Technical Brief Series

Digital Tomosynthesis – Theory of Operation

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Digital Tomosynthesis (DT) is a new radiographic imaging technique that is revived from the nearly century-old traditional film-screen tomography. This rejuvenation is all made possible by the recent advances in high frame-rate, high-sensitivity flat-panel digital radiographic detector, rapid pulsed-exposure sequence-capable high-frequency x-ray generator, the widely available and low-cost computer GPU processing power, and the precision motion controls built in the digital radiography system hardware.

Figure 1: An example of DT acquisition. Both wall stand and table positions are supported by the Carestream DT option.

Carestream Health implements the DT functionality as an upgradable option on the standard DRX-Evolution Plus Digital Radiography System (Figure 1). The portable DRXPlus detector can be placed inside either the wall bucky or the table bucky to accommodate different exam types and positions.

The major benefit of DT over the traditional film-screen tomography is that DT greatly simplifies the operator's workflow by separating the process of DT exposure acquisition from image volume formation; it needs only a single sweep of x-ray exposures and then relies on computer software in post-processing to generate as many DT slices as needed at any slice thickness and slice interval.

Background in Traditional Tomography

The traditional tomography acquisition uses synchronized, reciprocal mechanical motion of the x-ray source and the film cassette combined with a single, long-duration, continuous x-ray exposure. Many scan patterns have been developed for the x-ray source and cassette motion, such as linear, circular, elliptical, spiral, hypocycloidal, etc., but linear motion is the most frequently used in practice due to its simplicity.

Figure 2 illustrates how linear tomography works. Before a tomography procedure, the operator visually estimates the midline of the anatomical area of interest, determines the slice thickness requirement for the exam, and then sets the initial pivot level (fulcral plane) and the sweep angle for the tomography scan accordingly.

For each tomographic scan the anatomical details in the fulcral plane (e.g., object O in Figure 2) will be preserved while those anatomical clutters above or below the fulcral plane will be blurred or smeared (e.g., object X in Figure 2). The larger the sweep angle, the more blurred the anatomical clutters become. As anatomy clutter is the primary source of noise for radiography, tomography isolates the anatomy of interest in the fulcral plane from the unwanted clutters from the rest of the anatomy, and therefore improves contrast-to-noise ratio of the image details.

Each tomography acquisition uses one single continuous x-ray exposure, and many acquisitions are frequently needed in order to cover the anatomical area of interest fully. This would definitely increase the overall exam time and the total radiation dose by the total number of scans. As the overall exam time and the total radiation dose must be limited, the number of tomographic scans is limited, which may limit the smallest

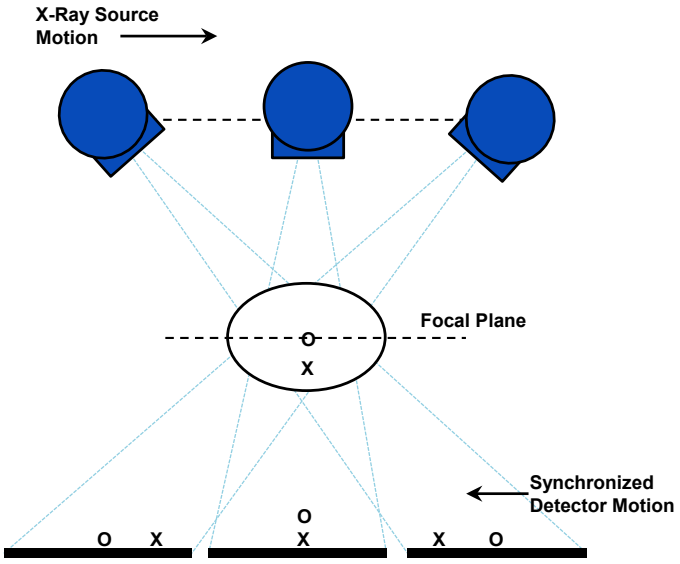

Figure 2: In traditional tomographic imaging, object structure details (e.g., Object O) in the fulcral plane stays focused (stationary in the film plane) while objects outside the focal plane (e.g., object X) become blurred or smeared due to motion.

tomographic slice interval (slice pitch) and the spatial resolution in the depth direction of the tomography volume.

Digital Tomosynthesis

Figure 3(a) illustrated how DT acquisition works. DT operates based on the same principle as tomography except the detector can either be mechanically motorized in synchronization with the x-ray source or simply be stationary during the exam. The DT implemented by Carestream chooses to use stationary x-ray detector for the purpose of reducing motion blur and improving spatial resolution. In addition, DT uses multiple, low-power, pulsed x-ray exposures instead of a single continuous exposure. Correspondingly the x-ray detector in a DT exam will capture each short x-ray pulse as individual images from different projection angles of the x-ray source. These projections are used to reconstruct a stack of DT slices for viewing, of which each slice is equivalent to a traditional tomogram with fulcral plane set at the center of the DT slice.

Because the image acquisition is separated from the DT image volume formation process, sophisticated reconstruction processes are used to maximize the anatomy contrast-to-noise ratio in the DT slices. Figure 3(b) and (c) shows the "Shift-and-Add" method used in some of the early DT systems. Individually captured images are shifted differently and added together in the software to generate DT slices focused at

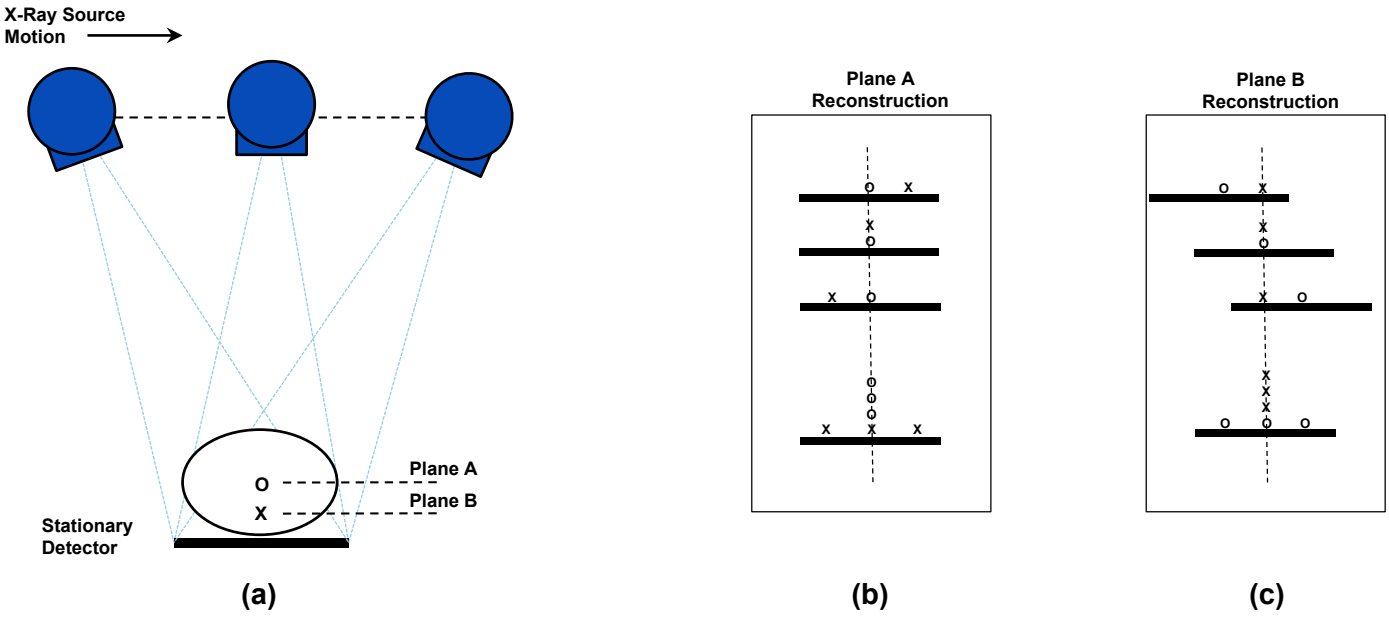

Figure 3: Schematic view of DT acquisition (a) and reconstructions of slices at different depth (b) (c).

different depths of the anatomy. The Carestream DT reconstruction software leverages the state-of-the-art algorithms that are the same in principle to those applied in the computed tomography (CT), such as filtered back projection or iterative reconstruction. As a consequence, the anatomical details are greatly improved with DT when compared to tomogram. Figure 4 shows two DT slices of the pelvis region at different depth locations.

The exam time is greatly reduced with DT than with traditional tomography, and the operator's trial-and-error process in locating the anatomical region of interest is eliminated. Multiple projections are acquired during a single DT acquisition sweep. Afterward the anatomical features at different depth locations are reconstructed mathematically. The total number of slices and the slice interval can be made arbitrarily large or small in the software as needed; and they are limited by only the computer memory capacity, network bandwidth, PACS storage space, and most importantly the diagnostic needs on the image resolution.

DT Scout

Each DT acquisition sequence starts with a scout view. The scout serves two purposes for DT: 1) collimation and anatomy positioning, and 2) exposure control. The scout view is captured at the same technique settings (kVp, mAs, etc.) as with a standard radiography except the projection angle is always straight on to the detector center and the SID is fixed (110 cm for table and 180 cm for wall stand). The scout is processed as a radiographic image and then presented to the operator to verify the collimation for anatomy coverage as well as the anatomy positioning. The scout image can be captured using either automatic exposure control (AEC) or manual technique settings. The operator would decide on the appropriateness of the image quality of the scout view for diagnosis or retake the exposure if adjustment is needed.

DT Sequence Exposure Control

Once the DT scout is captured and accepted by the operator, its exposure technique will be used as the basis to derive the total exposure for the DT sequence. This is an important

Figure 4: DT slice examples of the pelvis region at different depth locations.

operation step for automatic exposure control of the DT sequence.

The total exposure level, mAs in particular, of a DT sequence is set as the multiplication of the DT scout exposure level (mAs) and the DT Technique Scale Factor that is preconfigured in the Preference Editor. This is regardless of the total number of projections and the x-ray tube sweep angle specified. The total DT mAs is allocated equally to all the DT projections. The other exposure technique settings between the scout and the DT sequence, such as kVp and beam filtration, are kept the same.

DT Acquisition Modes and Reconstruction Resolution

DT projection images can be acquired in either high-resolution (HR) mode or high-speed (HS) mode. In the HR acquisition mode, the detector works in its native resolution (i.e., no pixel binning) and acquires images at 4.5 frames per second (fps); in the HS acquisition mode the detector uses 2x1 pixel binning and acquires images at 9.0 fps due to 50% reduced data rate. The primary usage of the HR mode is for musculoskeletal exams (hand, foot, knee, etc.), when the patient motion artifact due to the longer acquisition time is limited and it would not be a major concern to the DT image quality. The improved frame rate in the HS acquisition mode is directly translated into 50% reduction in total DT image acquisition time. Because the HS acquisition mode is 2X faster, it will be helpful to reduce the patient motion artifact. There is a potential image resolution loss due to 2x1 pixel binning; however, the impact is minimized in the system design by binning the pixels in the x-ray tube motion direction as well as applying sharpness enhancement filtering operation to compensate for the minor resolution loss. A comparative image quality example is shown in Figure 5.

Regardless of the acquisition mode, DT slices can be reconstructed and presented in two spatial resolutions during post processing: the native 1x1 pixel resolution (HR-res) or the 2x2 pixel average resolution (STD-res). The size of an STD-res DT volumetric image will be 1/8 (½ x ½ x ½) of that of the corresponding HR-res image.

In summary, the DT volumetric images can be generated in four combinations (see Table 1 for the recommended applications). In theory, the HR/HR-res combination will offer the best spatial resolution in the reconstructed DT slice image because both the detector and the reconstruction work in the native 1x1 resolution.

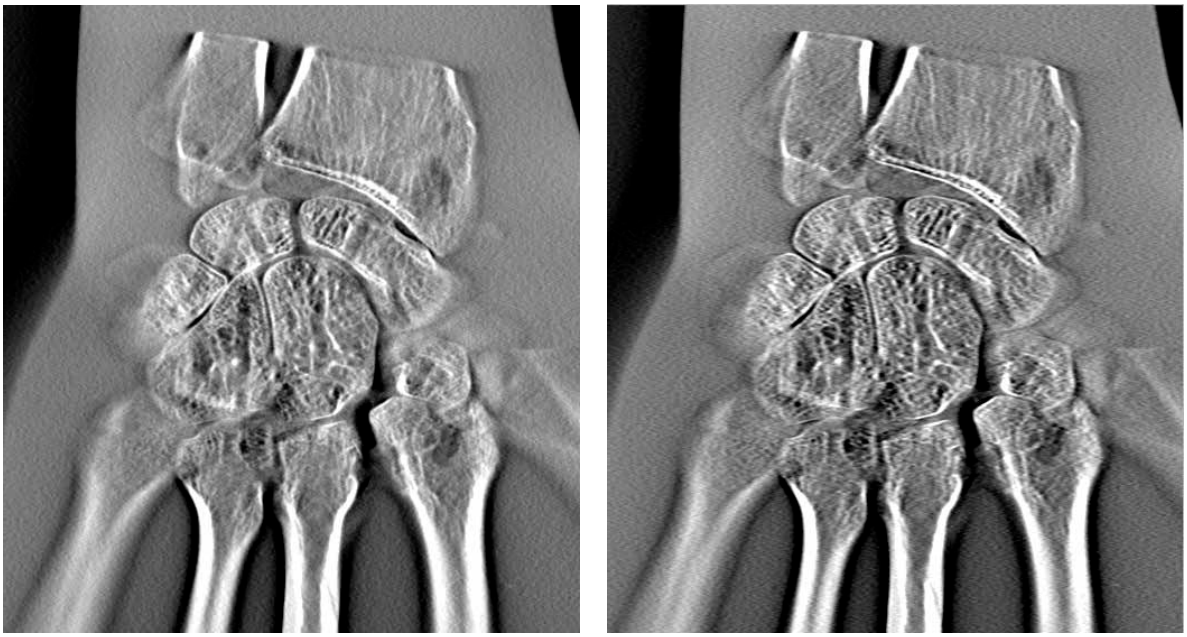

Figure 5: Image quality comparison of a hand phantom acquired in HR mode (left) and HS mode (right). Both images are reconstructed in HR-res using 0.3 cm slice thickness and 0.05 cm slice interval. Sharpness enhancement is applied automatically in the software to bring up the anatomical details in the image acquired in HS mode.

	HR	Std. Res
Acquisition HR (1x1)	Hand/Wrist Foot/Ankle Knee Shoulder	
Acquisition HS (1x2)	Hand/Wrist Foot/Ankle Knee Shoulder	Chest Abdomen Pelvis C-Spine

Table 1: Recommended DT operation for different exam types. HR-res reconstruction is optimal for musculoskeletal exams, and the HS acquisition helps to reduce patient motion artifact.

DT Section Thickness and Sweep Angle α

As mentioned before, DT imaging follows the same principles as traditional tomography. For any anatomical details that are outside the fulcral plane, the greater the sweep angle, the greater the blur effect. Because all the details in the fulcral plane are unchanged, increasing the sweep angle effectively reduces the clutter caused by anything that is outside the fulcral plane, which makes the tomographic slice appear "thinner." In practice, because the anatomical details gradually become blurrier as their distance from the fulcral plane increases, Section Thickness is used to define the region of the anatomy within which all the anatomical details are under a permissible blur level. Section Thickness is a value that is determined solely by the acquisition geometry and therefore is inherent to the acquisition. It is different from and should not be confused with the Slice Thickness used in the DT reconstruction. Table 2 shows the pre-calculated section thickness at different sweep angles α and 0.25 mm permissible blur values.

Sweep Angle α (Degrees)	Section Thickness (mm)
10	2.86
15	1.90
20	1.42
25	1.13
30	0.93
35	0.79
40	0.69

Table 2: Look up table for selecting DT sweep angle to achieve desired slice thickness, assuming the maximum permissible blur is 0.25 mm.

DT Slice Thickness *t* and Slice Interval *δ*

The DT image is presented as a stack of reconstructed 2D coronal slices. The center location of each slice corresponds to the fulcral plane at which anatomical details are maximized. The distance between the reconstruction slices is the *slice interval* (δ). The smaller the δ value, the finer the DT reconstruction resolution in the depth direction. The slice interval can be set accordingly by the operator, depending on the requirements on the anatomical features to be visualized for diagnosis. For example, for small musculoskeletal exams such as wrist, etc., the δ value can be set between 0.5 mm to 1.0 mm, and for chest exams between 1.0 mm to 2.0 mm.

Each DT slice covers a slab of anatomical region and its thickness (*t*) can be made arbitrarily by the DT reconstruction algorithm, which is independent of (i.e., decoupled from) the Section Thickness or the slice interval (δ). In practice the reconstruction slice thickness (*t*) should always be greater than or equal to the slice interval such that no anatomical void is created (see Figure 6), causing the slices to overlap each other partially. A smaller *t* value more likely helps to resolve the anatomical details better but at the potential expense of greater noise appearance. On the other hand, greater *t* value helps to reduce the image noise but potentially blends more

anatomical details from the region outside the fulcral plane therefore defeating the purpose of DT. A default slice thickness of 20.0 mm is a good starting point for all exam types.

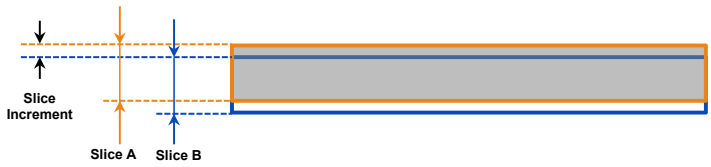

Figure 6: Thick slices can overlap with each other yet slice interval can be much smaller than slice thickness.

DT Projection Image Number *N*

The number of discrete DT projection images acquired across the sweep angle dictates the reconstruction rippling artifact. Figure 7 shows a DT slice of an ankle in the arterial-posterior view. The rippling artifact at the bottom of the image is caused by the sharp transitions between the open-air region and the foot, with each ripple corresponding to a DT projection. When the sweep angle is fixed, more projections will help to reduce the artifact but at the expense of increased exam time. The ripple artifact will manifest itself more with thicker anatomy, in which case increasing the DT projection number will help.

Figure 7: An example of ripple artifact in DT foot exam.

Summary

Compared to traditional tomography, DT significantly improves the workflow, reduces the overall exam time, minimizes exposure retakes, and offers improved image quality. Good radiographic practice in anatomy positioning and x-ray exposure technique selection should be followed for a DT exam, just as in standard radiography.

Patient motion during a DT exam degrades the image quality and therefore should be minimized as much as possible. In addition to taking measures to restrain patient motion, a better timing to start the DT sequence with respect to the patient motion pattern would help. Finally, patient motion artifact can be reduced by reducing the total exam time using the HS acquisition mode.

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