CT Perspective for the Hybrid CNMT

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Disclosures

• None
Learning Objectives

• After this presentation, the technologist will be able to:
  – Understand the basics of CT in the context of hybrid imaging
  – Describe various CT settings and parameters and understand their impact on image quality and radiation dose
  – Recognize CT artifacts that may be encountered in hybrid imaging
Hybrid Imaging

- Imaging techniques that combine a nuclear medicine technique with a conventional radiology imaging tool to produce fused imaging that can show anatomy as well as physiology
- HI can provide more thorough evaluation
  - SPECT/CT
  - PET/CT
  - PET/MRI
History of Hybrid Imaging

• Nuc Med started as non imaging with probes to measure radioactivity in certain regions of the body (thyroid)
• 1950 – rectilinear scanner (Benedict Cassen) made “life size” images that could be overlaid on plain x-rays
• 1957 - gamma camera (Hal Anger) allowed for imaging larger regions of the body simultaneously, but limited ability to perform direct correlation with anatomic images (image minimization)
Hal Anger and Benedict Cassen at the International Conference on Peaceful Uses of Atomic Energy in Geneva, Switzerland, 1955
History cont.

- 1980s-90s – Tomographic imaging techniques (SPECT and CT) renewed interest in image fusion
- Digital format images are amenable to software manipulation/fusion
- Development of hybrid scanners
  - Lang, Hasegawa and colleagues developed a prototype SPECT/CT imaging system in the early 90s
  - GE “Hawkeye” was the first commercially available SPECT/CT machine, the CT was suboptimal diagnostic quality
  - Subsequently, the development of combined PET-CT systems (with diagnostic quality CT) by Townsend and co-workers revolutionized hybrid imaging.
  - GE Discovery LS was the first commercially available PET-CT scanner
PET/CT and SPECT/CT

- PET and SPECT - excellent functional imaging techniques, but not very precise for anatomic localization
- CT – excellent anatomic imaging, but not very good for functional information
- PET/CT and SPECT/CT = dual modality hybrid imaging
- Functional and anatomic images are acquired ALMOST simultaneously
- Fusion of functional and anatomic information
- Precise anatomical localization of the PET
Integrated PET-CT Imaging Systems

- CTI Reveal (Somatom Emotion 2-slice)
- GE Discovery LS (Lightspeed Plus HiLite 4-16 slice)
- Philips Gemini GXL (6 or 16-slice)
- Philips Gemini TF (16 or 64-slice)
- Siemens Biograph TruePoint PET•CT (64-slice)
- GE Lightspeed VCT 64-slice
PET/CT
Purpose of CT in hybrid imaging

- Attenuation correction – CT attenuation map used in place of transmission scanning
- Anatomic localization – better delineation of structures
- Diagnostic CT evaluation – one stop shopping
Computed Tomography – basic physics

- CT is a tomographic imaging technique that generates cross sectional imaging in the axial plane
- CT images are maps of the relative linear attenuation values of tissues
- The relative attenuation coefficient ($\mu$) is normally expressed in Hounsfield units (HU) and varies for different tissues (HU for water = 0; HU for air = -1000, etc)
- These values are dependent on photon energy (keV), therefore HU values generated by a CT scanner are only approximate and related to the tube voltage used to generate the image

Huda – 2nd edition
HU of Common Tissues

<table>
<thead>
<tr>
<th>TISSUE</th>
<th>HU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>−1000</td>
</tr>
<tr>
<td>Lung</td>
<td>−500</td>
</tr>
<tr>
<td>Fat</td>
<td>−100 to −50</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
</tr>
<tr>
<td>CSF</td>
<td>15</td>
</tr>
<tr>
<td>Kidney</td>
<td>30</td>
</tr>
<tr>
<td>Blood</td>
<td>+30 to +45</td>
</tr>
<tr>
<td>Muscle</td>
<td>+10 to +40</td>
</tr>
<tr>
<td>Grey matter</td>
<td>+37 to +45</td>
</tr>
<tr>
<td>White matter</td>
<td>+20 to +30</td>
</tr>
<tr>
<td>Liver</td>
<td>+40 to +60</td>
</tr>
<tr>
<td>Soft Tissue w/ Contrast</td>
<td>+100 to +300</td>
</tr>
<tr>
<td>Bone</td>
<td>+700 (cancellous) to +3000 (dense bone)</td>
</tr>
</tbody>
</table>

Denser tissue have higher CT numbers & appear lighter/whiter
Bone (HU ~ +1000) appears white on CT.

Less dense tissues have lower CT numbers.
Air has the lowest HU at -1000 and appears black on CT.
HOUNSFIELD SCALE GRAPHIC

Air  Water  Compact Bone

-1000  0  1000  2000  3095

-100  -80  -60  -40  -20  0  20  40  60  80  100

Fatty tissues  CSF  Soft tissue
Gray Matter  White Matter
Cyst  Blood  Clot
Older Blood

Window Width (WW)

- The range of CT numbers displayed in the CT image (in gray scale) determines the max # of shades of gray that can be displayed on the monitor → how much contrast appears in the image.
- Wider WW → larger range of tissue information in the image → less variation between tissues with similar densities. Useful for lungs (lots of subject contrast)
- Narrow WW → for anatomy that has minimal inherent contrast between structures → increases the contrast between the tissues. Useful for brain (gray and white matter differ by only 5 to 10 HU). Narrow WW enhances image contrast and ensures that the transition from black to white takes place over a relatively few CT numbers.
- CT scanner can produce around 2000 shades of gray
- LCD monitor can display only 256
- Human eye can only distinguish 20
Window Level (WL)

- The center or midpoint of the range of CT numbers, can be placed anywhere within the window width.

- Determines how bright the image appears
  - Low WL → brighter image
  - High WL → darker image

- Should be set to the CT number of the anatomy being imaged
  - Example: Head CT → 40 HU as WL with narrow WW
# EXAMPLES OF CT WINDOWS

<table>
<thead>
<tr>
<th>MORPHOLOGY</th>
<th>WW, WL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Tissue/Abdomen</td>
<td>350, 40</td>
</tr>
<tr>
<td>Lung</td>
<td>-300, 2000</td>
</tr>
<tr>
<td>Bone</td>
<td>100, 170</td>
</tr>
<tr>
<td>Liver</td>
<td>200, 100</td>
</tr>
<tr>
<td>Pelvis</td>
<td>400, 40</td>
</tr>
<tr>
<td>Brain</td>
<td>120, 40</td>
</tr>
<tr>
<td>Head</td>
<td>80, 40</td>
</tr>
<tr>
<td>Posterior Fossa</td>
<td>250, 80</td>
</tr>
<tr>
<td>Subdural</td>
<td>150, 40</td>
</tr>
</tbody>
</table>
CT Window Examples

In head CT, 3 windows are commonly used

- **BRAIN** window: W:80 L:40
- **BONE** window: W:2500 L:480
- **SUBDURAL** window: W:350 L:90

http://www.slideshare.net/drlokeshmahar/approach-to-head-ct
CT Generations

- **First Generation**: pencil beam with 2 sodium iodide detectors that moved across the patient (translate), x-ray tube and detector rotated 1 degree between each projection (rotate); 5 mins for each pair of images
- **Second Generation**: translate-rotate with multiple detectors and fan beam, allowed faster scans; 1 min for each image
- **Third Generation**: rotating fan beam with large array of detectors (rotate-rotate)
- **Fourth Generation**: rotating tube and fixed ring of detectors (rotate-fixed)
CT Generations cont.

- Fifth Generation: electron beam CT (EBCT), electron gun deflects and focuses a fast moving electron beam, mostly for cardiac studies
- Sixth Generation: spiral/helical CT
- Seventh Generation: multi-detector CT (MDCT), Multi-slice CT (MSCT), multiple detector array scanner
Spiral or Helical CT

Sixth Generation

- X-ray tube and detectors continuously rotate around the patient.
- Acquire data continuously during scan.
- Referred to as "spiral" or "helical" scanners.
A 2-D array of detector elements instead of linear array of detector elements in typical conventional and helical CT scanners.

2-D detector array permits CT scanners to acquire multiple slices or sections (16 – 320 sections) simultaneously and greatly increase the speed of CT image acquisition.
MDCT

• Generation 1 – 5 CT scanners can acquire only 1 to 4 sections per rotation.
• MDCT can acquire data from between 16 and 320 sections per rotation (depending on detector configuration)
• Large amount of data in very short scan duration (15 seconds). Can reduce radiation exposure because photons from a single x-ray beam can convey image data to multiple rows of detectors simultaneously.
CT Image acquisition

- For a fixed position of the x-ray tube, a fan beam is passed through the patient.
- Measurements of the transmitted x-ray beam intensities are made by an array of detectors.
- X-ray transmissions measured by each detector is the result of the sum of attenuation by all the tissues a beam passes through (ray sum).
- Collection of ray sums for all detectors at a given tube position are called projections (1000 data points).
- Projection data sets are acquired at different angles around the patient (1000 projections for a CT image).
- CT images derived by mathematical analysis of projection data sets.

Huda – 2nd edition
Image reconstruction

• Generating an image from the data involves determining the linear attenuation coefficients of the individual pixels in the image matrix
• Mathematical algorithm (filtered back projection) takes the projection data (raw data) and reconstructs the cross sectional CT image (image data)
• Array processors can perform image reconstructions involving millions of data points in just a few seconds
• Different filters can be used in FBP reconstruction offering tradeoffs between spatial resolution and noise (bone, soft tissue, etc.) depending on the clinical task
Image Reconstruction Filters

• A convolution filter (or kernel) is applied to raw data to remove blurring and artifacts
• Kernels allow the viewer to see the scan in a variety of window settings
• Example – soft tissue, lung, bone, etc
Kernel Selection

- Trade-off between spatial resolution and noise
- Smooth kernel (brain, liver, soft tissue) – images have lower noise but lower spatial resolution; poor edge detection; enhance low contrast detectability; higher radiation dose
- Sharp kernel (lung, bone) – images have higher spatial resolution but more image noise; better edge definition; lower radiation dose
Kernel Selection

Standard Algorithm  Bone Algorithm

Images courtesy of Maureen Heldmann, MD
SEVERAL POSSIBLE RECONSTRUCTION ALGORITHMS

For attenuation correction, only the standard kernels are used

Images Courtesy Maureen Heldmann, MD
Contrast Agents

• Contrast medium is a substance used in imaging to permit visualization of internal body structures
• The most commonly used contrast agents are administered IV (vasculature, solid organs, etc.) and PO (GI tract)
• Types
  – Positive Contrast Agents – are radiopaque (white) on imaging (barium, gastrografin, iodinated IV contrast, etc)
  – Negative Contrast Agents – are not radiopaque; carbon dioxide (black), water, mannitol-LBG, etc (gray or fluid density)
Contrast Agents

Barium – positive contrast

mannitol-LBG – negative contrast

Radiology (2004) 230(2); 879-885
Remember contrast agents are drugs

• Adverse side effects do happen
• Risk factors for IV contrast reactions
  – Allergy – prior allergy life reaction to contrast administration or any significant allergy to on or more allergens
  – Renal insufficiency – contrast induced nephrotoxicity (CIN)
Contrast “Allergies”

• A patient with a prior allergic-like reaction or unknown-type reaction (i.e., a reaction of unknown manifestation) to contrast medium have an approximately 5 fold increased risk of a subsequent reaction if exposed to the same class of contrast medium again. This is the greatest risk factor for predicting future adverse events.

• Premedication - varies by institution but typically involves administration of a corticosteroid and an anti-histamine prior to the contrast administration.

From ACR Manual on Contrast Media - 2017
BUMC Premedication Policy

Elective premedication
- 32 mg Methylprednisolone PO 12 hours prior to contrasted study, and a repeat dose 2 hours before the study.
- 50 mg Diphenhydramine (Benadryl) PO/IV/IM 1 hour prior to study. (Optional and of questionable benefit).

Emergency Premedication
- 40 mg Methylprenisolone or 200 mg Hydrocortisone IV every 4 hours until contrast study required with 50 mg Diphenhydramine IV 1 hour prior to contrast injection.
BUMC Premedication Policy cont.

Other option

– 7.5 mg Dexamethasone or 6.0 mg Betamethasone IV every 4 hours until contrast injection in patients allergic to Methylprednisolone, aspirin, or NSAIDS.

– 50 mg Diphenhydramine IV 1 hour prior to contrast injection.

– If IV steroids are used, then doses should continue for at least 24 hours following the injection.
Unrelated allergies

• Patients with unrelated allergies are at a 2 to 3 fold increased risk of an allergic-like contrast reaction, but due to the modest increased risk, restricting contrast medium use or premedicating solely on the basis of unrelated allergies is not recommended.

• Patients with shellfish or povidine-iodine (e.g., Betadine®) allergies are at no greater risk from iodinated contrast medium than are patients with other allergies (i.e., neither is a significant risk factor).

From ACR Manual on Contrast Media - 2017
Renal Issues

• Contrast-induced nephropathy (CIN) is a sudden deterioration in renal function that is caused by the IV administration of iodinated contrast.
• ACR position – CIN is a real, albeit rare, entity
• Commonly used criteria – absolute increase of 0.5 mg/dL over a baseline serum creatinine
• Most important risk factor for CIN is pre-existing severe renal insufficiency
• Screening (baseline serum creatinine) is recommended in the following:
  – Age >60
  – History of renal disease (dialysis, post renal transplant, solitary kidney, renal cancer, renal surgery)
  – History of hypertension requiring medical therapy
  – History of diabetes (especially those taking Metformin or metformin containing drug combinations)
• The cutoff value for serum creatinine beyond which IV iodinated contrast would not be administered varies widely by institution, but range from 1.5 to 2.0 mg/dL
• Prevention – know patients at risk, IVFs, use of low osmolality contrast media, diuretics, sodium bicarb, N-acetylcysteine, etc
Contrast Extravasation

- Can occur with both hand and power injection, frequency is not associated with flow rate.
- Patients may or may not be symptomatic. On exam the site may be edematous, erythematous and tender.
- Extravasated contrast media is toxic to the surrounding tissues, especially the skin producing an acute local inflammatory reaction that sometimes peaks in 24 to 48 hours. Most are limited to the adjacent soft tissues and usually there is no permanent injury.
- Compartment syndrome can occur due to mechanical compression (usually large volume extravasations of LOCM).
- Uncommonly skin ulceration and tissue necrosis can occur as early as 6 hours after extravasation.
- Close clinical follow-up for several hours is essential for all patients where extravasation occurs.

From ACR Manual on Contrast Media - 2017
Adjustable CT Parameters

- Pitch
- Tube voltage
- Tube current
- Slice thickness
Pitch

- The distance the table travels during one revolution of the x-ray tube. Expressed as the ratio of distance the table travels per rotation of the total collimated x-ray beam width.
- If that distance equals the slice thickness (the thickness of the collimated beam) the pitch is said to be 1:1.
- A pitch of 1 = best image quality because data is collected on all anatomy.
- As the pitch increases = patient moves through the gantry faster = patient dose decreases.
- Keeping all other parameters same, if the pitch is increased by a factor of 2, the patient dose decreases by ½.
Tube voltage (kVp – kilovolt peak)

- Determines the energies of the x-ray photons (emitted from the anode target material)
- Higher tube voltage = higher photon energies and higher # of x-rays
- Indicates quality of the x-ray beam
- Affects penetration of patient (patient dose) and image quality (image contrast)
- Usual range from 80 to 140 kV (120 kV most common)
- Higher tube voltages are typically used for very attenuating body parts (skull) or large patients
- Higher kVp = higher energy photons = higher penetration = increased scatter radiation = less image contrast = increased patient dose
**Tube Current (mA)**

- Controls the temperature of filament and determines the # of electrons that flow to the anode
- Hotter filament = greater # of electrons and consequently x-rays
- Controls quantity of x-rays per scan
- The mA is a measurement of the current of x-ray photons across the x-ray tube

- **Tube Current – Time Product**
  - milliampere seconds or mAs
  - Proportional to # of photons in the defined exposure time
  - Increasing the scan time = increase # of x-ray photons produced = less image noise but increased patient dose
  - Technologists need to carefully consider the outcome of increased dose to the patient if a higher mAs is used.
mAs and slice thickness

- Usually in the range of tens to hundreds of mA (variable)
- Typically relatively high (~200 mAs) for diagnostic CT scans
- High mAs = less image noise
- For PET/CT: highly variable (from 30 to 200 mA)
- The increased capabilities of multi-slice scanners, which allow higher mAs values, longer scan lengths and multi-phase contrast studies, have the potential of directly increasing patient radiation dose.
- Another indirect but significant effect on dose can result from the imaged slice width. Scanning is usually performed with narrower slices than on single slice scanners, so for the same noise, higher mAs values would need to be used.
Radiation Dose - CTDI

- Manufacturers specify CT dose by the CT dose index (CTDI)
- CTDI – radiation dose of a single CT slice determined using acrylic phantoms (cylinders of a standard length and generally in diameter of 16 and 32 cm)
- CTDI$_{100}$ reflects dose contribution from a 100-mm range centered on the index slice.
- Weighted CTDI (CTDI$_w$) reflects weighted sum of 2/3 peripheral dose and 1/3 central dose in a 100 mm range in acrylic phantoms.
- Most commonly used is Volume CTDI (CTDI$_{vol}$) which is CTDI$_w$ divided by beam pitch factor (pitch/mAs)
- The dose profile in a CT scanner is not uniform along the patient axis.
- CTDI values for body scans are lower than for head scans because of the greater attenuation of x-rays in the body.
- CTDI doses do not quantify patient risk because they take no account of section thickness, the number of sections scanned, or the radiosensitivity of the organs.
Radiation Dose - DLP

- Dose length product = $\text{CTDI}_{\text{vol}} \times \text{scan length in cm}$ (ie slice thickness $\times$ # of slices)
- DLP is independent of what is actually scanned
- The reported DLP is the same whether a 10 lb infant or 100 lb teenager is scanned if the scan length and other scan parameters are the same.
- The DLP is proportional to the total dose (energy) imparted to the patient and can be used as an indicator of the relative risk of CT.
Effective Dose

- The major patient radiation risk in CT is the induction of cancer.
- Patient cancer risk depends on the dose and radiosensitivity of all exposed organs and tissues, and is best quantified by the effective dose parameter.
- Effective doses in CT are much higher than in those in conventional radiography.
- Effective doses in children are higher than in adults because of the much smaller organ sizes (dose is energy deposited divided by mass).
- Do not use the same parameters in children and adults.
ALARA Principle

• Acronym for As Low As Reasonably Achievable
• Radiation safety principle for minimizing radiation doses and release of radioactive materials by employing all reasonable methods.
• It is not only a sound safety principle, but it is a regulatory requirement for all radiation safety programs.
Reducing Radiation Dose

- The principle selectable parameters that contribute to radiation dose are tube current (mA), peak kilovoltage (kVp), pitch, and gantry cycle time (in seconds).
- mA and radiation dose: direct and linear relationship: ↓ mA by 50% = ↓ radiation dose by 50%.
- kVp and radiation dose: nonlinear relationship: 17%↑ in kVp (120 to 140) = 35-40% ↑ in CTDI_w.
Reducing Radiation Dose

• Pitch and radiation dose: inverse but linear relationship: ↑ pitch (from 1 to 1.5) = ↓ radiation dose by 33%

• Gantry cycle time and radiation dose: direct and linear relationship: ↓ gantry rotation time from 1.0 to 0.5 sec/rotation (faster gantry rotation or ↑ cycle speed of rotation) = ↓ radiation dose by 50%
Automatic Dose Modulation

- Dose modulation is an automatic exposure control (AEC) system for CT that uses the scout image data to calculate changes in anatomy and compute the required technical factors for each image in the scan range.
- Automatic dose modulation adjusts the mA or mAs as needed for each gantry rotation during the scan to compensate for changing patient anatomy.
- When used properly may result in significantly reduced radiation dose to the patient.
- Caveat: requires appropriate positioning for optimal function.
Artifacts

- Truncation
- Noise
- Motion
- Streak
- Beam Hardening
- Metal
- Partial Volume
Truncation Artifact

- Standard CT field of view is 50 cm, but many patients exceed this.
- Truncation appears as a rim of increased density at the edge of a truncated CT image with an adjacent low concentration area peripherally.
- Not often a problem for CT, but can be a problem when truncated CT is used for PET attenuation correction.
- Solution: use 70 cm FOV in larger patients.
Truncation
REMOVING CT TRUNCATION ARTIFACTS

50 cm CT FOV

Standard CT Reconstruction

70 cm PET FOV

Wide Field CT Reconstruction

Kinahan P. PET/CT Issues: CTAC, Fusion, Artifacts, Motion Correction. 2008 AAPM Summer School Proceedings
Max SUV changed from 3.4 to 12.7 with extended field of view CT

Kinahan P. PET/CT Issues: CTAC, Fusion, Artifacts, Motion Correction. 2008 AAPM Summer School Proceedings
CTAC w/ 50 cm DFOV

CT70 w/ 70 cm DFOV

Amol M. Takalkar, M.D.
Noise – photon starvation

• Related to statistical error of low photon counts, appears as grain on image, power supplied to x-ray tube is insufficient to penetrate the anatomy, more common with thin slice thickness

60 mA, 120 kVp, slice thickness 5 mm  440 mA, 120 kVp, slice thickness 5 mm

Motion Artifact

• On CT – seen as blurring and/or streaking caused by movement of the object being imaged.

• On PET/CT
  – external motion (patient moved between the PET and CT acquisitions), may need to rescan
  – Internal motion (respiratory, bowel movement, bladder distention), usually cannot be rectified
Motion Artifact

Motion causes blurring and double images (left), as well as long range streaks (right).

Beam Hardening

- Beam hardening and scatter both produce dark streaks between two high attenuation objects (such as metal or bone) with surrounding bright streaks.
- This is particularly a problem within the posterior cranial fossa and with metal implants.
- Can be reduced by increasing kVp, decrease slice thickness, use of certain filters, etc.
Beam Hardening

CT image shows streaking artifacts due to beam hardening effects of contrast medium.

Beam Hardening

http://dx.doi.org/10.1594/ecr2012/C-1377
Metal Artifact

- Streaks often seen around metal objects (aneurysm clips, dental amalgum, surgical hardware, etc) due to blockage of x-rays
- Factors: undersampling, photon starvation, motion, **beam hardening** and Compton scatter
- Can be reduced using newer reconstruction techniques such as metal artifact reduction (MAR), metal deletion techniques (MDT) or by angling the CT gantry
Metal Artifact

Sharp thin alternating streaks surrounding an aneurysm coil are mostly due to motion and undersampling.

MDT image reveals hemorrhage around the coil.

Metal Artifact

Dark streak between hip replacements is mostly due to beam hardening and scatter.

The MDT image more clearly shows a fluid collection adjacent to the left hip replacement.

Partial Volume Averaging

- Partial volume effect – “blurring” of edges, scanner is unable to differentiate between a small amount of high density material and a larger amount of lower density material.
- This is especially an issue along sharp edges.
- It can partially be overcome by using thinner slices or an isotropic acquisition on a modern scanner.
(7) Mechanism of partial volume artifacts, which occur when a dense object lying offcenter protrudes part of the way into the x-ray beam.

(8) CT images of three 12-mm-diameter acrylic rods supported in air parallel to and approximately 15 cm from the scanner axis.

(a) Image obtained with the rods partially intruded into the section width shows partial volume artifacts.

(b) Image obtained with the rods fully intruded into the section width shows no partial volume artifacts.

Ring Artifact

- Most common mechanical artifact seen on CT
- One or many “rings” on the image that occur close to the isocenter of the scan and are usually visible on multiple slices at the same location
- Cause is failure of one or more detector elements or miscalibration of an individual detector element
- Solution: recalibrate the scanner, replace faulty detector
Ring Artifact

Case courtesy of Dr Omar Giyab, Radiopaedia.org, rID: 22694
In conclusion . . .

Hybrid imaging is here to stay.
Balancing act - Image quality and radiation dose
Patient safety comes first.
At the end of the day, we want to do no harm.
Thank You!
Additional References


