Driving CT Developments the Last Mile: Case Examples of Successful and Somewhat Less Successful Translations into Clinical Practice

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ABSTRACT

CT technology has advanced rapidly in recent years, yet not all innovations translate readily into clinical practice. Technology advances must meet certain key requirements to make it into routine use: They must provide a well-defined clinical benefit. They must be easy to use and integrate readily into existing workflows, or better still, further streamline these workflows. These requirements heavily favor fully integrated or automated solutions that remove the human factor and provide a reproducible output independent of operator skill level. Further, to achieve these aims, collaboration with the ultimate end users is needed as early as possible in the development cycle, not just at the point of product testing. Technology innovators are encouraged to engage such collaborators even at early stages of feature or product definition.

This manuscript highlights these concepts through exploration of challenging areas in CT imaging in an Emergency Department setting. Technique optimization for pulmonary embolus CT is described as an example of successful integration of multiple advances in radiation dose reduction and imaging speed. The typical workflow of a trauma "pan-scan" (incorporating scans from head through pelvis) is described to highlight workflow challenges and opportunities for improvement. Finally, Dual Energy CT is discussed to highlight the undeniable clinical value of the material characterization it provides, yet also its surprisingly slow integration into routine use beyond early adopters.

Keywords: Computed tomography, trauma, pulmonary embolus, CT pulmonary angiography, dual energy CT, CT radiation dose, radiology workflow, clinical translation

1. INTRODUCTION

Computed Tomography (CT) is a mature technology, but continues to evolve. As new innovations develop, they are variably adopted into clinical practice, in part driven by the promise of added clinical value, and in part driven or hindered by the ease of or barriers to integration with existing workflows and procedures. These factors cannot be neglected if there is to be any hope of successful translation into clinical practice. The following sections explore three distinct challenge areas relevant to clinical CT operations, in order to highlight lessons about technology adoption into the clinic.

2. CT PROTOCOL OPTIMIZATION AND RADIATION DOSE REDUCTION

There have been widespread concerns about radiation exposure from CT.[1,2] This attention prompted broad efforts in recent years to reduce the radiation doses used in CT while maintaining image quality at a diagnostic level. The CT manufacturers responded with many new technology innovations and associated opportunities for CT protocol technique optimization. This section will outline some of the strategies that can be used in combination to achieve substantial reductions in radiation dose without hindering diagnostic quality. Pulmonary embolus CT scans are designed to detect potentially life threatening blood clots within the pulmonary arteries, and will be used as a case example.

2.1 Strategies for CT Radiation Dose Reduction

There are many available strategies to reduce CT radiation exposure while maintaining image quality.[3] One of the most widely available and robust tools is automated tube current modulation, in which the x-ray flux is adjusted based on the size of the patient to achieve the desired image quality. In the case of vascular imaging examinations, optimizing the IV contrast infusion to maximize enhancement within the target vasculature permits a subsequent reduction in mAs as more

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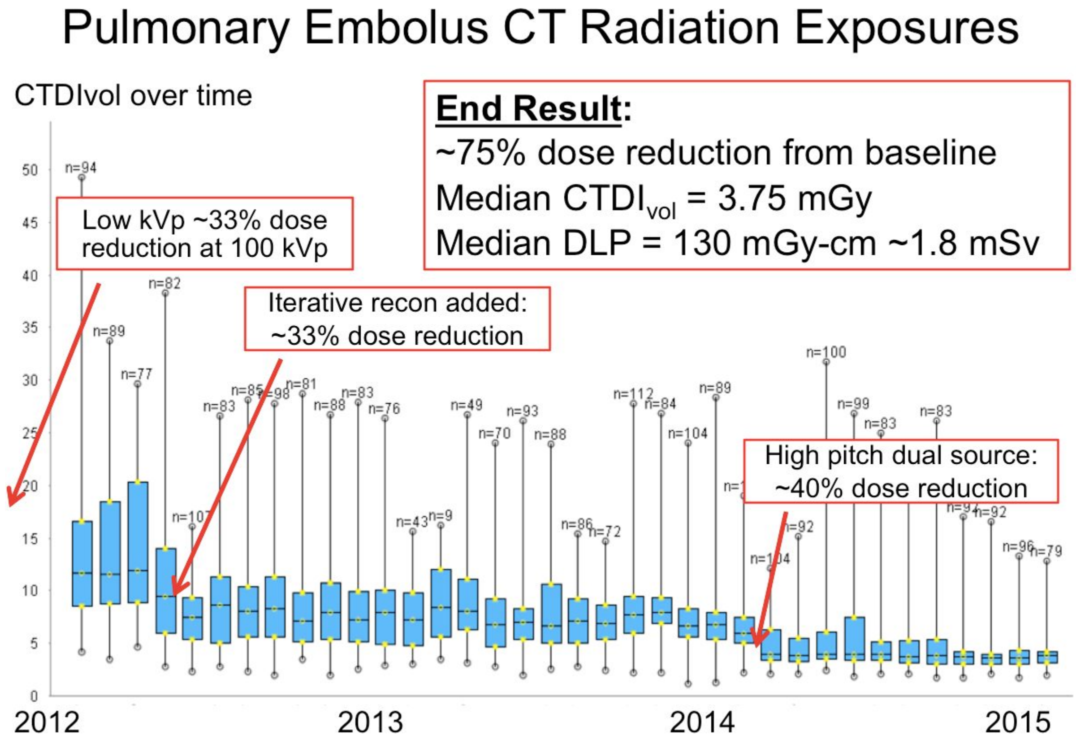
noise can be tolerated in inherently high contrast diagnostic tasks such as detection of intraluminal blood clots within densely enhancing vessels. Low kVp (peak kilovoltage) acquisition not only reduces radiation dose but also further increases the attenuation of vessels enhanced by iodinated contrast.[4] Noise reducing postprocessing methods such as iterative reconstruction methods may also be used, and permit lower dose acquisitions. A high pitch dual-source scan mode may be beneficial in reducing motion artifacts due to respiratory motion and cardiac pulsation, but also achieves radiation dose reduction, largely through use of a smaller bowtie filter. In addition, if the tube current is allowed to truncate at maximum mA through the shoulders, further radiation dose reductions can be achieved without impacting image quality in the portion of the scan that is crucial to diagnosis of pulmonary embolus.

2.2 Impact of Dose Reduction Techniques on Pulmonary Embolus CT

The use of these multiple approaches in combination has resulted in an approximately 75% dose reduction from the baseline technique historically used in our institution (figure 1). Data captured from our CT radiation dose monitoring software has demonstrated a reduction in median CTDIvol to 3.8 mGy, a fraction of the ACR-AAPM Diagnostic Reference Level of 21 mGy and Achievable Dose of 14 mGy.[5] Our median DLP of 130 mGy-cm corresponds to approximate effective dose on the order of 1.8 mSv, in comparison with traditional literature values of 7 mSv for chest CT and 15 mSv for pulmonary embolus CT.[6]



Pulmonary Embolus CT Radiation Exposures

End Result:
~75% dose reduction from baseline
Median CTDI_{vol} = 3.75 mGy
Median DLP = 130 mGy-cm ~1.8 mSv

Low kVp ~33% dose reduction at 100 kVp

Iterative recon added: ~33% dose reduction

High pitch dual source: ~40% dose reduction

Figure 1. Radiation dose reductions achieved for pulmonary embolus CT scans through sequential adoption of new technologies, each in moderation.

2.3 Continuing Technology Needs to Aid Adoption of Best Practices

Workflow automation is an important element to ensure that desired steps are performed without relying on human memory or variable levels of experience. For our pulmonary embolus scans for example, we frequently wish to use the highest possible pitch in order to reduce scan duration and associated motion artifacts. However, we still wish to achieve appropriate tube current modulation throughout the scan region of interest (the lungs), while allowing truncation at the maximum mA (with associated image degradation) through the shoulders. This can be accomplished through technologist training, but would be more robustly achievable through development of a tool in which the active tube current modulation scan range is selectable and is allowed to differ from the full scan range.

It is important to note that while outstanding tools exist, they ultimately add little value if end users cannot readily implement them in clinical practice. In order to drive advances into routine clinical implementation, technology manufacturers must go further and collaborate with expert users to determine how best to integrate their tools into optimized protocols and processes. This can be particularly challenging in situations in which interacting tools are used together, requiring optimized combinations of potentially competing imaging constraints and adjustable parameters. Automation currently exists to optimize certain parameters in small combinations, but the larger optimization problem has not been addressed, resulting in extensive variation within and between facilities in protocol configurations and scan output depending in large part upon the expertise of the local CT team developing the protocol, and the technologist responsible for its implementation.

3. TRAUMA "PAN-SCAN" WORKFLOW

The imaging evaluation of trauma patients mandates a rapid yet robust imaging workflow in order to accurately assess life threatening injuries as rapidly as possible. Institutional approaches for this imaging vary but in appropriately selected patients frequently involves a trauma "pan-scan" including imaging from head through pelvis.[7] Figure 2 summarizes the typical workflow used at our institution, along with some of the key decision points to be made in real time at the scanner to customize the imaging as preliminary information is revealed during the scan.

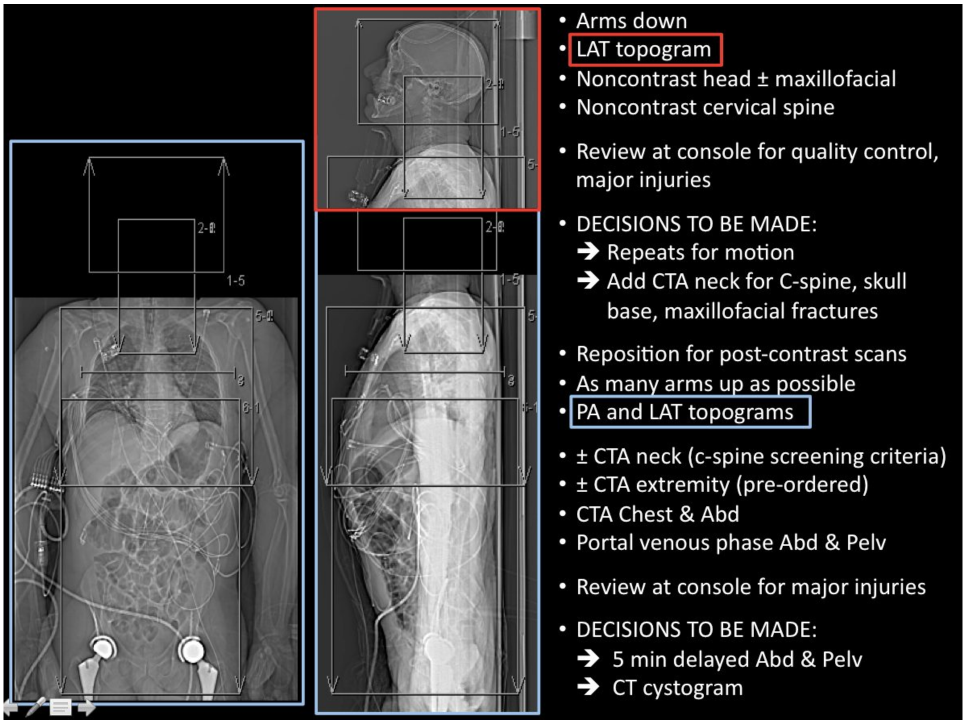

- Arms down
- LAT topogram
- Noncontrast head ± maxillofacial
- Noncontrast cervical spine
- Review at console for quality control, major injuries
- DECISIONS TO BE MADE:
  - ➔ Repeats for motion
  - ➔ Add CTA neck for C-spine, skull base, maxillofacial fractures
- Reposition for post-contrast scans
- As many arms up as possible
- PA and LAT topograms
- ± CTA neck (c-spine screening criteria)
- ± CTA extremity (pre-ordered)
- CTA Chest & Abd
- Portal venous phase Abd & Pelv
- Review at console for major injuries
- DECISIONS TO BE MADE:
  - ➔ 5 min delayed Abd & Pelv
  - ➔ CT cystogram

Figure 2. Our institutional trauma "pan-scan" acquisition and customization workflow. Real time decisions are made at the scanner console by the supervising radiologist. Technologists acquire each scan part, with subsequent post-processing workflow for each scanned body region including multiple steps incorporating different reconstruction kernels and multiplanar reformations.

Each scanned body region is reconstructed in the axial plane, and reformatted into coronal and sagittal planes, using either one or two reconstruction kernels to optimize detection and characterization of soft tissue, bony, or vascular injuries. Depending on the scope of the exam, the end result is typically 20-30 images series to be sent to PACS, typically encompassing 1500-2500 images. The need for this multi-step process in a critically injured patient mandates an efficient and streamlined workflow in which automation steps are vital.

One important innovation towards this end has been streamlined workflow for creating multiplanar reformations. On some older CT scanners (and alas some current scanners), technologists create coronal and sagittal reformations by first reconstructing thin axial source images, followed by their combination into the desired planes. This produces variable results depending on the non-standardized procedures used by technologists of varying experience level, with poor quality results occuring if source images are too thick, lack adequate overlap, or use too sharp a reconstruction kernel. Yet in clinical practice our scan output must be robust and reproducible despite varying levels of technologist experience. Many current-day scanner have accomplished this by eliminating the intemediate step: When reformatted images are created, the scanner automatically creates the necessary source images in the background, not only saving technologist time but also producing the desired high quality results every time.

Streamlined and efficient technologist workflow also mandates that all desired reconstruction, reformatting, or post-processing tasks are identified during the protocol design stage, and should be pre-programmed into the technologist workflow without the need to rely on technologist memory, protocol books, or notes which frequently fail to trigger appropriate action in a hectic environment such as the ED. In the trauma workflow example above, thoracic spine images are reconstructed from the acquisition through the chest and upper abdomen. This workflow includes multiple image series that must be reconstructed or reformatted from the acquired data, yet some scanners permit only 8 pre-programmed series within a scanner protocol, meaning that one or more of the desired reconstruction jobs needs to be abandoned, or technologists must be asked to remember to create the additional series on the fly, an error-prone and time consuming proposition in the midst of all of the other work the technologist must perform to create the full trauma image set for radiologist interpretation.

The trauma CT case highlights the importance of post-processing workflow optimization both to streamline operations so that time sensitive scans can be completed as efficiently as possible, and to achieve reproducible results across users of variable expertise levels.

4. DUAL ENERGY CT

Dual energy CT (DECT) has demonstrated undeniable value in extracting material information that was previously unavailable from conventional CT scanning. These methods have captured the enthusiasm of the reasearch community, with thousands of pubmed articles to date, but nearly 10 years after the introduction of the first commercial dual energy scanner, these techniques remain in the early adopter stage of implementation and have not yet broken through into mainstream use. This is in stark contrast to the technology enhancements described above that either improve workflow and image reproducibility, or reduce radiation dose while maintaining image quality. While those implementations meshed seamlessly with existing CT acquisition and postprocessing workflows, the fundamentally different workflow needs of DECT postprocessing have served as the most important barrier to routine clinical implementation.

4.1 Background of Dual Energy CT

Dual energy CT simultaneously gathers x-ray absorption data from both high and low energy x-ray spectra.[8,9] Since different materials exhibit different energy-dependent x-ray absorption behaviors, this allows certain types of materials to be differentiated from one another to a greater degree than is possible purely on the basis of Hounsfield Unit differentiation of traditional single-energy CT (SECT). Some of the many commonly used applications include identification, enhanced visualization, or virtual removal of iodine content; identification or virtual removal of calcium content; and simulation of virtual monoenergetic images at a variety of x-ray energy levels for purposes of material characterization, enhanced visualization, and beam hardening correction.

4.2 Clinical Applications and Added Value of Dual Energy CT

These post-processing applications can be used to clinical advantage in numerous ways.[9-12] DECT scans can be used to enhance visualization or detectability of image content that might otherwise be quite subtle on SECT, as by highlighting subtle enhancement differences through use of iodine maps or simulated low keV monoenergetic images. For example, detection of subtle pancreatic or bowel pathology may be improved in this way. Fundamentally new image content can be extracted that is not available on SECT. A particularly promising example is the evaluation of lesions detected incidentally on post-contrast scans that would typically require subsequent multi-phase CT or MRI for complete characterization. In this way, renal or adrenal lesions can often be fully characterized at the time of initial detection, rather than requiring the patient to return later for full assessment, at the cost of additional expense, inconvenience, and often substantial anxiety. Figure 3 demonstrates the use of iodine maps for renal lesions that cannot be fully characterized on a single post-contrast SECT scan. Other materials such as uric acid deposits can also be well identified by DECT, allowing for noninvasive diagnosis of gout, and for disease monitoring during treatment. DECT capabilities also permit opportunities to reduce imaging utilization, radiation exposure, or intravenous contrast volume. Imaging utilization is reduced by averting followup imaging through more definitive lesion characterization. Radiation exposure can be reduced by avoiding the need for followup scans, and also by eliminating the need for a preliminary non-contrast scan in many applications, since this information can be recoved from the "virtual non-contrast" images obtained by removing the iodine content from a post-contrast scan. Low keV simulated virtual monenergetic images can be used to salvage suboptimally enhanced scans, or can allow certain scan types to be performed using a reduced volume of intravenous contrast.

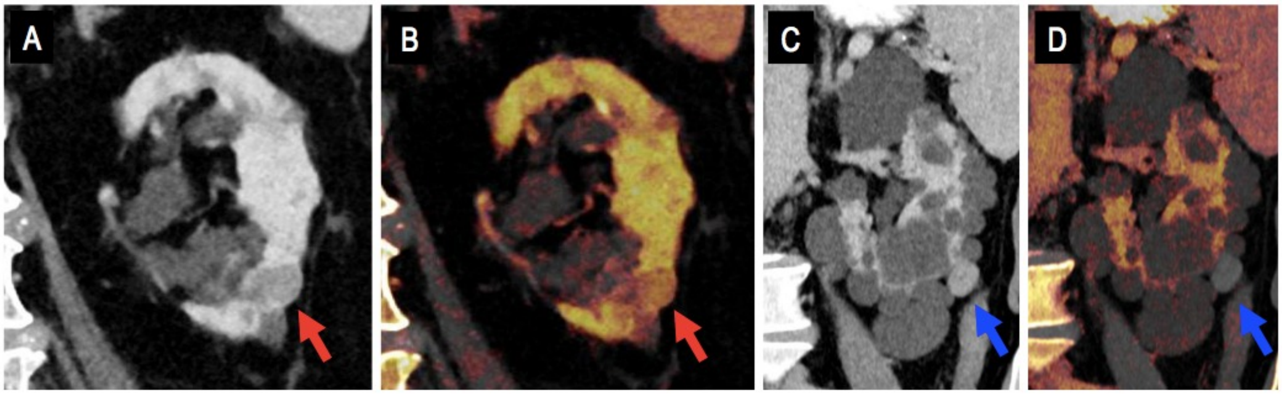


Figure 3. Dual Energy CT characterization of incidental renal lesions within polycystic kidneys. A) A lower pole mass (red arrows) measures higher than simple fluid attenuation, and B) demonstrates contained iodine content evident as orange shading on the iodine overlay image, characterizing it as a solid enhancing mass. C) A lower pole mass (blue arrows) measures higher than simple fluid attenation, and D) contains no orange shading on the iodine overlay image, characterizing it as a benign hyperdense cyst, and requiring no subsequent imaging evaluation. Due to concern for malignancy, both of these masses would otherwise have required an additional CT or MRI examination containing both a non-contrast and post-contrast scan in order to assess presence or absence of enhancement.

4.3 Workflow Limitations and Potential Solutions

Traditional CT postprocessing workflows are performed by the technologist at the CT scanner console, which serves as their main base of operations. In contrast, many DECT postprocessing applications have historically required use of either a separate freestanding workstation, or a thin-client server based solution. In these approaches, source data (either overlapping thin axial images or an extract of the projection domain data, depending on the manufacturer) is sent from the CT scanner to the workstation or server, and DECT postprocessing initiated there. In typical scenarios, the server can be configured to automatically run the desired DECT postprocessing applications so that the relevant DECT information is readily available for viewing by the Radiologist or technologist. However, with current server software, creation of image sets to be sent to PACS for viewing or archival typically requires additional manual steps to prescribe the desired image planes, slice thicknesses, and ranges. The DECT post-processing may be performed either by the Radiologist or technologist in this configuration, depending on the desired interpretive workflow and the need for qualitative versus quantitative DECT data analysis.

In a Radiologist-driven workflow, the server itself becomes the primary site for DECT processed image review. While this provides benefits of full information content, including the ability to perform quantitative measures (such as evaluation of iodine concentration within a region of interest), it requires the Radiologist to learn an unfamiliar viewing platform, and if images are to be archived in PACS, to learn to perform post-processing steps that are typically the responsibility of the technologists. This is a workflow drain on Radiologists who typically do not have additional time to devote to these tasks. As a result, most centers that have adopted this approach find that only a small minority of early-adopter, technology-focussed Radiologists take the time to learn these steps in order to incorporate the DECT information content into their intrepretations. Those who do not then squander the additional information content availble to them for more definitive diagnosis.

In a technologist-driven workflow, predetermined DECT postprocessing steps are performed by the technologist, in order for desired image datasets (such as the coronal iodine overlay images in figure 3) to be sent to PACS for qualitative assessment by the Radiologists in their familiar PACS viewing environment. This approach protects the Radiologists from the additional workflow burden, but requires additional time from the technologists, who often do not have additional time to devote to these tasks. Most centers that have adopted this approach find that only a small minority of early-adopter, technology-focussed technologists take to this new work enthusiastically, resulting in significant challenges in training and enforcement of the new workflow steps. However, if successful, this approach allows DECT information content to be assessed qualitatively by the Radiologists on PACS. The minority of cases that need more quantitative assessment or require live interaction with the data do require that the Radiologists learn to use the server software, with the same limitations outlined above.

The desired automated workflow replaces all rote manual processing steps by fully automating the DECT post-processing, including creation of the desired image sets with standardized image planes, slice thicknesses and ranges, and archival of these results to PACS, all without any user interaction from either the Radiologist or technologist. Further Radiologists interaction on the server software may however still be required for more advanced or quantitative applications.

4.4 Disruptive Technology Does not Need to Imply Disruptive Workflow

As a reflection of the barriers imposed by implementation and worflow challenges, many centers commonly report that they have dual-energy capable scanners but have not implemented these techniques into patient care. The manufacturers have heard consistent feedback from their end users about the need to better align DECT acquisition and postprocessing steps with traditional CT workflow models. In response to this feedback, these manufacturers are developing more streamlined and automated workflows to minimize the additional burdens that have historically kept this valuable technology from widespread clinical adoption. If these software improvements perform as intended, we may at last see DECT utilization scale to match the clinical promise of this potentially transformative technology.

5. CONCLUSIONS

The clinical CT scenarios outlined above highlight several key points about clinical adoption of new technology offerings. Technology advances must meet certain key requirements to make it into routine use: They must provide a well-defined clinical benefit. They must be easy to use and integrate readily into existing workflows, or better still, further streamline these workflows. These requirements heavily favor fully integrated or automated solutions that remove the human factor and provide a reproducible output independent of operator skill level. Further, to achieve these aims, collaboration with the ultimate end users is needed as early as possible in the development cycle, not just at the point of product testing. Technology innovators are encouraged to engage such collaborators even at early stages of feature or product definition.

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