Imaging for Target Volume and Organ at Risk Determination
Aim

To recognize and understand imaging procedures that can be used to determine target volumes and organs at risk for 3-D radiation treatment planning
Specific Learning Objectives

• Describe imaging tools that allow for the transition of 2-D RT to 3-D CRT
• Describe CT scanner use for treatment planning
• Compare the tools used for treatment simulation
• Describe alternate imaging modalities for target and organ at risk determination
• The process of radiation treatment is complex and involves multiple stages, beginning with patient assessment and diagnosis and ending with radiation dose delivery and follow-up.
• One crucial step in that process is the determination of the location and extent of the tumour that is to be irradiated as well as the critical normal tissues that are to be spared.
• This presentation deals with the use of imaging to determine the target volume(s) as well as the volumes of the organs at risk (OAR).
2-D Treatment Planning

• Single contour
  – Lead wire or plaster strips
  – Transcribed onto sheet of paper with reference points

• Simulation films
  – For planning and comparison with port films on treatment

• Irregular field calculations
  – Points can be identified on simulator film and SSDs and depths of interest determined at simulation

• Organs at risk identified
  – Depths determined on simulator films

• This slide describes the various procedures applied in 2-D treatment planning
• Special contouring devices are available for determining the central outline at the position of the target volume.
Various imaging modalities are available to help with the determination of target and organ at risk volumes.

Each has different capabilities, partly relating to dimensionality but also relating to the imaging technology and its capability of determining organs at risk.
When comparing the advantages and disadvantages of the available technologies it is useful to have a number of categories of comparison. These can then be ranked and evaluated in terms of determining their need in a particular setting.
Role of Simulators

- Tumour localization
- Normal tissue localization
- Treatment simulation
  - Fluoroscopic/radiographic
- Treatment verification
  - After completion of plan based on contour/image data
- Treatment monitoring

Understanding the transition from 2-D to 3-D becomes clear when we review the capabilities of the use of conventional simulation in comparison to the use of CT scanner in radiation therapy planning.
• The main aims of a simulator are to check if the treatment setup is possible, and to mark the field and isocentre
• Note that simulators have many degrees of freedom
• These degrees of freedom should match the geometric capabilities of what the radiation treatment machine can do
A simulator film uses kV diagnostic x-rays to provide a 2-D transmission image.
This image includes guide wires which demonstrate the field shape that will be used by the radiation therapy machine.
Double exposures are often used on the therapy machine with MV photons to demonstrate both the irradiation field as well as the surrounding structure.
Simulation Film vs Port Film

- MV portal image provides comparison with kV simulation image

- Note that the simulator (kV) image has a higher quality than the port film (MV image)
There is a significant limitation on the conventional therapy simulator in that a couch rotation combined with a gantry rotation is limited because of the image intensifier — a limit that is not on the treatment machine unless it has a beam stopper.
Simulators

• Advantages
  – Tumor localization (limited, 2-D)
  – Normal tissue localization (limited, 2-D)
  – Static/dynamic use
  – Beam selection
  – Beam confirmation
  – Reduces need for therapy verification films
  – Reproduces treatment geometry
  – Real time breathing motion on fluoroscopy
    • 2-D plus time, intra-fraction
  – Option - digital images from image intensifier
Simulators

• Limitations
  – Limited diagnostic value
  – Physical limitations - gantry/couch rotations
  – Limited external contour information (2-D)
  – Limited internal structure information (2-D)
  – No tissue density information
  – Not useful for dose calculations
  – Relatively slow process
A review of the capabilities of a CT scanner quickly shows the advancement to the third dimension.
In addition to its role in structure delineation, CT is the primary modality for treatment simulation and treatment planning, including dose calculation. The role of CT in simulation requires that geometric accuracy of the image representing the patient, both at the CT scanner and after transfer to the treatment planning system (TPS), is critical.
It has been said in the past that for treatment planning it may not be necessary to use a high quality CT scanner.

It needs to be recognized that the accurate determination of target volumes requires the best quality “diagnostic” CT scanner available and affordable.

While the quality of the scanner available may be limited by resources, it should not be limited by the philosophical perspective that a lower quality scanner is acceptable in the radiation therapy planning context.
The role of CT in dose calculation means that each pixel has a CT number which has to be converted into electron-density in the TPS, both for validation of the density of the object being scanned, as well as for the effect of heterogeneities on the dose calculation algorithm.
• CT images consist of a matrix of CT numbers

• On older scanners the matrix for a single slice was 256X256 elements (pixels), while on newer scanners the images are at least 512X512 pixels per slice with most scanners having 1024X1024

• A CT number relates to the linear attenuation coefficient of the pixel in comparison to the linear attenuation coefficient of water

• By definition, as shown in the equation, the CT number ($N_{CT}$) for water is zero and the CT number for air is -1000
Electron Density

- CT numbers - kV energies
  - Photo-electric & Compton interactions
- Dose calculations - MV energies
  - Compton effect $\propto$ electron density
- Electron density $[el/cm^3]$
  \[
  \rho_e = \left( \frac{NZ}{A} \right) \rho
  \]
- **Relative** Electron Density
  \[
  \rho_e' = \frac{\rho_e(tissue)}{\rho_e(water)}
  \]
- Want to convert CT Number to $\rho_e'$

- CT scanners operate with x-ray energies peaking at about 120 to 140 kV
- Thus, the radiation interactions with the patient are a combination of photoelectric effect and Compton effect
- For radiation treatment, however, we usually use megavoltage energies either with cobalt-60 machines or with linear accelerators having MV photons which generally interact with Compton effect
- The probability of a Compton interaction is proportional to the relative electron density of the medium, thus, for dose calculations we need relative electron densities
- Therefore, we need to convert the images that contain CT numbers to relative electron densities
• The slope of the curves representing the relationship between CT number and electron density is different for water-like tissues and bone-like tissues
Numerical values are now included in the equations 1 and 2 mentioned in the former slide.
**CT Scanner: Practical Considerations**

- **Considerations for RTP**
  - Scan patient in RT position
    - Flat couch top, lasers
  - Respiratory conditions
  - Reference marks – radio-opaque
  - Immobilization devices
  - Changeable organs
- **Auto injector for IV contrast injection**
- **Network interface**
  - Digital Imaging and Communications in Medicine (DICOM)

*Dedicated CT scanners for radiation oncology typically have fixed flat couch inserts, immediately available immobilization devices, lasers and software for CT simulation*

*A schedule controlled by radiation oncology is required that accommodates the increased time for CT simulations compared with CT scanning alone*
• CT scans for radiotherapy can be acquired with a CT scanner dedicated to radiation oncology, or shared with other resources, particularly radiology
• When a CT scanner is a shared resource, a flat couch insert and immobilization devices need to be available; there may not always be lasers for virtual simulation, and there can be time pressures
• CT images pervade the entire workflow of 3-D conformal and IMRT treatments and consequently appropriate staffing, protocols for use and quality assurance are required to safely implement CT-based treatments
• The shape and position of the target volume and normal tissues may vary enormously during a respiration cycle.
• Furthermore, the electron density of the lung will be lower during full inspiration compared to normal respiration
There is an increased focus on the management of respiratory motion in radiotherapy.

One approach to manage respiratory motion is to acquire respiratory-correlated, or 4-D, thoracic CT scans.

4D-CT can be used for estimated tumour and normal tissue motion and can form the basis of motion-inclusive, respiratory-gated or tumour-tracking planning and delivery.

4D-CT results in an order of magnitude more imaging data to be acquired, processed, stored and used for planning.

This technology is maturing, and further guidelines for the acquisition and specific applications of 4D-CT in radiotherapy are needed.
Computed tomography is and will be likely to remain the predominant volumetric imaging modality for radiotherapy.

In common with other volumetric imaging modalities, CT is used to delineate tumour (GTV), suspected tumour (CTV) and normal structures.

In addition to its role in structure delineation, CT is the primary modality for treatment simulation and treatment planning, including dose calculation.

**Capabilities**
- Tumour localization (3-D → 4-D)
- Normal tissue localization (3-D → 4-D)
- External contour data (3-D → 4-D)
- Internal density data (3-D → 4-D)
- Network to TPS
- Useful for dose calculations (CT number → \( \rho_e \))
- Follow-up
  - Tumour regression
  - Normal tissue response
Computed Tomography

• Limitations
  – Limited patient positioning
  – No beam geometry information (if no virtual simulation software)
  – Respiratory motion information minimal (if no 4D option available)
  – Training and competency required
  – Quality of imaging system should be guaranteed
Spiral computed tomography is a type of CT in which the x-ray source describes a helical trajectory relative to the object while an array of detectors measures the transmitted radiation.

In practice, the source and detectors are mounted on a rotating gantry while the patient is moved axially at a uniform rate.
Current CT technology applies a matrix detector that can be irradiated with x-ray beams having different size.
Oncology CT scanners need a large patient aperture ("bore hole") to position the patient in treatment position.
Modern oncology CT scanners have an 85 cm patient aperture thus allowing breast cancer patients to be scanned with the arms in treatment position.
Virtual Simulation

• Software tool
• Equivalent to 3-D RTP - beam geometry
• Features
  – Image display
  – Delineation of anatomy [Volume of interest (VOI)]
  – Beam definition and display
  – Beam's-eye view (BEV)
  – Digitally-reconstructed radiograph (DRR)
    • Superimpose VOI
    • Compare to simulator or port films
    • Can be used for defining fields/apertures
  – Observer's-eye view (OEV)
Virtual Simulation Concept

• Replacement of conventional simulation process
• Use of patient model (virtual patient)
  – Based on CT data set
• Use of computer software
  – To generate beam displays on patient model
  – To generate radiographs (DRR)
    • Includes
      – Beam shape
      – Target volumes
      – Critical tissues
<table>
<thead>
<tr>
<th>Simulation Process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional with CT</strong></td>
</tr>
<tr>
<td>• Preliminary simulation</td>
</tr>
<tr>
<td>• Scan patient</td>
</tr>
<tr>
<td>• Develop treatment plan</td>
</tr>
<tr>
<td>• Verification simulation</td>
</tr>
</tbody>
</table>

• Comparison of two approaches of the simulation process
Design of a CT scanner facility used for radiotherapy applications illustrating the position of the various components including the lasers for accurately positioning the patient.
Imaging Parameters for CT Simulation

• Slice thickness
  – Spiral/Helical – thin cut for clearer DRR
  – MultiSlice – \( \uparrow \) resolution, \( \downarrow \) acquisition time, \( \uparrow \) volume
• Pre-Set Scanning protocol
  – mAs, kV, index, pitch, FOV, pilot length, pilot orientation, etc
• No gantry tilt
• Contrast media and image quality

• A number of scan parameters influence the image quality and image acquisition time
Radio-opaque markers are used during CT scanning to indicate specific points on the skin with respect to the internal anatomy.
- The CT scan is used to contour the various target volumes and organs at risk
The BEV display allows a judgment of the position of the treatment field with respect to the patient anatomy.
• This slide shows the difference in field outline as observed in BEV between an MLC-collimated and lead–block beam.

• It should be noted that for the final decision about the exact leaf positions, the 3-D dose distribution should be used.
Another example of using the BEV option to correlate the various beams with respect to the patient anatomy and to each other.
Multi-planar reconstructions (MPR)

- Multi-planar reconstructions (MPR) formed from reformatted CT data
  - Effectively CT images through arbitrary planes of patient
  - Typically sagittal or coronal MPR cuts
    - Used for planning and simulation
    - Can be through any arbitrary plane

- Multi-planar reconstruction software allows the CT data to be represented in any plane
- The interpretation of images in other planes than the three orthogonal planes is often non-trivial
Digitally-Reconstructed Radiograph (DRR) Generation

• Ray line reconstructions through 3-D CT data sets
  – Based on 2-D CT slices
• Effective transmission image
  – “Radiograph”

• DRRs are used for comparison with portal films or beam’s-eye-view to verify patient set-up and beam arrangement
Digitally-Reconstructed Radiograph (DRR)

Not equivalent to transmission scan or “pilot” or “scout” scan
• The observer's–eye view is a way of displaying beams with respect to the anatomy of a patient
• It shows an observer the direction and orientation of the beams in relation to the surface of the patient, as well as to volumes delineated on the CT scan of the patient
Simulator-CT

- Simulator with CT scanning mode
- Primarily - simulator
- CT option added
  - Uses image intensifier or flat panel detector
  - Possibly added detectors
- Provides
  - Conventional simulation
  - Lower quality CT images
  - Internal/external contours
  - Possibly - tissue density information
CT Option
Permanent and Removable Hardware for CT Option Capabilities

- Normalizing Detector
- Bow Tie Profile Wedge
- Shielding Plate
- 32 Element Scintillation Crystal & Photo Diode Array
- Focused Grid
- Shielding Plate
- Dual Port Distributor
- CT Camera
- 512 Element Photo Diode Array

Optical Encoder for Gantry Position
S Distortion Coll
Fluoro Camera

Removable
Simulator-CT: Schematic

• From: Cossman, Schiefer, Seelentag, Website, St. Gallen, Switzerland
Simulator-CT: Sample Image

• From: Cossman, Schiefer, Seelentag, Website, St. Gallen, Switzerland
This slide shows the difference in image quality of comparable images made with a Simulator-CT and a “normal” CT scanner.

Figures from Redpath et al. in: Modern Technology of Radiation Oncology, Vol 1
• Varian Acuity
• From: www.varian.com
Simulator-CT

• Advantages
  – Images in treatment position
  – Simulation and CT in the same session
  – Larger effective scan aperture (>80 cm)
  – “Cheap” CT availability
  – Provides data in treatment position
  – Possibly tissue density information
Simulator-CT

• Disadvantages
  – Poor image quality
  – Slow scan time (1 min/slice)
    • Fewer images
    • No 3-D reconstructions
    • No DRRs
  – Extra time on treatment simulator
  – Risk
    • Inaccurate definition of target volumes due to inferior images

• Available as cone beam CT
## Comparison of Simulation Tools: Technical

<table>
<thead>
<tr>
<th></th>
<th>Sim</th>
<th>CT</th>
<th>CT-Sim</th>
<th>Sim-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis</td>
<td>-</td>
<td>***</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Localization</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Simulation</td>
<td>***</td>
<td>-</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Calc’n aid</td>
<td>-</td>
<td>***</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>Verification</td>
<td>***</td>
<td>-</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Monitoring</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Score (18)</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>12</td>
</tr>
</tbody>
</table>

*** very good, ** good, * marginal, - worst
### Comparison of Simulation Tools: Non-Technical

<table>
<thead>
<tr>
<th></th>
<th>Sim</th>
<th>CT</th>
<th>CT-Sim</th>
<th>Sim-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organizational</strong></td>
<td>***</td>
<td>-</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td><strong>Throughput</strong></td>
<td>**</td>
<td>***</td>
<td>***</td>
<td>-</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>***</td>
<td>*</td>
<td>-</td>
<td>**</td>
</tr>
<tr>
<td><strong>Score (9)</strong></td>
<td>8</td>
<td>4</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

### Total Score: Technical and Non-Technical

| Total (27) | 16 | 16 | 22 ✓ | 17 |

*** very good, ** good, *marginal, - worst
Simulation Tools: Conclusions

1. Requirements for therapy planning
   – (CT-) Simulators for most patients
   – CT/MR for many patients – increasing
   – PET/CT where available

2. CT-simulation
   – As one unit, not essential
     • If virtual simulation and dose calculations are available separately
   – Useful as controlled access to CT
   – Packaged CT-sim may have better image display and manipulation tools compared to TPS
Simulation Tools: Conclusions

3. Simulation-CT
   - If CT is available separately, of marginal use
   - If no CT is available, useful tool
     • Must recognize its diagnostic limitations

4. Virtual simulation
   - Used as part of CT, CT-sim or sim-CT
     • Does not stand alone
     • As part of CT-sim purchase
     • In 3-D TPS
Summary: CT-Simulation

• 3-D CRT requires use of CT
  – Diagnostic CT
  – CT-simulator

• CT (-simulator)
  – With virtual simulation and DRRs, some simulator use will become redundant
  – With advent of intensity-modulated radiation therapy and tomotherapy, simulators will not be useful

• Increased use of CT-simulation

• Oncology scanner and multi-slice CT
This slide shows the greater soft tissue contrast of MR compared to CT, and the better visibility of bony structures on CT images. After contouring the target volume on MR images, the MR and CT images are fused and the CT data are used for further treatment planning.
After fusing the MR and CT images, the CT data are used for further 3D treatment planning.

The figure at the bottom illustrates the principle of MR imaging and has been taken from: T Peters et al. Imaging for Radiation Therapy Planning (MRI, Nuclear Medicine, Ultrasound), Modern Technology of Radiation Oncology, Vol 1.
• This slide shows the difference in contouring when using MR or CT
• Because of the better visibility of soft tissue, MR imaging is for some tumour types often used in combination with CT for delineating target volumes
• CT scans of patients having a hip prosthesis show large imaging artifacts
• Delineating the target volume and OARs is in these cases easier when using MR compared to CT
• It should be noted that because of these distortions, some CT values may have wrong values resulting in rather large uncertainties in the dose calculation
This slide clearly shows the advantage of MR compared to CT in visualising soft tissue sarcoma and delineating the target volume.
• This slide shows how MR information can be used for treatment planning.
• The GTV of this base of skull (?) tumour can much better be delineated on the MR scan.
• After delineating the GTV by the radiologist and/or radiation oncologist, the CTV and PTV by the radiation oncologist, the MR and CT images will be fused.
• The CT data will then be used for treatment planning of this patient, including performing the dose calculation.
When deciding if MR images are useful for treatment planning of a specific tumour site, it is good considering the various pros and cons of MRI for such a case.

MRI for treatment planning

• Advantages
  – Better soft tissue contrast – better definition of target and critical structures
  – Potential for functional MRI imaging can be used to localize cancer

• Disadvantages
  – Distortion
  – Poor definition of bones
  – Loss of electron density information
  – Cost
In this slide the principle of a PET scanner is illustrated.

When a positron emitted by a radionuclide (blue line), annihilates with a negative electron (red line), two 511 keV annihilation photons (multi-colour lines) will be emitted in opposite directions, and can be detected by two detector elements positioned under 180 degrees to each other in the circular detector array (grey area).

\[ e^- + e^+ = 2\gamma \quad (2 \times 0.511 MeV) \]
A PET-CT scanner combines the two imaging modalities for a patient in the same position on the couch.
• Note that the patient has to be moved from the CT scan plane to the PET reference plane to image the same volume in the patient.
• The two imaging modalities are thus used sequentially.
PET-CT

- Combines PET and CT in a single gantry system
  - PET - Metabolic and functional imaging (tissue metabolic activity)
  - CT - Anatomic imaging
- Images acquired \textit{sequentially}
  - Same session and combined into single superposed image
  - Adds precision of anatomic localization to functional imaging
- PET/CT can be used for 3-D CRT planning
  - Laser alignment
  - Flat couch top
  - Network interface with treatment planning system

In addition to the use of PET for target delineation, PET is also capable of imaging a wide variety of biochemical and biologic features of the tumour which are of potential radiobiological importance and could be utilized for patient management and treatment planning.

By using specific tracers (e.g., of hypoxia, angiogenesis, proliferation) PET can provide prognostic information on the aggressiveness of the cancer as well as information for a “dose painting” treatment.

Such PET application, however, is not yet in routine clinical practice.
This figure shows the reduction in variation in target volume delineation when using CT/PET instead of CT alone.

By adding PET information to the CT data as shown in (a), tumour areas could be discriminated from areas such as lymph nodes and blood vessels that did not show increased FDG uptake as can be seen in (b).

As a consequence there was much better agreement between the radiation oncologists in delineating the target volume.

More than ninety percent of all PET studies performed worldwide today use [18F] fluorodeoxyglucose (FDG), because of its known uptake in viable cancer cells and its availability without on-site cyclotron.

As a consequence, current applications of PET for radiation oncology applications (in particular in less-developed countries) focus on FDG.

- Increased frequency of up-staging
  - Due to metastatic disease
• FDG is often used to better select patients undergoing radical radiotherapy by up- or down-staging disease as well as to assist in the determination of the GTV, including differentiation of viable from necrotic tissue.
This slide shows for 4 out of 10 patients having non-small-cell lung cancer (NSCLC) the change in FDG uptake during and after radiotherapy.

Local failure in NSCLC appears most common at the primary site and within the irradiated target volume with the highest FDG uptake. This observation may be useful for further optimization of radiotherapy of NSCLC, for example, by the application of additional radiation dose to sub-volumes of primary tumors with higher FDG uptake.

• PET-CT simulation, in which the FDG exam is fully integrated into the treatment planning process, is rapidly growing as a consequence of the increasing availability of these scanners

• As this technology takes off, it will be essential that a set of common quality control practices is adopted which includes scanner hardware QA tests to ensure constant instrument performance, as well as a reproducible and well-defined patient scan protocols that address questions such as scan time post tracer injection, respiratory gating and standard reconstruction parameters

Combined PET-CT Summary

• PET-CT combination adds accuracy in detecting and classifying tumours
• PET-CT planning changes cancer patient management
  – Target volume definition
  – Tumour staging
• PET-CT combination simplifies image registration
Single Photon Emission Computed Tomography (SPECT)

- SPECT imaging
  - Gamma camera
    - Multiple 2-D images from multiple angles

- The picture shows a SPECT-CT scanner with two options to perform a SPECT scan.
- Where SPECT gamma camera imaging is routinely employed for diagnostic studies, its use for RT treatment planning is limited by inadequate spatial resolution (around 12-15 mm).
SPECT imaging of the lungs is able to identify areas with high and low perfusion
• The area in the upper part of the right lung shows a low perfusion
• Consequently that part of the lung does not need to be spared if it helps in designing a treatment plan in which other parts of the lung that are still active (yellow/green and red areas) can be spared
In this slide the different options of the various imaging modalities used in radiotherapy are summarised.
• This slide illustrates that when using 4D CT it is possible to get a high quality image of a moving target
• The statement of Battista is no longer valid; currently there exist several irradiation techniques that can take intra-fraction movement of lung tumours into account, using a treatment plan based on 4D CT
In this study the inter- and intra-physician variation in target volume delineation was studied based on 4D CT images of 10 patients analysed by 6 radiation oncologists.

The automated 4D-CT propagation tool developed by these authors could significantly decrease the GTV delineation time without significantly modifying the inter- and intra-physician variability.

Intersection and Union of Contours During All Phases of Breathing Cycle

- Variations > 0.5 - 1.0 cm in margins

Courtesy S Gaede

As the frequency and variety of imaging increases, associated tasks such as the registration and fusion of sequential and multimodality images is increasing. Furthermore, the increased demand requires faster solutions to be developed. Understanding the limitations of the data input, and limitations of the algorithms used for registration is important to avoid geometric errors and therefore dosimetric errors during treatment. Ensuring that the input images are acquired in the treatment position using flat couch inserts and the same immobilization devices for the different modalities is of particular importance. Careful patient alignment, including the use of lasers, will reduce the difficulty of the registration problem.

Summary

• Increased capabilities of target volume delineation with greater convenience to the radiation oncologist
  – Image fusion using different modalities
    • CT, MR, PET, SPECT, US, MRS
  
• Additional consideration
  – Time for target volume delineation
Many thanks to:

J. Battista, K.Y. Cheung, S. Gaede, D. Mah, H. McNair, T. Peters, T. Redpath, M. Sontag,

and

ESTRO

for borrowing some slides used in this presentation