Physics and Treatment planning of Image Guided Radiotherapy

Dr. V. SUBRAMANI, Ph.D,
Chief Medical Physicist
Department of Radiation Oncology,
All India Institute of Medical Sciences, New Delhi

Learning objectives

- Basics of IGRT: Definition, goal, rationale, limitation
- Historical perspective of IGRT
- Modern IGRT technologies
- IGRT management for geometric uncertainties
- Correction strategies for patient positioning in IGRT
- Image registration in IGRT
- Imaging dose considerations in IGRT
- Summary and conclusion

Image Guided Radiotherapy

Basics of IGRT

What is image guided radiotherapy?

It is a process of frequent imaging in the treatment room during a course of radiotherapy that allows treatment decisions made on the basis of imaging

Goal

To manage the inter and intra fraction variation in shapes, volumes of target and patient positions and, organ motion to improve the geometric accuracy in dose delivery

Rationale of Image Guidance

- To account for geometric variation of
  - Target(s)
  - Organs-at-risk
  - Patient

- To address dosimetric variability
  - Inter-fraction
  - Intra-fraction

- To ensure that anticipated benefits from 3DCRT & IMRT are realized

Terminology

- Error: difference between planned and measured and its true value during treatment, however small
- Uncertainty: unpredictable errors occur quantified by standard deviations
- Variation: predictable or periodic errors occur quantified by amplitude or standard deviations
- Systematic error: average difference between planned and executed treatment
  - Patient group errors
  - Inter-patient errors
- Random error: uncertainty and variation in difference between planned and executed treatment
  - Inter-fraction errors
  - Intra-fraction errors

Need for image guidance in RT?

- Interfraction and Intrafraction setup error and organ motion are key parameters in determining the geometric accuracy

- In moving targets, large target motions due to the inherent movement within the patient such as physiologic or respiratory motion

- The magnitude of target motion is variable and unpredictable

- Necessitates higher degree of accuracy and precision in target localization and repositioning in-room verification during the course of treatment

- Geometric error translates to dosimetric errors, resulting in deviation in planned dose vs. delivered dose

Role of Imaging RT

Target and critical structure delineation

Multimodality imaging (CT, PET, SPECT, MRI, MRSI, US)

Treatment planning

Anatomy – based planning (CT and MRI)

Biology – based planning (PET, SPECT and MRS imaging)

Time-resolved CT (4D CT)

Treatment delivery

Radiographs, US, CT, CBCT, MRI

Treatment evaluation

Evaluate patient's setup and dose distributions

Follow –up and assessment of treatment outcome

Potential and limitation of IGRT

Advantage

- Improves the accuracy in the radiation field placement
- Determine the optimal margin to reduce the dose to the surrounding normal tissue
- Allows tumor dose escalation, thereby increasing local tumor control and survival

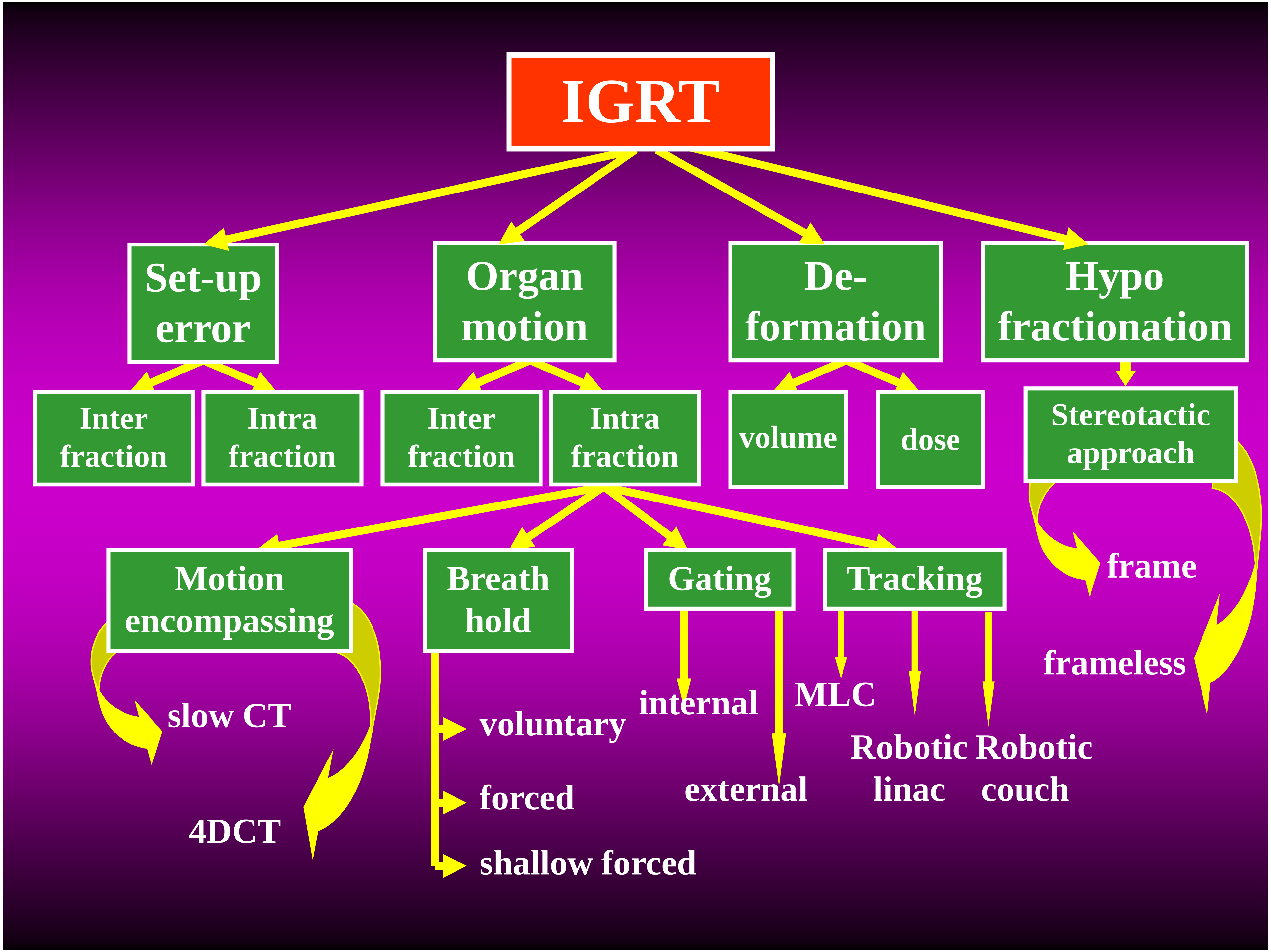
Disadvantage

- Imaging dose to Patient
- Redefining workload
- Resources/Infrastructure

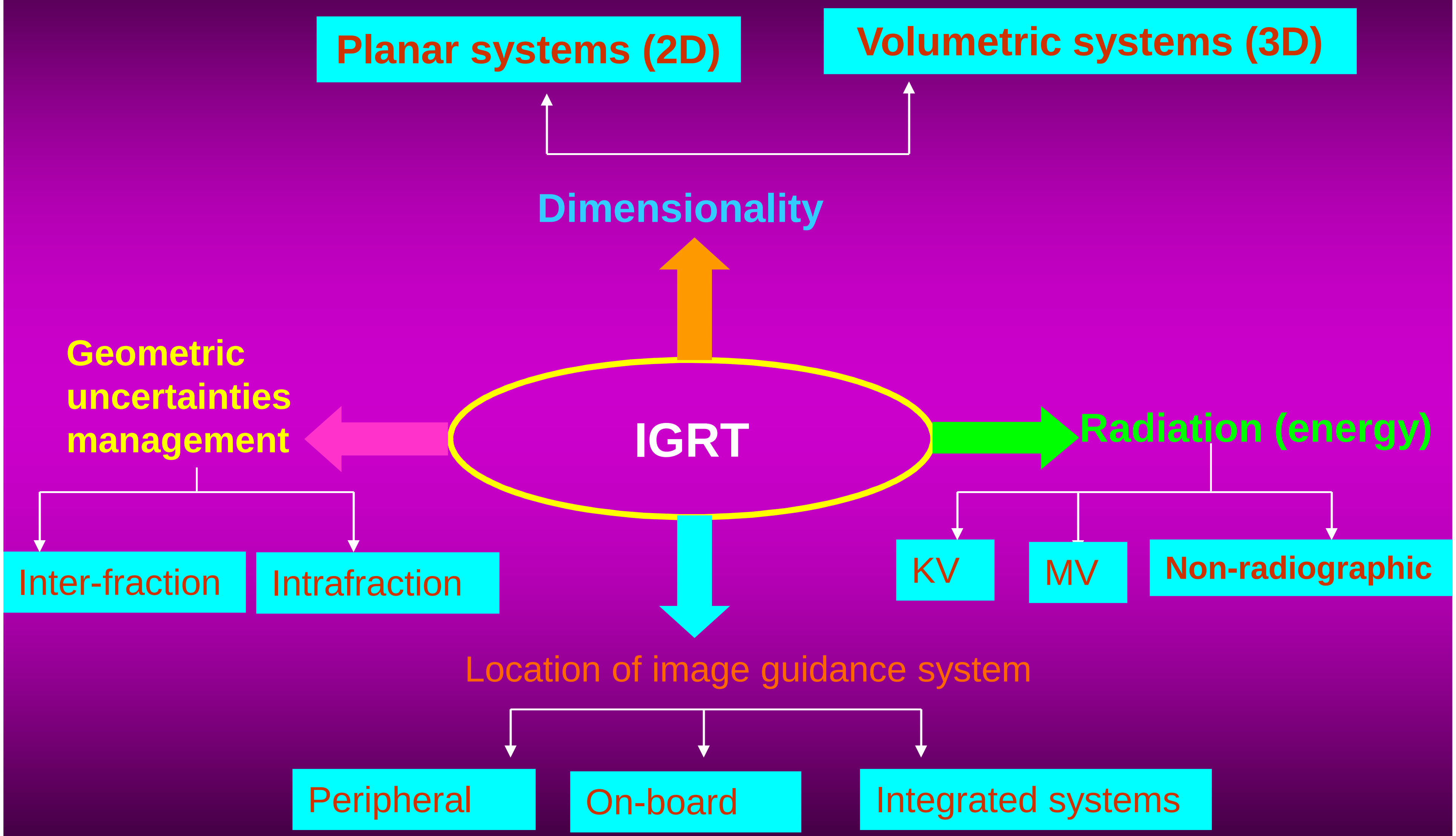
Clinical Indication for IGRT

- Tumors adjacent to critical structures
- Tumors prone to inter fractional motion
- Tumors prone to intra fractional motion
- Tumors prone to deformation
- IMRT, SRS/SRT/SBRT
- Hypofractionation scheme

Clinical sites: Thorax, Abdomen and Pelvis


IGRT
Set-up error
Organ motion
De-formation
Hypo fractionation
Inter fraction
Intra fraction
Inter fraction
Intra fraction
volume
dose
Stereotactic approach
frame
frameless
Motion encompassing
Breath hold
Gating
Tracking
slow CT
4DCT
voluntary
forced
shallow forced
internal
external
MLC
Robotic linac
Robotic couch

IGRT classification

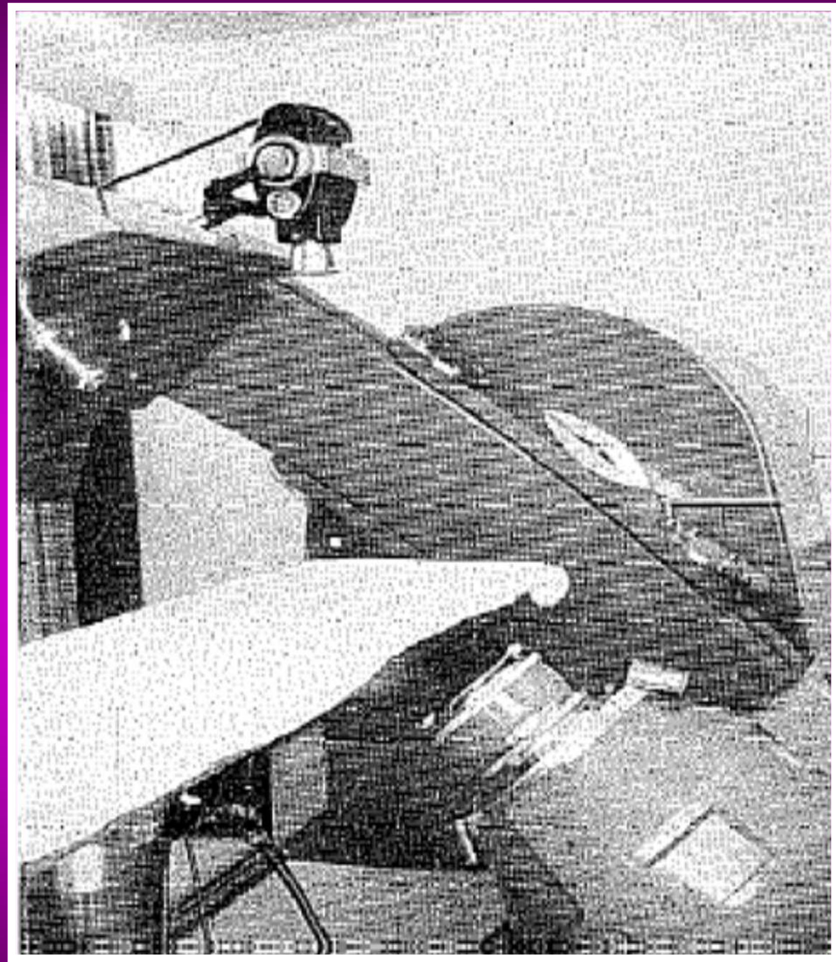


Historical perspective of IGRT

Evolution of Imaging for treatment verification

- 1980's - port films
- 1990's - emergence of MV portal imagers, in-room ultrasound localization, marker-based localization & Fluoroscopic tracking
- 2000's - Flat panel imaging, KV digital imaging, CBCT, MV CBCT and CT "on rails"
- Emerging - Electromagnetic localization and tracking
  in-room MRI

Historical IGRT technologies



1958- Holloway et.al reported portable x-ray machine mounted on the counter weight to TheratronCo-60 machine

"The XOTRON"

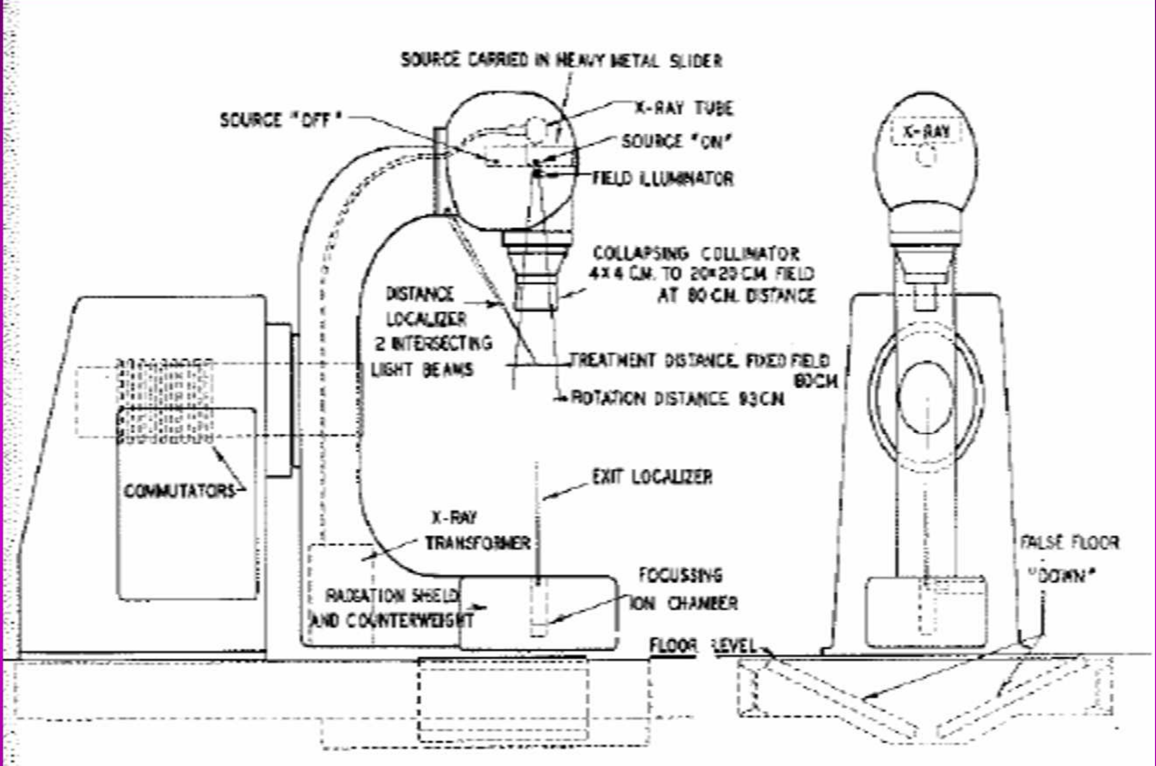
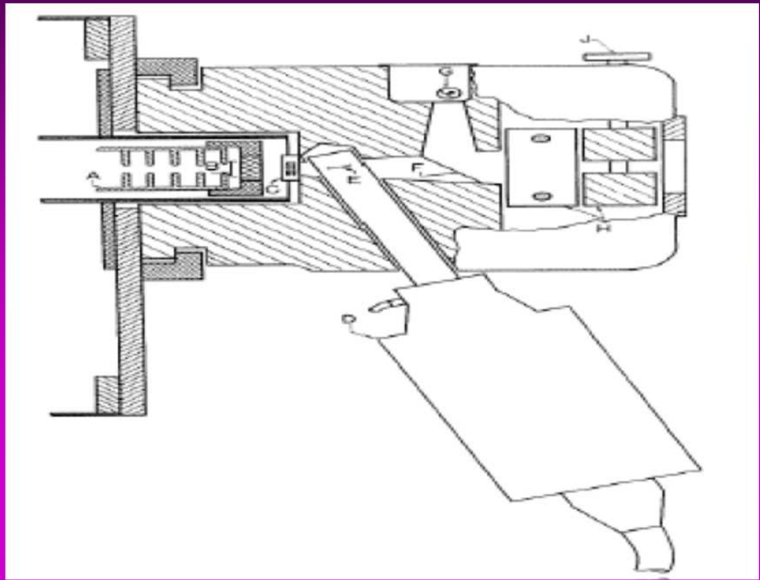
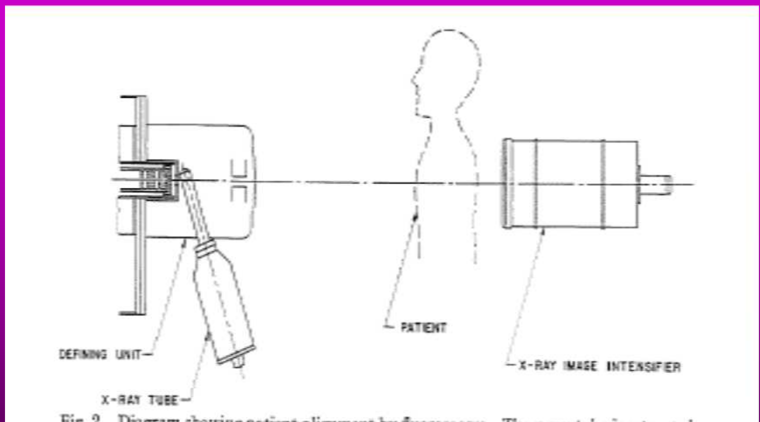


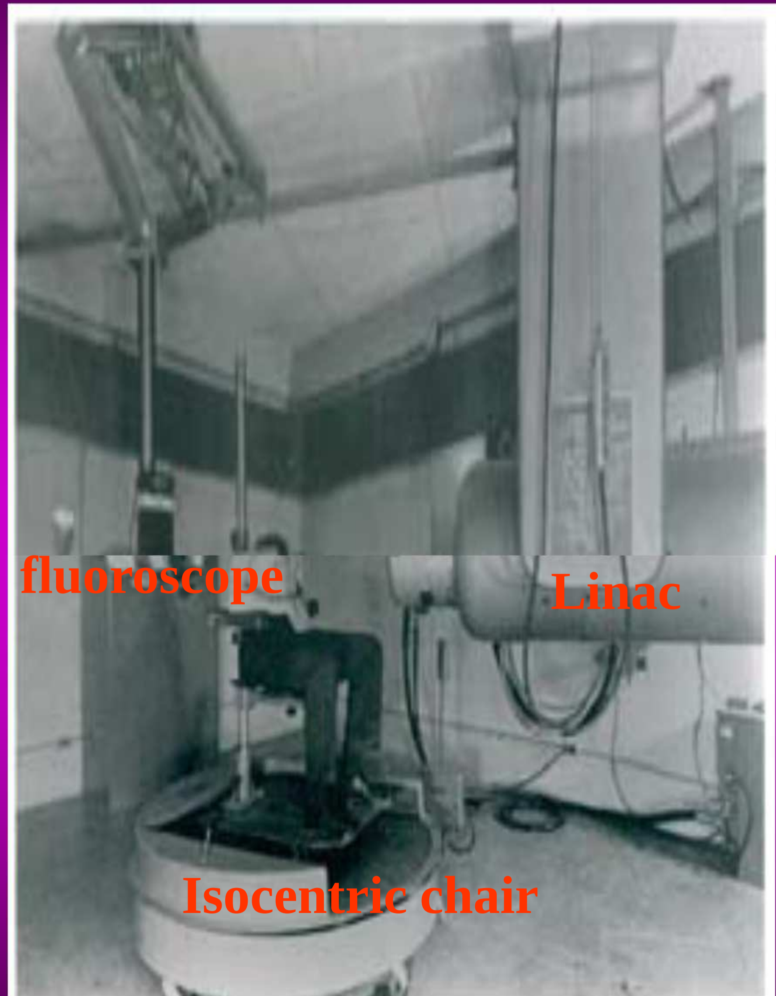
FIG. 1. A schematic diagram of the cobalt 60 unit showing the roentgenographic tube, the collapsing floor and the salient features of the device.

1959-John & Cunnigham described 60CO unit multivane collimator / ion chamber for invivo dosimetry. 100Kv x- ray source mounted in the CO-60 unit – "Xotron"

The Stanford Medical Linear Accelerator IGRT

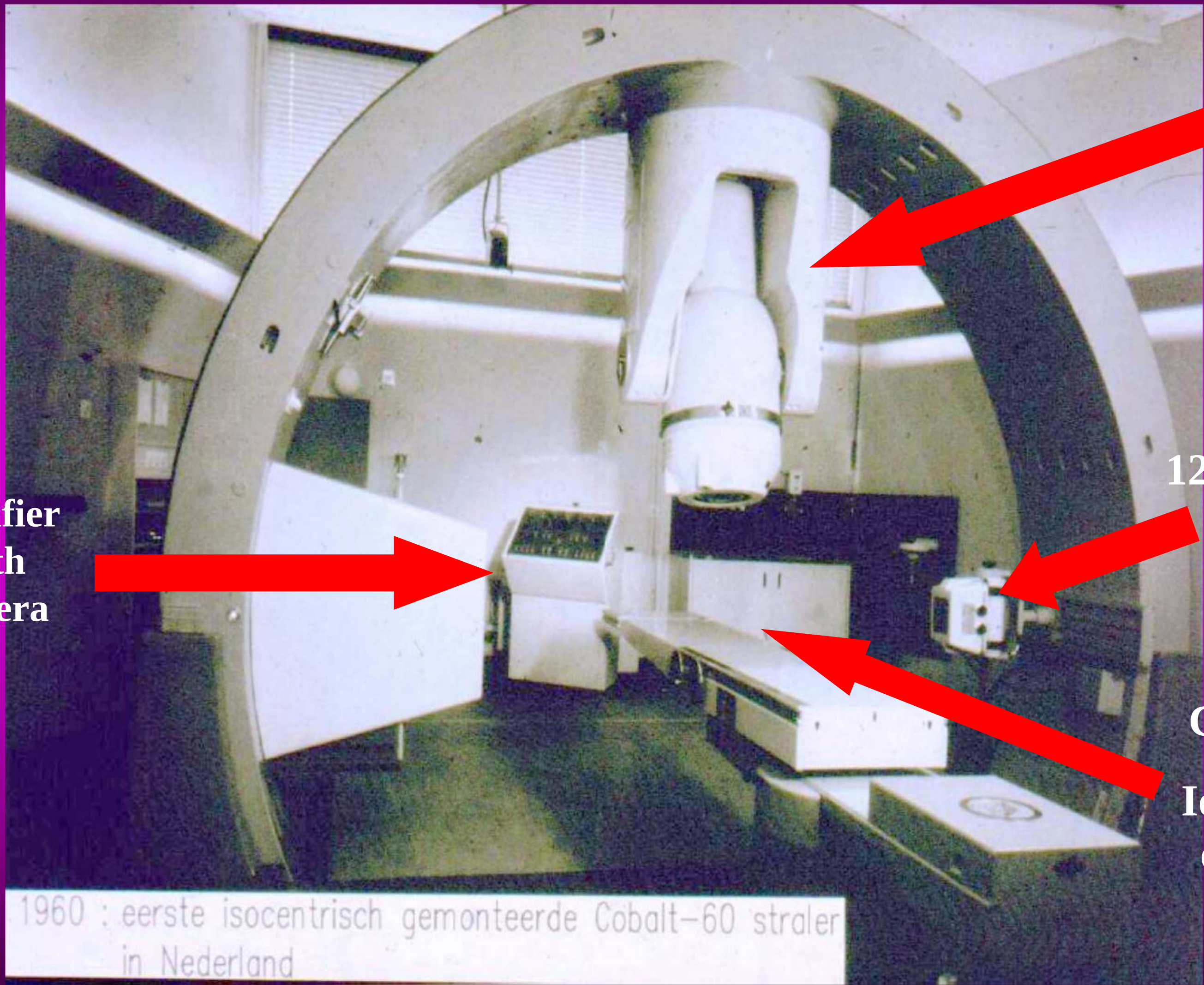






1958-Weissbluth et. al introduced the concept of in-room imaging with integrated diagnostic x-ray unit in the linac head. -Stanford Linear accelerator

Cobalt-IGRT



Co-60 head unit

120kV diagnostic X-ray unit

Image intensifier coupled with vedicon camera

Counter weight

Ion chamber for exit dosimetry

1960- Lokkerbol et al designed Cobalt based IGRT system: The base part of the construction is a sturdy ring (460mm) partly sunk in the floor enabling rotation of 540 degrees

Linac with IGRT

1985- Biggs et.al re-initiated the diagnostic (X-ray unit) quality portals for MV accelerators head

Diagnostic beam pass through the isocenter of the treatment beam center

Current IGRT Technologies

Current IGRT technologies

Ultrasound	Video-Based	Planar: X-Ray	Volumetric
BAT	Video Subtraction	EPID	In-Room CT
SonArray	Photogrammetry	CyberKnife	FOCAL, MSKCC
I-Beam	AlignRT	Novalis	CT-on-Rails
Restitu	Real-Time Video	RTRT	Primation
		Gantry-Mounted Prototype	Varian ExaCT
		Tohoku.	Tomotherapy
		IRIS Commercial	MV Cone Beam CT
		Varian OBI	Siemens
		Elekta Synergy	kV Cone Beam CT
			Mobile C-arm
			Varain OBI
			Elekta Synergy
			Siemens In-Line

Planar image guidance systems

<u>2D MV imaging: EPID</u>

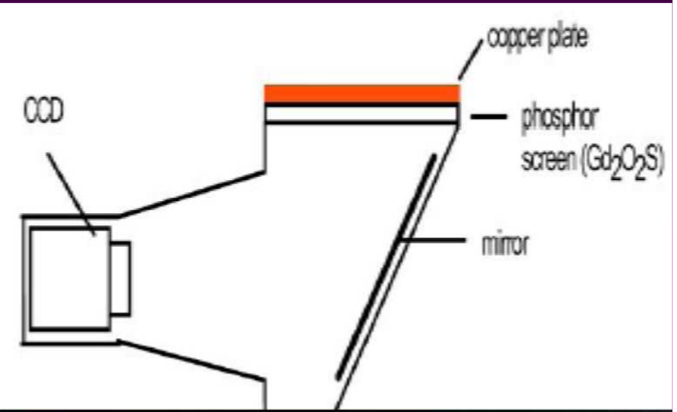
- Camera-based, Matrix liquid ionization chambers & a:Si Active matrix flat panel
- To align the patient position relative to the radiation beams/isocenter
- To verify the shape of the treatment portals

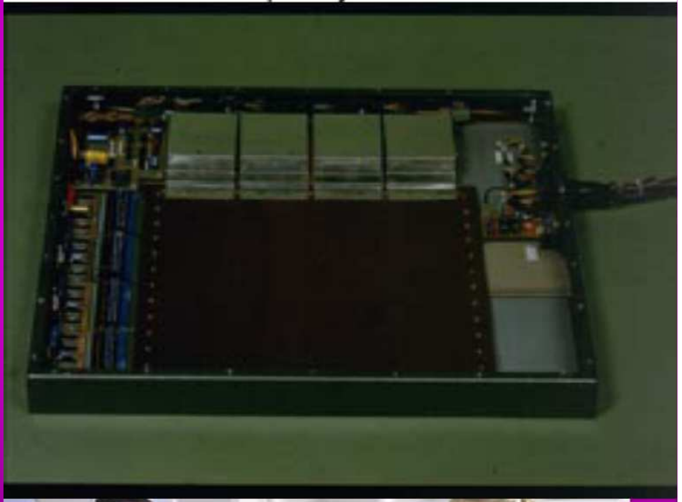
<u>Advantage:</u>

- Direct in-field verification of treatment

<u>Disadvantages:</u>

- MV imaging imaging dose (1 to 5 cGy)
- Poor image quality





EPID

Pros

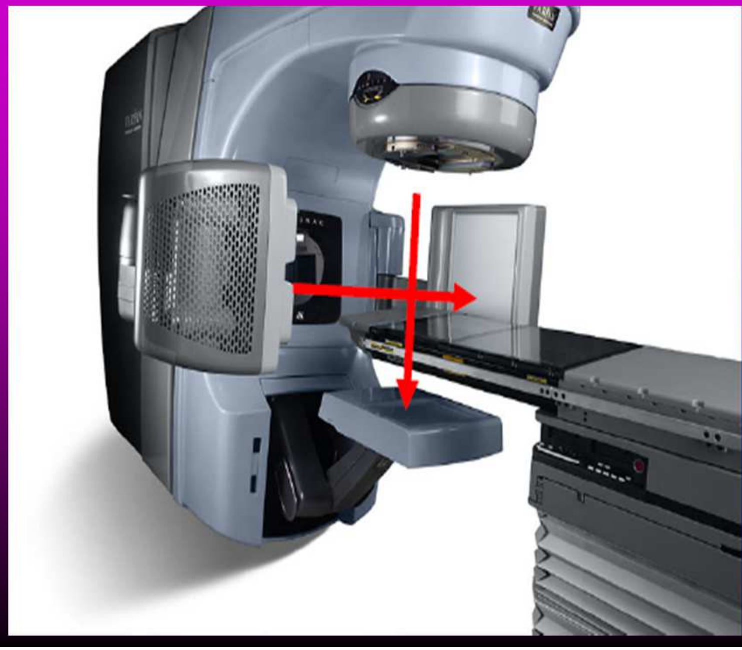
- Initiated the IGRT 'culture' both off-line and on-line
- Image created with treatment beam
- Direct verification of alignment target-beam
- Verification of field, MLC, dose, …

Cons

- Only 2D information (requires multiple gantry positions for 3D info)
- Requires surrogate to localize target
- Not straightforward to use during beam-on (e.g. IMRT, gating)
- Longevity of camera's & flat panels ?

2D KV x-ray imaging: On-board imagers

- kV x-ray tube, flat-panel imager
- diagnostic quality x-ray images



Advantage

- kV contrast is superior to MV imaging
- Imaging dose is low

Disadvantage

- 3D volumes of soft tissue targets is not possible

In-room kV 2D Stereoscopic kV imaging

- Orthogonal pair of x-ray images are used
- landmark point in 3-D space.

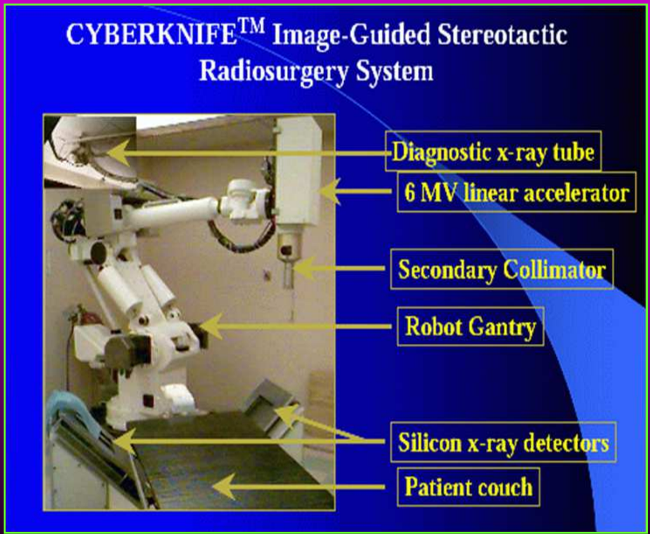
Advantage

- superior image quality to visualize bony structures
- low imaging dose

Disadvantage

- 3D target localization
- volume changes of target and OAR is not possible

BrainLAB-Novalis



Cyberknife

In-room kV-X-ray imaging : Hakkaido system

Real-time tumor tracking system

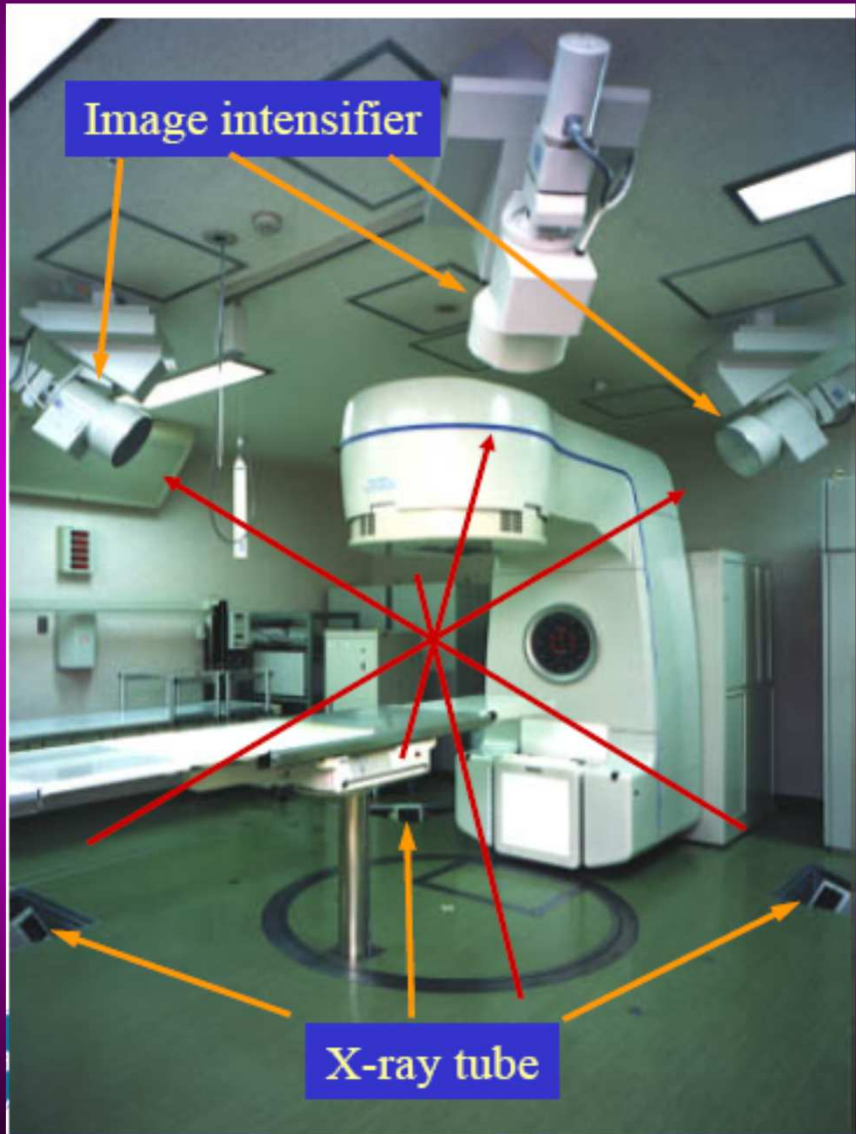
- combination of multiple x-ray source/ detector
- useful for internal gating

Advantage:

- high mechanical stability
- real time 3D information is available

Disadvantages:

- imaging isocenter is not treatment isocenter
- Requires surrogates



Shirato et al IJROBP 48:435-442, 2000

kV CT: In-room conventional CT or CT-on-Rails

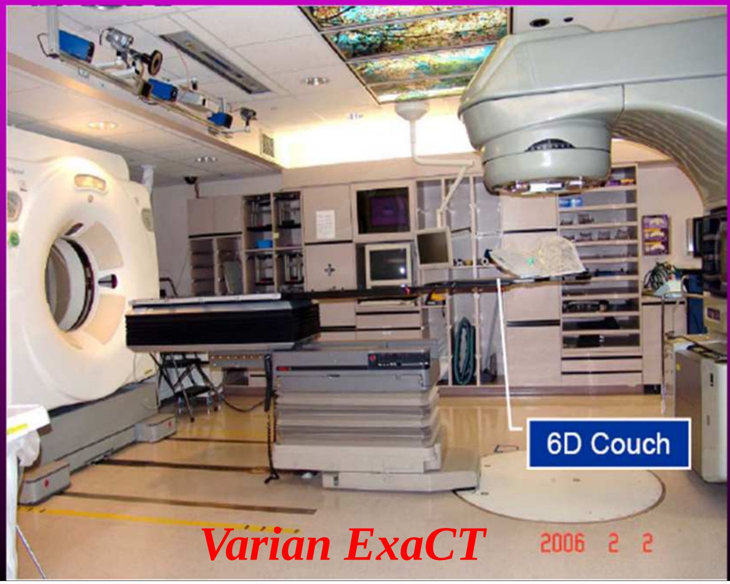
- 1996 -first integrated system of linac and CT in Tx room, Japan

<u>Advantages</u>

- simplest form of IGRT
- familiarity of the diagnostic quality CT images.

<u>Disadvantages</u>

- A couch correction is used to realign the patient
- In-room CT solution extends the treatment planning activities



Tomotherapy : Helical MVCT

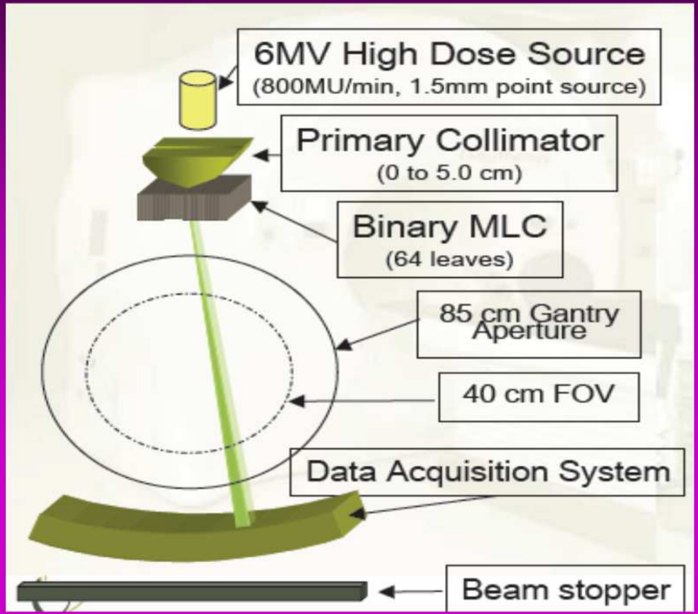
- Integrated unit of linac and CT units
- Ring-Gantry technology

<u>Advantage</u>

- Same MV beam is used for both imaging & treatment.
- Large field of view (FOV) of 40 cm

<u>Disadvantage</u>

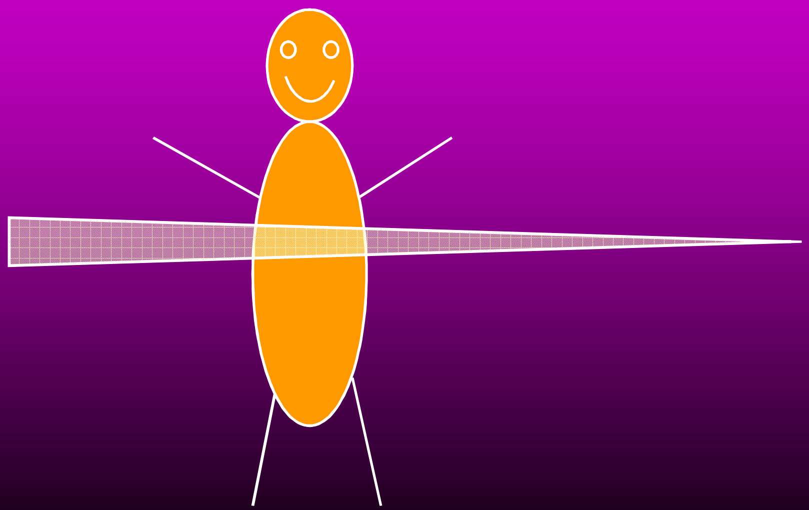
- Use of MV treatment beam for imaging may force compromises between the dose delivered and the image quality
- Noise level is high
- Low-contrast resolution is poor.
- Patient throughput is less



Conventional CT Vs Cone-beam CT

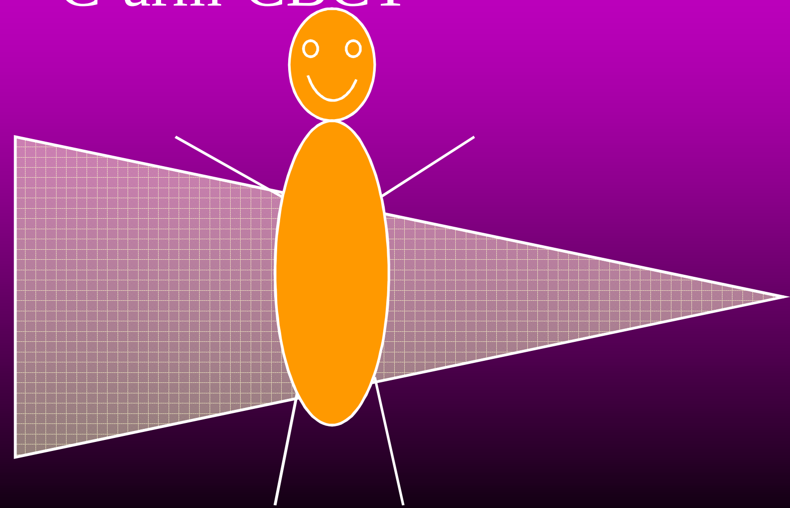
Conventional CT

- ‘Fan’ beam
- 1D detector
- 1 rotation = 1 slice



Cone-beam CT

- ‘Cone’ beam
- 2D detector
- 1 rotation = volume (many slices)
- MV-CBCT
- KV-CBCT
- C-arm-CBCT



Megavoltage cone-beam CT (MV-CBCT)

- Flat-panel detectors based EPID mounted on a linac gantry and the therapy MV x-ray
- Possible to acquire multiple, low-dose 2-D projection images

Advantages:

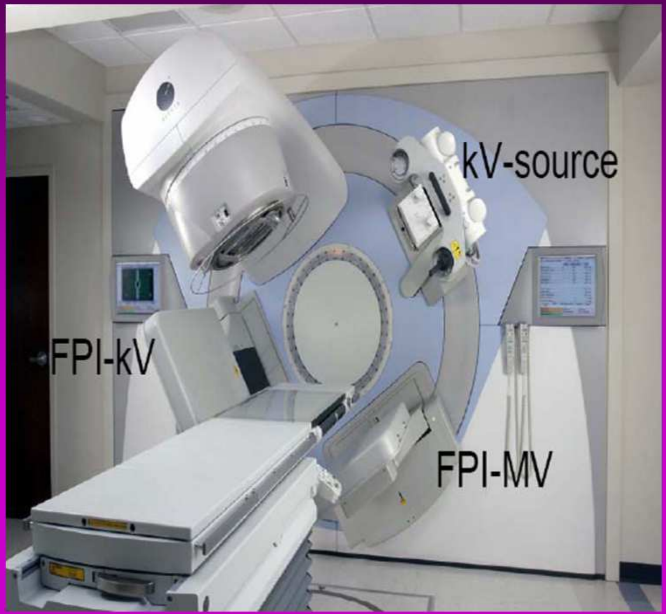
- Suitable for bony tumor
- uses a large detector and a single rotation

Disadvantage:

- lack of discrimination of soft tissue and bony objects by the physics of high-energy x-rays.

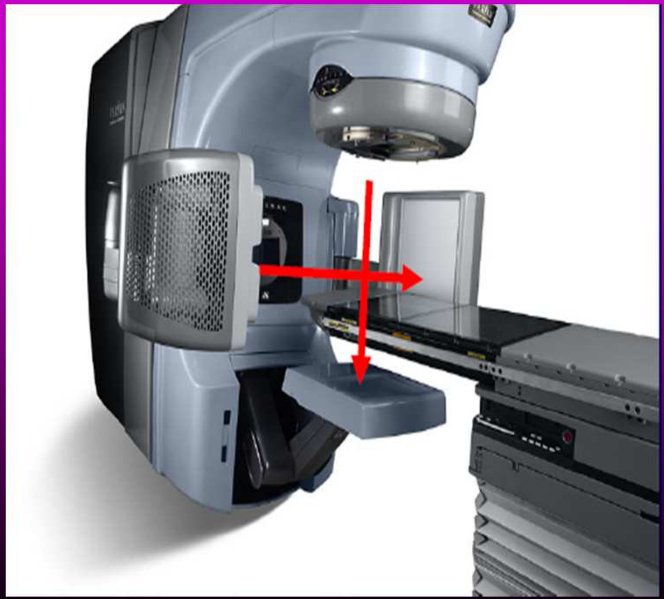
kV-CB CT : On-board imager

- Radiography, fluoroscopy, and CBCT
- large flat-panel imager
- kV x-ray tube mounted on a retractable arm at 90 degrees to the treatment beam line.
- Cone-beam CT reconstruction acquiring multiple kV radiographs as the gantry rotates through at least 180 degrees



Advantages

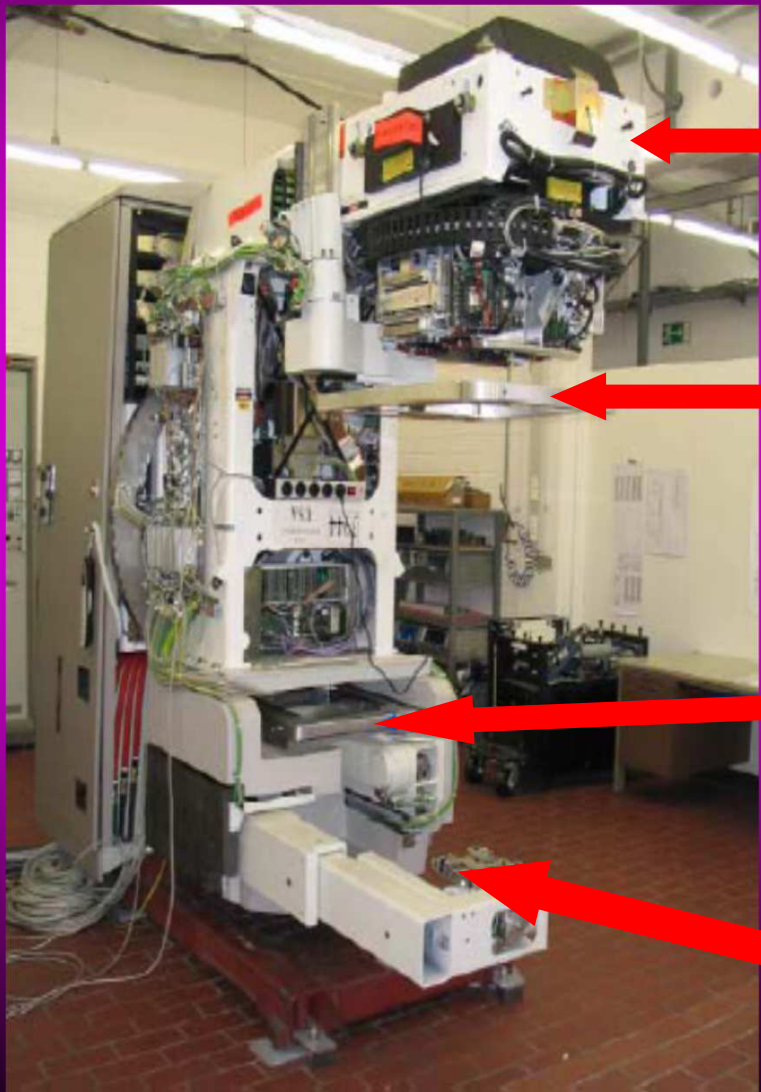
- real-time information is available
- no surrogates required



Disadvantages

- mechanically less stable
- requires careful calibration

Volumetric imaging: Siemens kV CBCT



MV-source

Flat panel: kV

Flat panel: MV

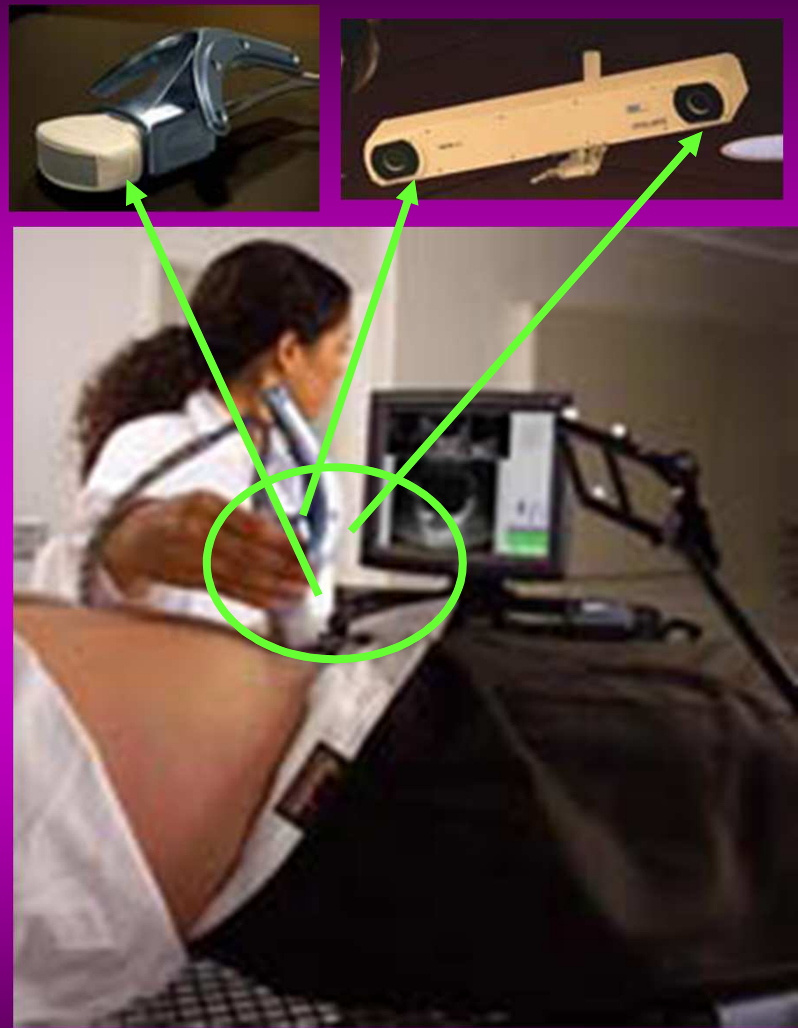
kV-source

Non-Radiographic techniques: Ultrasound

Non invasive

No radiographic

Relatively easy imaging



Advantages

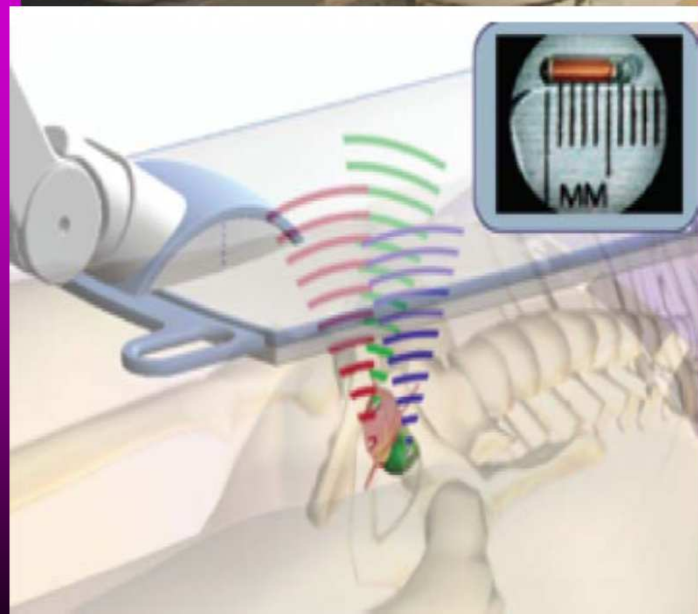
- no surrogate required (soft tissue visualization)
- remaining random error same magnitude as with initial set-up

Disadvantages

- CT-contour ≠US-structure
- Important inter-user variability

Electromagnetic Field Tracking: Calypso system

- to induce and detect signals from implanted wireless devices
- optical tracking system and a tracking station console
- **source coils & sensor coils**
- position of transponder without using the radiographic method



Advantage:

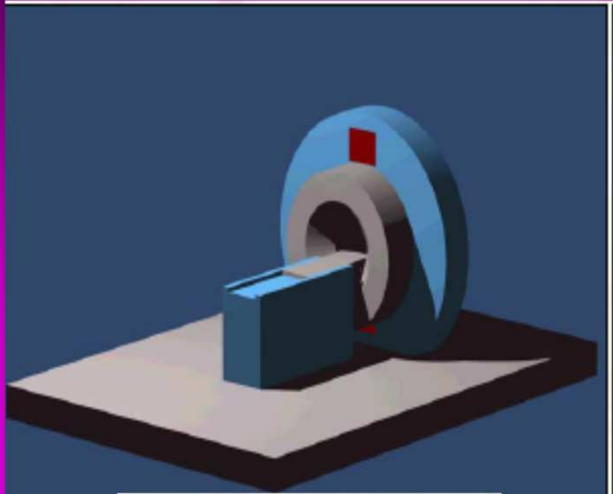
- update target position ten times / second & very fast
- sub millimeter tracking accuracy

MRI based Real-time Volumetric Tracking

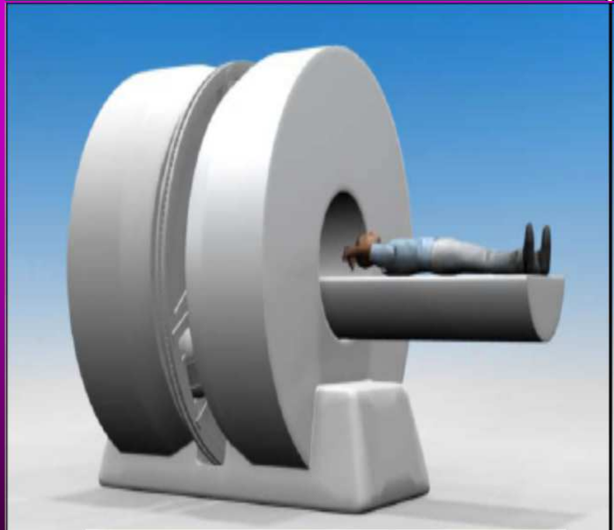
- Hybrid MRI-linac & MRI-cobalt-60 machines
- 3 Co-60 source & 0.3 T open field magnet
- MLC system provides gamma-ray intensity modulation

MRI

- track a patient's 3-D anatomy every 0.5-2.0s
- superior soft tissue contrast &
- near real-time, volumetric soft tissue targeting system.



1.5T Magnet, 6MV linac



Viewray:
MRI and Co^{60} IMRT

Adaptive Radiotherapy

ART

- Systematic improvement of a treatment plan in response to temporal patient/organ variations observed during therapy

Temporal variations

- Patient/organ geometrical shape and position
- Biological parameters of tissues

Key component of ART

- Time Adaptation of treatment parameters
- Feed Back' based on information provided by images
- Evaluation: requires treatment quality indicators

  e.g. accumulated dose

Adaptivity levels

Level I

<u>Observation prior to treatment</u>

Random + systematic setup errors

Organ motion (random, periodic)

Prediction of margins

Level II

<u>Observation prior to each fraction</u>

Random + systematic setup errors

Organ motion (random, periodic)

Adaptation of treatment parameters in each fraction

Level III

<u>Observation prior to and during each fraction</u>

Intrafractional setup errors, organ motion

Real time patient and organ movement

Dynamic adaptation of treatment parameters

IGRT and ART

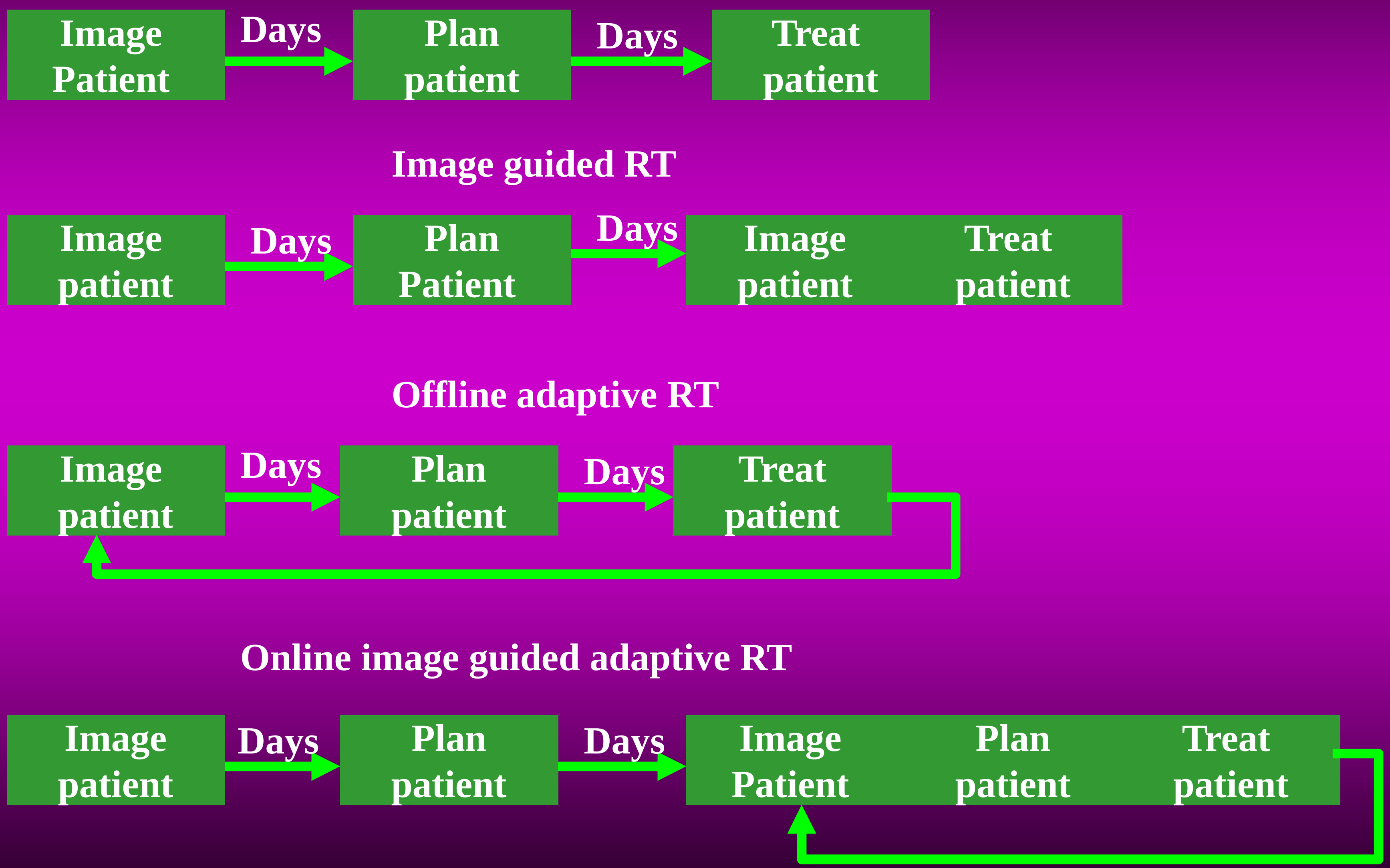


Image Patient
Days
Plan patient
Days
Treat patient
Image guided RT
Image patient
Days
Plan Patient
Days
Image patient
Treat patient
Offline adaptive RT
Image patient
Days
Plan patient
Days
Treat patient
Online image guided adaptive RT
Image patient
Days
Plan patient
Days
Image Patient
Plan patient
Treat patient

Stereotactic Body Radiotherapy (SBRT)

- **Treatment method using external beams to treat lesions of the <u>body targets</u> with ultra-high dose of radiation in a single dose (Radiosurgery) or (few) small number of fractions (Radiotherapy)**

- **With high precision tumor identification and relocalization employing "<u>stereotactic" and image guidance approaches</u>**

- **Extracranial Stereotactic Radiosurgery / Radiotherapy**

- **Radioablation / Body Radiosurgery / Radiotherapy called**

  "Stereotactic Body Radiotherapy (SBRT)"

IGRT management for Geometric uncertainties

IGRT for management of geometric uncertainties

Goal : Reduction of Set-up margin

Interfraction error is due to

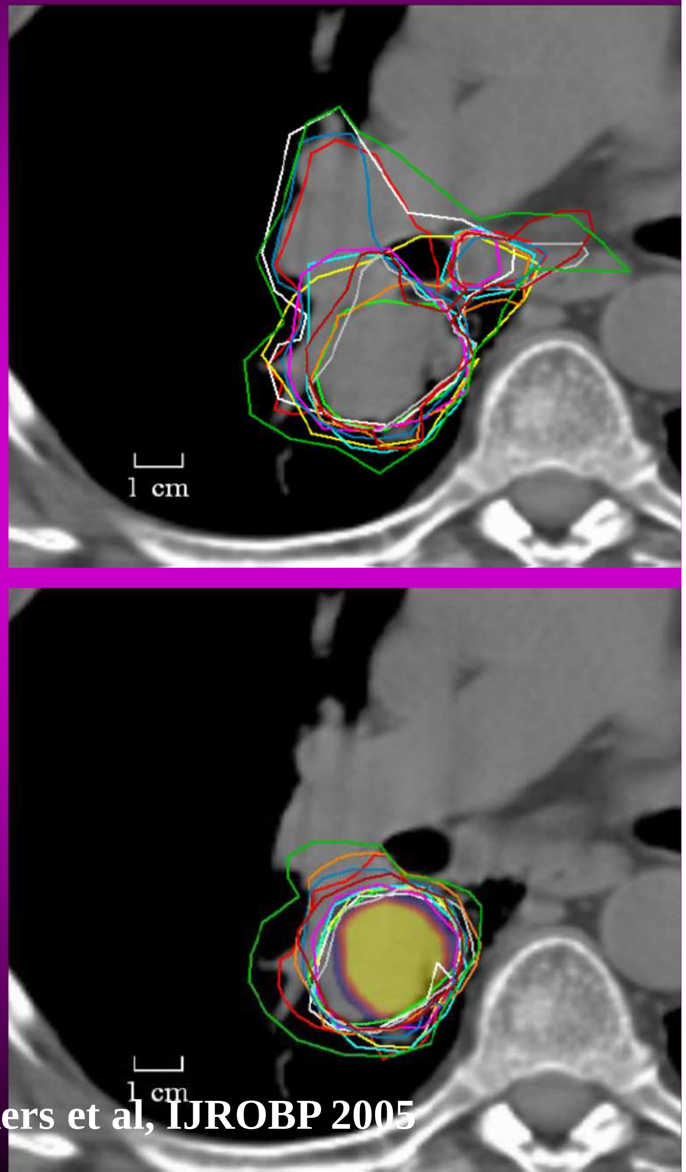
- Immobilization devices used
- Organ filling levels (day-to day situation
- Organ distenstion due to bowel and rectum gas pressure
- Supine vs prone position

Geometric uncertainties in Target definition

Accurate definition of target volume

- volumes not contoured may not get treated lead to geographical miss
- volumes varies with imaging modality
- subject to inter-observer variability
- remains as largest error of geometric uncertainties in radiotherapy
- systematic error originates from treatment preparation stage

Interface / region	CT SD (mm)	CT + PET SD (mm)
Tumor – lung	**5.9**	**3.3**
Tumor – mediastinum	**7.4**	**4.4**
Tumor – chest wall	4.0	3.7
Tumor – atelectasis	19.1	4.8
Lymph nodes	14.6	8.2
Total	**10.2**	**4.2**



Steenbakkers et al, IJROBP 2005

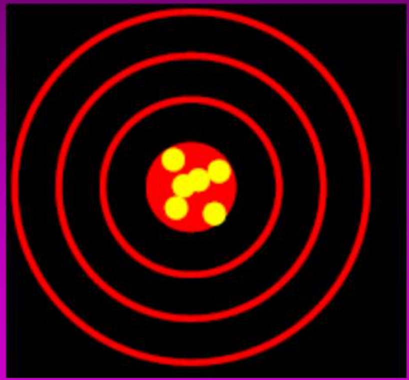
Geometric uncertainties in patient set-up

Systematic errors (Σ)

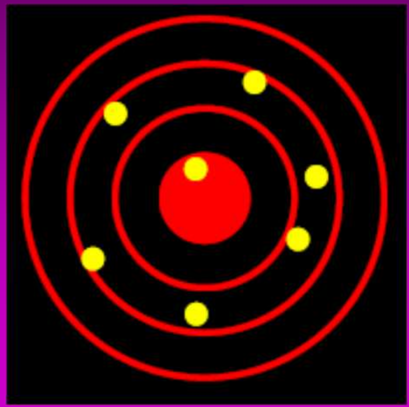
- treatment preparation errors
- influence all fractions
- deleterious effect
- larger

Random errors (σ)

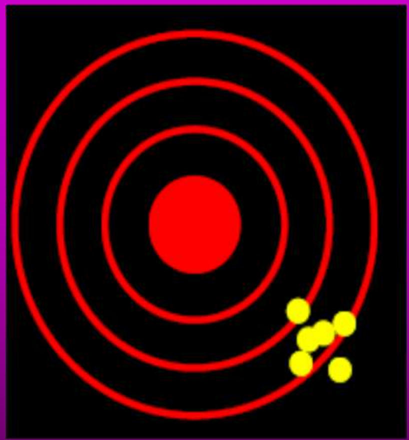
- treatment execution errors
- influence each fraction individually
- detrimental effect
- smaller



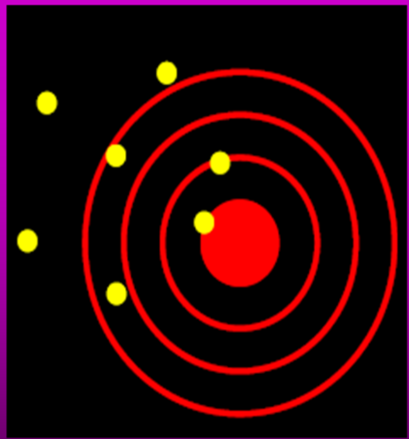
Σ small, σ small



Σ small, σ large



Σ large, σ small



Σ large, σ large

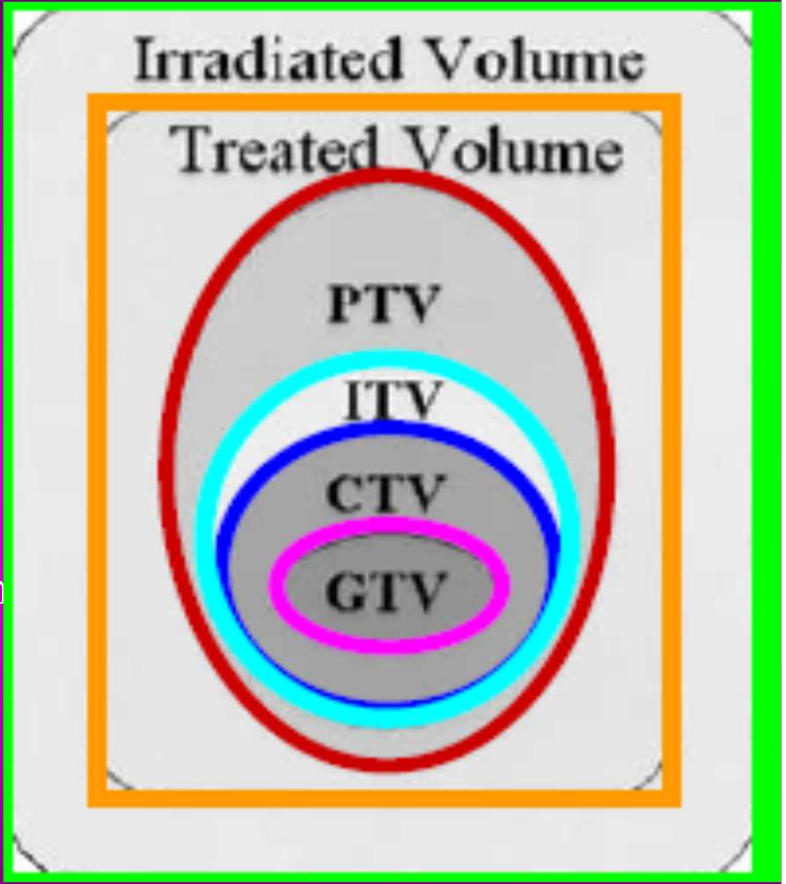
ICRU-62 Guidelines on Margins

Setup margin (SM)

- Variation in patient-beam positioning in reference to the treatment machine coordinate system
- Related to technical factors
- Can be reduced by:
  - Accurate setup and immobilization of the patient
  - Improved mechanical stability of the machine

Internal margin (IM)

- Variations in size, shape, and position of the CTV in reference to the patient's coordinate system using anatomic reference points.
- Caused by physiologic variations
- Difficult to control from a practical viewpoint.
- The volume formed by the CTV and the IM called Internal target volume (**ITV**)



Computing PTV margins

Error (SD)	Lung classic
Imaging snapshot setup Σ	4 mm
Imaging snapshot organ Σ	3 mm
Imaging snapshot respiration Σ	A=10 mm → 3.3 mm
Delineation Σ	4 mm
Treatment setup **σ**	4 mm
Treatment organ motion **σ**	3 mm
Treatment respiration **σ**	A=10 mm → 3.3 mm
Margin M	22 mm

$\mathbf{M \approx 2.5}\ \Sigma + 0.7\ \boldsymbol{\sigma}$

$\mathbf{2.5.{*}4^2 + 3^2 + 3.3^2 + 4^2 + 07 * (4^2 + 3 + 3.3^{2)} = 22.202mm}$

OAR Margin

- A margin is added around the organ at risk to compensate for that organ's geometric uncertainties
- Systematic errors : sensitive to shifts in a particular direction
- Random errors : impact of dose blurring
- Serial organs at risk : sensitive to hot spots
- Parallel organs at risk : some tolerance to limited hot spots

$$\mathbf{M \approx 1.3}\ \Sigma + 0.5\ \boldsymbol{\sigma}$$

Correction strategies

Corrections strategies: On-line vs Off-line

- To stratify treatment decision and to modify the treatment process is referred to as the correction strategy

On-line correction

- makes adjustment to the treatment parameters during the current treatment session.

off-line correction

- the intervention is determined from an accumulation of information that may be drawn from previous treatment sessions or at other times of measurement.

Types of setup errors

♦ **Translational errors**

- couch shift **X,Y,Z**

➢ **Rotational errors**

- Roll, Pitch and Yaw

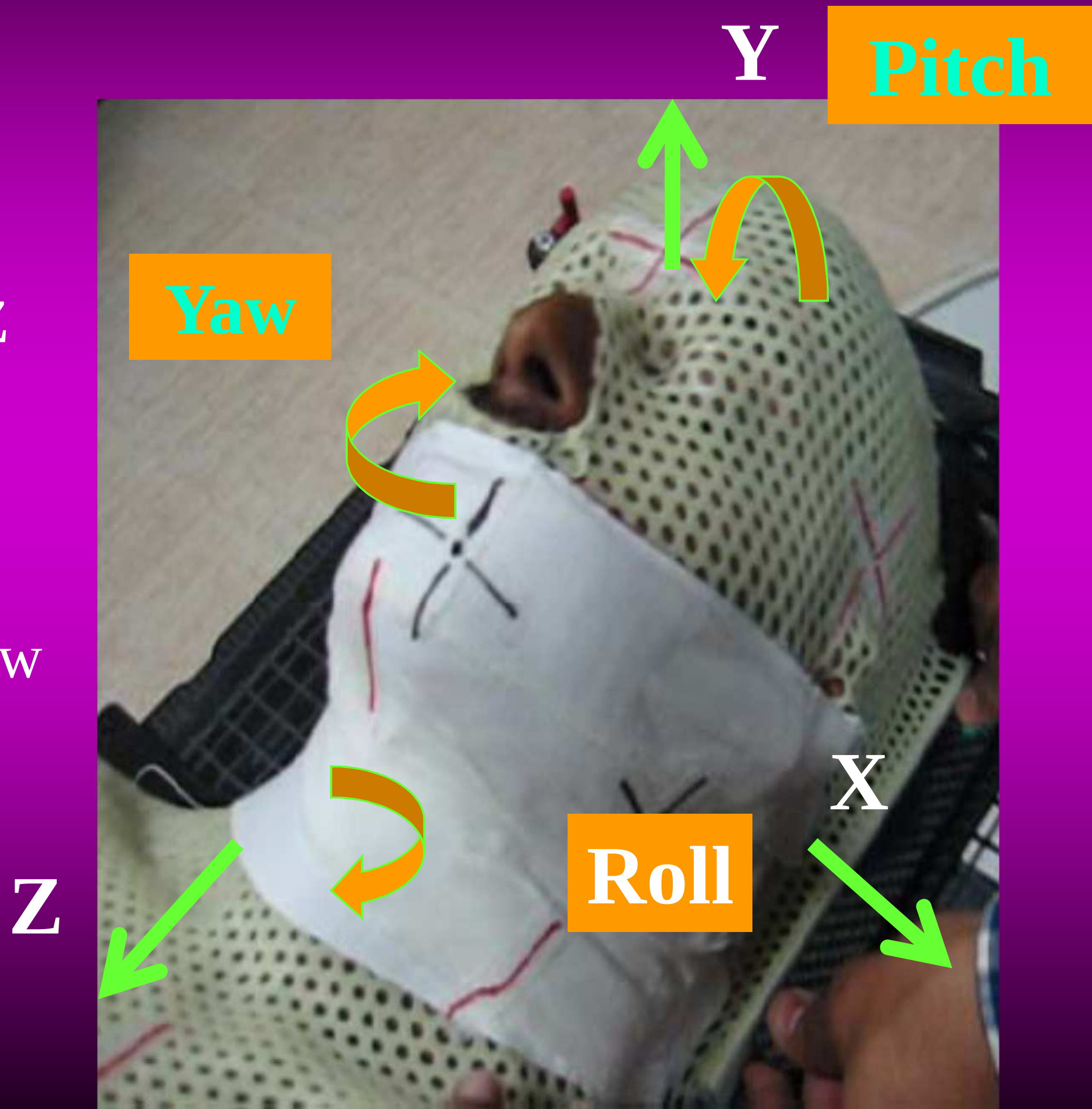
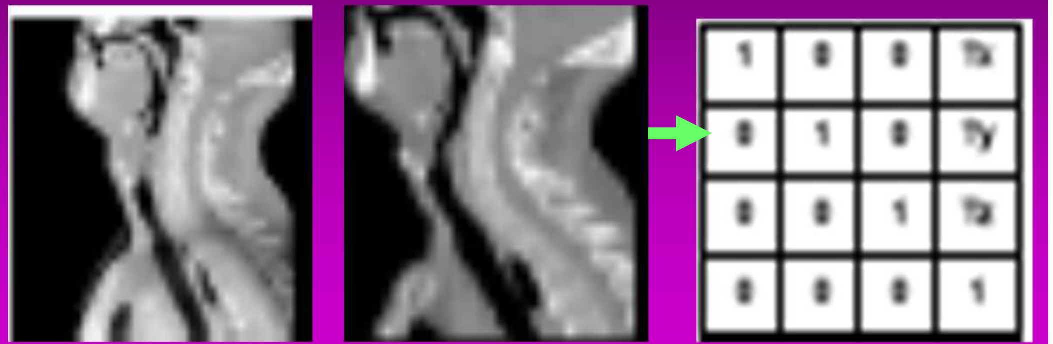


Image Registration in IGRT

- Find translation/ rotation/deformation to align two 2D..4D data sets
- Allows combination of scans on a point by point basis

Image Registration



Applications in radiotherapy

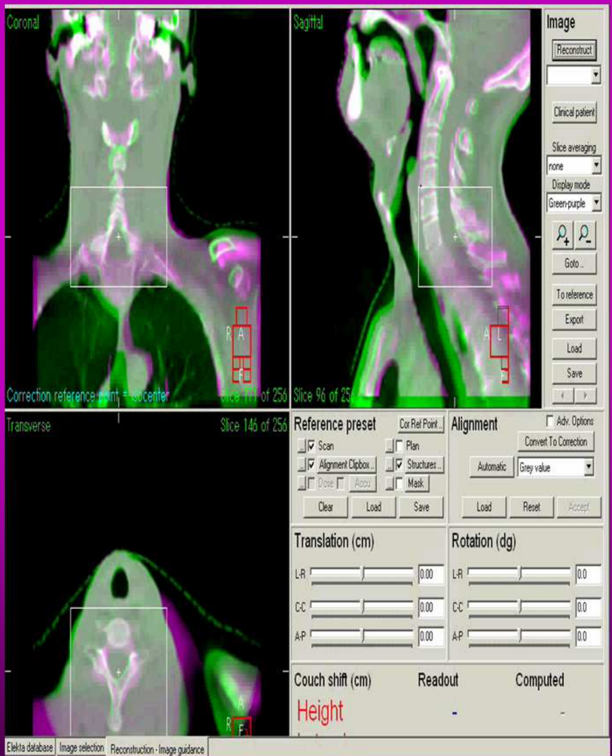
- Improvement of target definition
- Motion tracking
- Image guidance of treatment
- Dose accumulation

Image Fusion

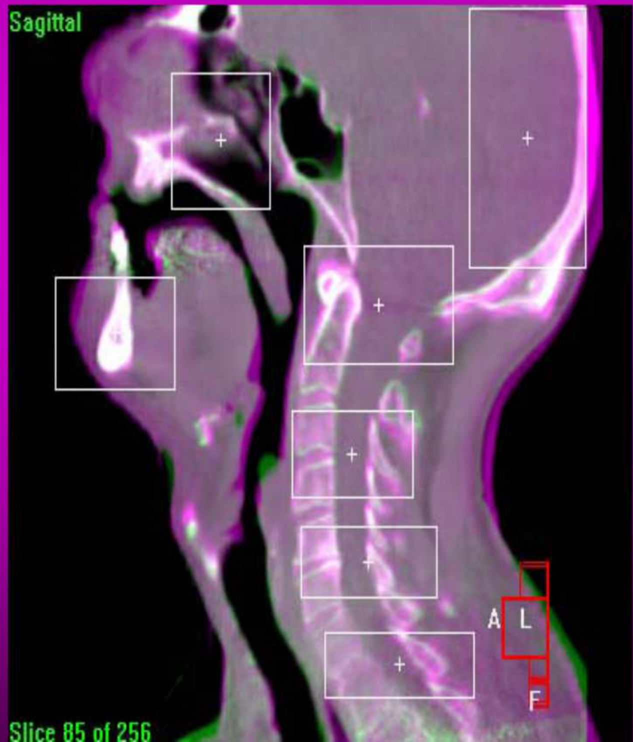
Displaying a combination of aligned images

Automatic matching: Registration methods

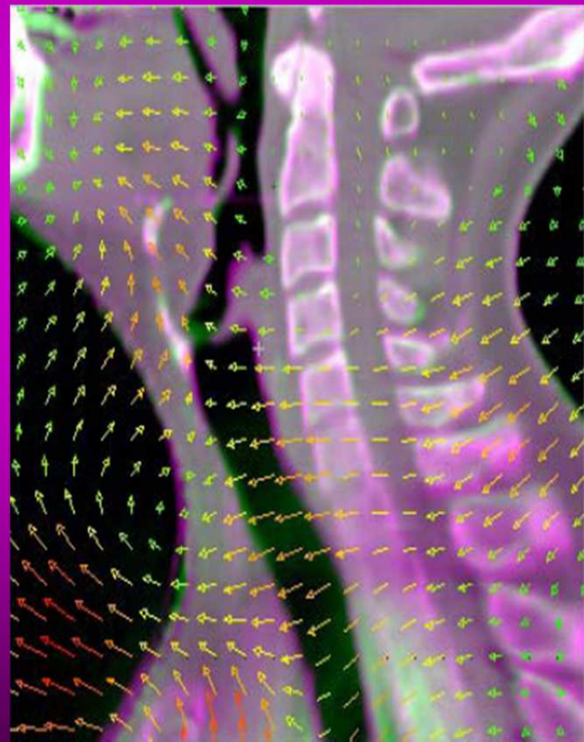
- **Bone-match**
- **Soft-tissue match (gray scale)**



Registration



Simple deformable registration



Full deformable registration

Treatment Time for IGRT

Patient setup in the room:	**2 – 5 min**
kV/kV or MV/kV imaging:	**~ 1 min**
2D2D matching analysis	**2 – 5 min**
CBCT imaging:	**3 min**
3D3D matching analysis:	**2 – 5 min**
Re-positioning:	**~ 1 min**
Treatment delivery:	**10 – 15 min**
Total treatment time for with CBCT	**20-35 min**
Total treatment time without CBCT	**15-25 min**

Patient dose due to IGRT

- ❖ planar kV x-ray imaging

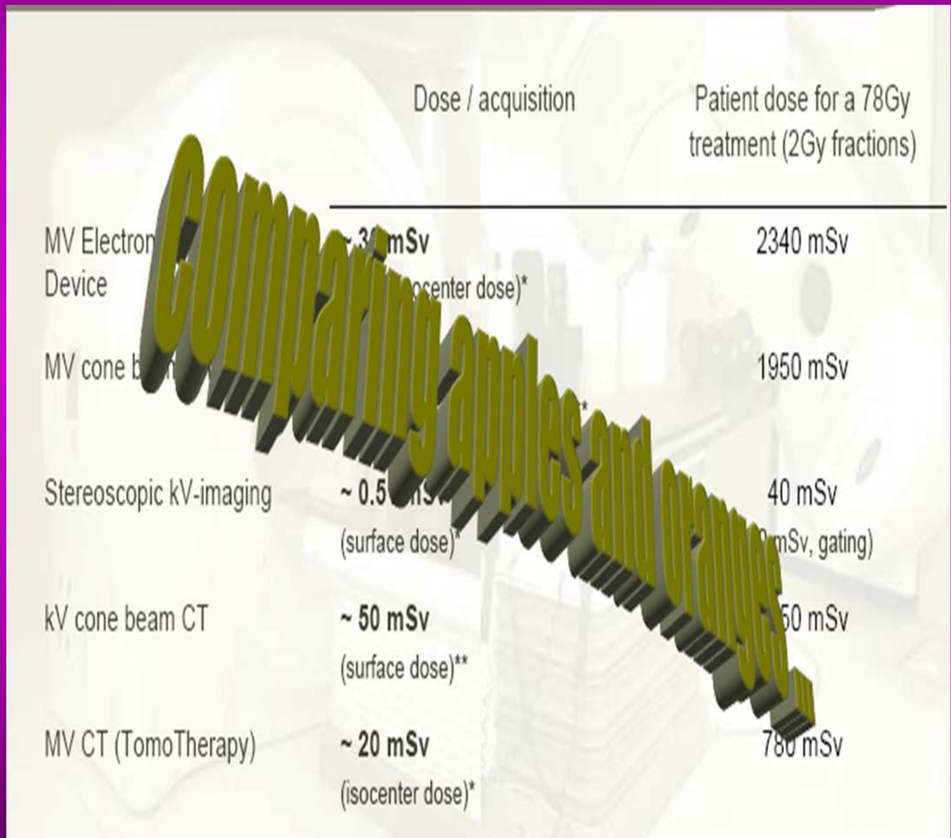
  - maximum dose can be concentrated on the skin

- ❖ Volumetric CT dose

  - distributes throughout the anatomical volume of

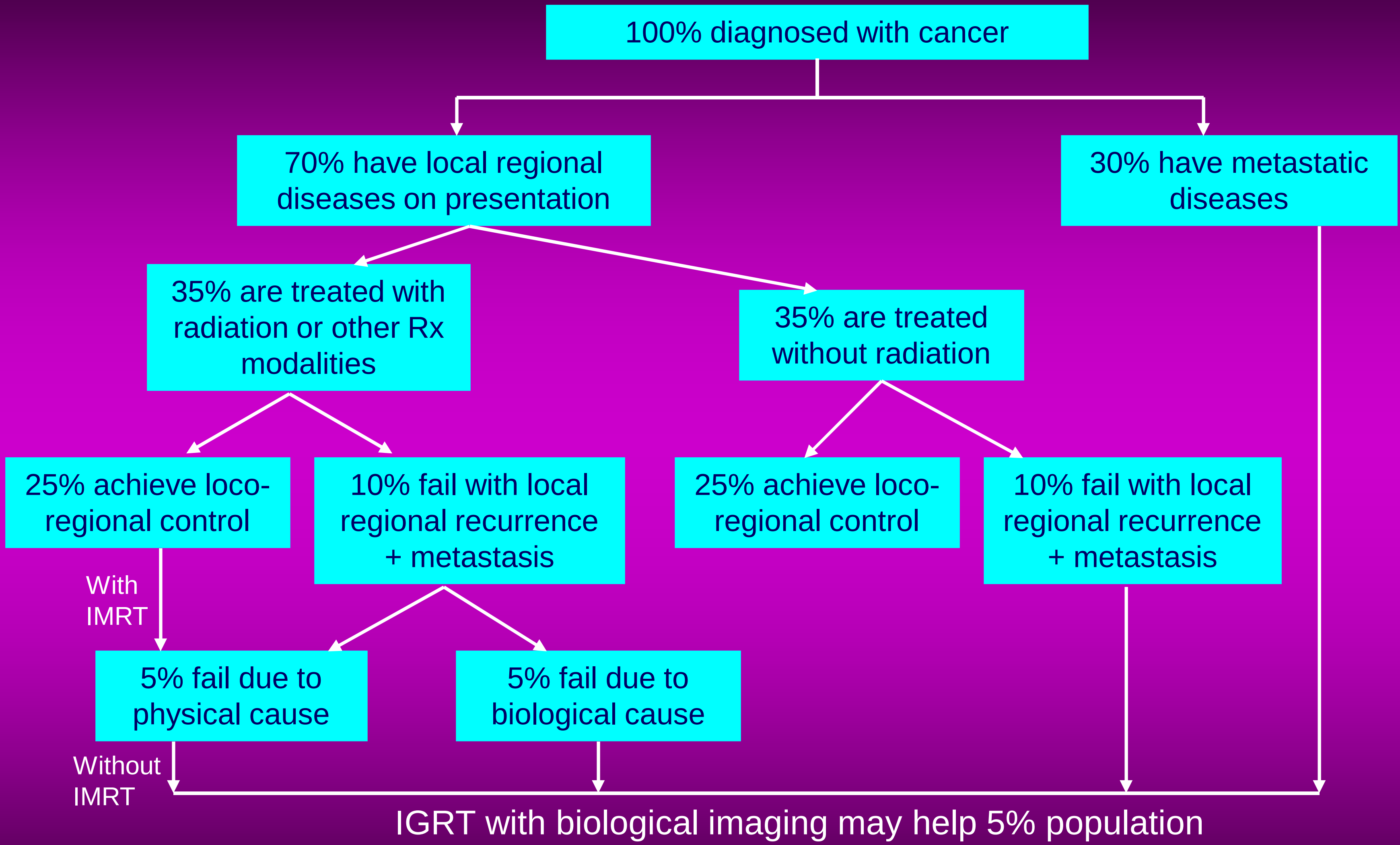
- ❖ Depends on

  - KV
  - MAs
  - Others Scanning parameters



	Dose / acquisition	Patient dose for a 78Gy treatment (2Gy fractions)
MV Electron[illegible] Device	~ 3[illegible] mSv ([illegible]center dose)*	2340 mSv
MV cone b[illegible]	[illegible]	1950 mSv
Stereoscopic kV-imaging	~ 0.5[illegible] (surface dose)*	40 mSv ([illegible] mSv, gating)
kV cone beam CT	~ 50 mSv (surface dose)**	[illegible]50 mSv
MV CT (TomoTherapy)	~ 20 mSv (isocenter dose)*	78[illegible] mSv

Cost-Beneficial analysis



Is 5% significant?

Total population is 287 million

1.28 million/year will be diagnosed with cancer

555,000/yr will succeeds 5% corresponds to saving over 64,000 lives/yr

Take-home messages

- 2D planar vs. 3D volumetric imaging
- Pre-treatment vs. real-time motoring/tracking
- Direct target localization vs. target surrogates
- Online vs. offline adaptation
- Anatomy-based vs. dose-based adaptation

IGRT for management of Inter and intra- fraction geometric uncertainities

	Interfractional	Intrafractional
EPID Planner imaging	Requires surrogate, difficult to assess 3D information	Not possible
Stereoscopic X-ray imaging	Requires surrogate, 6 DOF possible	Requires surrogate, 6 DOF possible, real-time target localization possible
Ultrasound imaging	NO surrogate required, limited to pathologies that can be imaged with US	NOT possible
KVCBCT	Requires no surrogate, 6 DOF possible	NOT possible
MVCT	Requires no surrogate, 6 DOF possible	NOT possible
Optical tracking, video,…..	unable to visualize target volume	unable to visualize target volume

Getting the patient set up correctly

In order of effectiveness

- CT-on-rails
- KV cone beam
- MV cone beam
- Positioning sensors
- Ultrasound
- EPID with fiducials
- Photography
- Laser setups
- Portal films

In order of safety

- Photography
- Ultrasound
- Positioning sensors
- Portal films
- EPID with fiducials
- CT-on-rails
- KV/MV cone beam

Errors and Margin

- Determine what these error sources are and what their impact is in your department
- Focus on correcting remaining systematic errors
- Image guidance systems can half the margin
- IGRT does not eliminate all errors; carefully consider the margins to be used
- IGRT introduces new errors and makes old errors more important
- Margin recipes assume that you know ALL ERRORS USE AT YOUR OWN RISK

Summary and Conclusion

- Patient setup error is systematic & larger than random error
- Target delineation error remains as systematic and large error
- Tracking reduce beam on time but not considered deformation
- IGRT reduces systematic error and accurate dose delivery
- IGRT provides dose escalation and hypofraction in lung cancers

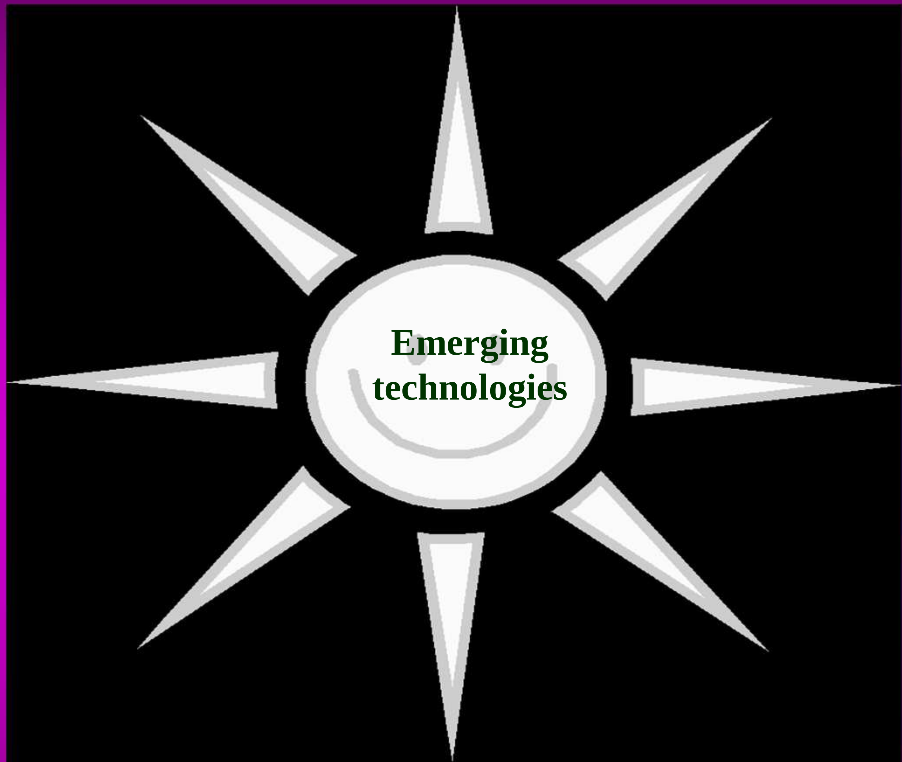
IGRT is a new technology and its clinical benefits yet to be proved

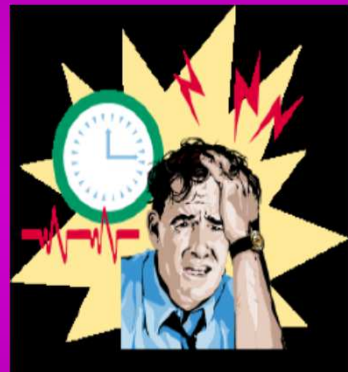
QA, RTPS, 4D CT, radiographic, fluoroscopic, & CBCT IGRT, image registration, fusion, US, 4D PET/CT....

Administration Budget

Technologist

Chief of Physics





Physicist

Residents

Dosimetrist

Physician