DICOM-CTPD User Manual

Version 3

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McCollough, C.H., Chen, B., Holmes, D., III, Duan, X., Yu, Z., Yu, L., Leng, S., Fletcher, J. (2020). Data from Low Dose CT Image and Projection Data [Data set]. The Cancer Imaging Archive.

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Introduction to the DICOM-CT-PD Format

➢ CT Projection Data in an Extended DICOM Format

The development of CT reconstruction algorithms requires direct access to CT projection data. The projection data collected from commercial CT scanners, however, contain proprietary information and are encoded in a vendor-specific, proprietary manner. Consequently, CT projection data are not directly accessible to most users. To bridge this gap, we have decoded CT projection data with the assistance of the respective manufacturer, extracted the projection data and necessary reconstruction-related information (scanning trajectory, detector geometry, etc.), and rewritten the information in an extended DICOM format, named DICOM-CT-PD.[1]

The DICOM-CT-PD files are vendor-neutral DICOM projection data. Each DICOM-CT-PD data file corresponds to a single projection of a CT scan, which is divided into two components following the DICOM standard, the **header** and the **raw data** (as shown in Figure 1). The header stores information regarding the gantry geometry, detector configuration, the x-ray energy spectrum, the table movement, and other information related to data acquisition. The raw data stores the projection data. One CT scan consists of a series of DICOM-CT-PD files, each corresponding to a projection at a specific view angle and table location.

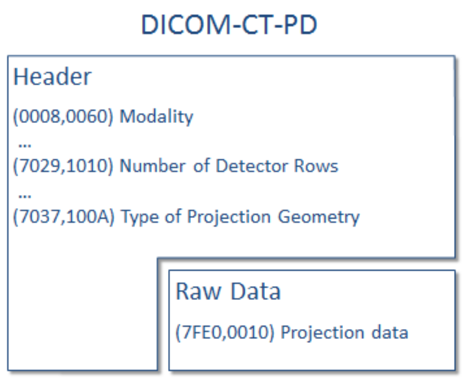

Figure 1: Each DICOM-CT-PD file can be divided into two sections.

Currently, the DICOM-CT-PD format provides sufficient information for the reconstruction of a third-generation-geometry CT scan with cylindrical, spherical, or flat-panel detectors. The format accommodates gantry geometries that use a flying focal spot [2,3], which is a periodic motion of the focal spot on the anode surface. The format also accommodates ECG-gated CT scans and scans that use multiple x-ray sources, tube potentials, detector layers, or energy bins.

[1] Chen, B., Duan, X., Yu, Z., Leng, S., Yu, L., & McCollough, C.H. (2015). Technical note: Development and validation of an open data format for CT projection data. Medical Physics, 42 (12), 6964

[2] Flohr, T. G., Stierstorfer, K., Ulzheimer, S., Bruder, H., Primak, A. N., & McCollough, C. H. (2005). Image reconstruction and image quality evaluation for a 64-slice CT scanner with z-flying focal spot. Medical Physics, 32 (8), 2536-2547

[3] Kachelrieß, M., Knaup, M., Penßel, C., & Kalender, W. (2006). Flying focal spot (FFS) in cone-beam CT. Nuclear Science, IEEE Transactions on, 53 (3), 1238-1247.

➢ Definition of Gantry Geometries

In order to record the gantry movement, a **cylindrical coordinate system (ρ, φ, z)** is defined (left-handed coordinate system), as illustrated in Figure 2. The coordinate system is attached to the patient, i.e. **the patient and table stay static while the source and detector move during translation of the patient table**. The z direction is perpendicular to the plane in which the anode rotates and points from the patient table base towards the gantry. The azimuthal angle φ is zero at the 12 o'clock position (viewing from the patient table side) and increases in a counter-clockwise direction. The origin of the coordinate system (the purple dot in Figure 2) is defined with respect to where the patient table is zeroed (default location is at the front of the patient table) and the isocenter (i.e., the intersection point between the axis of gantry rotation and the axial plane of the center of the detector rows along the z-direction).

- The detector elements are indexed with "column" and "row", as illustrated in Figure 2. With the detector locating at 6 o'clock direction (viewing from the patient table side), the furthermost row is the Row 1 and the left-most column is Column 1.
- For cylindrical detectors, **a detector's focal center is defined as the point that aligns with the isocenter and the center of the detector rows along the z-direction, and coincides with the focal point of the detector arc in the azimuthal plane** (the red dot in Figure 2). The coordinates of the detector's focal center is provided in (ρ_0, φ_0, z_0). Note that the shape of the detector can also be spherical or flat. In case of spherical or flat detectors, the definition of the detector's focal center is slightly different, as illustrated in Figure 3.
- The detector element that aligns with the detector's focal center and the isocenter is indexed as (Column X, Row Y). For example, (Column 369.625, Row 32.5) means that the line connecting the detector's focal center and the isocenter hits at a location that is 0.625 of a Column from Column 369, towards Column 370, and half-way in between Row 32 and Row 33. The coordinates of (Column X, Row Y) can be calculated based on (ρ_0, φ_0, z_0) and the distance between the focal center and detector elements in the azimuthal plane, d_0. Given the coordinates of (Column X, Row Y), the shape of the detector, and the widths of each element d_{Col} and d_{Row}, the locations of the rest of the detector elements can be calculated.
- The location of focal spot normally coincides with the detector's focal center, but can also be slightly biased from it (the green dot in Figure 2). To account for such bias, an adjustment of ($\Delta\rho$, $\Delta\varphi$, Δz) is provided so that the coordinate of the focal spot can be computed as ($\rho_0+\Delta\rho$, $\varphi_0+\Delta\varphi$, $z_0+\Delta z$). One example of such bias is found in data acquired with a Siemens Definition Flash scanner. As illustrated in Figure 4, the focal spot location for a Flash scanner is at Point A, slightly biased from the detector's focal center. Furthermore, if the flying focal spot technique is applied, Points A to F are all possible focal spot locations, each corresponding to a new set of ($\Delta\rho$, $\Delta\varphi$, Δz) values.
- The location of the body section being imaged is defined by z_0. If z_0 decreases as the projection number increases, the patient and patient table are moving towards the gantry during the data acquisition, and vice versa.
- If the user prefers to compute the geometry in the Cartesian coordinates defined in Figure 5 (left-handed coordinate system) instead of the cylindrical coordinates defined in Figure 2, the coordinates can be converted as $x = -\rho\sin\varphi$, $y = \rho\cos\varphi$, and $z = z$.

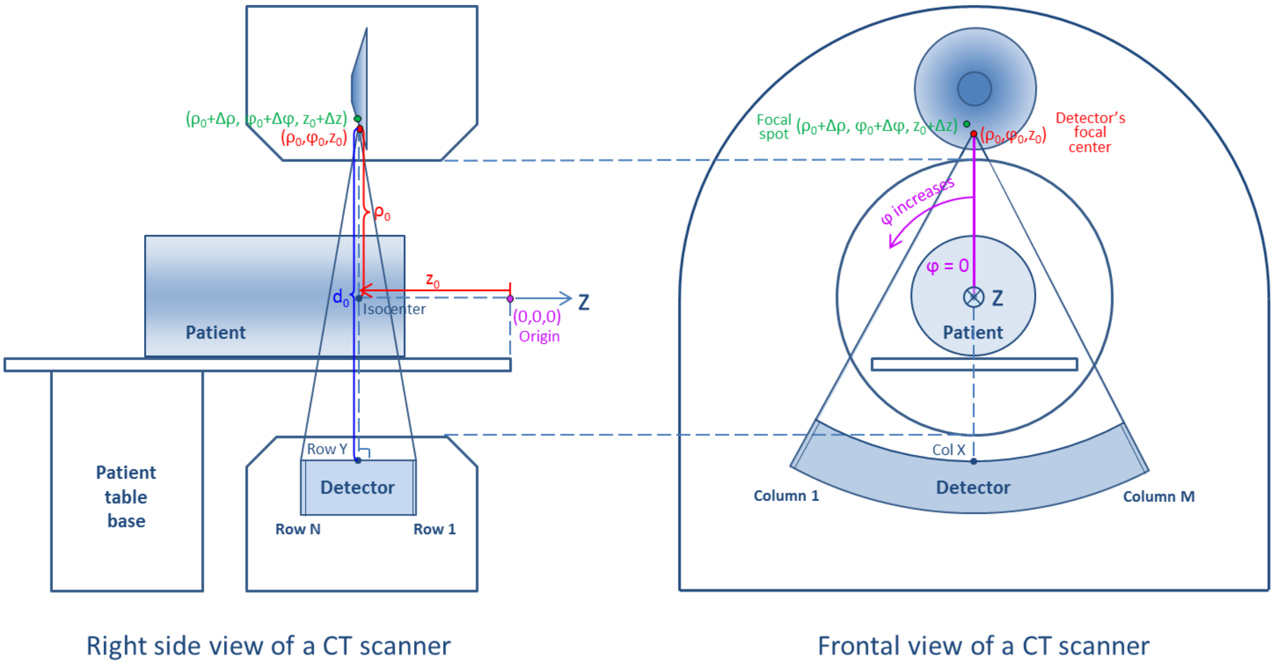

Figure 2: The definition of gantry geometries in a cylindrical coordinate system.

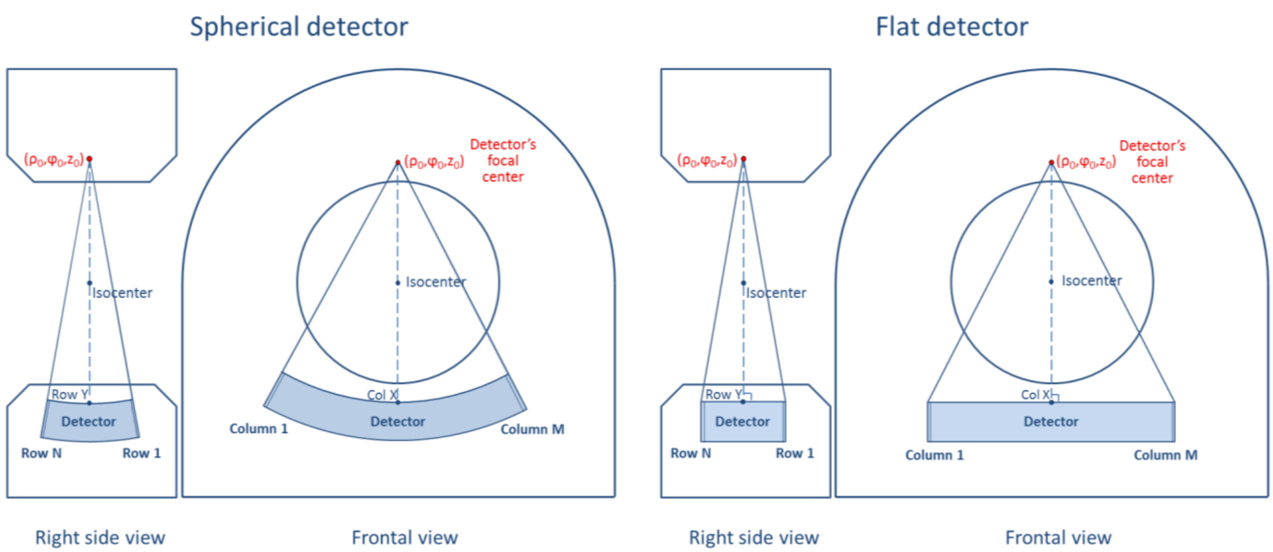

Figure 3: The definition of detector's focal center for spherical and flat detectors.

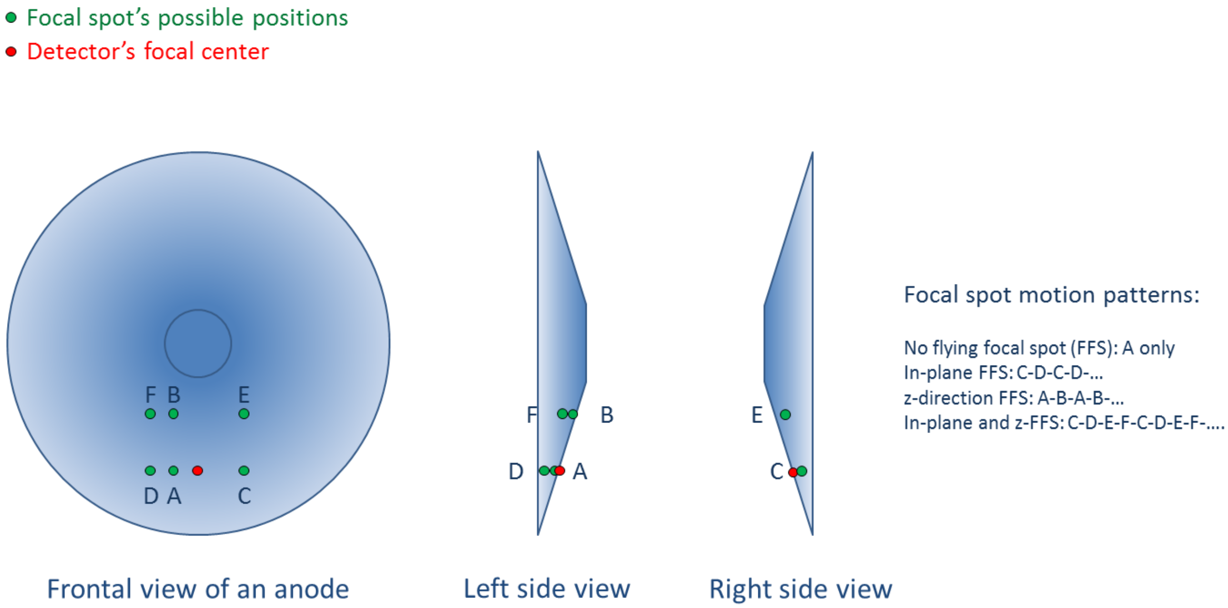

Figure 4: The movement pattern of focal spot with flying focal spot technique on Definition Flash scanners.

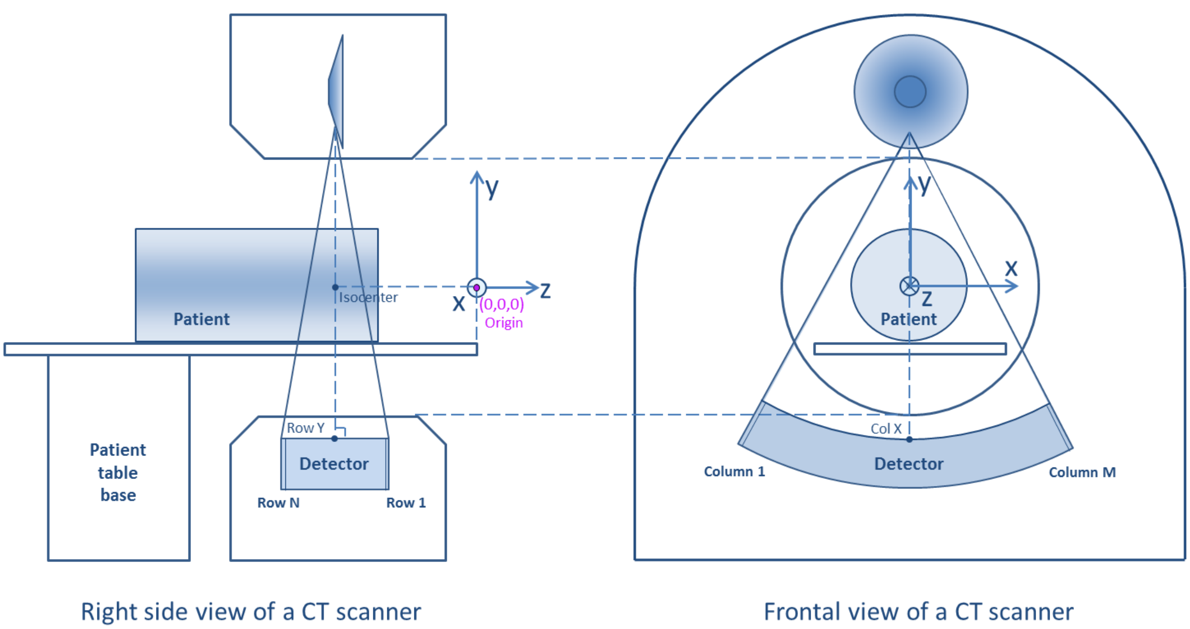

Figure 5: The definition of gantry geometries in a Cartesian coordinate system.

➢ Photon statistics

Knowledge of the photon statistics, i.e., the spatial distribution of the number of photons used for each projection, is often used by iterative reconstruction techniques. For example, a data weighting term proportional to the detected number of photons may be included in the objective function. Therefore, we provided an estimate of the number of photons incident on the patient (i.e., after the bowtie filter and before the patient) in the header of each DICOM-CT-PD file in Tag (7033,1065) (as explained in a later section). The incident number of photons are derived by measuring the variance of the transmission data in a series of air scans and assuming that the number of photons is the inverse of the variance [4]. This method provides the number of photons in terms of noise equivalent quanta. The noise data were measured for the specific scanner type, flat beam filter, bow-tie filter, and tube potential used in acquiring the projection data, and then scaled for the tube current of each specific projection. The results are presented along the direction of the detector columns (neglecting the variation across detector rows), as illustrated in Figure 6.

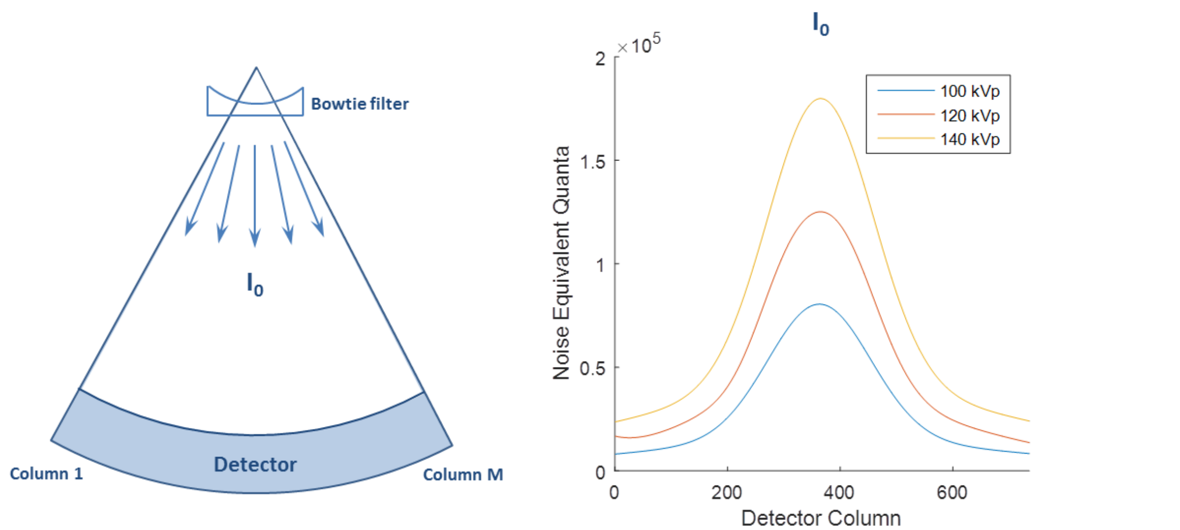

Figure 6: Photon statistics (Noise equivalent quanta) along the direction of detector columns at various tube potentials (100-140 kVp).

➢ Study, Series, and Instance

In the DICOM format, the terms “study”, “series”, and “instance” are used to define information entities, as illustrated in Figure 7. In the DICOM-CT-PD format, the same terminology is used to store different information entities as illustrated in Figure 7 and explained below.

Similar to the DICOM format, the DICOM-CT-PD “study” includes all data collected from the creation of the patient on the scanner console to the close of the patient. “Series” are nested below a “study”. A DICOM-CT-PD “series” refers to one scan (i.e. data acquisition), one x-ray source, one tube potential,

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[4] Yu, L., Shiung, M., Jondal, D., McCollough, C.H. (2012). Development and validation of a practical lower-dose-simulation tool for optimizing computed tomography scan protocols. J Comput Assist Tomogr, 36 (4), 477-487.

one energy bin or threshold, or one detector layer. One study typically consists of multiple series. Some examples include: 1) multi-phase exams, where each series corresponds to the data from one phase; 2) multi-source scans such as from dual-source CT, where each series corresponds to the data from one x-ray source; 3) scans with fast switching tube voltage, where each series corresponds to the data from one tube potential; 4) scans with multiple-layer detectors, where each series corresponds to the data from one detector layer; and 5) energy-resolved scans with multiple energy thresholds, where each series corresponds to the data from one energy threshold (or one energy bin). When multiple series are generated for one study, Tag(7033,1061) and Tag(7033,1063) in the header (as explained in the next section) can help specify the source/tube voltage/detector layer/energy threshold that corresponds to the series.

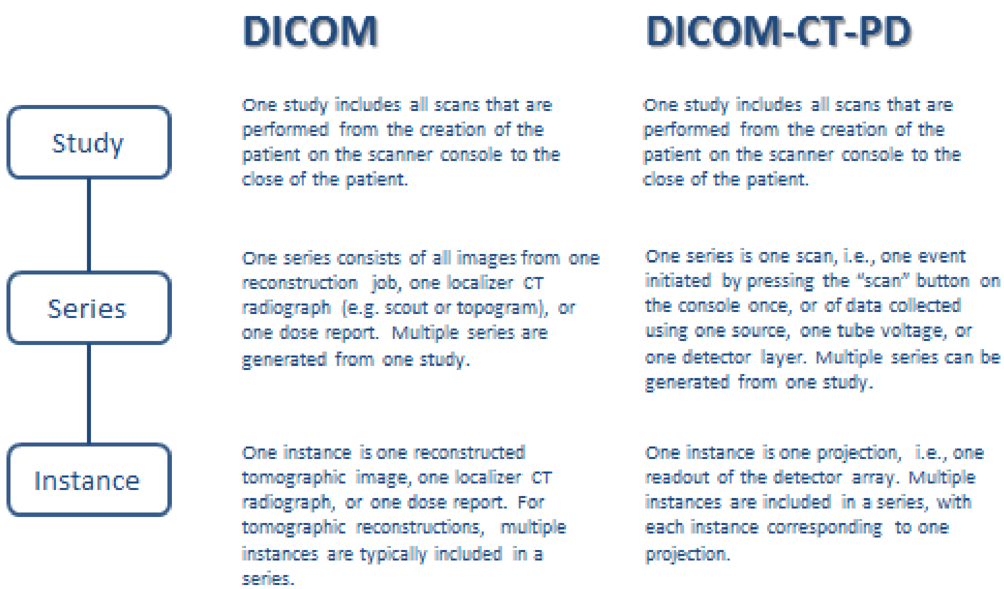

Figure 7: The definitions of study, series, and instance in DICOM format and DICOM-CT-PD format.

➢ Understanding and Accessing the Header

The aforementioned gantry geometries, together with information regarding the CT scanner model and the x-ray spectrum, are recorded in the header of the DICOM-CT-PD data. Following the DICOM standard, the header is indexed by "Tags", with each tag corresponding to a specific attribute. A list of tags is provided in Table 1and 2.

Table 1: Tags in the header of DICOM-CT-PD format.

Tag	Attribute Name	VR*	VL**	Description
(0010,0010)	PatientID	LO	1	Patients full name
(0010,0010)	PatientName	PN	1	Patient code name
(0010,0040)	PatientSex	CS	1	"M" or "F".
(0020,000D)	StudyInstanceUID	UI	1	The study unique ID.

(0010,1010)	PatientAge	AS	1	The age of the patient by year.
(0008,0060)	Modality	CS	1	"CT"
(0020,000E)	SeriesInstanceUID	UI	1	The series unique ID.
(0020,0011)	SeriesNumber	IS	1	The series number.
(0018,1030)	ProtocolName	LO	1	The name of the protocol
(0018,0015)	BodyPartExamined	CS	1	The body part of the patient being scanned, e.g., “ABDOMEN”.
(0018,5100)	PatientPosition	CS	1	Patient position descriptor relative to the equipment.
(0020,0052)	FrameOfReferenceUID	UI	1	Uniquely identifies the frame of reference for a Series.
(0008,0070)	Manufacturer	LO	1	e.g., "SIEMENS" or “GE”
(0008,0023)	ContentDate	DA	1	The date the raw data creation was started.
(0008,0033)	ContentTime	TM	1	The time the raw data creation was started.
(0008,9123)	CreatorVersionUID	UI	1	1.3.6.1.4.1.9590.100.1.2.2424756340 11743926727995869870927993451
(0020,0013)	InstanceNumber	IS	1	The instance (projection) number.
(0008,0016)	SOPClassUID	UI	1	A unique identifier for the Raw Data Storage SOP Class: 1.2.840.10008.5.1.4.1.1.66
(0008,0018)	SOPInstanceUID	UI	1	A unique identifier for an SOP instance
(0020,0012)	AcquisitionNumber	IS	1	A number identifying the single continuous gathering of data over a period of time
(0008,3010)	IrradiationEventUID	UI	1	Unique identification of the irradiation event(s) associated with the acquisition
(0018,0060)	KVP	DS	1	The peak kilo-voltage
(0018,0090)	DataCollectionDiameter	DS	1	The scan field of view (mm)
(0018,1150)	ExposureTime	IS	1	The gantry rotation time (ms).
(0018,1151)	XrayTubeCurrent	IS	1	The tube current (mA).
(0018,9311)	SpiralPitchFactor	FD	1	Ratio of the table feed per rotation to the total collimation width.
(0028,1052)	RescaleIntercept	DS	1	Pixel values of projection data need to be adjusted using the equation: Pixel value = Pixel value readout * RescaleSlope + RescaleIntercept
(0028,1053)	RescaleSlope	DS	1	Pixel values of projection data need to be adjusted using the equation: Pixel value = Pixel value readout * RescaleSlope + RescaleIntercept
(0028,0002)	SamplePerPixel	US	1	Number of samples (planes)

(0028,0004)	PhotometricInterpretation	CS	1	Specifies the intended interpretation of the pixel data. Shall have one of the following Enumerated Values: MONOCHROME1 MONOCHROME2
(0028,0010)	Rows	US	1	Number of rows
(0028,0011)	Columns	US	1	Number of columns
(0028,0100)	BitsAllocated	US	1	Number of bits allocated for each pixel sample. Each sample shall have the same number of bits allocated.
(0028,0101)	BitsStored	US	1	Number of bits stored for each pixel sample. Each sample shall have the same number of bits stored.
(0028,0102)	HighBit	US	1	Most significant bit for pixel sample data. Each sample shall have the same high bit.
(0028,0103)	PixelRepresentation	US	1	Data representation of the pixel samples. Each sample shall have the same pixel representation. Enumerated Values: 0000H = unsigned integer. 0001H = 2's complement
-	Contrast/Bolus	-	-	Use the DICOM standard Contrast/Bolus module.
-	Waveform	-	-	Use the DICOM standard Waveform module. This module will be used for EKG waveform data corresponding to the projection.

*VR: Value representation, http://www.dabsoft.ch/dicom/5/6.2/
**VL: Value length

Table 2: Private tags in the header of DICOM-CT-PD format.

Tag	Attribute Name	VR*	VL**	Description
(7029,1010)	NumberofDetectorRows	US	1	The number of detector rows.
(7029,1011)	NumberofDetectorColumns	US	1	The number of detector columns.
(7029,1002)	DetectorElementTransverseSpacing	FL	1	The width of each detector column, measured at the detector (mm).
(7029,1006)	DetectorElementAxialSpacing	FL	1	The width of each detector row, measured at the detector (mm).
(7029,100B)	DetectorShape	CS	1	The shape of the detector, such as “CYLINDRICAL”, “SPHERICAL”, or “FLAT”.
(7031,1001)	DetectorFocalCenterAngularPosition	FL	1	φ_0, the azimuthal angles of the detector’s focal center (rad).
(7031,1002)	DetectorFocalCenterAxialPosition	FL	1	z_0, the z location of the detector’s focal center (mm).

(7031,1003)	DetectorFocalCenterRadialDistance	FL	1	ρ_0, the in-plane distances between the detector's focal center and the isocenter (mm).
(7031,1031)	ConstantRadialDistance	FL	1	d_0, the distance between the detector's focal center and the detector element specified in Tag(7031,1033) (mm)
(7031,1033)	DetectorCentralElement	FL	1-n	(Column X ,Row Y), the index of the detector element aligning with the isocenter and the detector's focal center.
(7033,100B)	SourceAngularPositionShift	FL	1	$\Delta\varphi$, the φ offset from the focal spot to the detector's focal center (rad).
(7033,100C)	SourceAxialPositionShift	FL	1	Δz, the z offset from the focal spot to the detector's focal center (mm).
(7033,100D)	SourceRadialDistanceShift	FL	1	$\Delta\rho$, the ρ offset from the focal spot to the detector's focal center (mm).
(7033,100E)	FlyingFocalSpotMode	CS	1	The mode of flying focal spot (FFS). "FFSNONE" means no flying focal spot; "FFSZ" means flying focal spot along axial direction; "FFSXY" means in-plane flying focal spot; and "FFSXYZ" means flying focal spot in-plane and along axial direction.
(7033,1013)	NumberofSourceAngularSteps	US	1	The number of projections per complete rotation.
(7033,1061)	NumberofSpectra	US	1	The number of sources/tube voltages/detector layers/energy thresholds/energy bins used in the data acquisition.
(7033,1063)	SpectrumIndex	US	1	The index of the source/tube voltage/detector layer/energy threshold/energy bins.
(7033,1065)	PhotonStatistics	FL	1-n	An array describing the spatial distribution of photons along the direction of the detector columns, from Column 1 to Column M (neglecting the variation across detector rows). Each element of the array corresponds to a detector column.
(7033,1067)	Timestamp	FL	1	The timestamp in absolute time (ms).
(7037,1009)	TypeofProjectionData	CS	1	"AXIAL" or "HELICAL"
(7037,100A)	TypeofProjectionGeometry	CS	1	"FANBEAM" for third generation CT geometry.
(7039,1003)	BeamHardeningCorrectionFlag	CS	1	A flag used to define whether the projection data has been corrected for beam hardening effects. "YES" or "NO".

(7039,1004)	GainCorrectionFlag	CS	1	A flag used to define whether the projection data has been calibrated for detector response with respect to the dynamic range available. "YES" or "NO".
(7039,1005)	DarkFieldCorrectionFlag	CS	1	A flag used to define whether the background signals prior to the x-ray exposure has been subtracted from the projection data. "YES" or "NO".
(7039,1006)	FlatFieldCorrectionFlag	CS	1	A flag used to define whether the gradient of flood field introduced by the heel effect and the bowtie filter has been compensated in the projection data. "YES" or "NO".
(7039,1007)	BadPixelCorrectionFlag	CS	1	A flag used to define whether abnormal pixels have been removed from the projection data by interpolation. "YES" or "NO".
(7039,1008)	ScatterCorrectionFlag	CS	1	A flag used to define whether the projection data has been corrected for scattered radiation. "YES" or "NO".
(7039,1009)	LogFlag	CS	1	A flag used to define whether the projection data has been logarithmically transformed. "YES" or "NO".
(7041,1001)	WaterAttenuationCoefficient	DS	1	A calibration factor μ' for the conversion of measured linear attenuation coefficients μ to CT numbers (mm^{-1}): CT numbers = 1000 * (μ- μ') / μ'

*VR: Value representation, http://www.dabsoft.ch/dicom/5/6.2/
**VL: Value length

The header contents can be accessed using the following MATLAB command:

HEADER = dicominfo(RAWFILENAME, 'dictionary', DICTIONARYFILENAME); ,

where RAWFILENAME is the name of the projection data file, and DICTIONARYFILENAME is the name of the dictionary file that defines all attributes listed in Table 1 and 2. Note that **the dictionary file needs to be specified in order to correctly read out all attributes in the header**, otherwise the DICOM reader will try to understand the header using the standard DICOM format. As a result, standard DICOM readers that do not support self-defined dictionary files (such as *ImageJ*) may not be appropriate for inspecting the header of the DICOM-CT-PD format. Also note that **each attribute has a data type** specified by the value representation, VR. For example, the attribute of *DetectorCenterAxialPositionArray*, once read out, has the data type of FL, which is equivalent to *32-bit float* in C or *single* in MATLAB. The data type differences between attributes need to be kept in mind in order to **avoid loss of precision error**.

➢ Understanding and Accessing the Projection Data

The projection data (one view angle, i.e., one readout of the complete detector array) are stored in the pixel data part of the DICOM-CT-PD data as a matrix, at the tag location of (7FE0,0010).

Tag	Attribute Name	VR	VL	Description
(7FE0,0010)	PixelData	OW	1	Projection data, an unsigned 16-bit matrix of measured linear attenuation coefficients

The projection data can be accessed using DICOM readers, for example, MATLAB with the following command:

PROJECTIONDATA = dicomread(FILENAME);

where FILENAME is the name of the projection data file.

Note that **the projection data matrix, once read out, needs to be scaled first** using the equation described in Tag(0028,1052) and Tag(0028,1053). The scaled matrix represents the raw data in terms of either the line integral of the linear attenuation coefficients or the signal before or after specific data corrections. **The matrix has a dimension of (N_{col}*N_{row})**, where N_{col} is the number of detector columns and N_{row} is the number of detector rows. The matrix is arranged such that the first N_{col} elements correspond to the readout along the first row (Column 1 to Column M), the second N_{col} elements correspond to the readout along the second row, and so forth.

In case of **flying focal spot**, the focal spot moves periodically on the anode surface (Figure 4). One projection data matrix is acquired for each focal spot position, and is saved as a separate DICOM-CT-PD file.

To convert linear attenuation coefficient values to CT numbers in Hounsfield Units (HU), a calibration factor is provided in Tag(7041,1001), which is the linear attenuation coefficient of water. If the projection data has been through beam hardening correction, the calibration factor is the linear attenuation coefficient of water at the energy of beam hardening correction.

➢ Tracing Images Back to the Correct Projection Data Set

To help generate a relationship between the projection data and the reconstructed images derived from such data, an additional sequence of DICOM tags are utilized in the image headers. Reference Raw Data Sequence, Tag (0008,9121), identifies the set of Raw Data SOP Class/Instance pairs of the raw data that was used to derive the image. An example of this is illustrated in Figure 8.

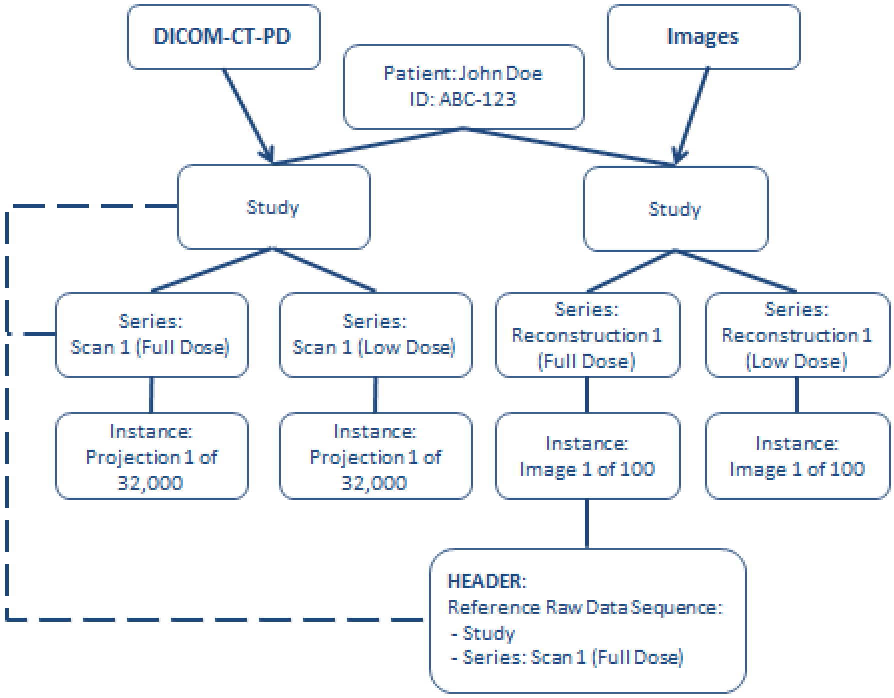

Figure 8: An example demonstrating how the relationship between Image Data and the corresponding Raw Data is maintained

- **Clinical Data Reports**

Data such as lesion location, diagnosis, and source of truth were acquired for each positive case and formatted into a reference report. This report is a supplementary excel document for each of the 3 body regions used in this data library: head, chest, and abdomen. This spreadsheet does not provide information about negative cases.

Within these Excel files there are two tabs. One is marked with the anatomic region of interest and contains the data collected for the positive cases, and the other tab is labeled with KEY. This KEY tab contains details about the units of measurement for the data collected, when appropriate, notes on any abbreviations used, as well as values for the coded columns in the data tab.

Links with a snapshot of the image containing each identified lesion is located within the Excel document. The identified lesion is located within the green region of interest. Be sure to save the JPG files and excel document in the same folder to maintain the link within the Excel document.