Conformal Radiation Techniques - An Evolution

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The Evolution of Radiation Therapy

- 1960s: First Linac and Basic Collimator
- 1970s: Cerrobend Blocking, Electron Blocking, Computerized 3D Treatment Planning, Multileaf Collimator
- 1980s: Dynamic MLC and IMRT
- 1990s: High-Resolution IMRT
- 2000s: High-Resolution IMRT
The Evolution of Radiation Therapy

1960's
- The First Clinac
- Standard Collimator
- The linac reduced complications compared to Co60

1970's
- Cerrobend Blocking
- Electron Blocking
- Blocks were used to reduce the dose to normal tissues

1980's
- Multileaf Collimator
- MLC leads to 3D conformal therapy which allows the first dose escalation trials.

1990's
- Computerized 3D CT Treatment Planning
- Dynamic MLC and IMRT
- High resolution IMRT
- Computerized IMRT introduced which allowed escalation of dose and reduced complications

2000
- Functional Imaging
- IMRT Evolution evolves to smaller and smaller subfields and high resolution IMRT along with the introduction of new imaging technologies
EVOLUTION OF RADIOTHERAPY

2D (pre 1990)
- Conventional Square/Rectangle
- Parallel Opposing
- Deep X-Ray / Cobalt-60

3D (post 1990)
- Blocks, Multileaf Collimator
- Conformal RT,
- SRS/SRT, IMRT

4D (Today)
- Motion and Time Real Time with Feedback
- IGRT, Cyberknife Tomotherapy
WHY ???

Accurate Treatment Delivery
High Tech Radiotherapy Machines

High Energy Linear Accelerator

Helical Tomotherapy
Types of Conformal Radiation

Geometrical Field shaping

Geometrical Field shaping with Intensity Modulation
WHAT IS 3-D CRT

To plan & deliver treatment based on 3D anatomic information, such that resultant dose distribution conforms to the target volume closely in terms of

- Adequate dose to tumor &
- Minimum dose to normal tissues.

The 3D CRT plans generally use increased number of radiation beams to improve dose conformation and conventional beam modifiers (e.g., wedges and/or compensating filters) are used.
Intensity Modulated Radiation Therapy

- In its purest sense IMRT is intensity modulation.
- The ability to create customized intensity patterns
- It is “an advanced form of 3D-CRT that uses non-uniform radiation beam intensities” *

*Int J Radiation Oncology Biology Physics vol.51, No. 4 pp.880-914, 2001
Intensity-Modulated Radiation Therapy

- IMRT is a process
  - Planning
  - Information Transfer
  - Delivery
  - Verification

- IMRT allows you to customize your treatment delivery based on a specific planning objective
IMRT Clinical Studies

August 2002 Review of the Literature
Arno Mundt MD, University of Chicago
IMRT – Clinical Process

- Imaging for staging
- Immobilization
- Imaging for treatment planning
- Treatment Planning – Forward or Inverse
- Plan verification
- Treatment verification
- Treatment delivery
WORKFLOW OF CONFORMAL RT
Step and Shoot vs. Dynamic

- Multiple Static Segments, aka:
  - Step and Shoot
  - Move and Shoot
  - Stop and Shoot
  - SMLC

- Fully Dynamic, aka:
  - Sliding Window
  - DMLC
  - Moving Gap
Organ Motion is the CONCERN

- "Interfraction" motion occurs between fractions and primarily is related to changes in patient localization.

- "Intrafraction" motion occurs during fractions and primarily is related to respiration.
Tumor Motion During Respiration

- All tumor motion is complex
# Tumor Motion: How Often?

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Anatomic “Motions” and the Timescale at Which They Occur</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day to day</strong></td>
<td>Skin motion</td>
</tr>
<tr>
<td><strong>Hour to hour</strong></td>
<td>Prostate motion</td>
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<tr>
<td><strong>Minute to minute</strong></td>
<td>Bladder filling</td>
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<tr>
<td></td>
<td>Neck flex</td>
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<tr>
<td><strong>Second to second</strong></td>
<td>Respiration</td>
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<tr>
<td></td>
<td>Heartbeat</td>
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<tr>
<td></td>
<td>Peristalsis</td>
</tr>
</tbody>
</table>

Van Herk M. Semin Radiat Oncol 2007; 17: 258-267
Factors influencing target localization and positioning

A. Patient motion

B. Weight loss

C. Absence or presence of fluid

D. Bone mineral losses
Factors influencing target localization and positioning

E. Periodic physiologic movements
- Peristalsis
- Blood flow
- Breathing
- Cardiac motion

F. Random physiologic movement
- Swallowing
- Coughing
- Hiccups
- Sneezing
Factors influencing target localization and positioning

G. Transfer errors

H. Transpositional errors

I. Setup errors (either initial or repeat)
Efficient Treatment Also Requires Accuracy!!!

Radiation shaped to target but missing target

The right target
With tight margins being taken in highly conformal radiotherapy techniques there is a risk of precisely missing the target with organ motion.
To Combat These Uncertainties

1. Use large margins, irradiating too much healthy tissues

Or

2. Use IGRT

volume = \( \frac{4}{3} \pi r^3 \)
a small reduction in margin (5mm) yields a reduction by half in volume

IGRT is defined as frequent imaging in the treatment room that allows treatment decisions to be made on the basis of these images.
Four- Dimensional Radiotherapy (4DRT)

- IGRT in which the localization accuracy— not only in space but also in time – is improved

- In comparison to that in 3DRT tumor position is monitored during the delivery of the therapeutic beam.

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

- Ca lung
- Ca Prostate
- Head and Neck
- Ca Rectum
- Ca Cervix
IGRT : Available Options

IGRT encompasses the following present day Technology

- **Volumetric**
  - CT on rails
  - Tomotherapy
  - MV cone beam CT
  - KV cone beam CT

- **Planar X ray based**
  - EPID
  - Cyber knife

- **Video based**
  - Real Time video guided IMRT

- **Ultrasound based**
  - BAT
# Current IGRT in Market

<table>
<thead>
<tr>
<th>Ultrasound</th>
<th>Video-Based</th>
<th>Planar: X-Ray</th>
<th>Volumetric</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAT</td>
<td>Video Subtraction</td>
<td>EPID</td>
<td>In-Room CT</td>
</tr>
<tr>
<td>SonArray</td>
<td>Photogrammetry</td>
<td>CyberKnife</td>
<td>FOCAL, MSKCC</td>
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<td>I-Beam Restitu</td>
<td>AlignRT</td>
<td>Novalis</td>
<td>CT-on-Rails</td>
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<td></td>
<td>Real-Time Video</td>
<td>RTRT</td>
<td>Primation</td>
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<td>Gantry-Mounted Prototype</td>
<td>Varian ExaCT</td>
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<td>Tohoku</td>
<td>Tomotherapy</td>
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<td>IRIS Commercial</td>
<td>MV Cone Beam CT</td>
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<td>Varian OBI</td>
<td>Siemens</td>
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<td>Elekta Synergy</td>
<td>kV Cone Beam CT</td>
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<td>Mobile C-arm</td>
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<td>Varian OBI</td>
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<td>Elekta Synergy</td>
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<td>Siemens In-Line</td>
</tr>
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## Related Technologies

- RPM gating/4DCT
- Optical-guided Approaches
Techniques of Tumor Tracking

• **Skin Markers**

  Not adequate for IGRT as margins required for uncertainty will be 1.5 – 2 cm

• **Internal markers**

  A. CT based Bony Anatomy tracking
  
  B. CT based Soft Tissue Tracking
  
  C. Implanted fiducials
    (Deformation is a problem, Less inter user variation, Good stability)
  
  D. Implanted radiofrequency transponders for electromagnetic tracking
    (miniature Global Positioning Systems)
  
  E. Endo-rectal balloon
    (can reduce rectal radiation dose, Renders rectal dosimetry more predictable by making rectal anatomy more reproducible)
CT in the treatment room
IGRT
How to Correct for Displacements

- Couch corrections
- Gantry and collimator angle adjustments
- Modification of multi-leaf collimator leaf positions
Couch Corrections

Correction by lateral couch shift

Methods to account for Respiratory motion

- Motion encompassing methods
- Respiratory Gating methods
- Breath-hold methods
- Forced shallow breathing with abdominal compression
- Respiratory tracking methods
Motion encompassing methods

(i) Slow CT scanning

(ii) Gated/breath hold CT
    Prospective respiratory correlation

(iii) 4DCT
    Retrospective respiratory correlation
RPM Respiratory Gating™ System

Varian patent 6,279,579

Literature:
- Kubo 1996, 2000a, 2000b
- Ramsey 1999a, 1999b
- Slotman & Lagerwaard 2004
- de Pooter & Alberty 2004
- Pedersen et.al. 2004

Data courtesy AZ Sint Augustinus, Wilrijk, Belgium
4D CT Image Acquisition

Prospective

Patient Immobilized on CT

RPM Respiratory Gating System Triggers X-ray on

RPM System Collects Respiration Phase Data

Advantage 4D Synchronizes Image Data With Respiratory Cycle

Planning

Patient Immobilized on CT X-ray on

Standard Geometric Planning
Prospective CT Image Acquisition

Respiration Waveform from RPM Respiratory Gating System

CT Scan

Axial scan trigger, 1\textsuperscript{st} couch position

Scan

Inhalation

Axial scan trigger, 2\textsuperscript{nd} couch position

Scan

Exhalation

Axial scan trigger, 3\textsuperscript{rd} couch position

Scan
Prospective Gating

Conventional CT Image  Gated CT Image

Images Courtesy Medical College of Virginia, Richmond VA
Principle of 4D scanning
Respiratory Gating

- Radiation delivery synchronized with the respiratory signal

- A reflective marker block is placed on the patient to detect respiration motion (or internal fiducial markers)

- Marker blocks are illuminated by infrared emitting diodes

- Software tracks the position of the marker
RPM is an external gating system

System consists of an infra-red camera that is mounted to the foot of the CT

Markers block containing 2 reflectors.

The marker block was placed on the patient’s skin in the abdominal region

Surrogate signal = abdominal surface motion correlation to tumor motion

The x-ray on signal from the CT scanner was recorded synchronously with the respiration signal
Active Breathing Control (ABC)

- Temporarily immobilizes patient’s breathing
- The inspiration and expiration paths of airflow are closed at predetermined flow direction
On-Board Imager – Marker Match™

Find Markers in Planning CT

FDA 510(k)
On-Board Imager – Marker Match™

Acquire Radiographic Images

FDA 510(k)
On-Board Imager – Marker Match™

Match/align Marker Template with actual setup images

➤ Calculate couch motion required to correct setup

FDA 510(k)
Marker Match – Clinical Results

FDA 510(k) - Images courtesy Karolinska University Hospital, Stockholm, Sweden
Marker Match - Shifts for one patient

Golden Marker

Data courtesy Karolinska University Hospital, Stockholm, Sweden
Marker Match - Markers vs. Anatomy

Data courtesy Karolinska University Hospital, Stockholm, Sweden
METABOLICALLY AIMED RADIOThERAPY MART

PET GUIDED IMRT

IMPROVED TUMOR/NON TUMOR RADIATION DOSE

HYPO-FRACTIONATION 30-40 → 5-10 fractions
PET – CT fusion for Planning

PET/CT Lung Primary

PET/CT Head and Neck Primary
Eclipse 4D – PET CT
TOMO is the Buzzword in Imaging Technology

Computed TOMography

SPECT TOMography

MR TOMography

Positron TOMography

Helical TOMOtherapy

All these revolutionary technologies are based on ring gantry design
What is Helical TomoTherapy?

- TomoTherapy literally means “Slice Therapy”
- It is derived from the word ‘Tomography’
- Helical Tomotherapy is the delivery of IMRT using helical rotational delivery in the manner of a CT scanner
- A modified Linac fitted into CT ring gantry configuration for therapeutic radiation using rotating fan beam modulated by multileaf collimators
- System uses tomographic imaging for treatment verification and tomographic reconstruction for optimal treatment
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

**Advantage**
- it does not require the extensive modification of a Linac
- CBCT imaging system 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
IMRT in a Single Arc
Dynamic Radiotherapy Objectives

- Single arc IMRT
- IMRT quality
  - Uniform target coverage
  - Improved normal tissue sparing
- Treat in 2 minutes or less
  - Highly efficient
  - Low peripheral dose
- Simple planning and delivery
2 min Imaging & Repositioning

2 min Treatment
- Less than 600 MU/ 2Gy
- Variable gantry speed
- Variable dose rate
- Inter-digitating MLC
- Dynamic MLC
Flattening Filter Free (FFF) Mode

Higher dose rates, lower scatter and out of field leakage are possible by removing the flattening filter

- Gains for IMRT, RapidArc or small field SRS
- Available in clinical mode for
  - 6 MV $\rightarrow$ 1400 MU/min
  - 10 MV $\rightarrow$ 2400 MU/min
Innovative

Transforms today’s treatments
Unlocks new treatment options
Opens opportunities for SBRT treatment of the most complex cancer cases: lung, liver, kidney, pancreas and paraspinal
Opens the door to surgical candidates
Increased Performance
Intelligent Imaging Automation
Faster treatments
rapid IMRT
“rapider” RapidArc
Maestro Real-time Control System
Hardware Overview - Accelerator
SBRT: Liver
Robotic Radiotherapy
Accuracy

- Sub-millimeter accuracy
- Treats all parts of the body
- Treats lesions that were previously untreatable
- So accurate, head and body frames are not required
Conformality

Non-Coplanar Beam Delivery, Non-Isocentric Beam Delivery

Highly collimated beams, Non-convergent beams
Automatically minimizes entrance/exit beam interactions
No patient or linac re-positioning required
Superior conformality while maximizing homogeneity
Treatment Procedure

1. Patient Consult
2. Patient Setup
3. Image Acquisition
4. Treatment Planning
5. Treatment Delivery
CyRIS™ MultiPlan™ Treatment Planning

Benefits

- Fast, multi-modality image fusion
- Simplified contouring
- Supports forward and inverse planning methods
- Achieves desired plan results quickly and efficiently
- Streamlines overall planning process
- Maximize the capabilities of CyberKnife System
Possible Treatment Areas

CRANIAL RADIOSURGERY
- Metastasis
- Meningioma
- Glioma
- AVM
- Trigeminal Neuralgia

HEAD & NECK RADIOSURGERY
- Schwannoma
- Nasopharynx tumor
- Primary and Metastatic Cancer

LUNG/THORACIC RADIOSURGERY
- Primary and Metastatic Tumor

LIVER RADIOSURGERY
- Primary and Metastatic Cancer

SKULL BASE RADIOSURGERY
- Acoustic Neuroma
- Cavernous Sinus
- Paraseellar Meningioma
- Pituitary Adenoma

SPINE RADIOSURGERY
- Cervical
- Thoracic
- Lumbar
- Sacral

PANCREAS & RENAL RADIOSURGERY

PROSTATE RADIOSURGERY

SKELETAL METASTASIS
<table>
<thead>
<tr>
<th>Dose/fraction</th>
<th>TDF equivalent Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8 Gy/5f (24.00 Gy)</td>
<td>40 Gy</td>
</tr>
<tr>
<td>5.1 Gy/5f (25.50 Gy)</td>
<td>45 Gy</td>
</tr>
<tr>
<td>6.1 Gy/5f (30.5 Gy)</td>
<td>60 Gy</td>
</tr>
<tr>
<td>7.5 Gy/5f (37.5 Gy)</td>
<td>76 Gy</td>
</tr>
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</table>
ADVANCES IN RADIOTHERAPY

PARTICLE THERAPY
BEST FORM OF CONFORMAL RADIOTHERAPY
PARTICLE THERAPY

Depth dose profiles

- photons 21 MeV
- $^{12}$C 270 MeV/u
- protons 148 MeV/u

The Bragg peak

Straggling and multiple scattering

Fragmentation
PROTON THERAPY

The diagram illustrates the relative dose (y-axis) versus depth in water (x-axis) for different radiation sources and energies:

- **5 cm SOBP**
- **8 MV X-RAYS SSD = 100 cm**
- **20 MeV ELECTRONS**
- **200 MeV PROTONS**

Each curve represents the absorbed dose pattern at different depths, highlighting the unique dose distribution characteristics of each radiation type.
PARTICLE THERAPY

Protons and ions are more precise than X-rays

Tumour between the eyes

9 X ray beams
1 proton beam

Single beam comparison

X rays
Protons or Carbon ions
High precision RT with proton beams
**Clinical Benefits**

- **Staged/Fractionated Radiosurgery**
  - 1-5 fractions/stages
  - Larger lesions
  - Lesions next to critical structures/organs at risk

- **Improved Patient Quality of Life**
  - Short treatment course: 1-5 days CyberKnife vs. 6-8 wks Radiotherapy

- **Optimal for patients**
  - Optimal for patients with limited life expectancy

- **Increased convenience**
  - No infection risk
  - No general anesthesia
  - Minimal to no recovery time, as compared to open surgery

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**High precision RT with proton beams**
PREMIER PROTON THERAPY CENTRES

University of Heidelberg, Germany / GSI and Siemens

NIRS Chiba, Japan / Mitsubishi, Hitachi, Sumitomo

PSI
Villigen,
Switzerland / Varian-Accel

MD Anderson Houston, USA / Hitachi

MGH Boston, USA / IBA
Current Trends in Brachytherapy

• Recently established practices
  – “Image-based” BTx: design and post-insertion evaluation based upon correlating 3D dose distribution and anatomy
  – “Image-guided” BTx: intra-op imaging to help place sources in correct anatomic location

• Clinical developments
  – TRUS-guided prostate BTx
  – Increasing use of CT-guided interstitial HDR
  – Increasing use of MR
  – Replacement of LDR temporary by permanent seeds or HDR
The GYN GEC ESTRO group has developed and promoted a novel systematic approach with the integration of 3D sectional imaging (MRI (CT)) into the procedure of application and medical-physical brachytherapy treatment planning.

Aim of this method is to enable an individualized adaptation of dose distribution to a target at high or intermediate risk for recurrence (HR CTV/LR CTV) and to the adjacent organs at risk.

During the last years the MRI-based approach has gained in importance and has increasingly replaced the well established traditional x-ray based methods.
The GEC-ESTRO and American Brachytherapy Society groups have recently made recommendations on the use of 3D image-based treatment planning in gynecological brachytherapy.

Applicators compatible with both CT and MR imaging modalities are essential for IBGT.

Applicators – Titanium
CT Based – MUPIT
Promising Technologies in Cervix Cancer

Image Guided Brachy: MR-Based (RTOG 0417)
- Point A was not designed for dose prescription

Ca Prostate
Prostate Seeds Implant
Permanent Seed Implant – Brachytherapy

1. Low Risk → Permanent Brachytherapy alone
2. Intermediate Risk → EBRT (40 – 50 Gy) + ADT + Brachy
3. Iodine 125 / Palladium 103
4. Preplanning on previous day
5. Monotherapy – 145 Gy for I-125 & 125 Gy for Pa-103
6. EBRT (40-50 Gy) → 110 Gy I-125 & 100 Gy for Pa-103
7. Advantage : Short Duration
8. Not in INDIA
Template with USG probe
Temporary Implant
Ca Breast
MammoSite
INTRA OPERATIVE RADIOTHERAPY

- Intraoperative Single Dose Radiotherapy delivered with the INTRABEAM System is supported by experience gained from over 10 years of clinical experience.

- INTRABEAM radiotherapy delivered as a single definitive treatment has been effectively introduced through an internationally, randomized controlled clinical trial, comparing a single dose of radiation given intraoperatively versus conventional external beam radiotherapy in women with early breast cancer.
INTRABEAM’s platform flexibility expands beyond traditional radiation therapy systems, requiring no structural infrastructure modifications or specialized radiation protection.

Without the limitation of traditional radiation treatment rooms, INTRABEAM Radiotherapy increases control in treatment, delivery and site-of-service, providing a one-of-a-kind radiation treatment option as unique as the patients you treat.
Low Energy X-rays

- The INTRABEAM radiation source accelerates electrons with a maximum voltage of 50 kV onto a gold target. It is here that the low-energy X-ray radiation is generated and then emitted isotropically, penetrating the tissue to a depth of about 1-2 cm. Published dosimetry results confirm the quality and constancy of the radiation field.
Future of Brachytherapy

- Thermo – Brachytherapy
- Brachy – Robotics