Dose Reduction in Interventional Computed Tomography Procedures: Optimizing Helical Scan Parameters

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Teaching Points

1. Define common CT procedures, workflow, and different scan mode options for procedures.

2. Discuss clinical considerations and image quality requirements for diagnostic CT versus CT procedures.

3. Review protocol parameters relevant to dose optimization including automatic tube current modulation and iterative reconstruction settings.

4. Identify multiple strategies for CT dose optimization in CT procedures.

5. Understand that adjustments can be made to the helical scan utilized during the procedure to significantly reduce patient dose.

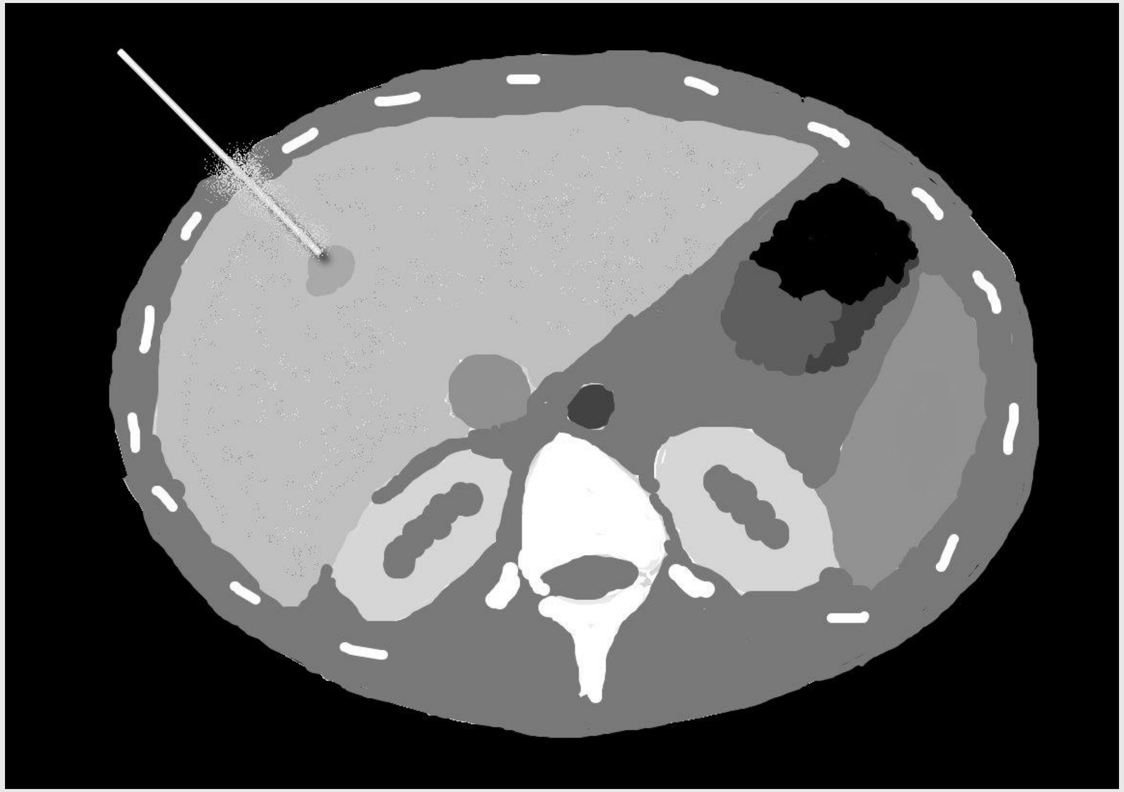
Teaching Point 1:
Introduction to Common CT Procedures, Workflow, and Scan Mode Options

Introduction

Computed tomography (CT) is commonly used as a diagnostic tool, but it is also used for image guidance during procedures that require 3D localization.

There are a variety of scan mode options that could be utilized during CT procedures.

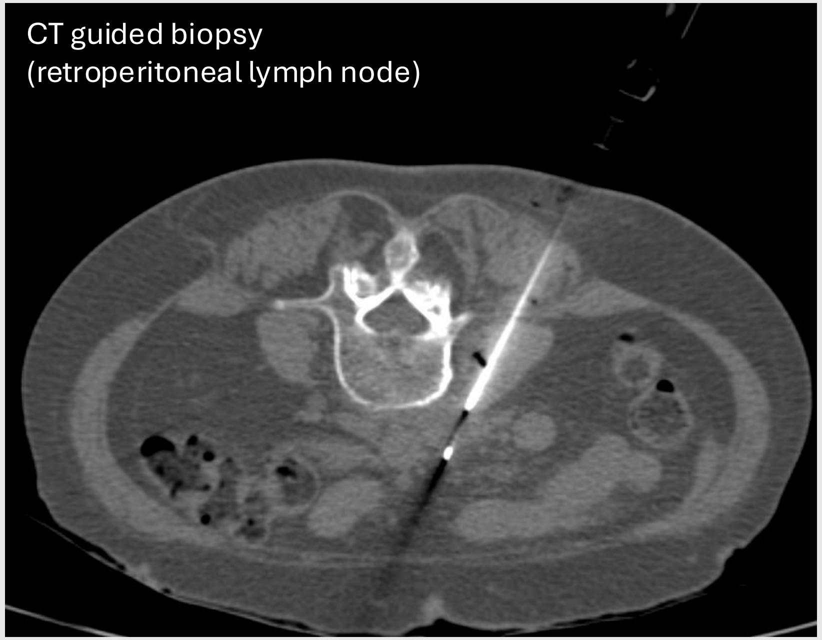
It is important to understand the workflow of procedures being performed, the different scan mode options, and ways to optimize these scan modes.

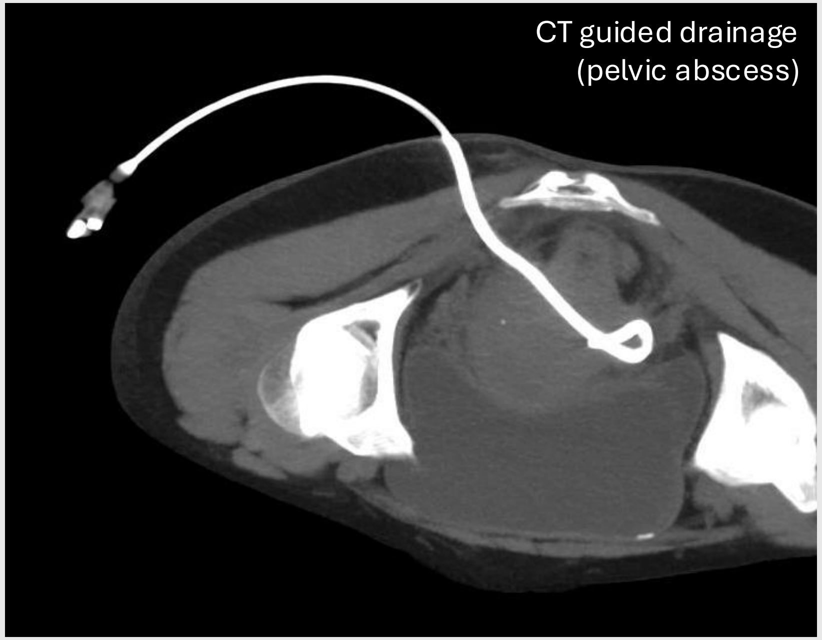


Common Types of CT Procedures

Biopsy

Needle insertion to sample tissue, typically to diagnose cancer



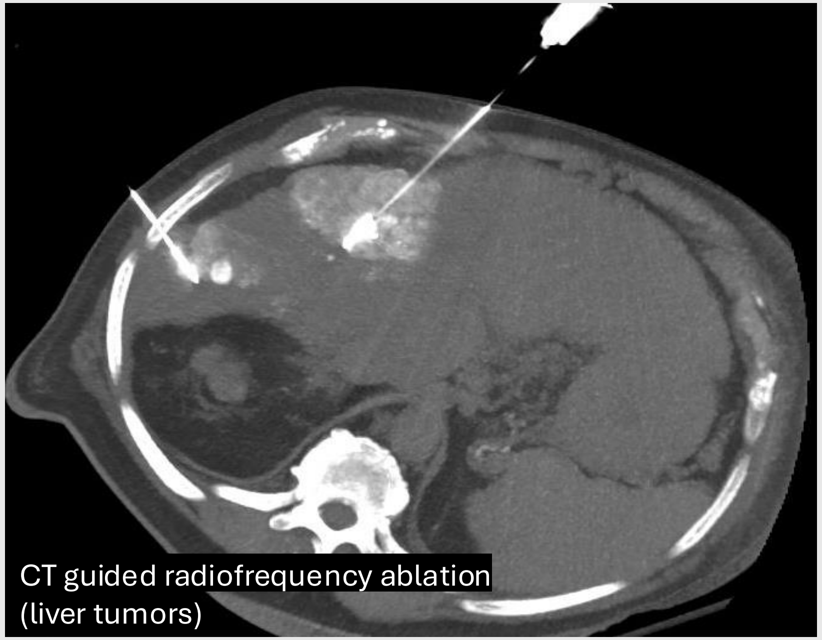


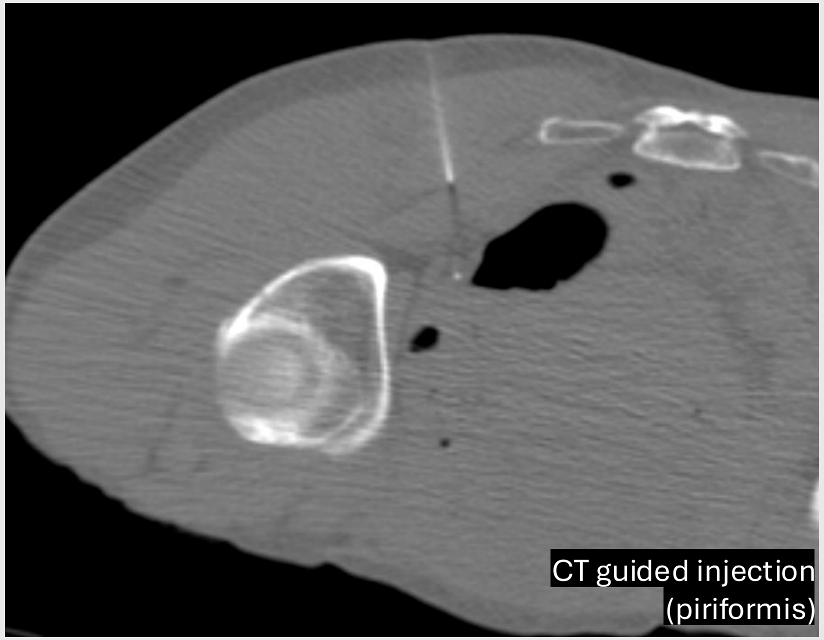
Drainage/Aspiration

Needle and/or catheter insertion for drainage of fluid

Ablation

Thermal tumor destruction





Injection

Injection of a local anesthetic and/or steroid to help in diagnosis or in a therapeutic way[1]

CT Procedures Typical Workflow

Pre-Intervention

The helical scan is primarily used for the planning CT, but it is also used during active intervention.

Scout and Helical Scan

Active Intervention

Visualization is needed throughout the procedure. Radiologists determine which mode to utilize, the possible scan mode options are listed below.

Biopsy Mode (Intermittent Axial)

Interventional Intermittent CT Fluoroscopy Mode

Interventional Continuous CT Fluoroscopy Mode

Helical Scan

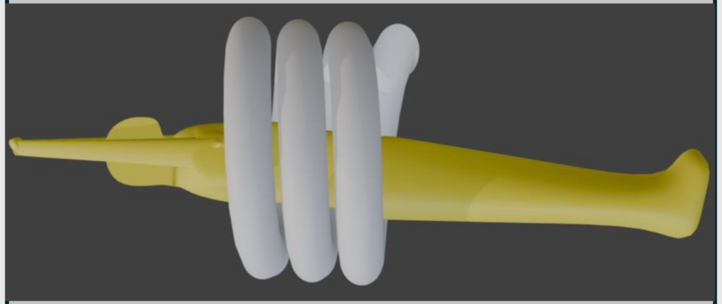
Post-Intervention

For evaluation of post procedure complications, a helical scan may be performed.

Optional Helical Scan

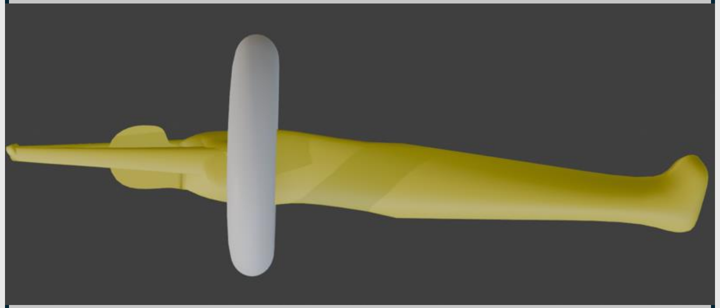
CT Procedure Scan Modes

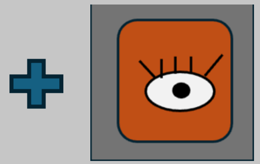
Helical Scan



X-ray is on and the gantry rotates while the table moves simultaneously. Helical scans are performed from the control room.

Interventional Intermittent CT Fluoroscopy Mode

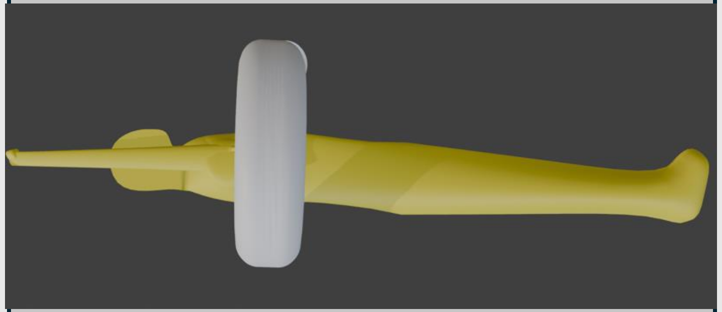


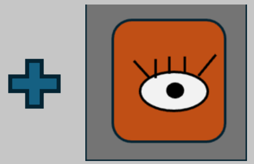


Intermittent axial scans acquired each time the foot pedal is pressed from inside the CT room.

Terminology may be interchanged with Biopsy Mode

Interventional Continuous CT Fluoroscopy Mode

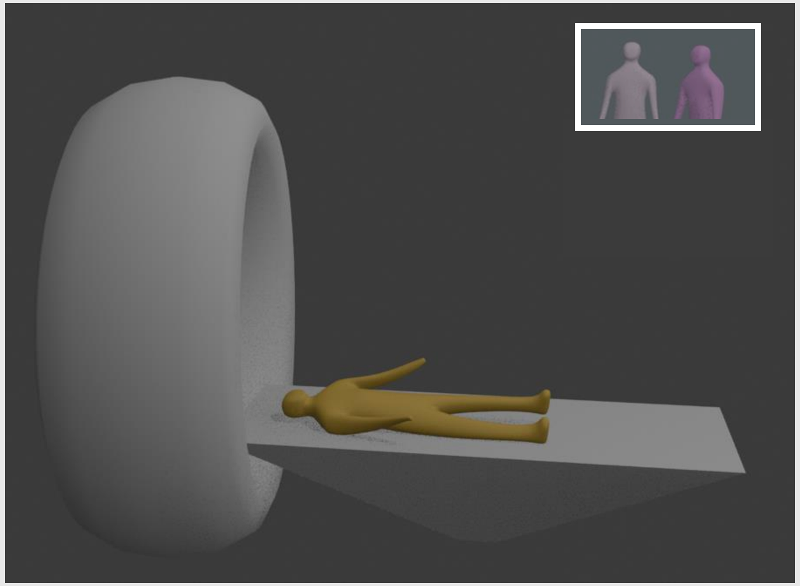




Axial images will be acquired and displayed continuously while the foot pedal is pressed from inside the CT room.

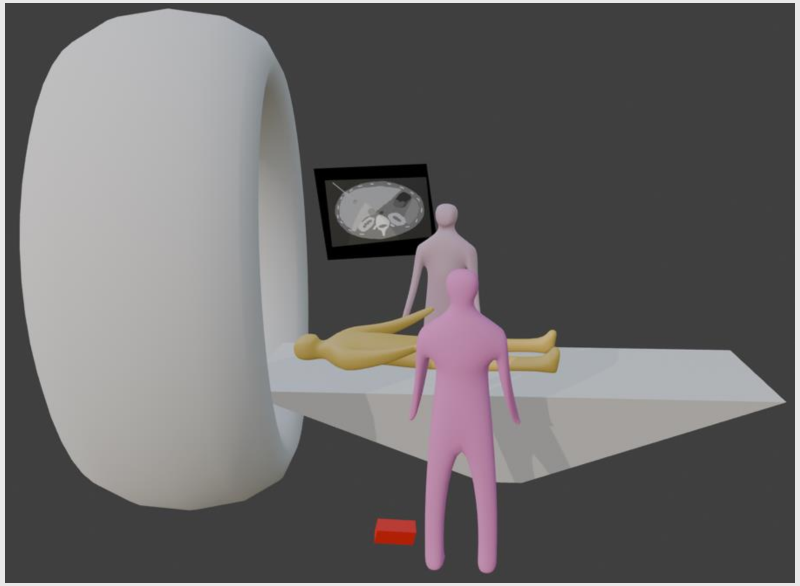
CT Procedures Scan Modes Dose Comparison

Helical Scan



Scan Type	Helical
Workflow	Staff steps out of room as with standard diagnostic CT
Technique	Automatic tube current modulation typically employed; dose reduction methods available
Scan Range	Not limited in scan range

Interventional Intermittent CT Fluoroscopy Mode

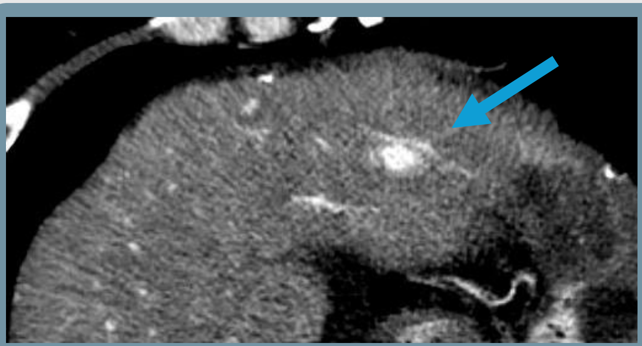


Scan Type	Axial
Workflow	Staff in room, utilization of foot pedal; 1 foot pedal press = 1 single rotation axial scan
Technique	May have fixed technique, low mAs
Scan Range	Single axial acquisition has fixed scan range (1-2 cm)

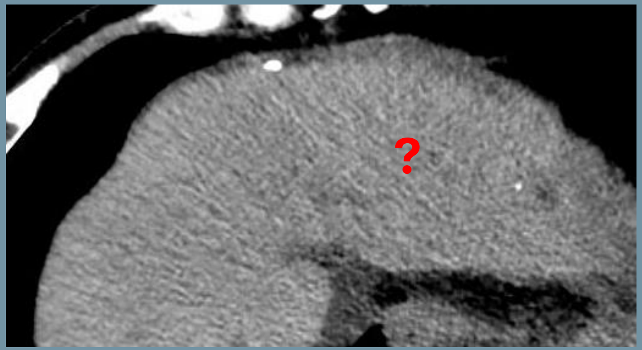
Teaching Point 2:
Clinical Considerations and Image Quality Requirements for Diagnostic CT vs. CT Procedures

Image Quality Considerations for CT Procedures

While IV contrast can be used during procedures to enhance lesion conspicuity, it is typically avoided, when possible, as it adds complexity. **Lesions well seen at diagnostic contrast enhanced CT may be inconspicuous without contrast.**



Diagnostic liver CT shows arterial **enhancing liver mass with good conspicuity** and visualization.

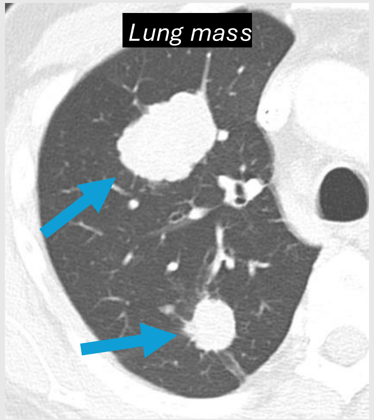


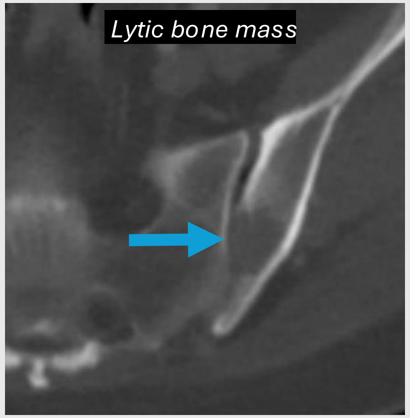
On non-contrast CT the lesion is not seen, precluding CT biopsy. Patient was sent for US-guided biopsy instead.

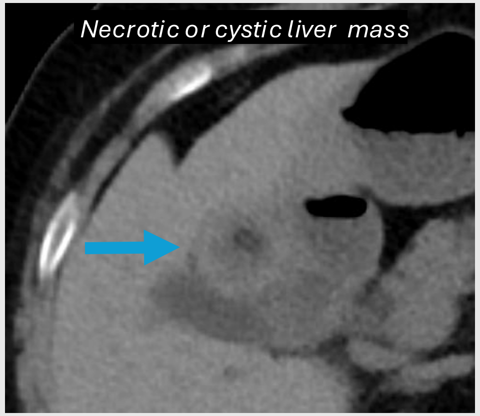
Poor lesion conspicuity is the result of a combination of factors:

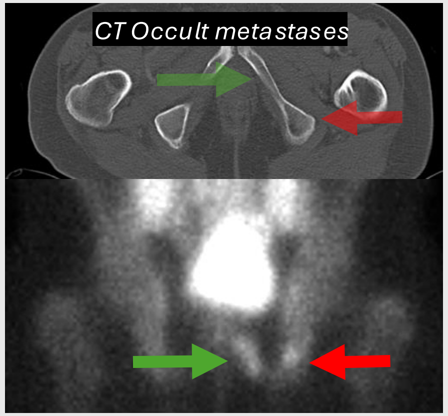
- Similar attenuation of lesion and background tissues resulting in poor contrast to noise ratio
- Large BMI or extra body parts in the FOV resulting in excessive scatter and noise
- Small lesion size
- Motion blur (i.e., in organs that move with breathing such as lung, liver and kidney)

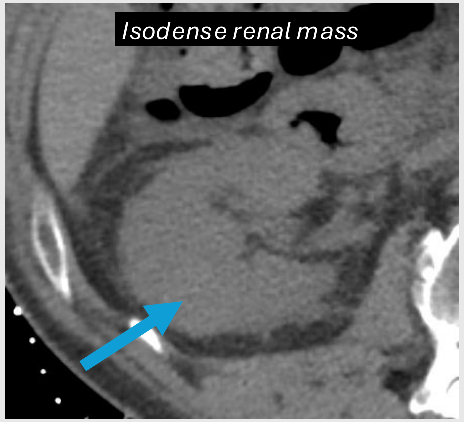
High lesion contrast, well visualized at lower helical CT and CT fluoroscopy doses → **Low lesion contrast,** may need higher doses for helical CT and CT fluoroscopy (without contrast) to visualize









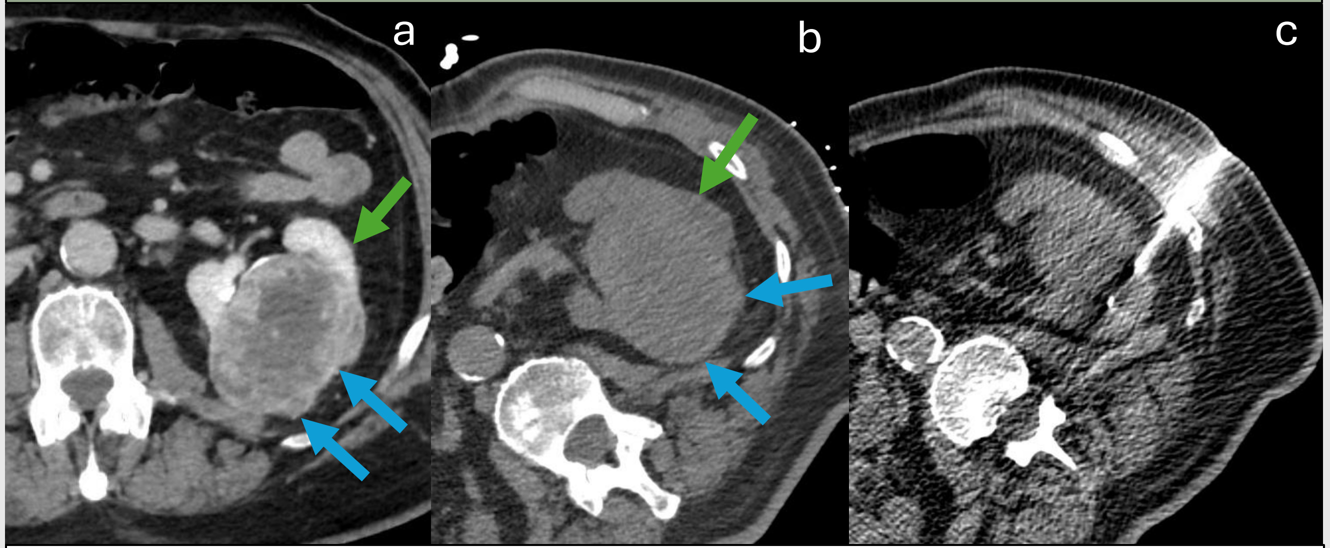


Lesion Size, Location, and Conspicuity Impacts Patient Dose

Difficult to visualize lesions may result in:

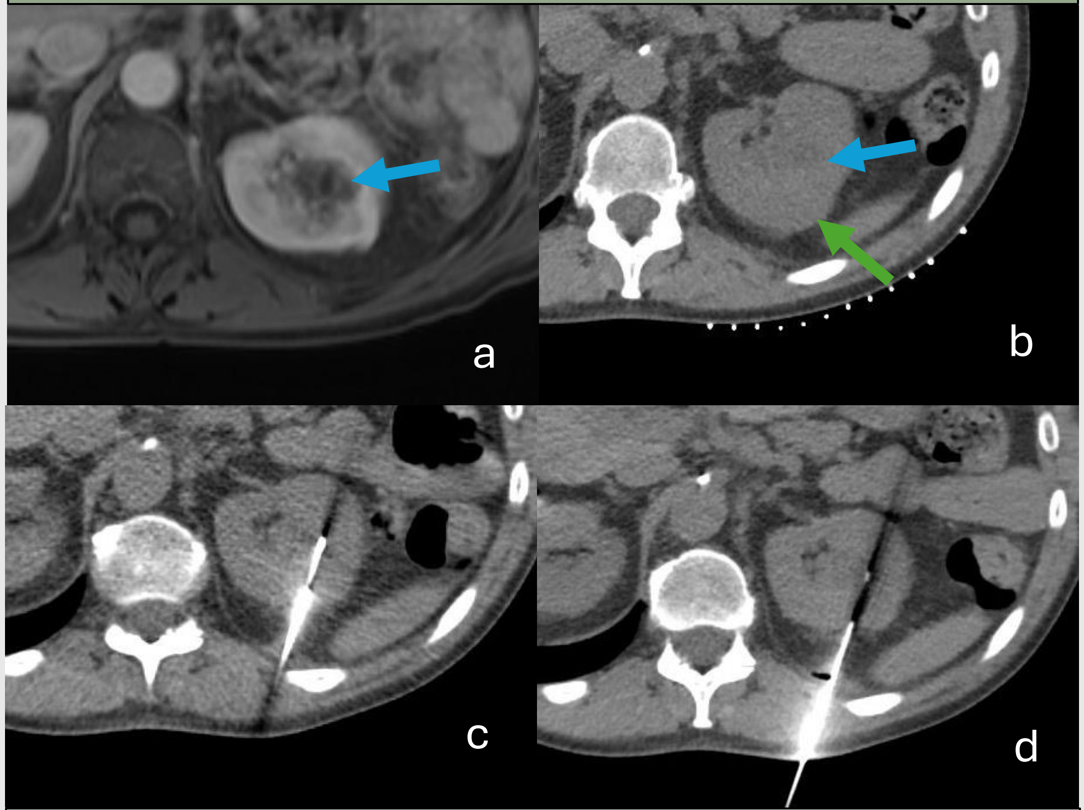
- Increased intermittent CT fluoroscopy utilization to ensure correct targeting and for radiologists' reassurance
- Increased techniques to improve lesion conspicuity
- Increased utilization of helical scans

Well Visualized Mass



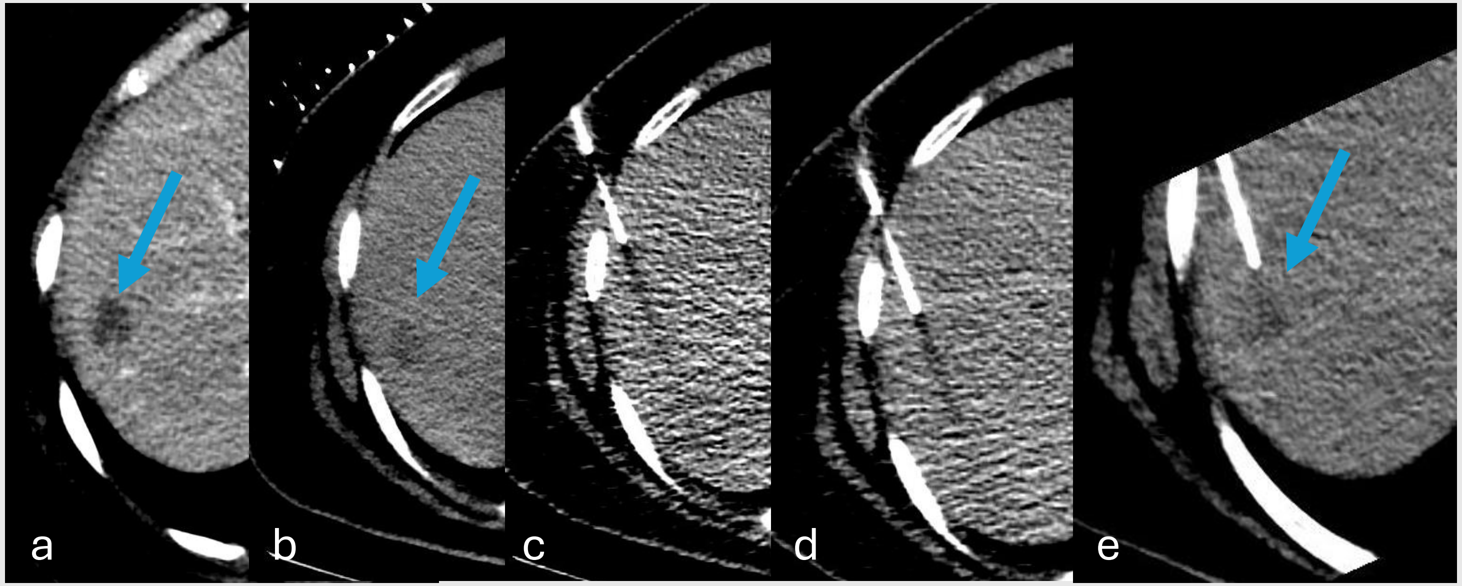
(a) Diagnostic CECT shows large left renal mass.
(b) Biopsy planning helical CT shows mass well compared to normal kidney due to large size and well-defined borders.
(c) Therefore, lower dose intermittent CT fluoroscopy (30 mAs) shows the mass well and allows for accurate targeting without the use of additional helical scans or higher CT fluoroscopy doses.

Poorly Visualized Mass Required Additional Helical Scans



(a) T1 C+ MRI shows large left renal mass.
(b) On biopsy planning helical CT the mass is difficult to separate from normal kidney due to isoattenuation.
(c) Low confidence in accurate targeting on intermittent CT fluoroscopy mode even at moderate dose (45 mAs) due to poor definition of the border of the mass and normal kidney.
(d) Utilization of the helical scans with the needle in place increases confidence that the needle is in the mass.

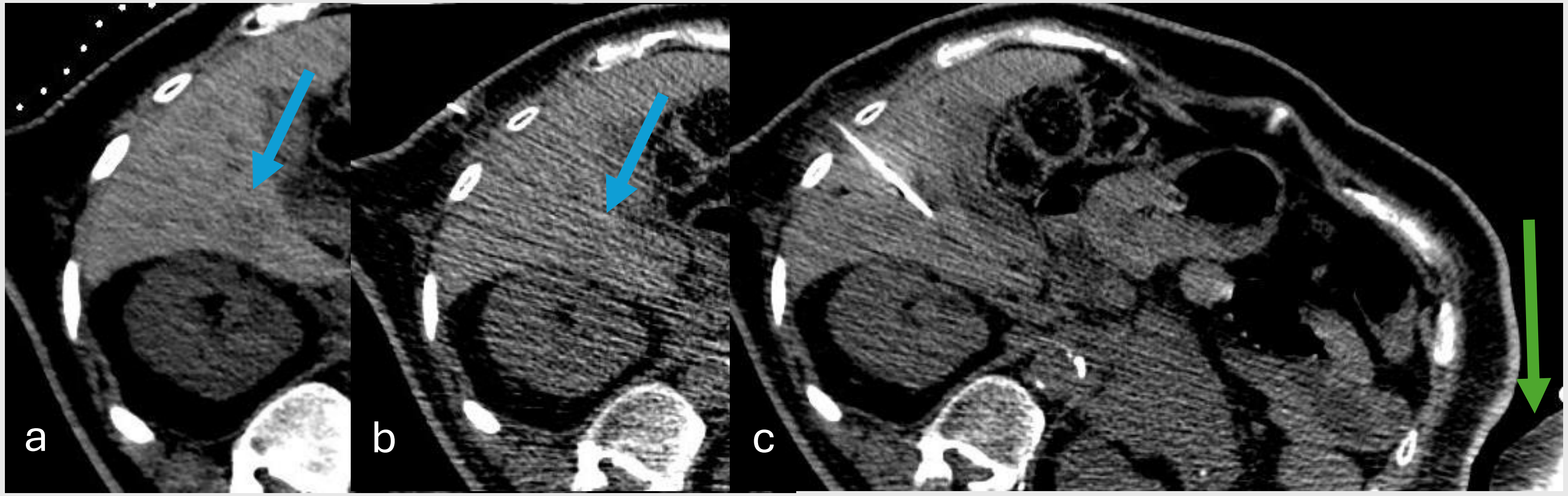
Small Lesion Comparison: Variation in Body Habitus & Arm Position



Small liver mass with BMI 33 and arms positioned outside of the FOV.

a. Diagnostic CECT shows a small right liver mass.
b. Biopsy planning helical non-contrast CT shows mass well compared to normal liver.
c. Initial lower dose intermittent CT fluoroscopy scan (30 mAs) with needle in place does not visualize the mass.
d. Intermittent CT fluoroscopy technique was increased (60 mAs) and the mass was still not visualized.
e. Helical CT scan (144mAs) shows the mass similar to (b) and confirms accurate targeting with the needle.

Small lesion visualization is highly dependent on body habitus and ability to position the arms outside of the FOV.



Small liver mass with BMI 27 and arms positioned in the FOV.

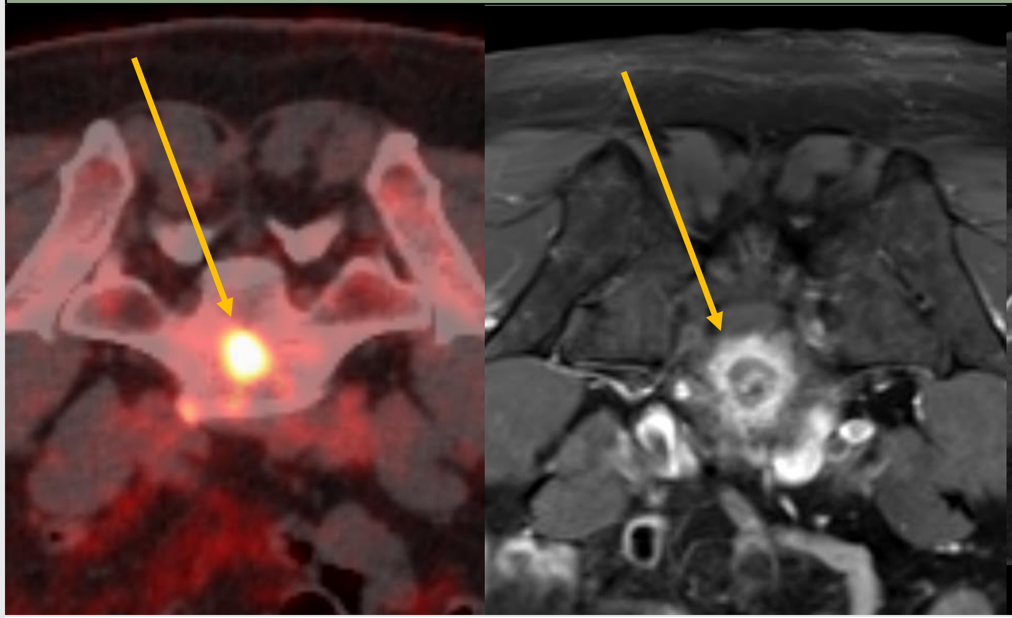
a. Biopsy planning helical non-contrast CT shows right liver mass.
b. Initial intermittent CT fluoroscopy scan (50 mAs) does not visualize the mass well.
c. Intermittent CT fluoroscopy technique was increased (100 mAs) allowing for accurate targeting. Left arm was unable to be raised and therefore was positioned in the FOV contributing to the excessive noise, streaking and poor lesion conspicuity.

CT-Occult Lesions: Targeting Options

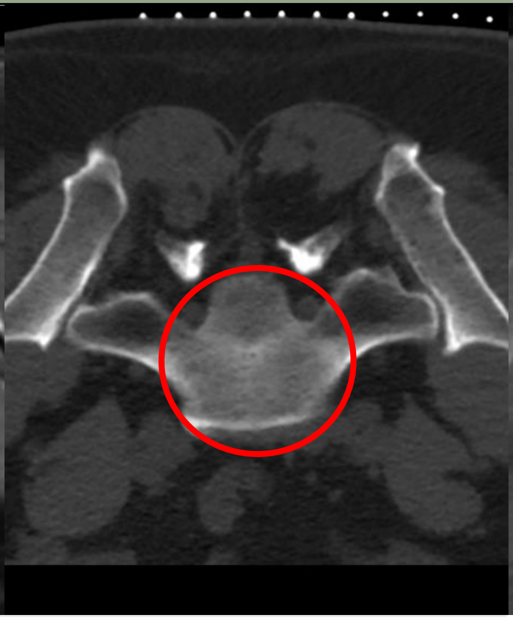
Some lesions are CT occult. However, CT often remains the best guidance modality, especially for bony lesions given overall regional visibility, availability, cost, efficiency, and lack of additional risks.

- Anatomic landmarks can be used for targeting rather than higher-dose acquisitions
- IV contrast material can also be avoided, decreasing number of acquisitions, dose, and medication related risks

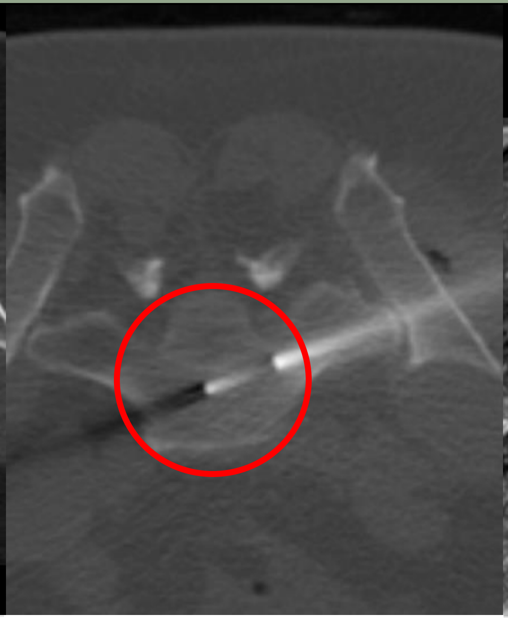
CT-Occult Lesion Case Example



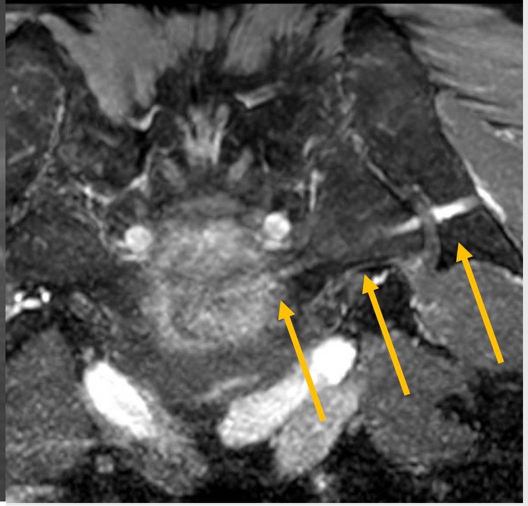
Solitary S1 likely metastasis on PET/CT and Contrast MRI is clearly visible (arrows). Findings are highly suspicious, and confirmation would significantly change treatment of known Head and Neck squamous cell carcinoma.



Known S1 lesion is occult on subsequent CT (circle).



In lieu of adding increasing dose to improve conspicuity, bony landmarks were used for targeting, with low-dose bony CT Fluoroscopy technique.



Metastasis was pathologically confirmed. Follow-up MRI shows the biopsy tract entering the lesion (arrows).

Operator Inexperience May Contribute to Dose

CT guided biopsy of a retroperitoneal lymph node by an inexperienced radiologist

The following video shows all CT fluoroscopy acquisitions from a procedure with a total of 29 activations of the pedal (3 successive slices acquired per pedal press).

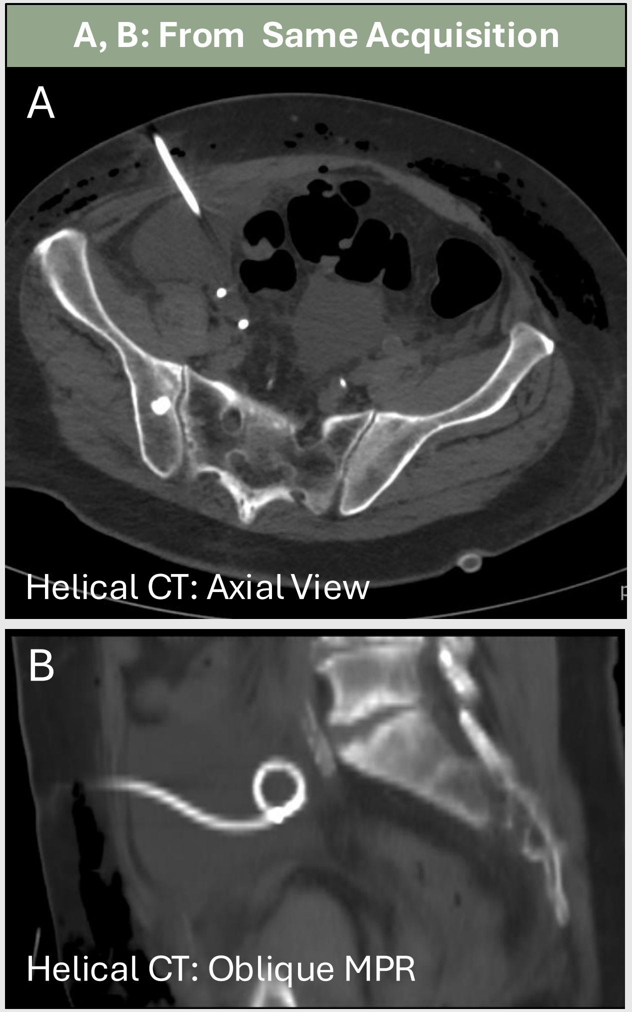
Given the straight path to the target and no critical structures along the needle, an experienced operator would typically advance the needle greater distances between pedal activations, requiring much less imaging (e.g. 5 or 6 CT fluoroscopy acquisitions) to complete the procedure.

Inexperience or resident training may lead to an increased number of acquisitions and thus, increased doses.

Multiplanar Reconstructions (MPRs) Can Improve Targeting

The generation of MPRs can improve targeting of small or deep lesions as well as improve craniocaudal targeting[2,3]

- In some situations, the needle trajectory is out of the axial plane in order to avoid injury to sensitive structures.
  - CT fluoroscopy is often not used as it only covers a few slices and cannot show the entire needle trajectory.
- Helical scans with MPRs are therefore used as it allows best visualization of cranial or caudal angulation.
  - Improved targeting can decrease risk to major nerves, vessels, lung/pleura, and other sensitive structures prone to frequent or severe injury.
  - This may contribute to increased procedure dose.

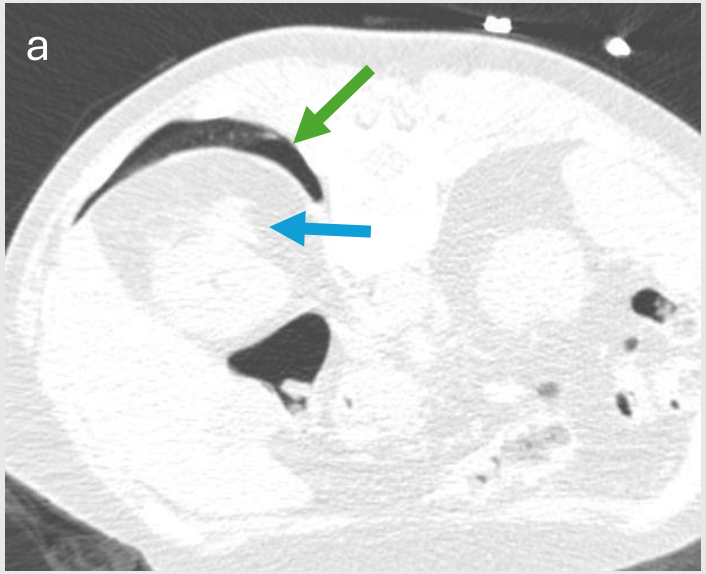


Post Intervention Scan Mode Selection

For some bone interventional procedures, a limited intermittent CT fluoroscopy scan may suffice to exclude a complication. However, for higher risk interventions, radiologists often perform a helical scan to look for complications.

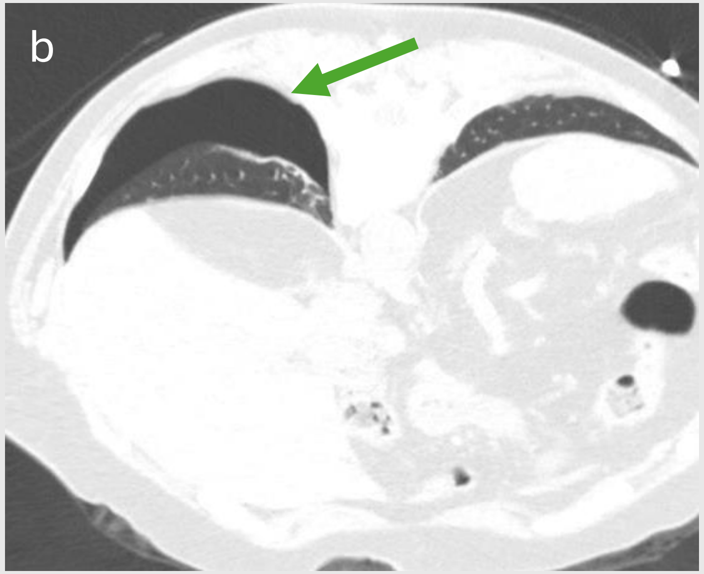
The post procedure scan z-axis coverage is typically extended beyond the biopsy site for several reasons:

1. To ensure that a **complication is not missed** superior or inferior to the needle puncture site
   - Example: Scanning the entire length of the kidney after a renal mass biopsy to look for hemorrhage superior or inferior to the biopsy site.
2. To **quantify a complication** only partially seen with CT fluoroscopy
   - Example: Hemorrhage seen at the biopsy site on CT fluoroscopy images during the procedure but difficult to quantify. Scan range extended to quantify volume and extent of hemorrhage.
3. To ensure that a nearby **organ is not inadvertently injured**
   - Example: After liver biopsy, extending the scan superiorly to include the lung bases to look for pneumothorax.



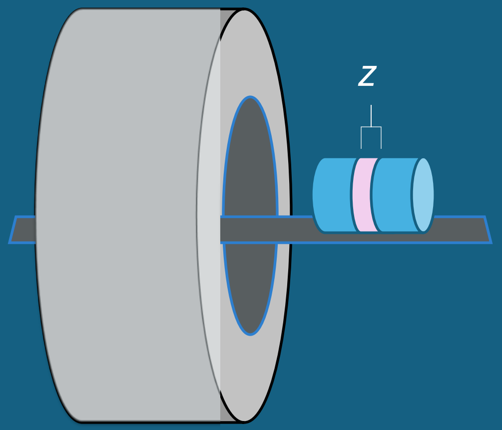
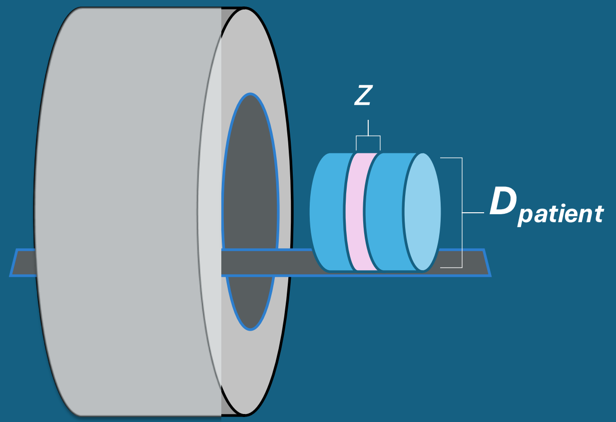
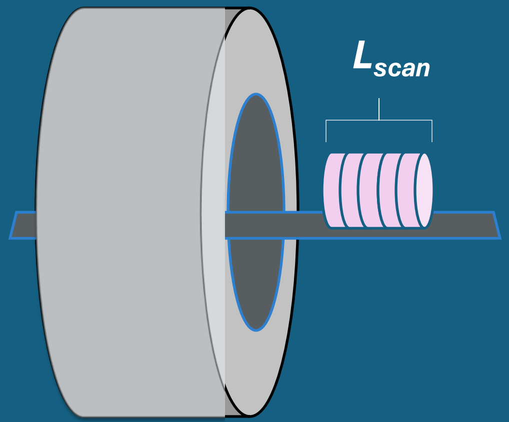
Renal mass cryoablation complicated by pneumothorax:

(a) CT fluoroscopy during renal mass ablation shows a tiny pneumothorax at the right lung base.
(b) Helical scan was performed with larger coverage to quantify pneumothorax and decide on treatment (in this case chest tube placement was necessary).



Teaching Point 3:
Review of Protocol Parameters Relevant to Dose Optimization

Review of Dose Parameters

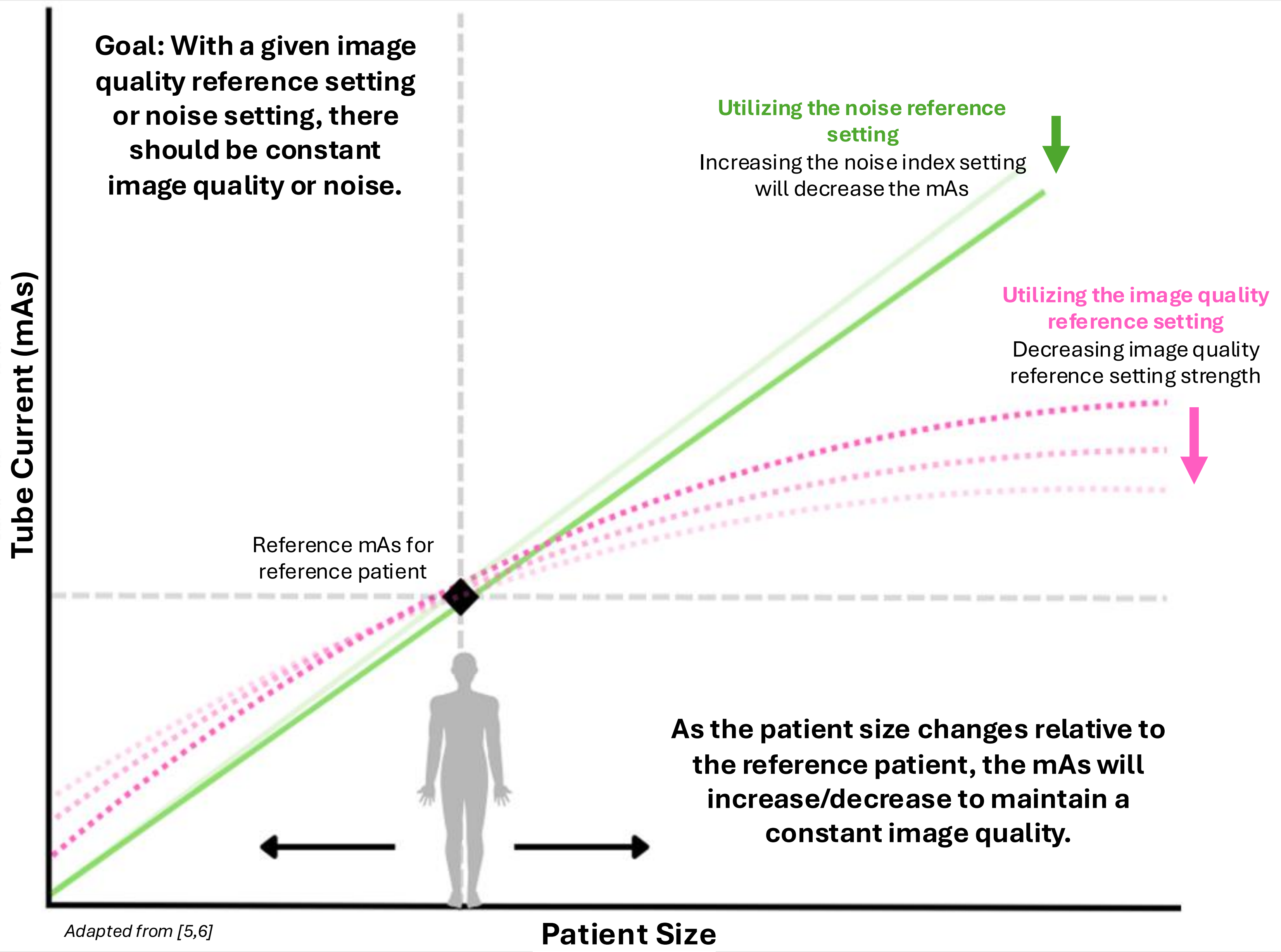
Computed Tomography Dose Index Volume ($CTDI_{vol}$)	Size Specific Dose Estimate (SSDE)	Dose Length Product (DLP)
The average absorbed dose at the center of the scanned region. Describes the radiation output of the scanner. [4]	Corrects $CTDI_{vol}$ for patient size and/or attenuation. Correction factors based on the measured effective diameter or water equivalent diameter are multiplied by the $CTDI_{vol}$. [4]	Represents total energy imparted. Scan length is multiplied by the $CTDI_{vol}$. [4]
 **$CTDI_{vol}$ [mGy] = 1/pitch x $CTDI_w$**	 **SSDE [mGy] = $CTDI_{vol}$ x f**	 **DLP [mGy cm] = $CTDI_{vol}$ x L_{scan}**
$CTDI_w$ = CT dose index that accounts for the spatial variation of dose [mGy] **Pitch** = Table distance traveled per rotation divided by the beam width	f = Correction factor for patient size *TG 204: Provides correction factors based on the patient's effective diameter.* *TG 220: Provides correction factors based on the water equivalent diameter which accounts for patient size and attenuation.*	**L_{scan}** = the total scan range [cm]

Automatic Tube Current Modulation (ATCM)

ATCM is an algorithm that uses a protocol-specific image quality reference setting to adapt the tube current depending on the patient size, anatomy being scanned, and their associated attenuation properties typically obtained from the scout image.

Reference settings differ across vendors:

- Depending on the manufacturer there could be either a noise or an image quality (IQ) reference setting that is used to ensure adequate and consistent image quality throughout a patient's scan and across different patients.
- Philips and Siemens both use an image quality reference setting while General Electric (GE) and Canon (Toshiba) use noise as a guide for the ATCM.



ATCM Reference Setting - Major Vendor Comparison

Vendor	Tube Current Modulation Reference Setting [7]	Mode of Operation
Philips	DoseRight Index (DRI)	**IQ reference setting** ATCM will adjust mAs to ensure the DRI setting that was set in protocol parameters is being met regardless of attenuation material and thickness of the patient. ⇩ **Decrease DRI** ⇩ **Decreases mAs** ⇧ **Increases noise**
Siemens	Quality Reference mAs (QRM) Noise Index	**IQ reference setting** QRM is in terms of effective mAs and establishes the image quality for a reference patient. [8] ⇩ **Decrease QRM** ⇩ **Decreases mAs** ⇧ **Increases noise**
Canon (Toshiba)	Standard Deviation (SD)	**Target standard deviation of noise** With the use of three global settings (high quality, standard, or low dose) for each body region where each setting has its own target standard deviation of noise. [9] ⇧ **Increase SD** ⇩ **Decreases mAs** ⇧ **Increases noise**
General Electric (GE)	Noise Index (NI)	**Target standard deviation of noise** The system changes the mA to ensure constant standard deviation (noise) at the center of each slice. [10] ⇧ **Increase NI** ⇩ **Decreases mA** ⇧ **Increases noise**

Iterative Reconstruction (IR)

- Iterations of the original projection data are made and compared to a model until a set criteria is met, utilized to reduce noise.
- Iterative reconstruction could allow for reduction of noise, artifacts, and dose.
- IR settings vary across manufacturers.

Major Vendor Comparison	Iterative Reconstruction [7]
Philips	iDose
Siemens	SAFIRE, ADMIRE
Canon (Toshiba)	AIDR, AIDR 3D
General Electric (GE)	ASiR, ASiR-V

↑ Iterative Reconstruction Setting

↓ Noise

With noise reduction capabilities of iterative reconstruction, dose can be reduced while maintaining adequate image quality

Teaching Point 4:
Optimization Strategies for CT Procedures

Recommendations for CT Procedures

Best Practices Guidelines for CT-Guided Interventional Procedures [11]

Hardware Recommendations:

- CT scanners should be **multidetector (MDCT)**
- CT scanners should be able to **cover at least 10 mm** of the patient for a single axial scan and **produce at least 3 images**

Recommendations for the Planning Helical Scan CT:

- Technique should **adapt to the patient**
- Scan length should be **limited to 75 mm**
- Should contribute to **no more than 50% of the total DLP**

Optimization Strategy 1:

Review site-specific CT procedure dose averages and compare with nationally published data to determine opportunities for dose reduction

An initial step of optimizing CT procedures is to review typical DLP values for common procedures at the site.

Yang et al. performed a retrospective study and evaluated dose metrics associated with CT interventional procedures.[12] The evaluation was focused on the helical scans used during interventional procedures; DLP values for 4 different types of procedures are shown below.

Typical Procedure Dose Ranges From One Study[12]

Procedure	Number of Procedures	DLP (mGy*cm) 25th Percentile	DLP (mGy*cm) 50th Percentile	DLP (mGy*cm) 75th Percentile
Liver Ablation	394	1612	**2351**	3405
Chest Aspiration	282	488	**657**	929
Liver Biopsy	997	771	**1175**	1903
Abdominal Drainage (1 drain)	1571	748	**1125**	1866
Overall Procedures	8213	643	**1043**	1798

Adapted from [12]

Optimization Strategy 2:
Use intermittent CT fluoroscopy scan mode over helical acquisitions

Intermittent CT fluoroscopy is an axial scan with fixed technique that typically has low mAs and a small fixed scan range.

Multiple studies have found that patient dose can be reduced by utilizing intermittent CT fluoroscopy mode instead of helical acquisitions.

- Cahalane et al. evaluated dose of two cohort groups: one group utilized only helical scans, and the second cohort group utilized only intermittent CT fluoroscopy (except for the planning helical CT scan) for musculoskeletal needle biopsies.[13]
  - **It was found that the DLP and $CTDI_{vol}$ were significantly higher for the group that utilized only helical scans compared to the intermittent CT fluoroscopy group.**

- Goiffen et al. evaluated procedure time and patient dose with a cohort group that utilized only helical scans versus a cohort group that utilized at least one intermittent CT fluoroscopy scan during the procedure.[14]
  - **It was found that by utilizing intermittent CT fluoroscopy the procedure time decreased by 27%, $CTDI_{vol}$ decreased by 23% and DLP decreased by 50%.**

Takeaway: Although helical acquisitions may be clinically necessary, whenever plausible, the use of intermittent CT fluoroscopy instead of helical acquisitions could allow for a greater reduction in patient dose.

Optimization Strategy 3:
Adjust the helical scan parameters with use of fixed techniques

Although intermittent CT fluoroscopy is a lower dose mode option for CT-guided procedures, there may still be a clinical need for performing procedure helical scans. However, since procedure CT use is not for diagnosis, the helical scan should not have scan parameters that are identical to a site's diagnostic protocol.

Thus, a way to reduce patient dose is by adjusting the helical scan parameters with the use of fixed techniques.

- Tam et al. standardized their CT guided biopsy procedures by creating a technique chart based on patient size and body part so that the technique could be set fixed for the helical scans utilized during the procedure.[15]
  - **The new protocol with utilization of a technique chart showed a decrease in DLP by 72.3% and noise increase without affecting the procedure.**

- Amrhein et al. evaluated CT fluoroscopy guided lumbar pain injections by targeting the planning CT and using fixed technique instead of tube current modulation. The fixed technique was 100 mA if the patient diameter was greater than 30 cm and 50 mA if the patient diameter was less than 30 cm. [16]
  - **The new protocol with fixed technique was acceptable and had a mean $CTDI_{vol}$ reduction by a factor of 9.**

Takeaway: CT for procedures is used as a guidance tool not for diagnosis, so helical scans do not require the same scan parameters as diagnostic helical scans. Thus, scan parameters can be adjusted by setting fixed techniques based on patient size.

Optimization Strategy 4:
Adjust the Helical Scan Parameters with Adjustment of ATCM

While setting a fixed technique for procedure helical scans can reduce patient dose, using a limited number of mAs values can result in inconsistent procedure image quality between patients.

Adjusting ATCM instead of using fixed techniques enables mAs values to be based on patient-specific size and attenuation properties. Dose reduction can be accomplished by adjusting the noise setting or reference mAs parameters of ATCM and can result in more consistent image quality for procedures.

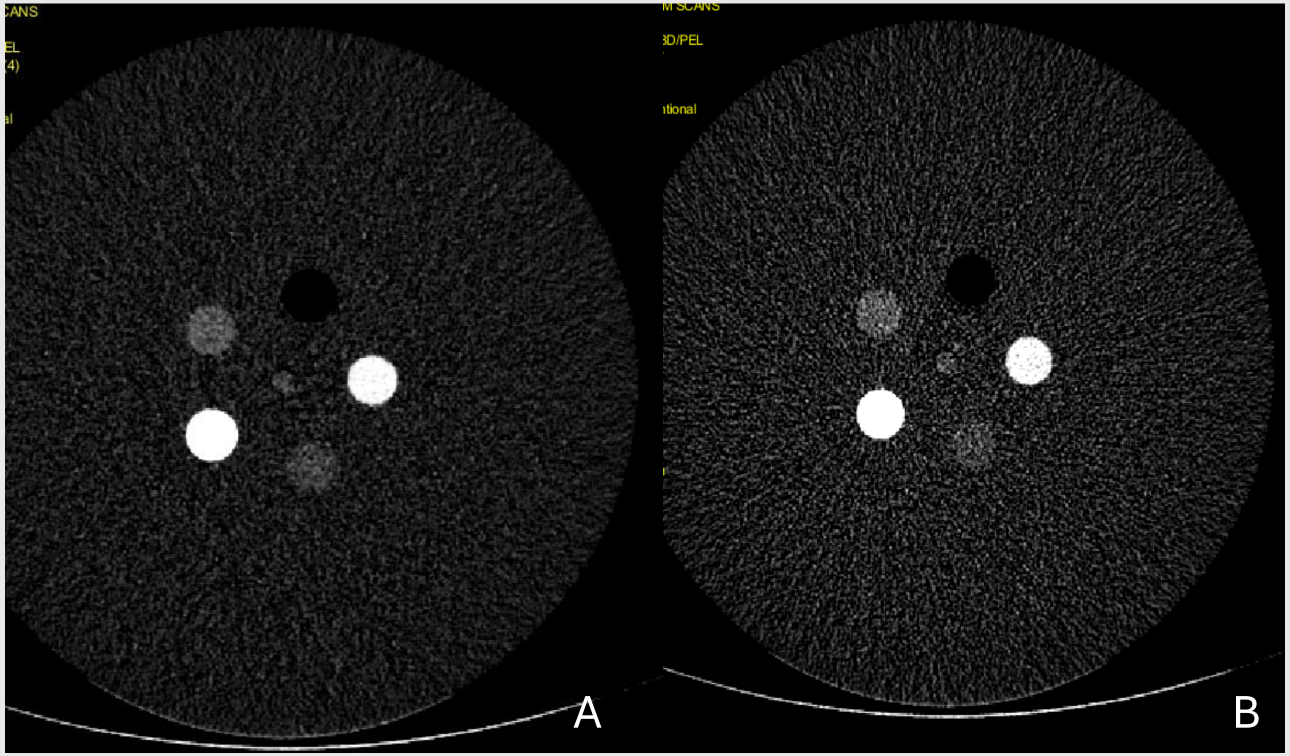
- Leng et al. wanted to adjust the helical scan that was used for CT guided renal tumor cryoablations, that had similar scan parameters to their diagnostic routine abdomen CT protocol. With the use of a noise simulation tool and radiologists scoring of imaging they were able to determine an acceptable amount of dose reduction.[17]
    - **It was found that 50% dose reduction from their original helical scan protocol was the most amount of dose reduction acceptable for this procedure.**

Takeaway: Adjusting the ATCM of helical scans allows for patient dose reduction as well as more consistent image quality.

Optimization Strategy 5:
Change filtered back projection (FBP) to iterative reconstruction for intermittent CT fluoroscopy mode

Some scanners offer iterative reconstruction for the reconstruction of intermittent CT fluoroscopy mode acquisitions. Utilizing iterative reconstruction instead of FBP allows for improvement of image quality with the possibility of dose reduction.

- **If adjusting the settings from FBP to Iterative Reconstruction**
    - Radiologists could decide to utilize intermittent CT fluoroscopy scan mode over a helical scan due to the improvement of image quality, which would result in dose reduction.
    - The technique utilized for intermittent CT fluoroscopy could possibly be reduced since the iterative reconstruction settings can decrease noise, thus a possibility for dose reduction.



Phantom Images
A: Intermittent CT Fluoroscopy (CCT Single) with increased iterative reconstruction level (iDose 4)
B: Intermittent CT Fluoroscopy (CCT Single) with FBP

Teaching Point 5:
Helical Acquisition Optimization Can Lead to Dose Reduction in CT Procedures

A Single Institution Study for CT Procedure Optimization

Purpose

To investigate the most common CT procedures and scan modes utilized and to optimize ATCM helical scan parameters and iterative reconstruction strength.

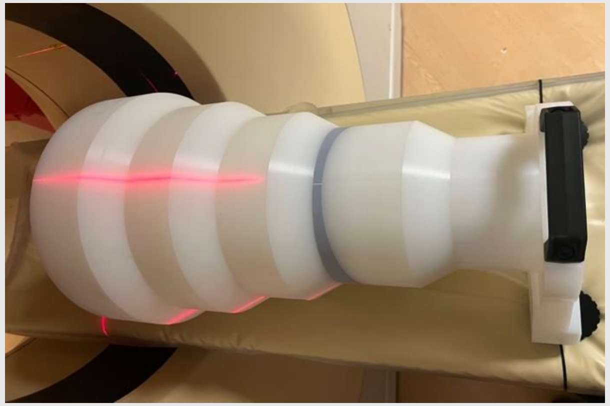
Methods to Adjust ATCM and Iterative Reconstruction

1. Cohorts for top procedures performed at the facility were evaluated.

Results:

- Biopsy and drainage procedures were the top procedures performed
- Radiologists utilized two scan modes: Helical Scan and Intermittent CT Fluoroscopy Scan
    - Biopsy Cohort: 82% of the total DLP was from the helical scans (including the planning CT)
    - Drainage Cohort: 93% of the total DLP was from the helical scans (including the planning CT)

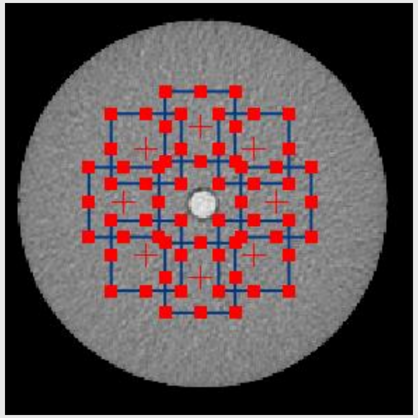
The parameters of the helical scan were similar to the facility's routine diagnostic abdomen pelvis protocol (DRI 15 and iDose 3) and thus helical scan was targeted for dose optimization.

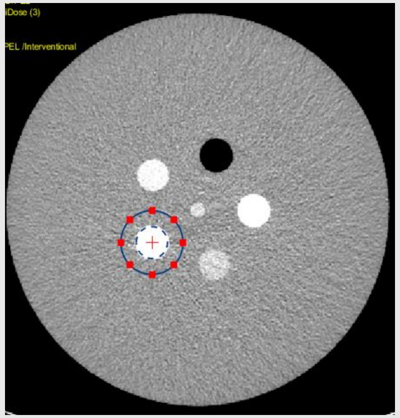


2. Performed a phantom analysis of the helical scan protocol when adjusting parameters: ATCM and iterative reconstruction settings.

Results:

- With the use of the Mercury Phantom and imQuest software, helical scans were performed with a combination of setting adjustments to determine possible dose reduction and the impact on image quality.





3. Had discussion of findings and recommendations with the radiologists.

Results:

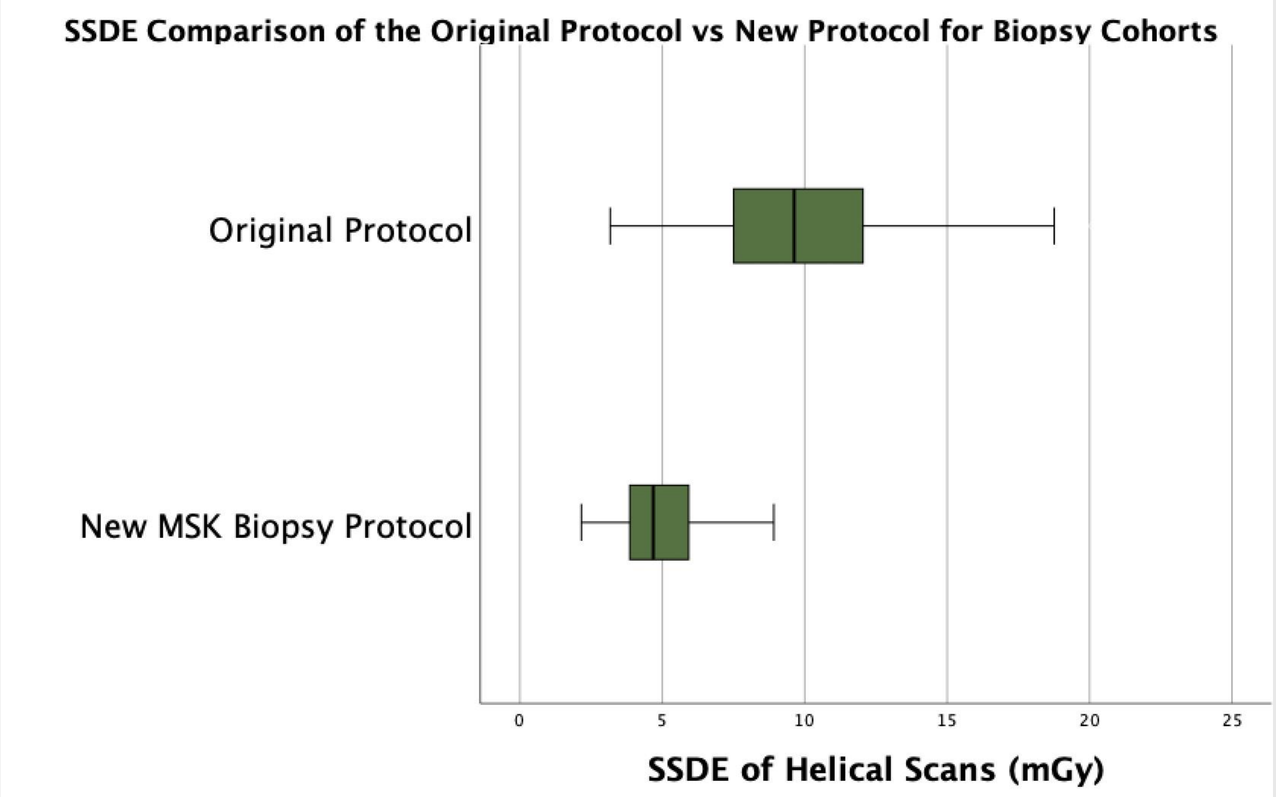
Two new protocols were developed:

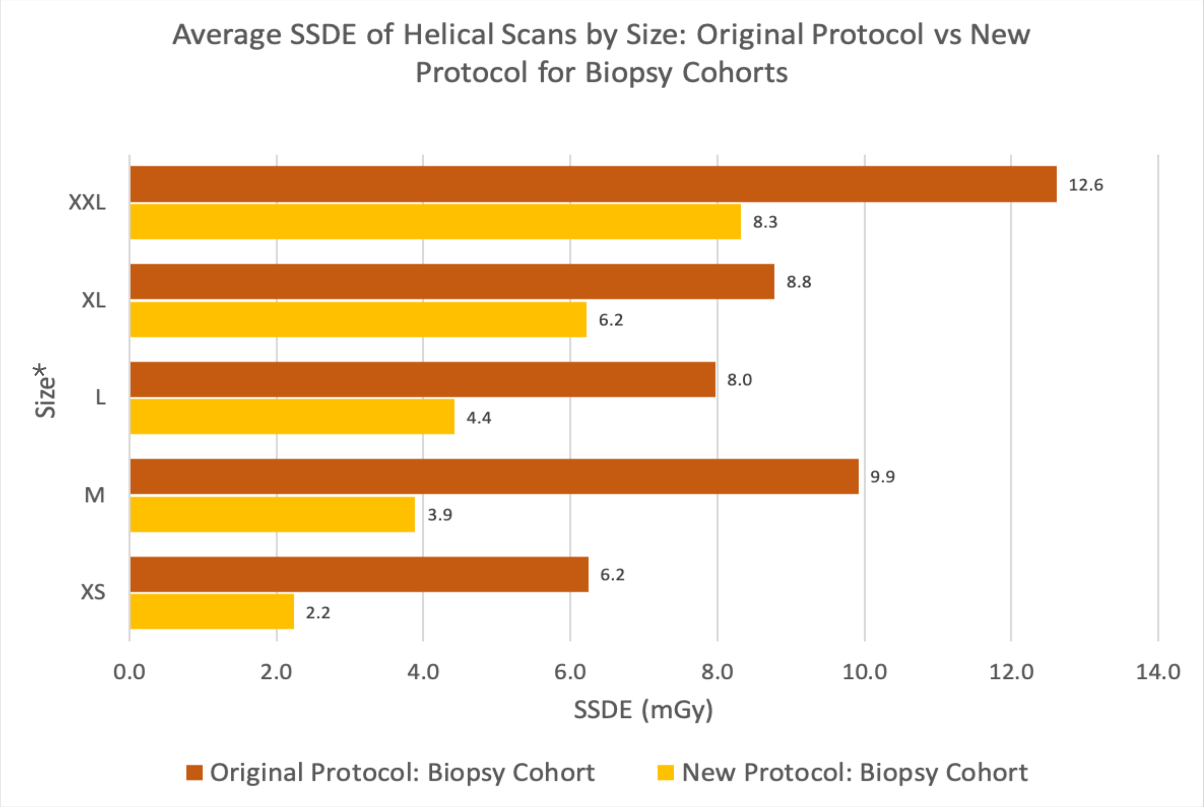
1) Adjusted original protocol parameters (ATCM and IR) to new settings (DRI 12 and iDose 4) for an approximate dose reduction of 29% with 9% noise increase.

2) Created a new protocol (DRI 11 and iDose 4) for musculoskeletal biopsy procedures with a dose reduction of approximately 37% with noise increase of about 14%.

4. Implemented the new protocols.

Optimization Results: Bone Biopsy Cohort

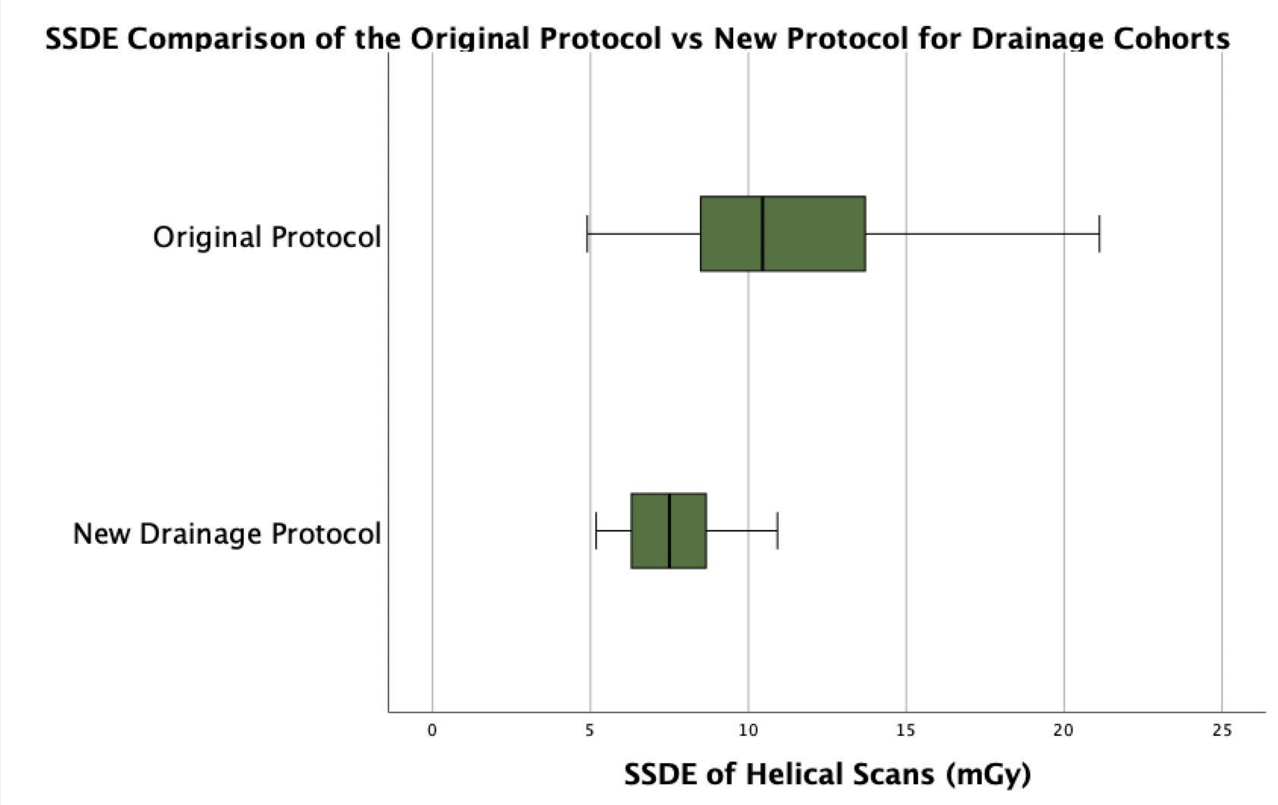


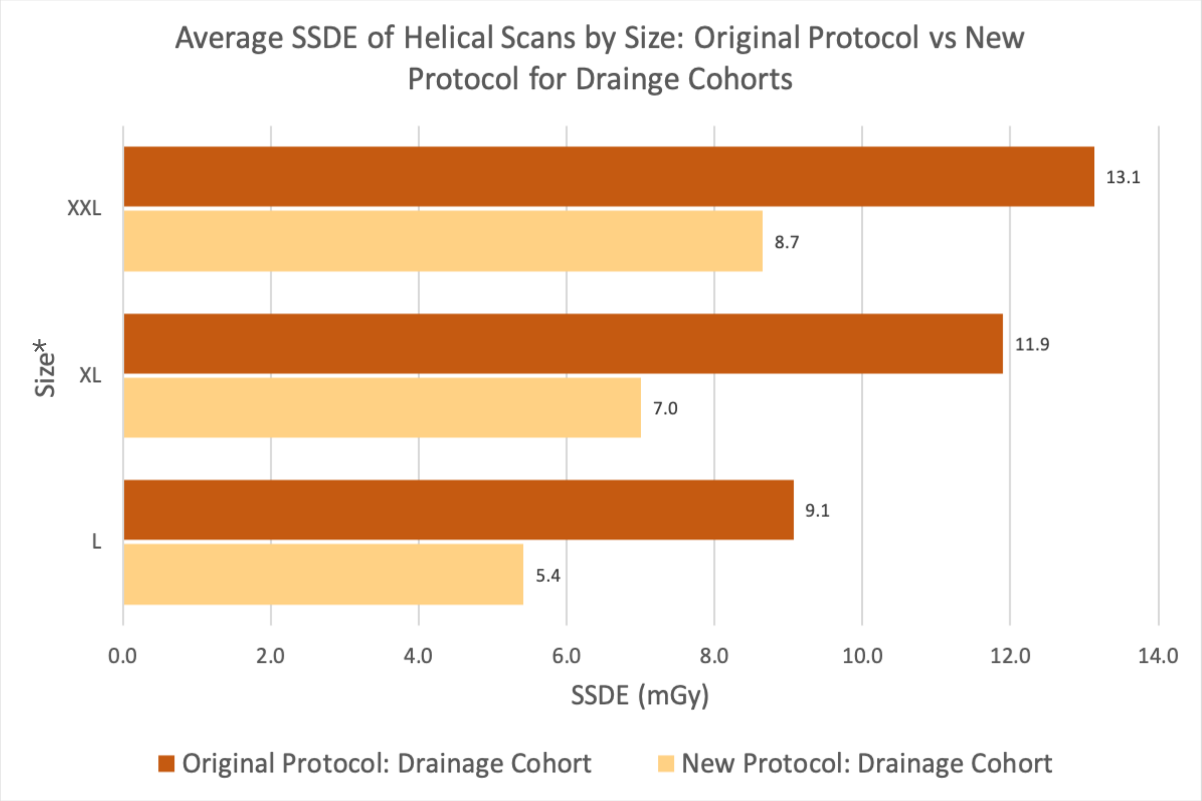


**no patients in S category*

Resulting dose metric analysis found a statistically significant **dose reduction with a mean percent change of 51%** between the original protocol and new protocol for the biopsy cohort, specifically for musculoskeletal biopsies, as well as acceptable physician approved image quality.

Optimization Results: Drainage Cohort





****no patients in XS, S, or M category***

Resulting dose metric analysis found a statistically significant **dose reduction with a percent change of 34%** between the original protocol and new protocol for drainage procedures, as well as acceptable physician approved image quality.

Single Institution Study Conclusions

- The helical scan utilized for procedures often **does not require diagnostic image quality**.
- Two protocol parameters can be adjusted:
  1. The automatic tube current modulation **image quality reference parameter can be decreased.**
  2. **Iterative reconstruction settings can be increased** (noise reduction) to optimize the protocol for procedure tasks.
- **A dose reduction of over 30% as compared with the original diagnostic helical scan can be achieved while maintaining acceptable image quality for the physician.**

Conclusions

Analyze the protocols used for CT procedures

- Look at procedure workflow, the scan modes used, and their scan parameters
- Compare site-specific average total DLPs for different procedure types with published values to determine which procedures need optimization
- Utilize intermittent CT fluoroscopy instead of helical acquisitions when possible
- MPRs can be used to improve targeting

Adjust the helical scan parameters

If the helical scan has scan parameters similar to a routine diagnostic quality helical scan, then adjustments can be made to lower patient dose, such as:

- Set a fixed technique based on patient size
- Adjust the automatic tube current modulation settings
- In combination, adjust the automatic tube current image quality reference setting and the iterative reconstruction setting
- Limit the helical scan range

Takeaway: Utilizing helical scans during CT procedures may be necessary to enhance lesion conspicuity, however scan parameters do not need to match routine diagnostic protocols. Thus, patient dose can be reduced by examining the protocol and adjusting the scan parameters.

References

1. Bogdanovic S., Sutter R., Zubler V. (2023). Spine injections: the rationale for CT guidance. *Skeletal Radiol*. 52, 1853-1862. https://doi.org/10.1007/s00256-022-04188-1
2. Saba L., Saba F., Dagan R., De Filippo M., Marcy P.Y. (2022). Technical efficacy and safety of CT-guided transforaminal periradicular infiltration using CT foot switches and MPR images. *Acta Biomed,* 92(6), e2021315. https://doi.org/10.23750/abm.v92i6.10588.
3. Huang W. M., Chen C. H., Liang S. H., Huang C. Y., Cheng S. M., Sheu C. Y., Huang C. C. (2018). Multiplanar reconstruction technique for difficult computed tomography-guided lung biopsy: Improved accuracy and safety. *Thorac Cancer,* 9(10), 1333-1337. https://doi.org/10.1111/1759-7714.12835.
4. X-Ray Dosimetry in Projection Imaging and Computed Tomography. In Bushberg J. T., Seibert J. A., Leidholdt E. M. Jr., Boone J. M. (2021). *The Essential Physics of Medical Imaging (4th edition)*. Lippincott Williams and Wilkins.
5. Philips iPatient, *Patient-centered CT imaging: New methods for patient specific optimization of image quality and radiation dose*. (2012). www.philips.com/iPatient
6. Rego, S., Yu, L., Bruesewitz, M., Vrieze, T., Kofler, J., & McCollough, C. (2007). Care DOSE4D CT Automatic Exposure Control System. *Radiological Society of North America 2007 Scientific Assembly and Annual Meeting*. Mayo Clinic. https://www.mayo.edu/research/documents/care-dose-4d-ct-automatic-exposure-control-system/doc-20086815
7. AAPM CT Lexicon v2.0. *American Association of Physicists in Medicine*. (2022). https://www.aapm.org/pubs/ctprotocols/documents/ctterminologylexicon.pdf. Retrieved Oct. 2024.
8. Siemens Healthcare GmbH. *Somatom Instructions for Use - Force syngo CT. Siemens Healthineers Document Library*. (2023). https://content.doclib.siemens-healthineers.com/rest/v1/view?document-id=983114
9. Angel, E. (2012). *SUREExposure™ Low Dose Diagnostic Image Quality*. Canon (Toshiba) Medical Systems.
10. GE Training in Partnership. *AutomA / SmartmA Theory*. *GE Healthcare*. (n.d.). https://www.gehealthcare.com/-/jssmedia/05670158f22f497190e3b163ad1fd581.pdf?la=en-us
11. Jones, A. K., Dixon, R. G., Collins, J. D., Walser, E. M., Nikolic, B. (2019). Best Practices Guidelines for CT-guided Interventional Procedures. *J Vasc Interv Radiol*. 29(4), 518-19. https://doi.org/10.1016/j.jvir.2017.10.021
12. Yang, K., Ganguli, S., DeLorenzo, M. C., Zheng, H., Li, X., & Liu, B. (2018). Procedure Specific CT Dose and Utilization Factors for CT-guided Interventional Procedures. *Radiology*. 289, 150-157. https://pubs.rsna.org/doi/epdf/10.1148/radiol.2018172945
13. Cahalane, A. M., Habibollahi, S., Staffa, S. J., Yang, K., Fintelmann, F. J., & Chang, C. Y. (2023). Helical CT versus intermittent CT fluoroscopic guidance for musculoskeletal needle biopsies: impact on radiation exposure, procedure time, diagnostic yield, and adverse events. *Skeletal radiology*, *52*(6), 1119–1126. https://doi.org/10.1007/s00256-022-04226-y
14. Goiffon, R. J., Best, T. D., Wrobel, M. M., McDermott, S., Sharma, A., Chang, C. Y., Yang, K., Fintelmann, F. J. (2021). Reducing Time and Patient Radiation of Computed Tomography-guided Thoracic Needle Biopsies With Single-rotation Axial Acquisitions: An Alternative to "CT Fluoroscopy". *J Thorac Imaging*, 36(6), 389-396. https://doi.org/10.1097/RTI.0000000000000609
15. Tam, A. L., Ensor, J. E., Zvavanjanja, R. C., Philip, A., Abdelsalam, M. E., Huang, S. Y., Gupta, S., & Jones, A. K. (2015). JOURNAL CLUB: Standardizing CT-Guided Biopsy Procedures: Patient Dose and Image Noise. *American Journal of Roentgenology*, *205*(4), W390–W399. https://doi.org/10.2214/AJR.14.13324
16. Amrhein, T. J., Schauberger, J. S., Kranz, P. G., Hoang, J. K. (2016). Reducing Patient Radiation Exposure From CT Fluoroscopy–Guided Lumbar Spine Pain Injections by Targeting the Planning CT. *American Journal of Roentgenology,* 206(2), 390-394. https://doi.org/10.2214/AJR.15.14436
17. Leng, S., Atwell, T.D., Yu, L., Mandrekar, J., Lewis, B. D., Woodrum, D.A., McCollough, C. H. (2011). Radiation dose reduction for CT-guided renal tumor cryoablation. *American Journal of Roentgenology,* 196(5), W586. https://doi.org/https://doi.org/10.2214/AJR.10.5144