White Paper

Evaluation of the Direct Density Algorithm for Energy-Independent Radiotherapy Treatment Planning

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Abstract

Purpose: The commonly accepted practice in RT is to image all patients at 120kVp in order to avoid potential errors with the energy dependent electron/mass density calibration curve. While this is safe practice, the disadvantage is in missing potential superior soft tissue contrast when you vary the tube voltage. A novel Direct Density™ (DD) algorithm is available to allow use of energy-independent CT# to density, simplifying clinical workflow with one calibration curve. In order to commission DD for our clinic, we compared the dose calculated from DD reconstructed CT images at a variety of tube potentials to doses produced using the standard 120kVp images.

Methods: Four different phantom studies were conducted. Two with tissue equivalent slabs (homogenous solid water and heterogeneous using ICRU slabs (solid water, bone, and lung equivalent slabs)); and two using thorax Rando phantoms. Scans were performed using a standard reconstruction at 120 kVp and a DD reconstruction for differing kVp (70 – 140kVp) on a SOMATOM Definition Edge (Siemens GMBH, Forchheim, Germany). Two distinct CT density curves were implemented in the treatment planning system (RaystationV9) to read both standard and DD images. Average CT numbers for each ROI were recorded. Point doses were calculated and measured for 200 MU AP plans at 6, 10, and 15 MV, and dose differences were compared. The Rando phantoms were scanned using both kernels at 120kVp, and a VMAT plan was simulated on each. DVH plots were created for assessment.

Results: In all instances, computed DD doses were nearly identical to the standard kernel dose. Point dose measurements differed by ≤1%. The largest difference was for the 70kVp AP plan, producing dosimetric error of around 3cGy. VMAT plans showed negligible differences.

Conclusions: With an appropriate CT density curve, DD reconstruction algorithm is as accurate as standard algorithms at dose prediction, but allows the flexibility of using variable kVp to improve image quality for certain tissues.

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Introduction

Siemens Healthineers has recently introduced DirectDensity™ (DD), a novel technique that allows the reconstruction of images acquired at any kV to be directly interpreted as electron density images, thus eliminating the need to perform a Hounsfield Unit (HU) to electron density calibration. While the principles behind DD have been summarized in an earlier white paper[1], incorporating a new technology in the clinic can often be challenging and time consuming. While as a community we continue to explore how best to integrate the new technology in the clinic, the goal of this work is to establish a step-by-step methodology to assist the successful implementation of DD in clinical routine. In this paper, we describe the commissioning process at our clinic and present on the dose calculated from DD reconstructed CT images at a variety of tube potentials to doses produced using the 120kVp reconstructed images using the standard filtered back projection (FBP) algorithm.

Brief Background

What is Direct Density?

Direct Density is a reconstruction algorithm/kernel (not to be confused with Siemen's Dual Energy scanning protocol) that provides HUs scaled to the Relative Electron Density. (These scaled HU values will be referred to as CT #s.) The CT #s are energy independent, meaning that any scan, at any energy, will produce values that give an accurate representation of the true relative electron density or relative mass density (RD or relative density) of the material. This can be especially useful for differentiation of soft tissues that would benefit from lower energy scans, or scans requiring the use of higher energies for harder density materials; no matter the energy used, by selecting the direct density reconstruction, the RD value doesn't vary with energy. Since it represents a physical property of the materials, the CT #s, which directly then represent the RD, will remain the same.

Implementation

How can my TPS read RD values via CT#s?

CT #s are simply RD values that have been scaled so that they resemble traditional HUs:

$$RD = \frac{CT\ \# + 1000}{1000}$$

In modern treatment planning systems (TPS), the HU to mass density function is usually required to perform dose calculations. Similarly, for DD implementation, CT#s to mass density function will be required and then inputted into the TPS. This can be accomplished by scanning the CT Density phantom, as usually done now in the clinic, with known mass density plugs (it is recommended that scans performed using these phantoms use plugs that range in density from very low to very high, or near zero to roughly 3-4 g/cm³). After the CT acquisition and applying the DD recon kernel Sd-40, each plug is contoured as a Volume-of-Interest (VOI) and then a table that relates the average CT #s for each VOI and its mass density can be created. This table can then be entered into the TPS.

Relative electron density	DirectDensity image value
0.000	-1000
1.000	0
4.072	3072

Table 1 RED to CT#s values provided by Siemens Healthineers

Creating the CT- Mass Density Curve

A high quality CT Density Phantom, such as CIRS (Norfolk, VA, U.S.A.) and Gammex (now Sun Nuclear, Middleton, WI, U.S.A.) should be used. These phantoms are composed of tissue-equivalent materials with a variety of "plugs," or different density materials, ranging in composition from lung to dense bone or even titanium, duplicated around both an inner and an outer ring.

To verify that the Direct Density kernel mapped all tissue densities to the appropriate mass density, the density phantom was scanned at 70, 80, 100, 120, and 140 kVp, respectively, using a standard, clinical acquisition protocol of Br38 and then reconstructed using the DD Sd40 kernel. For comparison, the density phantom was also scanned with conventional 120kVp protocol and reconstructed using a standard FBP kernel (Br38). VOIs were created for each plug type, using a single ROI for both the inner plug and outer plug of a given tissue equivalent materials (e.g. two "exhale lung" plugs both were contoured under the same VOI name). The ROIs were expanded volumetrically to include as much of the plug as possible without taking the VOI to any edge, resulting in volumes of around 20 cm^3 for all but the smallest plugs. Average CT #s were noted for each ROI, per energy, and plotted in a table with their physical mass density provided by the vendor of the CT density phantom.

To ensure that the TPS is reading the materials densities properly, plots were constructed from the CIRS CT density phantom and compared to that provided by Siemens Healthineers' literature (Fig. 3).

In the treatment planning system (TPS), in order to have a single mass density curve for all energies, the new CT Mass Density curve was created by entering the average CT# over the ROI produced by all Direct Density scans (70 – 140 kVp) for each material plug.

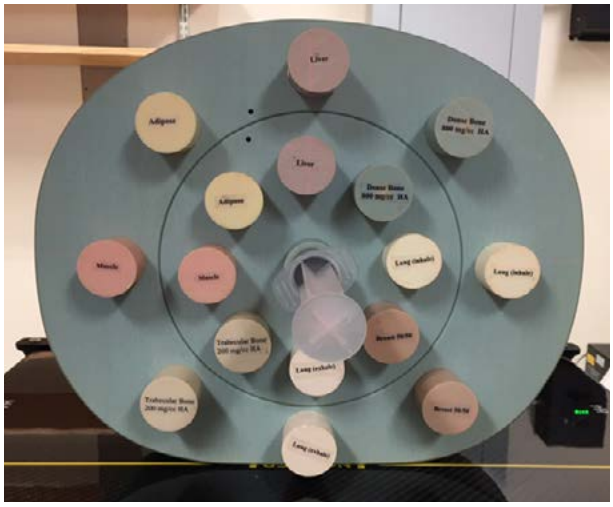

Figure 1 CIRS model 62 density phantom shown with water plug in center (syringe). Titanium plug not pictured.

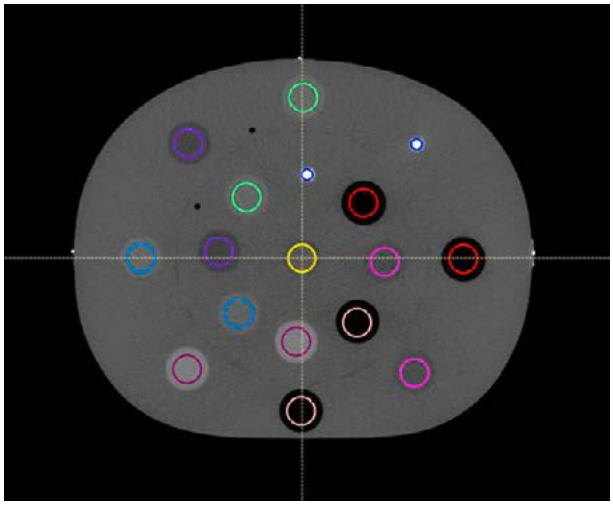

Figure 2 Contoured ROIs for each plug on the CT density phantom

	Sd40 70 kVp CT#	Sd40 80 kVp CT#	Sd40 100 kVp CT#	Sd40 120 kVp CT#	Sd40 140 kVp CT#	Sd40 AVG CT#	Br38 AVG CT#	Physical Density (g/cm³)
Air	-955	-955	-955	-955	-955	**-955.0**	**-955.0**	0.00121
Lung inhale	-763.7	-781.4	-771.3	-782.1	-778.8	**-775.5**	**-780.0**	0.195
Lung exhale	-456.2	-474.6	-470.6	-477.4	-476.3	**-471.0**	**-478.0**	0.495
Adipose	-92.0	-80.0	-67.3	-62.2	-57.3	**-71.8**	**-61.0**	0.967
Breast	-62.6	-46.4	-44.5	-36.3	-34.4	**-44.8**	**-36.0**	0.991
Water	-21.6	-14.7	-5.6	-6.6	-3.05	**-10.3**	**-13.0**	1
Muscle	9.7	23.49	34.9	42.1	41.9	**30.4**	**40.0**	1.062
Liver	25.3	38.17	47.7	51.3	52.5	**43.0**	**53.0**	1.071
Trabecular Bone	116.4	123	114.52	118.65	116.2	**117.7**	**208.0**	1.161
Dense Bone	413.1	425.6	439.7	464.6	466.2	**441.8**	**836.0**	1.609
Titanium	2907	2912	2918	2941	2953	**2926.2**	**3072.0**	4.51

Table 2 Average CT# per VOI per energy for the CIRS CT Density Phantom reconstructed using both Direct Density (Sd40) and a standard, Br38 kernel used on a 120 kVp image

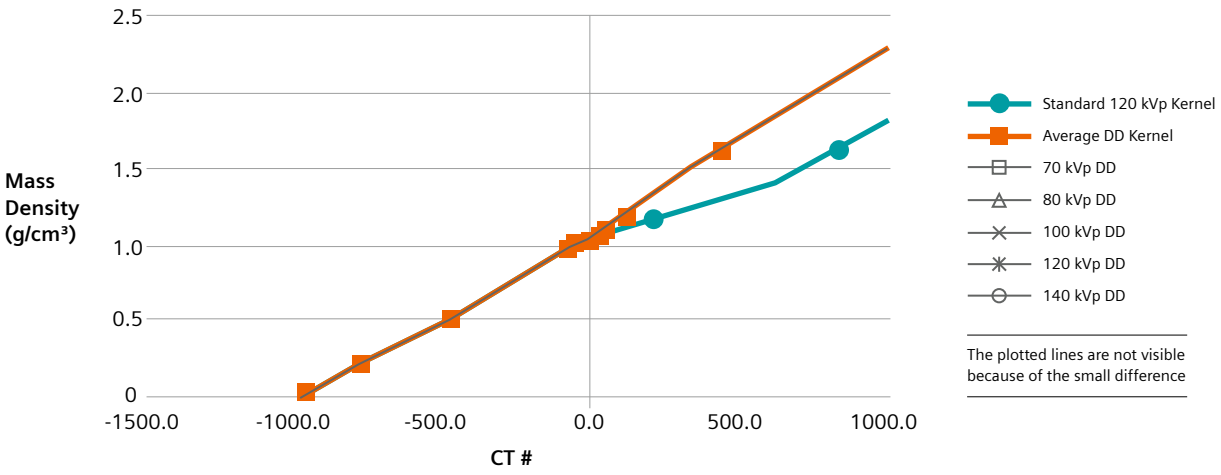

Figure 3 CT # to mass density curve taken using Sd40 (Direct Density) scans at various energies and comparing this curve to the traditional density curve done at 120 kVp for a standard, Br38, reconstruction kernel

Verification

Is the Direct Density kernel accurate for dose calculation?

Several material slabs of different densities were assembled, scanned using the Siemens Healthineers EDGE CT scanner in our radiation oncology department, and reconstructed using the DD kernel. The first setup was for a homogenous phantom of solid water only. The second setup was for a heterogeneous phantom using a mixture of solid water, lung, and bone tissue-equivalents.

1. Homogenous Phantom
A TPS plan was created in the TPS (Raystation V9A, RaySearch, Stockholm, Sweden) to deliver 200 MUs to the homogenous slab configuration. Absorbed dose measurements were made and compared to the predicted dose from the TPS. Table 3 depicts the CT#s for the homogenous phantom using both version of *syngo*.via VB10 and VB20, indicating the importance of recommission when the software version has changed. Table 4 depicts the dosimetric point dose results for the standard 120 kVp Br38 kernel and the Sd40 DD kernels.

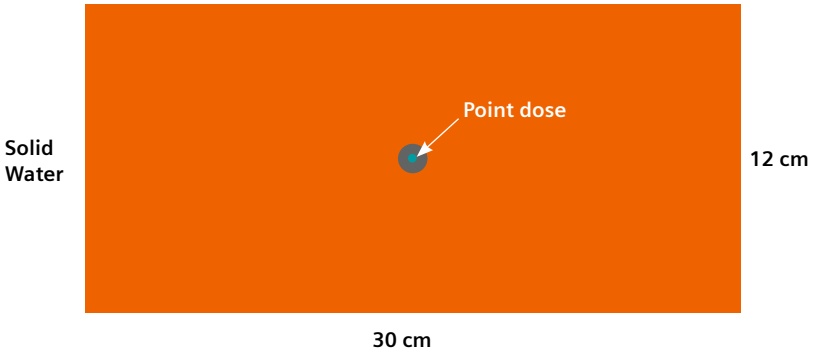

Figure 4 Homogenous slab setup

	syngo.via VB20 CT#
Br38_120kVp	23.73
Sd40_120kVp	21.97
Sd40_70kVp	21.01
Sd40_80kVp	22.96
Sd40_100kVp	22.75
Sd40_140kVp	21.44
Sd40 Ave. CT#	22.03
%CV	3.8%

*Data could not be acquired retrospectively

Table 3 Average CT #s reported by Raystation TPS for the homogenous solid water phantom for *syngo*.via VB20. %CV is percent coefficient of variation

	6 MV Dose (cGy)	10 MV Dose (cGy)	15 MV Dose (cGy)
Br38_120kVp	165	175	179
Sd40_120kVp	165	175	179
Sd40_70kVp	165	175	179
Sd40_80kVp	165	175	179
Sd40_100kVp	165	175	179
Sd40_140kVp	165	175	179
Average Dose	165	175	179
%CV	0%	0%	0%

Table 4 Predicted Dose from 200 MUs at 100 SSD for the Homogenous Phantom for photon energy of 6, 10, and 15 MV, respectively. All TPS results are calculated for the syngo.via VB20. Ave Dose is for Br38 and Sd40 kernels. %CV is percent coefficient of variation

2. Heterogenous Phantom

A TPS plan was created in the Raystation (V9A, RaySearch, Stockholm, Sweden) to deliver 200 MUs to the heterogenous slab configuration, consisting of ICRU slabs of solid water, bone, and lung (Fig 5). Absorbed dose measurements were made and compared to the predicted dose from the TPS. Table 4 depicts the CT#s for the heterogenous phantom using *syngo*.via VB20. Table 5 depicts the dosimetric point dose results for the standard 120 kVp Br38 kernel and the Sd40 DD kernels.

Table 6 shows the ion chamber measurements to those calculated by Raystation for both phantoms, for the three photon energies used in our clinic.

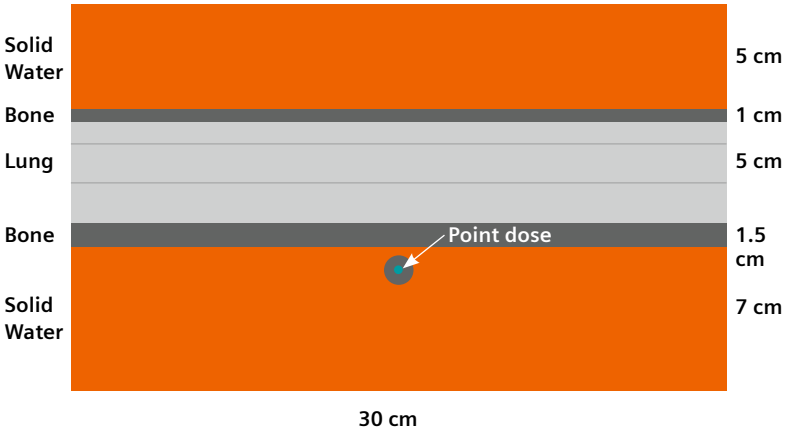

Figure 5 Heterogenous slab configuration

	Solid Water CT#	Solid Water–Top CT#	Solid Water–Bottom CT#	Lung CT#	Bone CT#	Bone–Top CT#	Bone–Bottom CT#
Br38_120kVp	51.4	44.7	54.9	-653.5	438.9	262.8	447.7
Sd40_120kVp	46.6	40.9	49.8	-657.9	279.9	150.2	288.3
Sd40_70kVp	46.8	35.6	53.0	-625.1	199.7	108.3	206.1
Sd40_80kVp	49.6	39.9	55.1	-637.9	218.5	122.0	224.6
Sd40_100kVp	45.6	35.4	51.8	-649.2	249.0	136.9	256.4
Sd40_140kVp	44.1	35.97	49.1	-660.5	296.2	161.2	306.1
Sd40 Ave. CT#	46.5	37.5	58.1	-646.1	248.6	135.7	256.3
%CV	1.5%	1.2%	1.3%	1.3%	1.3%	1.3%	1.3%

Table 5 Average CT #s as reported by Raystation TPS for the Heterogenous Phantom, see Figure 6 for the slab arrangement. The "Solid Water" and "Bone" columns are the averages of the Top and Bottom solid water and bone columns, respectively. %CV is percent coefficient of variation.

Predicted Dose from 200 MUs at 88 SSD for Heterogenous Phantom

	6 MV Dose (cGy)	10 MV Dose (cGy)	15 MV Dose (cGy)
Br38_120kVp	142	155	161
Sd40_120kVp	142	155	161
Sd40_70kVp	141	154	160
Sd40_80kVp	142	154	161
Sd40_100kVp	142	155	161
Sd40_140kVp	142	155	161
Average Dose	141.8	154.6	160.8
%CV	1.4%	1.1%	1.4%

Table 6 Depicts the dosimetric point dose results for the standard 120 kVp Br38 kernel and the Sd40 DD kernels. Ave Dose is for Br38 and Sd40 kernels. %CV is percent coefficient of variation. SSD = Source-to-Surface Distance, MU = Monitor Units

	TPS Dose (DD) (cGy)	Measured Dose (cGy)	% Difference
	6 MV		
Homogenous	165	166.8	1.1%
Heterogeneous	141.8	143.2	1.0%
	10 MV		
Homogenous	175	174.8	0.1%
Heterogeneous	154.6	154.6	0.0%
	15 MV		
Homogenous	179	180.2	0.7%
Heterogeneous	160.8	162.5	1.1%

Table 7 Ion chamber point dose measurements for the 1) homogenous phantom setup and 2) the heterogenous phantom setup. TPS calculations performed with the average DD curve shown in Figure 5.

Do the CT #s remain constant?

A Sensitivity Analysis

There were some data during our investigation that suggested that CT #s for lower density materials changed for scans that contained both low and high density materials. This is likely due to the method in which the DD kernel searches for and establishes bone densities first, in conjunction with the non-typical case of large heterogeneous slabs of bone on top of soft-tissues (see Discussion section).

Variations of the CT #s were the most pronounced when comparing the difference between the DD (Sd40) kernel at 70 kVp and at 120 kVp. However, clinically, these differences appeared to result in dose differences of less than 1% as shown in Figures 6 and 7 (right).

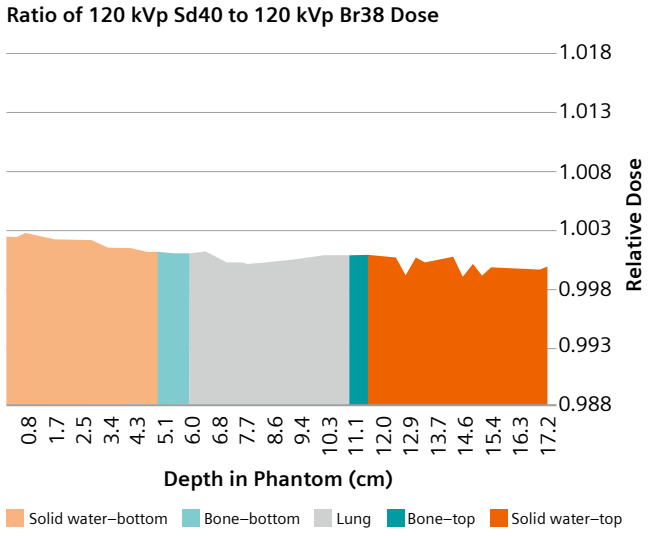

Figure 6 Ratio of calculated line doses through the heterogenous phantom for two scans at 120 kVp, one using a standard Br38 reconstruction kernel and the other using DD

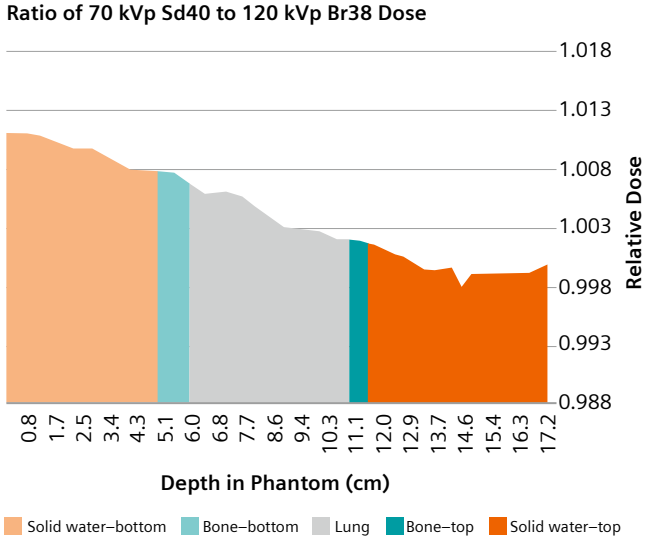

Figure 7 Ratio of calculated line doses through the heterogenous phantom for two scans, one using standard reconstruction at 120 kVp Br 38 and the other using DD at 70 kVp Sd40

Thorax Phantoms evaluation

The performance of the Sd40 kernel was also evaluated on heterogenous phantoms that are more clinically realistic. Two different humanoid phantoms were used for this investigation - the IROC-Houston lung phantom[2] and an in-house RANDO Thorax phantom.

A. The IROC lung phantom model, as shown in Figure 8, is well described in the literature[2]. It was scanned using the Siemens Healthineers EDGE scanner with the standard 120 kVp Br38 FBP and then reconstructed with 120 kVp Sd40 direct density kernel. No dosimetric differences were seen between any of the VMAT plans (Fig 9) as shown in the DVH results below were essentially identical (Fig 10).

Figure 8 Images from: Steinmann, A., Alvarez, P., Lee, H., Court, L., Stafford, R., Sawakuchi, G., Wen, Z., Fuller, C. and Followill, D. (2019), MRIgRT dynamic lung motion thorax anthropomorphic QA phantom: Design, development, reproducibility, and feasibility study. Med. Phys., 46: 5124-5133. doi:10.1002/mp.13757 and rpc.mdanderson.org/RPC

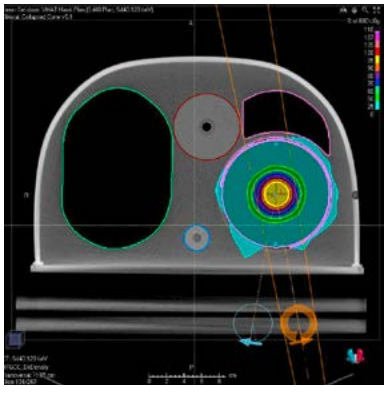

Figure 9 VMAT plan on PTV on IROC phantom

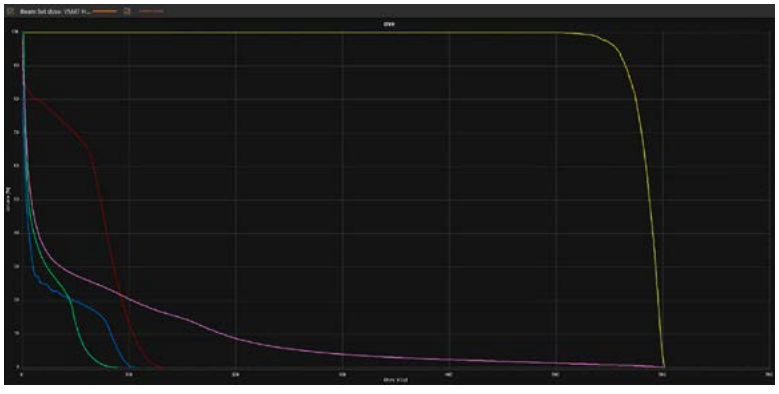

Figure 10 DVH comparison for VMAT plan on IROC phantom using Br38 and Sd40 images taken at 120 kVp. DVHs are overlapped and no difference detected

B. Rando thorax phantom: This method of clinical verification was repeated for a more complex, more true-to-life Alderson RANDO thorax phantom (http://rsdphantoms.com/radiation-therapy/the-alderson-radiation-therapy-phantom/). CT #s were noted for relevant ROIs, then 3D plans and VMAT plans were made on a standard kernel image at 120 kVp and on Direct Density images taken at all available kVp (140-70 kVp).

Figure 11 Alderson RANDO phantom used to verify DD-based dose calculations in Raystation

CT Recon Kernel	PTV	Left Lung	Right Lung	Heart	Cord	Sternum
Br38 120 kVp	-44.5	-507.3	-507.6	25.6	42.5	146.4
Sd40 120 kVp	-47.4	-504.0	-504.4	23.6	49.0	63.7
Sd40 70 kVp	-62.2	-499.3	-501.5	14.0	48.6	62.0
Sd40 80 kVp	-51.1	-500.0	-503.3	16.7	47.4	66.0
Sd40 100 kVp	-47.6	-500.2	-503.3	20.7	47.6	67.7
Sd40 140 kVp	-57.1	-504.7	-508.5	30.7	47.2	64.0
Sd40 Average CT#	-51.6	-502.6	-504.8	21.8	47.1	64.7
%CV	12.1%	-0.5%	-0.5%	30.6%	1.7%	3.4%

Table 7 CT#s for Rando Thorax phantom

CT Recon Kernel	Calc Point cGy	Max Dose cGy	PTV Average Dose cGy
Br38 120	4,600	5,327	4,676
Sd40 120	4,600	5,330	4,676
Sd40 70	4,600	5,328	4,689
Sd40 80	4,600	5,340	4,692
Sd40 100	4,600	5,345	4,694
Sd40 140	4,600	5,328	4,692
Average Dose (cGy)	4,600	5,333	4,686.5
%CV	0%	0.1%	0.2%

Table 8 Predicted Dose for 3D Rando Thorax Plans

CT Scan	Dose at Volume, cGy	Max Dose, cGy	% PTV at 5000, cGy	Heart Dose, cGy
Br38 120	5,014	5,658	96.36	56
Sd40 120	5,033	5,666	97.91	67
Sd40 70	5,034	5,552	98.45	67
Sd40 80	5,066	5,721	99.6	71
Sd40 100	5,028	5,482	98.82	72
Sd40 140	5,058	5,537	99.25	78
Average Dose (cGy)	5,038.8	5,602.7	98.4	68.5
%CV	0.4%	1.6%	1.2%	11%

Table 9 Predicted Dose for VMAT Rando Thorax Plans

Discussion

Our results indicate that the DD algorithm has produced CT#s with a variance from the original 120kVP Br38 kernel (filtered back projection (FBP)) used in our clinic. It is important to realize this and evaluate the magnitude of the dosimetric impact. This is expected since DD relies on single energy two-material decomposition, there are of course slight variations in CT values depending on the setting/patient.
Siemens Healthineers indicates that variations in the order of up to 20-25 CT #s are normal and to be expected.

As shown in Table 4, the largest deviation in CT#s is found in the bone area (CT# of 33) for the heterogenous slab phantom. As always in CT (and especially for corrections and reconstruction), assumptions are made on the objects that are typically to be imaged in clinical situations (i.e. patients). Some of those assumptions are: an overall oval shape, the high-density objects are bones (or implants) and that they are always “far” from the edges of the patient (in other words, we assume that the patient is always surrounded by some fat/soft tissue). The design of presented heterogeneous phantom is typical of an RT phantom (successive layers of material with a hole for an ion chamber, etc....). This is typically used to verify predicted delivered dose for external beam, but those phantoms are suboptimal for imaging studies, due to their abrupt heterogenous nature, and users should exert caution when analyzing results obtained with those type of phantoms. The square design causes some serious challenges from a “patient outline” continuity standpoint, which can significantly affect the homogeneity of the CT values within the object. Secondly, one should consider the fact that when the CT tube is either at 90 degrees or 270 degrees (assuming the 0 degree position is above the phantom), the x-ray beam “sees” 2 slabs of bone that have the same thickness as the object (which of course goes against the assumption we make as to what a patient usually looks like). This creates some significant disturbance in the sinogram and has non-negligible beam hardening effects that would also translate to variations in CT values. The dosimetric impact was largest for the 70 kVp Sd40, and on the order of 1% compared to the standard Br 38 120kVp kernel dose predictions.

Several reports using clinical patient data have reached similar findings. Flatten et al conducted a phantom study (simple and anthropomorphic) which also included metallic implants. Differences were found mainly in pure air and high-density materials such as bones[3]. The difference of the mean dose was below 0.7%, in most cases below 0.4%. No indication was found that the algorithm is corrupted by metal inserts, enabling the application for all clinical cases. van der Heyden et al performed a retrospective study on the accuracy of DD dose calculation using 33 patients with various cancer types[4]. All CT acquisitions were reconstructed with the standard FBP and DD. The mean tumor doses and the volume percentage that receives more than 95% of the prescribed dose were calculated for the planning target volume. Relevant parameters for the organs at risk for each tumor site were also calculated. The relative mean dose differences between the standard 120 kVp FBP CT scan workflow and the DD CT scans (80, 100, 120 and 140 kVp) were in general less than 1% for the planned target volume and organs at risk.

Changes to Clinical Workflow

Implementing DirectDensity in the clinic is fairly straightforward. As stated, a new CT Density curve will need to be created in the TPS. Then, appending the DirectDensity reconstruction as a secondary reconstruction for all existing protocols, will also need to be done. In this manner, physicians will be able to use the standard protocol, done at a different kVp from the usual 120 kVp, to draw the GTV/CTV and OARs contours with the benefits of enhanced tissue contrast. Dosimetry/Physics will map the contours using rigid registration tools in the TPS to the DD-reconstructed image and continue with treatment planning as normal.

Conclusions

With an appropriate CT density curve, DD reconstruction algorithm is as accurate as standard algorithms at dose prediction but allows the flexibility of using variable kVp to improve image quality for certain tissues. Our next step is to implement DirectDensity™ for routine clinical CT simulation in our clinic. Future report of the clinical outcomes will be documented in Part II of this white paper.

Notes

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The scientific overlay is not that of the individual pictured and is not from a device of Siemens Healthineers. It was modified for better visualization.

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