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Dual Energy CT Application in the Abdomen

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Abstract The evolution of dual energy computed tomography (DECT) and associated clinical advances continue to permeate the landscape of abdominal imaging. This article reviews general topics and recent contributions pertinent to progressive clinical implementation of this technology. Recent studies underscore the recognition of the dependence of the Hounsfield unit (HU) on keV and the resultant need for the translation of traditional diagnostic criteria. Similarly, critical assessment of virtual unenhanced imaging and its potential to replace true non-contrast imaging has been reflected in a number of studies that explore this critical radiation dose control function. The introduction of novel protocols includes the use of biphasic contrast technique, which, coupled with material discrimination, highlight capabilities unique to the DECT technique.

Keywords Dual energy CT (DECT) · Virtual unenhanced imaging (VUE) · Hounsfield unit (HU) · Monochromatic · Dual source dual detector (DSDD) · Dual source DECT (dsDECT) · Single source single detector (SSSD) · Rapid switching DECT (rsDECT) · keV · kVp

Introduction

The clinical efficacy of dual energy computed tomography (DECT) has been rapidly maturing, as demonstrated by the number, scope and complexity of articles published during the past year. From its prescient conceptualization by none other than Sir Godfrey Hounsfield in his seminal CT article [1] to the availability of a commercially available scanner in 2006, a lull existed, waiting for technology, engineering and clinical curiosity to adequately merge for clinically effectual CT use. No longer instruments relegated to research institutions, the mainstream availability of DECT has now provided for a widespread clinical presence, although waiting for commensurate clinical data for optimal use. Predictably, we are now undergoing an evolution of clinical research accumulating a body of knowledge sufficient for the use of these new capabilities. The following article will attempt to highlight significant advances, as reflected in recent literature and felt to hold the greatest potential for clinical impact in the near-term. This is intended as a timely overview for those currently using DECT, seeking to initiate this novel technique in their practice or to expand its capabilities.

Principles

While the detailed science of DECT is beyond the scope of this article, a review of basic principles and methodology is in order. Many summary articles [2–4] exist to provide thorough basic and moderately advanced understanding of the associated principles and mathematics.

Conceptually, DECT gains its additional utility based upon its ability to generate useful diagnostic information and discrimination beyond the simple assignment of attenuation values towards creation of an image matrix. Standard CT examinations reconstruct images based on the attenuation values derived during pre-selected single polychromatic x-ray scanning. That is, a polychromatic energy (peak kilovoltage, kVp) is selected, commonly 120

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or 100 kVp, and a diagnostic acquisition is obtained with resulting attenuation values assigned to an image matrix during image reconstruction (classically filtered back projection, now increasingly an iterative reconstruction variant).

Dual energy scanning utilizes scans obtained at low and high kVp, each providing a differing attenuation data set from which to reconstruct an image. Because the specific linear attenuation of a substance is based on photoelectric and Compton attenuation properties, materials of sufficiently different attenuation allow for characterization based on effective atomic number (Zeff). This provides the basis for both the strength and weakness of current dual energy technology. Typically encountered materials such as calcium, iodine, and water possess sufficiently different linear attenuation at low and high energies to allow for good discrimination (primarily based on the lower useful energies where the photoelectric effect dominates). However, materials with very similar attenuation curves, such as soft tissue, fat and water, are more problematic and require more advanced analytical techniques (beam prefiltering, three compartment analysis [4]).

Characterization and quantitation of materials is based on differential absorption at sufficiently separate energy levels to provide for mathematical decomposition and compartment analysis. Additionally, creation of synthetic monochromatic energies allows for optimizing contrast based on tissue and contrast properties. Of significance is the fact that the greatest attenuation differences typically exist at lower energies, thus providing for natural contrast differentiation in this lower range. Synthetic monochromatic energy reconstruction (keV) and presentation theoretically reduces artifacts associated with beam filtration effects resulting from differential absorption of the polychromatic beam.

Differences in DECT Implementation

DECT scans can be obtained in various ways. The earliest techniques simply employed two separate scans that were obtained sequentially, typically at 80 and 140 kVp. While satisfactory for laboratory analysis and static subjects, clinical use of this technique is limited by the significant potential for misregistration, length of scan time and challenges of satisfactory integration.

DECT scanners are commercially available from Siemens (SOMATOM Definition Flash Siemens Medical Solutions, Erlangen, Germany) and GE (Discovery CT750 HD General Electric Healthcare, Waukesha, WI, USA). Platforms from other vendors are either limited to a double scan technique, which is ineffectual for clinical use due to lack of spatial and temporal resolution, or are limited to research evaluation. Almost all clinically relevant studies have therefore been performed on various iterations of these two systems. While both provide DECT data sets, there are fundamental differences in both the hardware and software approach, with consequential outcomes. Promising solutions from Philips (sandwich detector, energy binning) and Toshiba have yet to gain significant clinical use, but will likely provide similar data that is now basic to DECT work—selectable energy display, material analysis and quantitation, basis pair display with iodine mapping and virtual unenhanced imaging (VUE).

Technological differences exist between the two current vendors, and quite literally begin at the source. The Siemens solution utilizes a dual source dual detector (hereafter referred to dsDECT) solution with fixed angular offset (90° or greater), allowing for simultaneous, but physically offset scanning. Geometry constrains the available region of overlap (25 or 33 cm), and thus the region of effective DECT scanning. Data is processed and displayed in "image space", thus low and high kVp scans are separately available and subsequently processed for DECT calculations. Variable blending and weighting of these scans is therefore available and provides for direct HU measurements.

The GE solution utilizes a single source, single detector geometry with rapid switching of tube kVp and an advanced detector (Gemstone) with very low latency and afterglow characteristics. While frequently referred to as a single source single detector (SSSD) scanner, it is more precise to describe the technology as a single source rapid switching single detector scanner, hereafter described as rapid switching DECT (rsDECT). The full bore is thus available for DECT imaging (50 cm), and spatial/temporal resolution is high with only 0.5 ms tube potential switching and minimal angular rotation offset. Image processing of both energies is performed in "reconstruction space", with direct provision of synthetic mono-energy keV and material density display in mg/cc. Synthetic monochromatic (keV) DECT images are thus directly selectable for display or transmission to Picture Archival and Communication System (PACS), in addition to material quantitation and basis pair analysis. Direct HU measurements have been available on the keV sequences, but have only recently become available on virtual unenhanced reconstructions.

With such fundamental hardware and software differences, uniform DECT implementation can become complex. Fortunately, a large body of conventional CT image and diagnostic criteria exists from which to drive performance and diagnostic criteria expectations. As a minimum, we expect image presentation and measured HU to align with classical data in such a manner to allow for meaningful translation. We expect radiation dose neutrality or reduction for diagnostic equivalence and diagnostic superiority if dose increases. Driven by these clinical requirements and competitive realities, there continues to be convergence of scanner and software capabilities. Thus, as we move forward, the baseline features of selectable energy display, material decomposition, virtual unenhanced images, material characterization, quantitation and artifact reduction will broaden.

Nomenclature

DECT is no different from other new technologies in its prolific ability to generate confusing and redundant abbreviations. As noted earlier, even the type of scanner is subject to significant variation of description. The following represent our preferred abbreviations based on precision of technical details.

dsDECT—dual source DECT—Siemens Somotom
rsDECT—rapid switching DECT—GE CT750 HD.
VUE—virtual unenhanced imaging

Hounsfield Unit (HU) Dependence

Recognition of the dependence of HU upon the keV is critically important. To date, virtually all diagnostic criteria and algorithms are based on studies utilizing classical single polychromatic beam protocols. Attenuation is obtained from this blend of energies, only a small part contributed from the peak energy and most distributed approximately 1/3 lower. Thus, great care must be taken to recognize these differences and to develop translational mechanisms and criteria.

Overview of Abdominal Use

Much of the early DECT work has been dominated by large organ evaluation, with high net gain based on evaluating diseases of high prevalence and severity, as well as those with historically challenging detection or characterization. The value of DECT has been established based on earlier detection and improved specificity of diagnosis with the expectation of improved outcomes. Such evaluation strategies have dominated tumor detection and characterization, including assessment of solid and cystic liver, pancreatic and renal tumors. Evolving data also suggests improved quantitation of lesion behavior and response to therapy based on the ability to better visualize contrast enhancement and tissue characteristics, and also measure iodine dynamics and concentration [5–7].

Prior studies and published data have demonstrated the diagnostic utility of parenchymal and lesion characterization including liver, pancreas and renal assessment. Thus, abdominal uses have primarily included tissue and material characterization, lesion conspicuity, quantitation and characterization of enhancement patterns. Numerous studies have also evaluated optimized image presentation keV and contrast to noise ratio (CNR) [7].

Material analysis is particularly useful in characterizing renal stone composition [8] or quantification of parenchymal deposition disease, and therefore guidance of therapy. Evaluation and material quantitation of tissue deposition disease such as fat, iron, copper, and iodine (including drugs containing iodine such as amiodarone) is of intense interest [9–12].

Radiation Dose Management

Given the necessity of dual scanning, management of overall radiation exposure is obviously important, requiring strategies to appropriately quantify and reduce the total examination radiation dose [13]. Logical actions include elimination of unnecessary series (for example substituting VUE or virtual non-contrast derivation for a true non-contrast series), acceptance of greater noise (detrimental image quality effects typically offset by greater contrast) and sophisticated image processing with greater use of iterative processing, asymmetric blending or combination techniques. Continued hardware and software advances have provided progressive quality improvement and dose reduction.

Importance of Virtual Unenhanced Imaging (VUE)

Perhaps the key to widespread adoption of DECT rests in the creation of satisfactory virtual unenhanced images. Successful use of VUE not only leads to simplified and more universally applicable examination protocols, but also remains a key element for X-ray dose reduction justifying the low and high double scanning requirement. Together, these are critically important, and remain a priority providing for reduced cost, time and X-ray dose. Not surprisingly, evaluation of the acceptability and use of VUE as part of a standard study protocol has been a primary research topic as well as a common element for many recent studies [14].

Principles and Generation of VUE

Conceptually, a virtual unenhanced image is generated from a single contrast enhanced scan, with application of a material decomposition calculation that separates contributions from water and a contrast agent, typically iodine. Based on differential attenuation at the two energies and using compartment assumptions of what contributes to the total attenuation, individual contributions are derived and mapped. Thus, two images are created, emphasizing one component as opposed to the other and displayed as such. In the case of the VUE image, water is displayed at the expense of iodine, leading to an "unenhanced" appearance. To be quantitatively useful, HU values should be available and faithfully reflect those from a true non-contrast scan. Specifically, HU values should be diagnostically accurate and reproducible. As previously noted, ssDECT, through its image space processing, has provided this capability, with only recent availability on rsDECT (GSI VUE option).

Use of Virtual Unenhanced Images

Typical examples of the use of VUE include detection of stones in a post contrast environment (for example, contrast filled ureter [15–17]), unenhanced and contrast enhanced characterization of solid and cystic lesions [18], measurement of avidity of contrast enhancement, presence of fat and determination of acute hemorrhage derived from a single contrast enhanced scan. Thus, creation of an "unenhanced" image series from a single contrast enhanced series has the potential to reduce X-ray dose to the patient (30–47 % [19]). Additionally, perfect registration of unenhanced and enhanced images theoretically allows for better discrimination and characterization of enhancement patterns and structure. A growing number of studies have contributed to a better understanding of the use and limitations of VUE imaging under various conditions and diagnostic protocols. These include evaluation of the acute abdomen, such as characterization and detection of acute hemorrhage, renal stone detection under various conditions [19], gallstone and bile duct stone detection [20].

Recent work continues to evaluate the performance and limitations of VUE. For example, multiple studies have demonstrated a lower threshold for stone detection below which stones may be masked [21•] when using VUE as opposed to true non-contrast imaging. Studies have demonstrated stones below 4 mm may not be visualized, likely due to subtraction limitations resulting volumetric analysis and material differentiation.

Additional work has described the general use of DECT VUE and material evaluation within the abdominal cavity. Contributory articles include assessment of the acute abdomen, oncologic applications, appearance of penetrating injury with contrast extravasation and novel fusion techniques.

Recent Literature Overview

A significant number of studies and review articles have contributed to a better understanding of practical as well as novel uses of DECT in clinical practice. Several stand out because of broad applicability, as well as potential for future impact.

We may consider the following categories, although studies may overlap to a variable degree.

1. General use and application of VUE images
2. Genitourinary applications
3. Hepatic and biliary applications
4. Pancreatic applications
5. Gastrointestinal tract evaluation
6. Vascular and endovascular assessment

Genitourinary applications

Perhaps the greatest number of contributions has been in the arena of genitourinary assessment. This includes continued evaluation of renal stone detection using VUE imaging, characterization of stone composition, detection and characterization of renal masses and enhancement. As previously noted, understanding the operational performance and limitations of VUE under different conditions is important for its validation as a substitute for true non-contrast imaging.

Because VUE images represent a subset of data (removal of iodine contribution), spatial and image contrast resolution can suffer to a variable degree. Most studies indicate a threshold below which small calcifications are masked and may not be detected, typically 1–4 mm. This masking effect is affected by the density of the local environment (for example very dense iodine contrast in the collecting system, and quality of the scan (motion, patient size). Understanding of these limitations allows for improved patient selection and protocol design.

For example, in an attempt to optimize protocol design, Karlo et al. [21•] studied image quality and stone detectability using a split–bolus urography protocol. They noted improved quality and diagnostic performance when performed with tin-filtered 100/140 kVp) imaging parameters (likely due to improved low kVp contribution, offsetting greater attenuation that affects the virtual unenhanced calculation).

The clinical value of practical in vivo renal stone characterization has progressed with increasing recognition of its usefulness by our urology colleagues. Because of the measurable Zeff differences obtained from renal stones of sufficient size, categorization of the dominant stone composition is possible (uric acid, cystine and calcium) [22].

Further characterization of solid and cystic renal lesions has been performed, including iodine quantification of solid renal lesions and analysis of enhancing versus non-enhancing renal lesions [23]. Ancillary and necessary characterization of the appearance of surgical material is also being evaluated, as demonstrated by an article evaluating stent appearance in the renal collecting system [24].

Adrenal Adenoma Characterization

Adrenal adenomas are sufficiently common as to represent a diagnostic dilemma necessitating further evaluation. They are frequently detected on routine abdominal evaluation (reported 4–5 %) [25]. Thus, cost-effective and minimally invasive characterization, and optimal analysis of incidental adrenal lesions is strongly desirable. Consequently, studies have yielded diagnostic parameters widely accepted for the determination of adenomas with high clinical sensitivity and specificity [26]. It is noted, however, that with variable keV presentation, measured HU can vary significantly. Additionally, diagnostic evaluation frequently utilizes non-contrast imaging for initial HU measurements, as well as relative and absolute washout calculations following contrast administration. While some studies have demonstrated good correlation of true and virtual unenhanced values in small series, until recently, no larger population study and more complete analysis has been performed.

Kim et al. [27••] describe a retrospective study reviewing the performance of DECT characterization of adrenal adenomas based on standard criteria (non-contrast HU, early virtual unenhanced [EVU] and delayed virtual unenhanced [DVU]) with comparison of diagnostic criteria. The study was adequately powered (49 cases) and performed using a dual source (Siemens) scanner. The sensitivity for adenoma characterization was 100 % (33 of 33) using percentage loss of enhancement, calculated from VUE CT, early and delayed enhancement CT, and early and delayed contrast enhanced CT. The study is particularly important, because it directly emphasizes an issue with translation of virtual unenhanced versus standard non-contrast HU values. As a consequence, HU values obtained from the virtual unenhanced series is greater than standard non-contrast acquisition, yielding higher values, and therefore contributing to reduced sensitivity for detection of lipid rich adenomas (39 % EVU and 61 % DVU). However, the sensitivity for adenoma with percentage loss of enhanced values calculated from virtual unenhanced CT and early and delayed contrast enhanced CT was 100 %. The authors concluded that while adrenal protocol DECT using VUE and washout rate can help diagnose all lipid poor adenomas, lipid rich adenomas that may be diagnosed with true non-contrast CT may be missed due to higher measured virtual unenhanced values.

The study is important, because it underscores the potential pitfalls of VUE without adequate validation and referencing, which is needed to accurately align VUE HU values with those obtained using standard non-contrast scans. It is likely that accurate referencing can be accomplished through a better quantitative validation process, but this work must be performed and standardized.

Hepatobiliary Applications

Hepatic mass detection and characterization continues to be an area of active research. The benefits of variable keV imaging with improved lesion visualization and material analysis are evident particularly at institutions with large hepatology and hepatic transplant programs. DECT allows characterization of the enhancement pattern of lesions and quantification of enhancement and therapeutic response. Assessment of hepatic fat content is now undergoing extensive evaluation, due to the importance of accurate fat quantification resulting from disease and iatrogenic causes, and as a predictor for associated steatohepatitis and metabolic syndrome. A novel collateral use includes a technique for evaluation of secondary hepatic parenchymal effects following acute alcohol intoxication [28].

Studies have attempted to characterize hepatic fatty infiltration based on attenuation curves, material quantitation and multi energy subtraction analysis, with varying results. In short, prior studies [29] and more recent studies suggest no accuracy advantage of DECT data over what CT attenuation can provide, except in specific circumstances of coexisting iron overload and presence of iodine [30, 31], while another study indicates advantages based on dual energy subtraction technique [32]. Additional studies and further analysis will be needed to assess the true benefits of DECT as a hepatic fat quantitation tool, but this remains a promising area of research due to the potential for broad impact as an accurate quantitation technique.

Pancreatic Applications

Most recent DECT articles evaluating the pancreas have been based on oncologic applications [33]. The detection of pancreatic tumors, particularly those of a non-contour deforming and iso-attenuating nature, remains a diagnostic challenge. Improved contrast visualization achieved through the use of low keV imaging and iodine mapping has been shown to improve detection over standard MDCT [34]. Characterization of more complex pancreatic lesions such as hypo-attenuating, hyper-attenuating and cystic variants may benefit from improved contrast, iodine mapping and material evaluation (non-published data).

Klauss et al. [35] performed a feasibility study of DECT perfusion imaging analyzing histologically confirmed pancreatic carcinomas versus healthy pancreatic tissue. While the sampling size was limited to 24 patients, all lesions could be identified using perfusion, permeability and blood volume evaluation with color-coded mapping. It is conceivable that radiation dose may limit widespread use, however, given the local volume exposure necessitated by the dynamic sequence of 34 dual energy acquisitions. The mean reported dose of the complete exam (three phase CT and perfusion) was 21.1 mSv of which 6.3 mSv was attributed to the perfusion sequence. Introduction of improved beam filtration techniques and iterative reconstruction methods will likely reduce the total dose, however.

Lin et al. [36] compared DECT to conventional multidetector CT (MDCT) for preoperative diagnosis of insulinomas, and found improved sensitivity using DECT techniques. Again, although a small group (39 lesions in 35 patients), the sensitivity for diagnosis was increased from 68.8 % (conventional MDCT) to 95.7 % (DECT using monochromatic images and iodine density mapping).

Gastrointestinal and Bowel Applications

Qu et al. [37•] report a unique application of DECT that leverages its potential for material discrimination. Evaluation of biphasic contrast (enteral bismuth and mural iodine) was studied in an animal model of penetrating abdominopelvic injury. Based on significantly different attenuation curves (bismuth salicylate/iodine contrast), it was possible to discriminate between the two agents, and thus the compartment origin of leak—enteral versus vascular—a potentially valuable diagnostic tool for patient management in cases of penetrating injury. More importantly, it brings to light the potential for multi-agent imaging, and with it a plethora of future diagnostic algorithms.

Additional work has been published relating to improving the staging accuracy of gastric carcinomas [38]. Specifically, quantitative iodine analysis was found to improve evaluation of differentiated versus non differentiated gastric tumors and metastatic versus non metastatic lymph nodes (T and N staging).

Creative use of contrast enhanced DECT for evaluation of colon tumors in non-prepped, non-distended patients was also evaluated, with promising results [39•]. Specifically, patients were studied without cathartic administration or fecal tagging and without insufflation, a technique that may be applicable to certain patient populations for whom a standard colon prep and insufflation is not possible. Briefly, blinded readers were able to detect 96.7 % of colon cancers of sufficient size (median 43 mm) when using iodine map reconstruction (post IV contrasted scans).

Vascular Applications

In theory, vascular evaluation is particularly well suited to the use of DECT. Elimination of the non-contrast scan reduces the overall patient radiation dose. Similarly, the availability of variable keV imaging provides for optimal image contrast, while also potentially reducing contrast dose, particularly desirable in a patient group with all too frequent coexisting renal insufficiency. Monochromatic and material decomposition images reduce associated metal filtration artifact and may accentuate or eliminate calcification, albeit to a variable degree. Applying material specific curves with the use of alternate contrast agent imaging may also be possible.

Maturen et al. [40••] evaluated patients undergoing aortic endograft surveillance, and assessed two key components—adequacy of endoleak detection and radiation exposure. The study supported the premise that VUE can substitute for true non-contrast imaging. Additionally, they found radiation dose reduction of 64 % (monophasic) and 41 % (biphasic) as compared to standard triphasic CT. Furthermore, they achieved increased negative predictive value for endoleak detection on venous-phase imaging. These findings led them to suggest that monophasic venous phase DECT may be optimal for long-term endograft surveillance in stable patients.

These findings parallel our experience with aortic endostent surveillance. Clinically relevant reduced metal artifact and optimized contrast opacification have been observed while using lower doses of contrast agent and variable keV reconstruction.

Summary

The evaluation and application of DECT techniques continue at an increasing pace. The efficacy of DECT for optimizing contrast, and therefore lesion detection, is well established. A multitude of analytical tools now exist and continue to evolve, including tools for variable keV display, VUE imaging, material differentiation and concentration, as well as "mapping" and subtraction of materials.

It has become increasingly apparent that sophisticated and optimized use of dual energy technology requires commensurate attention to interpretive details and translation of traditional diagnostic criteria. This is particularly true when applying diagnostic criteria based on Hounsfield Unit measurements, given HU's dependence on keV imaging. Work has just begun in this area, but is being undertaken, as noted in some of the cited studies [15, 18, 27]. Similarly, understanding the appropriate use of VUE, critical for radiation dose reduction and simplification of scan protocols, is underway.

The non-uniformity of DECT implementation remains a confounding issue. Differences of equipment and software, varied terminology, and associated challenges surrounding the translation of research and clinical results must be overcome for optimal and cost effective adoption.

The increasing presence of clinical scanners capable of DECT provides for widespread implementation of this technology. However, examination designs taking into account radiation dose management and optimized protocols are needed to take advantage of this technology and to continue to evolve.

Compliance with Ethics Guidelines

Conflict of Interest David N. Bolus receives honoraria, payment for development of educational presentations, and travel expenses from General Electric Healthcare.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by the author.

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