Dual Energy CT cookbook

A guide to Monoenergetic Plus imaging in RT

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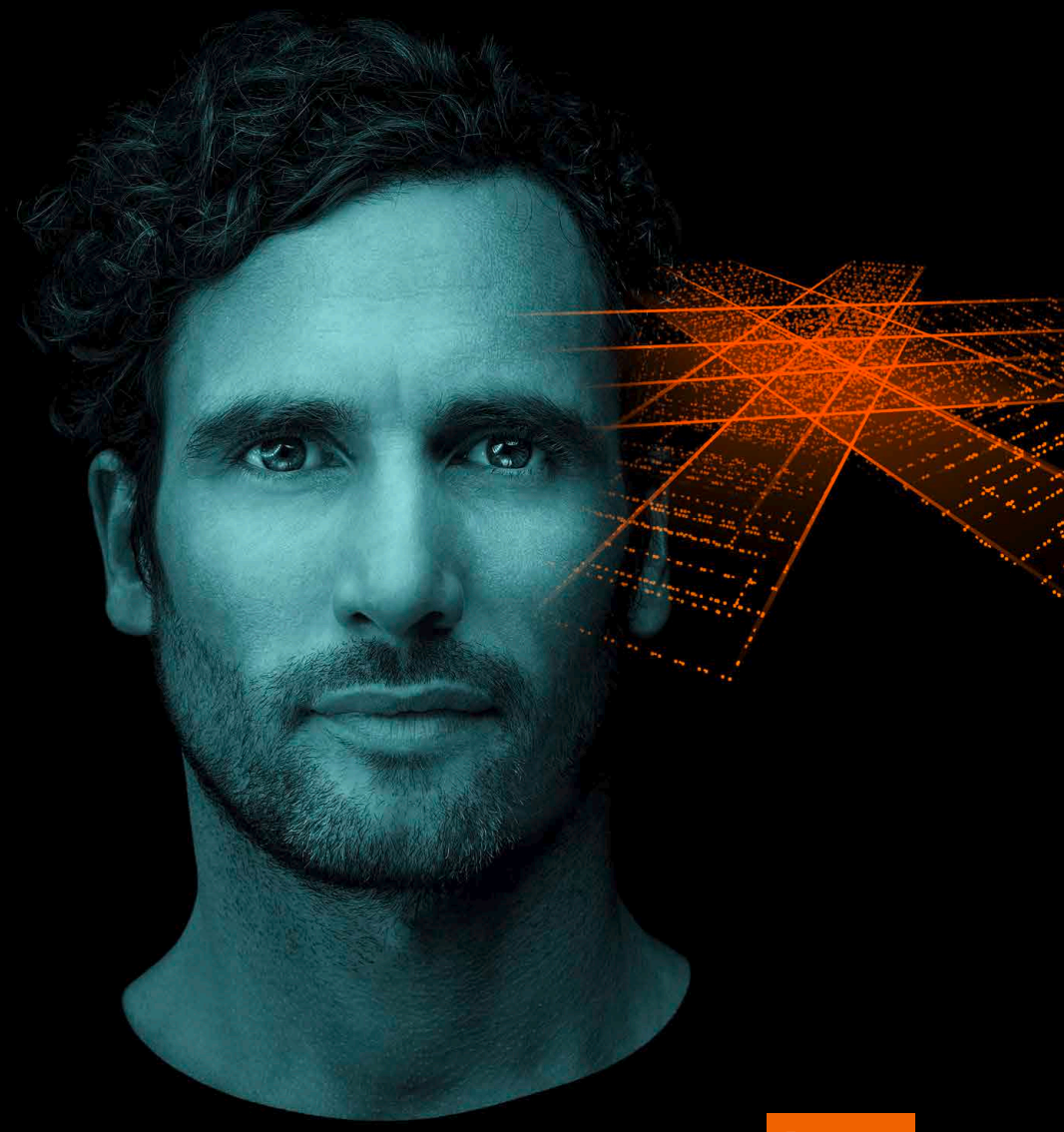

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For SOMATOM CT users

SIEMENS Healthineers

Foreword

Radiation Oncology is experiencing growth in the use of Dual Energy imaging in treatment planning. While it can seem daunting to start integrating this technology in Radiation Therapy departments, the trend is inevitable and has been embraced by physicists and physicians alike.

Hospital del Mar, Barcelona, Spain, together with Siemens Healthineers, have investigated and developed optimal way of using Dual Energy CT for treatment planning. We are pleased to share the knowledge and insights we gathered.

This publication is a attempt to propagate this information for Siemens SOMATOM Dual Spiral Dual Energy users. It presents a series of study protocols and practical tips and tricks for several body regions so that everyone can benefit from Hospital del Mar's experience. The information provided in this booklet can help support your entire clinical team in optimizing your workflow and providing the best imaging possible to cancer patients undergoing radiation therapy.

Finally, we look forward to hearing your feedback and suggestions, so that we at Siemens Healthineers can continually improve and partner with you in the care of your patients.

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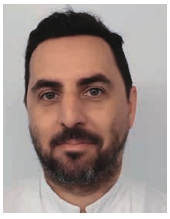

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Content

Evaluation methods
Qualitative image assessment **4**
Quantitative image assessment **5**

Three key points to understand Dual Spiral Dual Energy for RT
1. What is Dual Energy? **6**
2. What is Monoenergetic Plus? **6**
3. What are the potential benefits in Radiation Oncology? **6**

Head and neck imaging
Motivation **7**
Scan protocol **7**
Tips and tricks **7**
Iodine contrast tips and tricks in RT **9**
Key takeaway **9**

Brain imaging
Motivation **10**
Scan protocol **10**
Tips and tricks **12**
Key takeaway **12**

Breast imaging
Motivation **13**
Scan protocol **13**
Tips and tricks **13**
Key takeaway **14**

Prostate imaging
Motivation **15**
Scan protocol **15**
Tips and tricks **15**
Key takeaway **16**

Results
Optimum series for target delineation **17**
Practical implementation of Dual Energy **17**

Conclusion **18**

Theory **19**

References **22**

Evaluation methods

The goal of this evaluation was to establish the best keV level for the target delineation at the different clinical area, because Monoenergetic images can be generated with a range of 40–190 keV. Before going to the evaluation, four different keV levels were selected in the pre-study and the following evaluation was performed.

Qualitative image assessment

The different image series (Monoenergetic Plus 40 keV[1], 45 keV[1,2], 50 keV[1], 55 keV[1,2], and mix series (120 kV equivalent)) were assessed in a random order by four radiation oncologists with different levels of expertise (20, 10, 3, and 2 years in experience) in CT imaging for four different body regions: 1) Head and neck (8 cases), 2) Brain (10 cases), 3) Breast (10 cases), and 4) Prostate (7 cases) in order to evaluate qualitative image assessment.

The reviewers were blinded to the applied reconstruction technique, but were aware that every case has cancer on the assessed image series. Images were displayed using the standard soft tissue window (window level 150; window width 600) as axial slices. Radiation oncologists were allowed and encouraged to alter the window settings at all available CT series if required in order to improve visualization. Qualitative image assessments were rated using a 5-point Likert scale (1 = not usable for target delineation, 2 = limited, 3 = moderate, 4 = good, 5 = excellent) for overall image quality, ease of target delineation (ranging from 1 = no delineation possible to 5 = clear border is provided for target delineation).

Example of the qualitative results

Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Overall image quality (1–5)					
Target delineation (1–5)					

Image quality: 1 = not usable for target delineation, 2 = limited, 3 = moderate, 4 = good, 5 = excellent
Target delineation: from 1 = no delineation possible to 5 = clear border is provided for target delineation

[1] *Optional*
[2] *Requires syngo.via and syngo.CT DE Monoenergetic Plus*

Quantitative image assessment

Region of interests (ROI; size 12–36 mm^2) were placed in a tumor and surrounding tissue (e.g., ipsilateral sternocleidomastoid muscle, brain tissue, iliopsoas muscle) to measure signal attenuation in mean Hounsfield units (HU). In cases where tumor necrosis was present, the ROI was placed in an peripheral vital tumor area. In general, ROI_S were placed as large as possible, but with an adequate distance to surrounding anatomical structures and to avoid focal areas of heterogeneity. These measurements were performed three times and resulting values were averaged to ensure data consistency. The formula for calculating the tumor contrast-to-noise ratio (CNR) was as follows:

$$\mathbf{CNR = (ROI_T - ROI_S) / SD_S}$$

(ROI_T: average tumor enhancement, ROI_S: attenuation of surrounding tissue, SD_S: standard deviation of the surrounding tissue)

All ROI measurements and calculated CNR were considered as quantitative image assessment parameters. Interobserver variability for target delineation was also evaluated by intersection (overlap of the ROIs) over the union, because union reflects the spread of volumes. The high value of this parameter indicates a variability among observers.

Example of the quantitative results

Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Interobserver variability (intersection / union; %)					
Tumor enhancement (HU)					
Surrounding tissue attenuation (HU)					
CNR					

Three key points to understand Dual Spiral Dual Energy [1] for RT

1. What is Dual Energy?

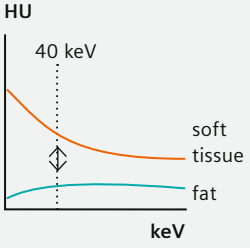
Unlike a standard 120 kV scan, Dual Energy (DE) CT requires two spiral scans acquired at 80 kV and 140 kV (Dual Spiral DE). The two scans at two different energies provide images with different HU values, varying by the tissue type [1]. This information is then used to generate Monoenergetic Plus [2], [3] image by projecting the measured HU values of the low and the high kV scan.

Radiation dose in DE scans is equal to single energy acquisition.

2. What is Monoenergetic Plus [3]?

Monoenergetic Plus is an application that simulates what the actual image would look like if the study was acquired with a monochromatic X-ray beam at that energy in a range of 40–190 keV.

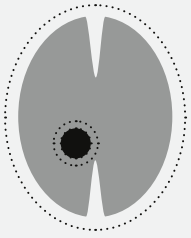
The following steps are automatically performed in order to create the result: 1) fully automated Dual Energy acquisition, 2) non-rigid registration is performed to ensure the exact matching of both kV images, 3) the results are automatically reconstructed based on user's preference.



3. What are the potential benefits in Radiation Oncology?

- Fewer beam-hardening artifacts due to virtual monochromatic spectrum
- Monoenergetic Plus lets users easily compare and quantify lesions and tissues.

This means:
- Target delineation improvement [4]
- Target margin reduction [4]
- Potentially less target delineation variability



Head and neck imaging

Motivation

One challenge of CT head and neck imaging compared with MRI is the lower soft tissue contrast, which makes it difficult to differentiate lymph nodes, tumor, and blood vessels for target delineation. CT Dual Energy Monoenergetic Plus has the potential to improve target delineation and higher CNR. In order to validate this hypothesis, qualitative and quantitative assessments were performed.

Scan protocol

Scan protocol	Scan parameters	Reconstruction parameters	Important remarks
Topogram			• Craniocaudal position
Neck RT	120 kV CTDI: 18.17 mGy	Slice thickness: 1.5 / 1.2 mm Reconstruction kernel: B30 / Br38	• Optimized kV with DirectDensity™,[1] if available • Used for dose calculation
Contrast	Delay 100 s		• Total amount: 110 ml (300 mgI iodine) • Injection rate: 2-2.5 ml / second (variable amount based on body weight may be considered)
Dual Energy Head and neck	1) 80 kV Pitch: 0.6 CTDI: 8.57 mGy 2) 140 kV Pitch: 0.8–1.2 (it may vary by scanner type) CTDI: 9.88 mGy	Slice thickness: 1.5 / 1.2 mm Reconstruction kernel: D30 / Qr36 Auto post processing: DE_Mono_40 keV	• Iterative reconstruction such as SAFIRE[2] may be used • Body part: Head & Neck • iMAR[2] should be applied when metal artifacts are observed (e.g., dental implant)

Tips and tricks

- Standard Dual Energy protocol[3] is used in order to create RT Head and neck protocol. Adjustments of CTDI, slice thickness, and reconstruction kernel as well as auto postprocessing results are required before saving as RT protocol.
- To ensure the exact matching of both kV images, non-rigid registration is performed automatically prior to generating Monoenergetic Plus images.
- Delay time should be at least 75 seconds, because contrast is plateauing during Dual Energy acquisition.

[1] *Optional; DirectDensity™ reconstruction is designed for use in Radiation Therapy Planning (RTP) only. DirectDensity™ reconstruction is not intended to be used for diagnostic imaging.*
[2] *Optional*
[3] *Protocol: DE_Abdomen_LiverVNC_late*

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Qualitative image assessment	Overall image quality (1–5)	4.1	3.7	4.0	3.3	3.0
	Target delineation (1–5)	4.0	3.7	3.6	3.6	3.0

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Quantitative image assessment	Interobserver variability (%)	36.9	30.8	27.9	31.6	31.6
	Tumor enhancement (HU)	230.7	193.4	163.1	139.8	92.8
	Noise (HU)	16.0	13.9	12.0	10.6	8.7
	Soft tissue attenuation (HU)	99.0	89.7	82.5	77.0	66.4
	CNR	8.9	8.0	7.2	6.3	3.2

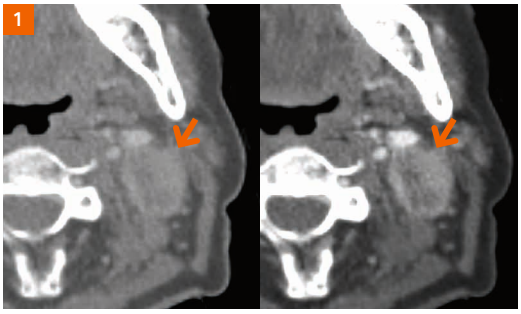


Figure 1:
left: 120 kV
right: Monoenergetic Plus 40 keV

Overall image quality is rated highest at 40 keV.

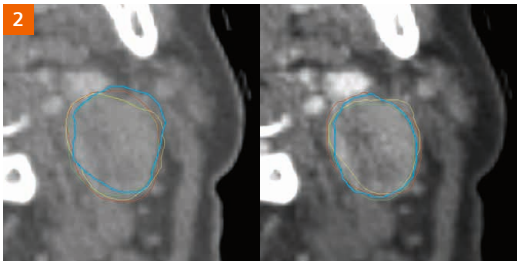


Figure 2:
left: 120 kV
right: Monoenergetic Plus 40 keV

Interobserver variability is rated the best at 40 keV, improved from 3.16 (120 kV) to 2.71 (40 keV); this means less variability.

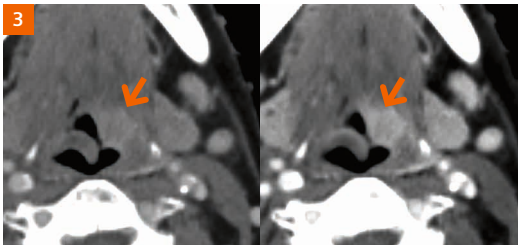
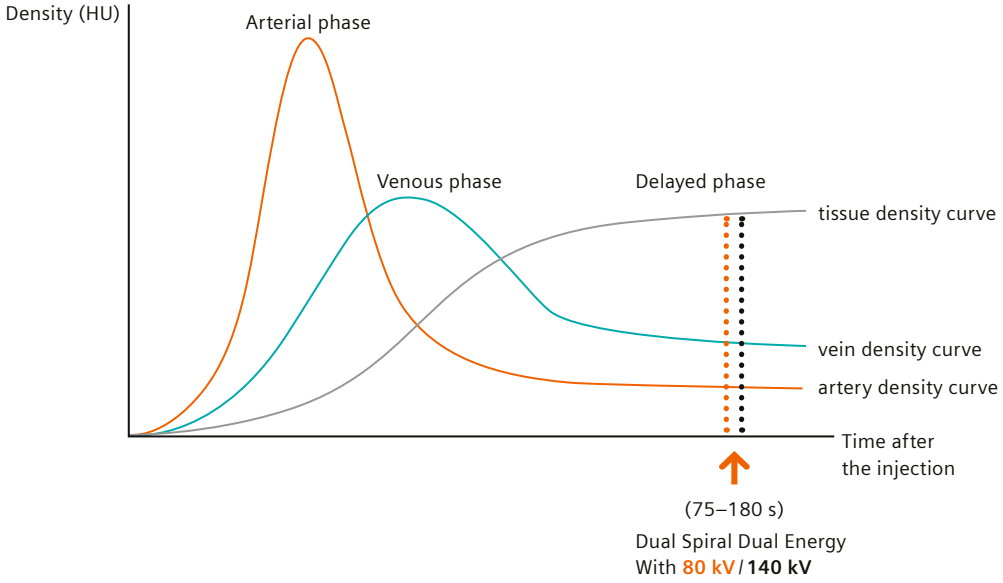


Figure 3:
left: 120 kV
right: Monoenergetic Plus 40 keV

Overall, tumor visualization is considerably improved at 40 keV.

Iodine contrast tips and tricks in RT

One of the inherent issues of computed tomography (CT) versus magnetic resonance imaging (MRI) is the soft tissue contrast. Use of iodine contrast allows enhanced visualization of target volumes and adjacent organs at risk; making delineation of radiotherapy target volumes and organs at risk potentially easier, particularly for head and neck imaging. Here is the summary of how the iodine contrast is used when applying Dual Spiral Dual Energy for RT. (The theory is applicable for all clinical areas.)



- When using Dual Spiral Dual Energy with iodine contrast, keep in mind that delay time is set to at least 75 seconds (delayed phase) where the time density curve is close to flat, so that two consecutive scans at 80 kV and 140 kV have almost the same amount of iodine contrast information.
- Intravenous cannula is required prior to imaging

Key takeaway

- Based on the assessment, 40 keV was found to be the optimum keV level for target delineation, because it showed significant improvement for 1) overall image quality, 2) target delineation, 3) CNR, and 4) interobserver variability.
- Two acquisitions are needed for head and neck imaging: 1) 120 kV acquisition without iodine contrast for dose calculation and 2) Dual Energy acquisition with the iodine contrast used for target delineation. Therefore, non-contrast image is matched with Monoenergetic Plus 40 keV in the TPS.

Brain imaging

Motivation

The current utilization of CT in brain tumor typically involves alignment with MRI scans. MRI provide the soft tissue contrast necessary for tumor identification and improved structure delineation, while CT images support convenient generation of the electron density maps necessary for dose calculation.

However, due to the fact that 1) MRI is not always applicable due to its availability and 2) patients may have a contraindication for MRI, CT still plays a very important role to address the target delineation.

Scan protocol

Scan protocol	Scan parameters	Reconstruction parameters	Important remarks
Topogram			• Craniocaudal position
Brain RT	120 kV	Slice thickness: 1.5 / 1.2 mm Reconstruction kernel: B30 / Br38	• Optimized kV with DirectDensity™,[1] if available • Used for dose calculation
Contrast	Delay 180 s		• Total amount: 80 ml • Injection rate: 3 ml / s
Dual Energy Brain	1) 80 kV Pitch: 0.6 CTDI: 8.57 mGy 2) 140 kV Pitch: 0.8–1.2 (it may vary by scanner type) CTDI: 9.88 mGy	Slice thickness: 1.5 / 1.2 mm Reconstruction kernel: D30 / Qr36 Auto post processing: DE_Mono_40 keV	• Iterative reconstruction such as SAFIRE[2] may be used • Body part: Head • iMAR[2] should be applied when metal artifacts are observed (e.g., dental implant)

[1] *Optional; DirectDensity™ reconstruction is designed for use in Radiation Therapy Planning (RTP) only. DirectDensity™ reconstruction is not intended to be used for diagnostic imaging.*
[2] *Optional*

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Qualitative image assessment	Overall image quality (1–5)	4.0	3.7	3.5	3.5	3.5
	Target delineation (1–5)	3.6	3.7	3.6	3.6	3.4

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Quantitative image assessment	Interobserver variability (%)	38.5	28.6	34.5	37.0	34.5
	Tumor enhancement (HU)	115.6	98.3	83.5	74.1	53.6
	Noise (HU)	21.0	17.5	12.6	11.1	12.0
	Soft tissue attenuation (HU)	86.1	78.6	72.1	68.5	59.8
	CNR	2.3	2.2	2.2	1.9	1.6

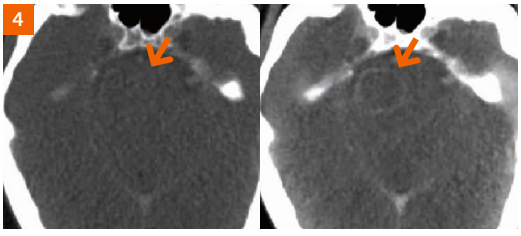


Figure 4:
left: 120 kV
right: Monoenergetic Plus 40 keV

A lot of guesswork needed at 120 kV, while the border of the tumor is clearly shown at 40 keV.

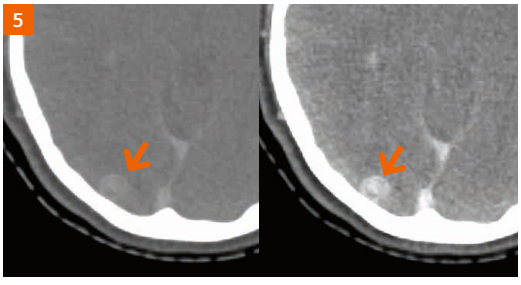


Figure 5:
left: 120 kV
right: Monoenergetic Plus 40 keV

Clear soft tissue contrast is demonstrated for brain metastasis at 40 keV.

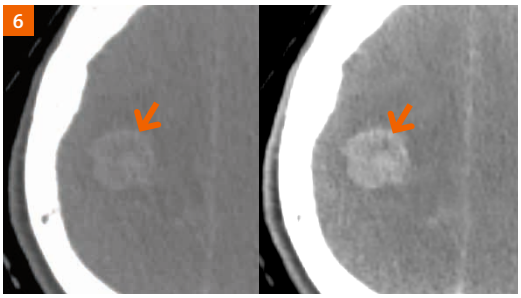


Figure 6:
left: 120 kV
right: Monoenergetic Plus 40 keV

Overall, tumor visualization is markedly improved at 40 keV.

Tips and tricks

- Standard Dual Energy protocol[1] should be used in order to create RT Head protocol. Adjustments of CTDI, slice thickness, body part (to Head), and reconstruction kernel as well as auto postprocessing results are required in order to optimize the RT Brain protocol.
- Two acquisitions are needed for brain imaging: 1) 120 kV acquisition without iodine contrast for dose calculation and 2) Dual Energy acquisition with the iodine contrast used for target delineation. Therefore, non-contrast image is matched with Monoenergetic Plus 40 keV in the TPS.
- When using iodine contrast with Dual Spiral Dual Energy, delay time should be set to at least 75 seconds (delayed phase) where the time density curve is close to flat, so that two consecutive scans at 80 kV and 140 kV have almost the same amount of iodine contrast information.

Key takeaway

- Based on the analysis, 40 keV was found to be the optimum keV level for target delineation in terms of overall image quality, interobserver variability, soft tissue attenuation, and CNR. However, there was no remarkable difference between 40–55 keV, probably because of its higher noise level and intermediate CNR improvement, although 120 kV was found to be the most difficult for target delineation.
- Interobserver variability seemed to be improved slightly with lower keV levels. (More samples are needed to be statistically significant.)
- In cases with patients who have not undergone surgery, Dual Energy shows the best results due to higher contrast of the tumor.
- Postoperative cases provide visualizations that allow discrimination of parenchyma from surgical cavity with Dual Energy Monoenergetic Plus 40 keV.

[1] *Protocol: DE_Head_BrainHem_post_intervention*

Breast imaging

Motivation

Elective radiation therapy of early-stage breast cancer has proved to be very effective in lowering the risk of recurrences and improving overall survival, and it is therefore offered to many patients in the postoperative setting. However, there is also treatment-related morbidity in breast, heart disease, and secondary cancer development [5]. The risk of local recurrence has progressively decreased over the last decades [6], while overall survival of breast cancer patients improved considerably [7]. It is therefore increasingly important to provide optimal target delineation for the patients to obtain a maximal effect at the lowest risk of late morbidity [8].

Within this study, Dual Energy acquisition was performed for postoperative patients, and targets are delineated in order to perform the dose escalation.

Scan protocol

Scan protocol	Scan parameters	Reconstruction parameters	Important remarks
Topogram			• Craniocaudal position • Supine position
Dual Energy Breast	1) 80 kV Pitch: 0.6 CTDI: 8.57 mGy 2) 140 kV Pitch: 0.8–1.2 (it may vary by scanner type) CTDI: 9.88 mGy	Slice thickness: 1.5 / 1.2 mm Reconstruction kernel: B30 / Qr36 1) Dose calculation a) mixed 120 kV B30 / Q36 2 mm (for dose calculation) b) DirectDensity™,[1] at 140 kV 2) Target delineation Auto post processing: DE_Mono_40 keV (for target delineation)	• Iterative reconstruction such as SAFIRE[2] may be used • Body part: Breast • iMAR[2] should be applied when metal artifacts are observed (e.g., pace maker)

Tips and tricks

- Standard Dual Energy protocol[3] is used in order to create RT Breast protocol. Adjustments of CTDI, slice thickness, and reconstruction kernel as well as auto postprocessing results are required before saving as RT protocol.
- Since breast imaging with Dual Energy offers sufficient soft tissue contrast (tumor and fat), iodine contrast was not used in the examination.

[1] *Optional; DirectDensity™ reconstruction is designed for use in Radiation Therapy Planning (RTP) only. DirectDensity™ reconstruction is not intended to be used for diagnostic imaging.*
[2] *Optional*
[3] *Protocol: DE_Abdomen_LiverVNC_late*

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Qualitative image assessment	Overall image quality (1–5)	3.7	3.7	4.0	4.1	3.9
	Target delineation (1–5)	4.0	4.0	4.0	3.9	4.0

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Quantitative image assessment	Tumor enhancement (HU)	24.6	20.9	18.1	16.2	11.3
	Fat tissue attenuation (HU)	-180.4	-162.2	-148.0	-137.6	-114.1
	Noise (HU)	22.8	20.5	18.9	17.4	16.3
	CNR	9.0	8.9	8.8	8.8	7.7

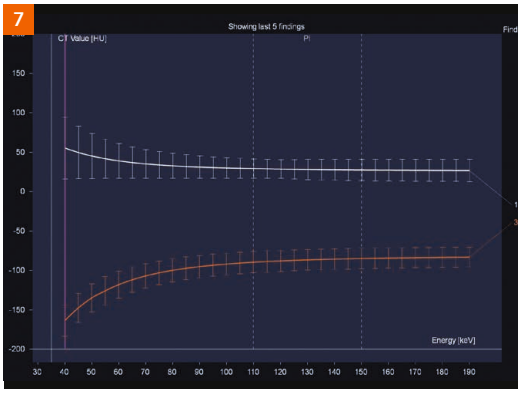


Figure 7:
Monoenergetic graph shows how the HU value (y-axis) changes when different keV (x-axis) is selected. It shows better soft tissue contrast at lower keV because the HU value of the fat (orange line) decreases, whereas HU of tumor (white line) increases.

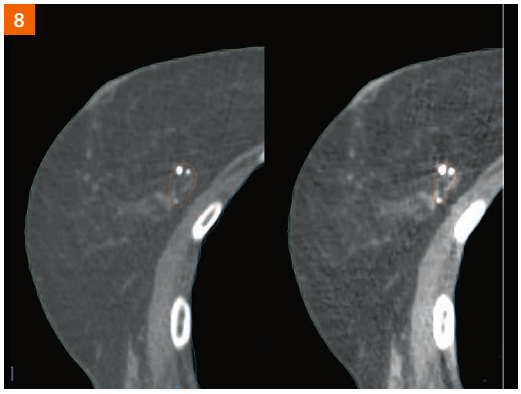


Figure 8:
left: 120 kV-equivalent image
right: Monoenergetic Plus 40 keV

Tumor visualization is improved at 40 keV although sufficient contrast is available at 120 kV-equivalent image.

Key takeaway

- All series rated good overall image quality and target delineation (incl. 120 kV).
- No remarkable differences are observed among the series. This could probably be caused by sufficient CNR at 120 kV even without using Dual Energy due to sufficient contrast between fat and tumor.
- This study focused on patients who received radiation therapy after surgery. Target delineation of the tumor was done for dose escalation purposes. Further investigation is needed to evaluate lymphatic areas (axillary / supraclavicular / internal mammary chain), because those have less soft tissue contrast.

Prostate imaging

Motivation

The current practice in prostate radiotherapy is for the treatment volume to encompass the entire prostate gland and a variable portion of the seminal vesicles. The intended treatment volumes need to be properly defined so that the radiotherapy beams can be accurately focused on the target volume and avoid a geographic miss that would reduce local tumor control.

There are limitations to the accuracy of CT-defined radiotherapy volumes, owing to difficulties in the visualization of the soft tissue boundaries between the prostate gland and its surrounding pelvic organs, especially in the determination of the apex of the prostate gland. The use of CT Dual Energy Monoenergetic Plus has potential to improve the target delineation by higher CNR. Within this study, the prostate was delineated as target to evaluate the benefit of Monoenergetic Plus.

Scan protocol

Scan protocol	Scan parameters	Reconstruction parameters	Important remarks
Topogram			• Craniocaudal position
Dual Energy Prostate	1) 80 kV Pitch: 0.6 CTDI: 8.57 mGy 2) 140 kV Pitch: 0.8–1.2 (it may vary by scanner type) CTDI: 9.88 mGy	Slice thickness: 1.5 / 1.2 mm Reconstruction kernel: B30 / Qr36 1) Dose calculation a) mixed 120 kV B30 / Q36 2 mm (for dose calculation) b) DirectDensity™,[1] at 140 kV 2) Target delineation Auto post processing: DE_Mono_40 keV (for target delineation)	• Iterative reconstruction such as SAFIRE[2] may be used • Body part: Prostate • iMAR[2] should be applied when metal artifacts are observed (e.g., Hip implant)

Tips and tricks

- Standard Dual Energy protocol[3] is used in order to create RT Prostate protocol. Adjustments of CTDI, slice thickness, and reconstruction kernel as well as auto postprocessing result are required before saving as RT Prostate DE Protocol.
- To ensure the exact matching of both kV images, non-rigid registration is automatically performed when Monoenergetic Plus image is generated.

[1] Optional; DirectDensity™ reconstruction is designed for use in Radiation Therapy Planning (RTP) only. DirectDensity™ reconstruction is not intended to be used for diagnostic imaging.
[2] Optional
[3] Protocol: DE_Abdomen_LiverVNC_late

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Qualitative image assessment	Overall image quality (1–5)	4.1	3.7	4.0	3.3	3.0
	Target delineation (1–5)	4.0	3.7	3.6	3.6	3.6

	Parameter	40 keV	45 keV	50 keV	55 keV	120 kV
Quantitative image assessment	Interobserver variability (%)	47.6	47.6	50.0	41.7	43.5
	Prostate attenuation (HU)	52.2	49.1	47.3	45.2	41.4
	Fat tissue attenuation (HU)	-152.6	-133.2	-119.4	-107.5	-81.1
	Noise (HU)	22.1	20.3	18.0	16.4	13.6
	CNR	9.2	9.0	9.2	9.2	9.0

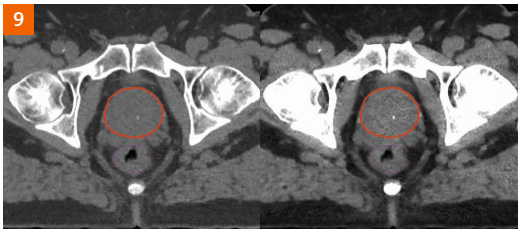


Figure 9:
left: 120 kV-equivalent image
right: Monoenergetic Plus 40 keV

Monoenergetic Plus slightly increases the HU value on the prostate.

Key takeaway

- Based on the analysis, 40 keV was found to be the optimum keV level for prostate imaging for target delineation because it showed 1) good overall image quality, and 2) best score for target delineation.
- There was almost no CNR change between different series; however, CNR depends on which organs are considered as comparison (with this study, fat was used), because prostate has many surrounding organs (e.g., fat, seminal vesicles, rectum, bladder, etc.). Therefore, further investigation might be needed in order to identify the optimum series.
- Further investigation is needed to differentiate bladder and prostate by using iodine contrast. Dual Energy may potentially benefit by enhancing the iodine for target delineation.

Results

Optimum series for target delineation

Target delineation	Best series for target delineation	Comments
Head and neck	40 keV (with contrast medium)	40 keV shows the best result for all criteria.
Brain	40 keV (with contrast medium)	40 keV shows the best result for non-operative patients, while postoperative cases show intermediate improvement for outline of the cavity.
Breast	40 keV or 120 kV (single energy)	When target delineation is performed for boosting purpose, 120 kV might be sufficient because adequate contrast between tumor and surrounding tissue (fat) is available even with 120 kV. In cases with delineating lymphatic areas with iodine contrast, 40 keV is probably beneficial. (Further investigation is needed.)
Prostate	40 keV	Study shows intermediate improvement at 40 keV compared with 120 kV. Using iodine contrast to differentiate prostate and bladder is potentially improved further by using Dual Energy.

Moving organs such as liver, kidney, and pancreas were not considered due to the limitation of two consecutive acquisitions (temporal coherence).To address these organs, TwinBeam Dual Energy[1] is recommended by enabling simultaneous acquisition for moving organs.

Practical implementation of Dual Energy

Perspective	Consideration
Therapist	Acquisition and postprocessing is as easy as when you're doing a single energy scan.
Physicist	No changes in the workflow.
Dosimetrist	No changes in the workflow because only Monoenergetic Plus images are sent directly to the TPS, thanks to auto-transfer.
Radiation oncologist	Monoenergetic Plus data handling is as easy as standard 120 kV images but benefits from better tumor contrast.
Patient	Acquisition is as simple as standard 120 kV acquisition, although acquisition time takes longer (10–15 seconds) than single energy acquisition.

[1] *Available on SOMATOM Definition Edge and SOMATOM Definition Edge Plus*

Conclusion

From the initial planning to treatment adaptation, target delineation is one of the most decisive parts of the RT workflow, and it is well documented that it can be subject to large interobserver variations. With Dual Energy CT, we now have the opportunity, during this crucial task, to make target delineation clearer and more reproducible, potentially by improved CNR and object demarcation without having an impact on radiation therapy workflow.

Theory

Dual Energy Monoenergetic formula

Monoenergetic formula is described for your further reference or research.

$$\mu_x(E) = x_p \bullet f_p(E) + x_c \bullet f_c(E)$$

$\mu_x(E)$: Attenuation coefficient of a material x, at a certain energy E.

x_p, x_c: Constants, depending only on material properties (like atomic number and density), which scale the Photoelectric effect and the Compton effect, respectively.

$f_p(E)$, $f_c(E)$: Functions which represent Photoelectric effect (i.e., absorption of X-rays) and Compton effect (scattering), respectively. These two functions don't depend on the materials, but only on the energies.

$f_p(E)$, $f_c(E)$: Are known from fitting experimental data. Only unknowns are : x_p, x_c That's why, in principle, two different measurements at two different energies are sufficient to calculate these x_p and x_c constants.

Since $f_p(E)$, $f_c(E)$ don't depend on the material but only on the energy, we can write different equations for different materials (x, y, z). What changes will be only the unknown constants, not the Photoelectric and Compton functions themselves.

$$\mu_x(E) = x_p \bullet f_p(E) + x_c \bullet f_c(E)$$
$$\mu_y(E) = y_p \bullet f_p(E) + y_c \bullet f_c(E)$$
$$\mu_z(E) = z_p \bullet f_p(E) + z_c \bullet f_c(E)$$

Thus, Photoelectric and Compton functions are explicit and are written in terms of $\mu_y(E)$ and $\mu_z(E)$.

$$\mu_y(E) = y_p \bullet f_p(E) + y_c \bullet f_c(E) \rightarrow f_p(E) = \frac{\mu_y(E) \bullet z_c - \mu_z(E) \bullet y_c}{y_p \bullet z_c - y_c \bullet z_p}$$

$$\mu_z(E) = z_p \bullet f_p(E) + z_c \bullet f_c(E) \rightarrow f_c(E) = \frac{\mu_z(E) \bullet y_p - \mu_y(E) \bullet z_p}{y_p \bullet z_c - y_c \bullet z_p}$$

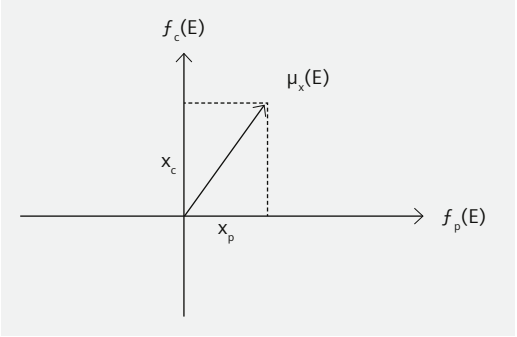
If substituted, the new, rewritten forms of $f_p(E)$ and $f_c(E)$ in our first equation (for the material x) are:

$$\mu_x(E) = x_p \bullet f_p(E) + x_c \bullet f_c(E) \rightarrow \mu_x(E) = a_y \bullet \mu_y(E) + a_z \bullet \mu_z(E)$$

What we have just performed is a change of variables. We progressed from expressing $\mu_x(E)$ in terms of its Photoelectric and Compton contributors to expressing $\mu_x(E)$ in terms of $\mu_y(E)$ and $\mu_z(E)$ – that is to say, in terms of the attenuation coefficient of two other materials. This is called two-basis material decomposition.

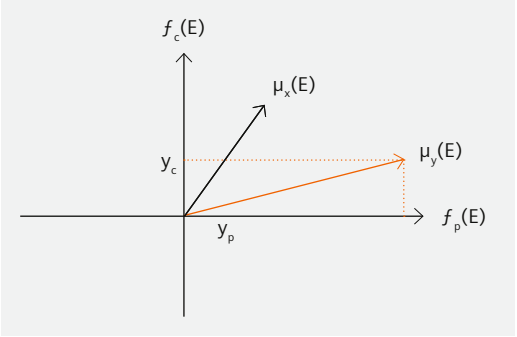
Graphically, this can be understood as a change of coordinate system:

$$\mu_x(E) = x_p \bullet f_p(E) + x_c \bullet f_c(E)$$



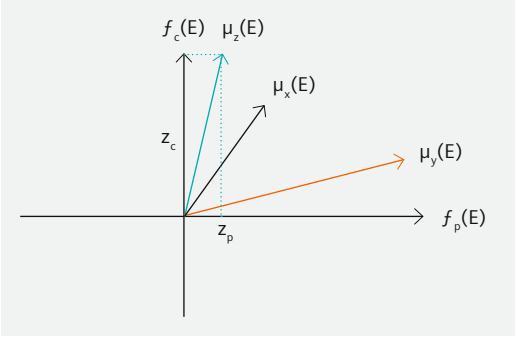
Another material (y) will be displayed as another vector with different compositions:

$$\mu_y(E) = y_p \bullet f_p(E) + y_c \bullet f_c(E)$$



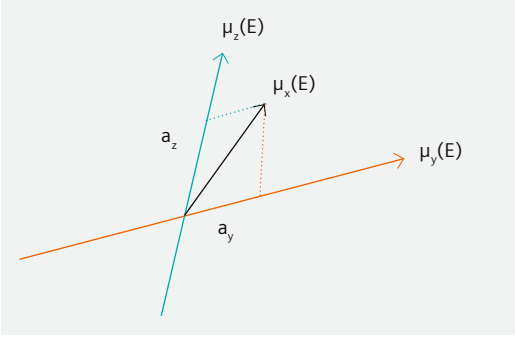
Another material (z) will be displayed as another vector with different compositions:

$$\mu_z(E) = z_p \bullet f_p(E) + z_c \bullet f_c(E)$$



We can express any vector in terms of two other vectors:

$$\mu_x(E) = a_y \bullet \mu_y(E) + a_z \bullet \mu_z(E)$$



With this equation: $\mu_x(E) = a_y \bullet \mu_y(E) + a_z \bullet \mu_z(E)$

the only unknowns are now a_y and a_z, which are respectively the contributors of basis material y and basis material z. Doing two scans at two different energies, we have:

$$E_{low} = a_y \bullet \mu_y(Low) + a_z \bullet \mu_z(Low)$$
$$E_{high} = a_y \bullet \mu_y(High) + a_z \bullet \mu_z(High)$$

We are free to choose any couple of (known) basis material that we wish. In our approach we choose for the sake of simplicity: y: water, z: iodine. We know the attenuation coefficients of these materials at different energies.

Solving the system and substituting the HU to the attenuation coefficient, remembering that

$$\left(HU_x(E) = \frac{\mu_x(E) - \mu_{water}(E)}{\mu_{water}(E)} \bullet 1000 \right)$$

we obtain: $HU_x(E) = w_{x,low}(E) \bullet HU_x(Low) + w_{x,high}(E) \bullet HU_x(High)$

Where $w_{x,low}(keV) + w_{x,high}(keV) = 1$ and the weight are just a combination of a_y and a_z that we calculated before.

So basically, moving the monoenergetic slider will perform a mixed series but with a wider range.

Dual Energy Monoenergetic Plus [3]

Besides the established technique of Monoenergetic imaging, Siemens Healthineers has developed Monoenergetic Plus to avoid noise increase at lower calculated energies, which is a known drawback of virtual monoenergetic images. At low keV a regional spatial frequency-based recombination of the high signal at lower energies and the superior noise properties at medium energies is performed to optimize CNR in cases with Monoenergetic Plus images. The CNR and low-contrast detectability were evaluated.

References

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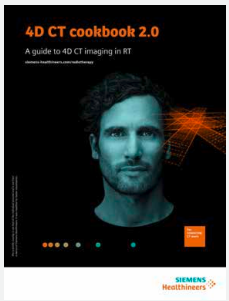

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