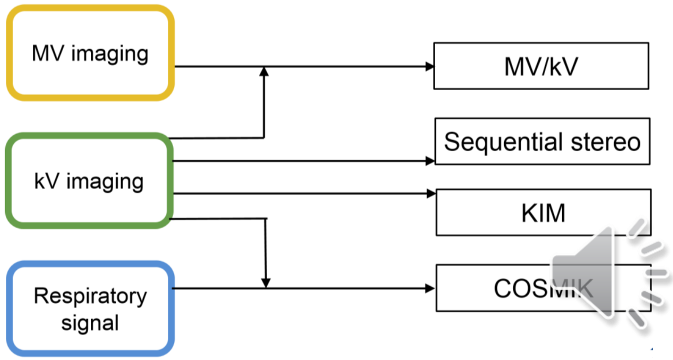
Conclusions: Real-time IGRT on conventional linacs

- Technologies are being developed by researchers
- Used for real-time treatment adaptation or tumor dose reconstruction
- Potential for widespread use



Conclusions: Real-time IGRT on conventional linacs

- Technologies are being developed by researchers
- Used for real-time treatment adaptation or tumor dose reconstruction
- Potential for widespread use
- Broad adoption requires commercial solutions closely integrated with the clinical workflow
- MR-linacs may become driving a force for broader adoption
- IMRT, VMAT, CBCT: Fast clinical implementation of new technology
- Further development of markerless localization and image dose reduction may facilitate broader adoption of real-time IGRT.



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