Dual energy imaging in cardiothoracic pathologies: A primer for radiologists and clinicians

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ABSTRACT

Recent advances in dual-energy imaging techniques, dual-energy subtraction radiography (DESR) and dual-energy CT (DECT), offer new and useful additional information to conventional imaging, thus improving assessment of cardiothoracic abnormalities. DESR facilitates detection and characterization of pulmonary nodules. Other advantages of DESR include better depiction of pleural, lung parenchymal, airway and chest wall abnormalities, detection of foreign bodies and indwelling devices, improved visualization of cardiac and coronary artery calcifications helping in risk stratification of coronary artery disease, and diagnosing conditions like constrictive pericarditis and valvular stenosis. Commercially available DECT approaches are classified into emission based (dual rotation/spin, dual source, rapid kilovoltage switching and split beam) and detector-based (dual layer) systems. DECT provide several specialized image reconstructions. Virtual non-contrast images (VNC) allow for radiation dose reduction by obviating need for true non contrast images, low energy virtual mono-energetic images (VMI) boost contrast enhancement and help in salvaging otherwise non-diagnostic vascular studies, high energy VMI reduce beam hardening artifacts from metallic hardware or dense contrast material, and iodine density images allow quantitative and qualitative assessment of enhancement/iodine distribution. The large amount of data generated by DECT can affect interpreting physician efficiency but also limit clinical adoption of the technology. Optimization of the existing workflow and streamlining the integration between post-processing software and picture archiving and communication system (PACS) is therefore warranted.

1. Introduction

In conventional radiographic and computed tomography (CT) imaging, the materials with different elemental compositions can demonstrate same or very similar attenuation. Therefore, soft tissue contrast is low and differentiating between different tissues is challenging. The emergence of newer dual-energy technology improves upon this limitation by using the differing attenuation characteristics of tissue at two different X-Ray energies. Understanding the basic physics and common dual-energy images/reconstructions is important for radiologist and clinicians alike to increase diagnostic confidence. Large amounts of post-processed data from dual-energy imaging, particularly dual-energy computed tomography (DECT), poses a challenge for image storage; therefore existing workflow and imaging protocols require

Abbreviations: DECT, dual-energy computed tomography; DESR, dual-energy subtraction radiography; keV, kilo electron volt; SNR, signal to noise ratio; CAD, computer-aided detection; VMI, virtual mono-energetic images; VNC, virtual non-contrast images; PACS, picture archiving and communication system; TAVI, transcatheter aortic valve implantation; SPECT, single photon emission computed tomography; PET, positron emission tomography; NIH, national institute of health; AI, artificial intelligence; PPV, positive predictive value; NPV, negative predictive value; kV, kilo volt; CR, computed radiography; BT, blalock-taussig; eGFR, estimated glomerular filtration rate; SVC, superior vena cava; TNC, true non contrast; PCD, photon-counting detector.

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The concept of dual-energy CT is based on how X-Ray photons interact with matter at clinically used energy levels. The two most important interactions that contribute to X-Ray attenuation in the clinical spectrum are the photoelectric effect and the Compton scatter. The photoelectric effect is dependent on the atomic number of a given material and represents the interaction of incident photons with the inner shell electron, which primarily occurs at lower energy levels. Compton scatter is deflection of photons by outer shell electrons which is influenced mainly by the physical density and contributes more to the overall attenuation in higher energy ranges.

In order for the photoelectric effect to take place, a minimum amount of energy in the photon is required, which is also the most likely energy for those events to occur. Photons with higher or lower energy would have a lower likelihood to cause photoelectric events. This is referred to as the k-edge, which is the energy needed to eject the most strongly bound innermost electrons (K-shell electron). Soft tissues with dominant elements C, H, O and N have very low K-edges ranging from 0.01 to 0.53 kilo electron volt (keV) and thus attenuate low-energy X-rays. However, k-edges of calcium (4.0) and iodine (33.20) are much higher than soft tissues, thus resulting in different attenuation spectrum, making them distinguishable on dual energy imaging. (Fig. 1). Imaging at low x-ray tube energy or spectrums. Dual-energy systems can provide distinct information available for acquisitions. These result in CT or radiography images with far more quantitative material decomposition in x ray projection domain. Dual-energy subtraction radiography and DECT, reviews the commercially available techniques for acquiring dual-energy imaging, and discusses common dual-energy reconstructions available with their added value in cardiothoracic pathologies. Emerging and future clinical applications will also be reviewed.

2. Basic principles of dual energy imaging

The principle of dual-energy technology was developed in the 1980s to help resolve some of the limitations of inherent single-energy detector systems both in radiography and CT [1,2]. Single-energy systems are unable to reliably discern between materials of similar density [3]. This limitation was partially solved by using iodinated contrast agents for better tissue differentiation. These agents carry an added risk of nephrotoxicity and other adverse reactions. [4,5].

Dual-energy systems attempt to overcome single-energy limitations by using the phenomenon that tissues respond differently at altering X-Ray energy or spectrums. Dual-energy systems can provide distinct images for specific tissue types as well as iodine concentration maps. These result in CT or radiography images with far more quantitative interpretation compared to single-energy HU based images. Due to technical limitations such as more noise, errors in registration, and increased acquisition times, dual-energy technologies did not enter clinical application until the last decade. Due to advancement in technology, at present, these systems offer several advantages in clinical image reading compared to single-energy systems (Table 1) [6].

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3. Single exposure versus double exposure dual-energy subtraction radiography (DESR)

There are two methods for acquiring dual-energy X-Ray images, the two most commonly used are double exposure and single exposure-based methods [11,12]. Each technique has its own pros and cons; the dual-exposure method has a fast readout capability and has a high signal modification to effectively utilize this technology.
Fig. 1. Concept of dual energy imaging. (a) Graph showing dependency of photoelectric effect/attenuation on x-ray beam energy and tissue composition/atomic number. The different tissues are better separated on low keV images as compared to high keV images, as annotated by vertical dotted lines. (b and c) Virtual monoenergetic images (VMI) show attenuation comparable to that would be obtained with a true monoenergetic images at specific energy level. Relationship of the image contrast and beam hardening artifacts (Arrows in b) with increasing energy is demonstrated; while image contrast is best at low keV (950 HU at 40 keV versus 130 HU at 140 keV in b), beam hardening artifacts are least at higher energies (blue arrows). Note: P.E. = Photoelectric Effect, $Z = $ Atomic number, keV = kilo electron Volt.

Fig. 2. Illustration showing basic principles behind Single exposure and Double exposure Dual-Energy Subtraction Radiography. Double exposure technique requires two exposures to generate high energy and low energy images (typically at 60 kV and 120 kV with 150 ms delay). Subsequent energy subtraction and image post processing yields standard chest radiograph, soft tissue image and bone image. Single exposure technique requires a single x-ray exposure. The cassette is composed of a thin copper filter sandwiched between two phosphor computed radiography plates. X-ray beam reaching the first CR plate has both the high and low energy photons, which produces a normal chest radiograph with both bones and soft tissues. The second plate registers the high energy photons only because of intervening first image plate and the filter. After equalization of image contrast and noise characteristics using post processing, weighted subtraction of the images from both layers is performed to generate soft tissue and bone images.
4. Clinical utility of DESR

Clinical use of single and dual-exposure subtraction radiography has been studied in evaluating different disease conditions involving different body parts (Table 2). When the dual-energy technique is used in chest radiography, images are displayed in three forms: a regular radiograph without subtraction, a bone selective radiograph, and a soft tissue-selective radiograph.

Overlapping structures like bones can be removed on reconstructed soft issue images. It is possible to enhance visualization of abnormalities in hidden areas compared to conventional radiographs including lung apices, retrocardiac regions, and areas behind bony structures. Low-energy bone images help to improve detection and characterization of bony lesions including primary and secondary neoplasms, fractures, erosions, sclerotic lesions and post-operative changes [13,15,16].

4.1. Lung nodule detection

Using the soft tissue-selective DESR image improves identification of lung nodules particularly those obscured by overlapping bone [17]. DESR also increases confidence in identifying the presence or absence of calcification within a lung nodule, an important marker for benignity (Fig. 3) [15]. The addition of computer-aided detection (CAD) with conventional radiograph or dual-energy subtracted soft tissue-selective radiograph has the potential for increasing nodule detection. In one study, Baikman et al. found more nodules combining CAD with dual-energy subtraction radiography when compared to conventional radiography [18]. However, additional studies have failed to show superiority of combining CAD with dual-energy subtraction vs dual-energy subtraction alone. False positive rate of the combined technique in these studies ranged from 1.27 to 5.9 % [19-21].

4.2. Lung parenchymal abnormality

The role of DESR is also evaluated in lung parenchymal processes other than nodule detection. In one study, authors found increased sensitivity and interobserver agreement of dual-energy subtracted image over conventional radiographs for the diagnosis of infectious and interstitial lung diseases. There was possible increasing use in patients where detection of parenchymal changes like pneumonia was very important for timely care such as immunocompromised patients [22].

4.3. Pleural and mediastinal abnormalities

Dual-energy subtraction radiography may play a role in detecting calcified plaques and identifying patients with asbestos-related pleural plaque disease [15,23]. Soft tissue-selective images from the dual-energy subtraction imaging also helps in improving the ability to identify mediastinal and hilar lesions [24]. Removing the thoracic spine projecting over the airway on frontal radiograph using the dual-energy technique can help visualize tracheal abnormalities including tracheal narrowing and mass effect from adjacent structures [16]. Soft tissue-selective images can also improve the sensitivity of pneumothorax detection (Fig. 4) [25].

4.4. Foreign bodies and medical devices

Subtracted images (mostly using the low-energy bone image) is useful in improved visualization of medical support devices and radiopaque materials, including surgical clips, retained postsurgical materials, breast implants, catheters, stents, and other foreign bodies [13,26,27].

4.5. Cardiovascular calcifications

Low-energy bone images from DESR is useful in detecting calcifications, including vascular, valvular, pericardial, myocardial and coronary calcifications. This helps in better detection of coronary artery disease, initiating further workup, and diagnosing conditions such as constrictive pericarditis and valvular stenosis (Fig. 5). Studies have shown improved coronary calcium detection with DESR as compared to plain radiography and sensitivity of DESR ranging from 42 to 52% when compared to CT scanning [28,29]. Mafi et al. in a pilot study evaluated DESR ability to identify high risk patients with coronary artery disease and found excellent correlation between the DESR score and CT coronary calcium score (Correlation coefficient of 0.87), although the accuracy at lower calcium scores was poor. Therefore, refinement and further validation is necessary before DESR can establish itself as an inexpensive and low-radiation imaging tool to risk stratify patients with coronary artery disease. [30]

Aortic valvular calcification is typically present in patients with aortic stenosis and accepted as a marker for severity of aortic stenosis.

Table 2 Clinical applications and benefits of Dual Energy Radiography.

| Clinical application       | Type of image (Soft tissue or Bone image) | Added benefit of dual energy radiography                                                                 |
|----------------------------|----------------------------------------|----------------------------------------------------------------------------------------------------------|
| Lung nodule/parenchymal abnormality | Soft tissue                           | Better detection and assessment of blind spots and hidden areas, such as lung apices, retrocardiac lung field and bony rib. |
|                            | Bone image                             | Improves performance of computer aided detection (CAD)                                                  |
|                            | Bone image                             | Improved characterization by confirming presence or absence of calcification                            |
|                            | Soft tissue                           | Better detection of pleural thickening and pleural based masses.                                       |
| Pleural Disease            | Bone image                             | Confirming the calcified pleural plaques in asbestos related pleural disease, reducing need for additional imaging. |
| Mediastinal and hilar lesion | Soft tissue                           | Improved detection of lympadenopathy and mediastinal masses.                                           |
|                            | Bone image                             | Better visualization of calcifications, important sign of benignity/ granulomatous disease               |
|                            | Bone image                             | Removing overlying bony structures helps in better detection of central airway lesions/masses,           |
| Airways                    | Soft tissue                           | Better assessment of airway compromise from masses/ lympadenopathy and in other situations, such as post intubation, subgltotic stenosis in Croup. |
| Pneumothorax               | Soft tissue                           | Increased sensitivity of detection by removing overlying bony structures                                 |
| Vascular disease           | Bone image                             | Improved detection of vascular calcified atherosclerotic disease                                      |
|                            | Bone image                             | Better visualization of myocardial, pericardial and valvular calcifications.                           |
|                            | Bone image                             | Improved detection of benign and malignant oncous lesions and fractures                                 |
| Bony lesions               | Bone image                             | Improved visualization of radio-opaque foreign bodies, retained postsurgical materials, pacemaker leads, breast implants, catheters and stents |
| Other incidental findings  | Bone image                             | Improved visualization of radio-opaque foreign bodies, retained postsurgical materials, pacemaker leads, breast implants, catheters and stents |

4. Clinical utility of DESR

to noise ratio (SNR) but because of the delay between the two exposures, there is an increase in motion artifacts. Also, due to need for two exposures, this also results in more radiation exposure than single-exposure DESR technique [13,14]. The basic principles behind DESR methods and their comparison is highlighted in Fig. 2 and Table 1.
Fig. 3. Improved pulmonary nodule detection in a 50-year-old male, s/p stem cell transplant with neutropenia and fever. Conventional radiograph (a) appears unremarkable, but the soft tissue image (b) shows a discrete nodular opacity posterior to the right second rib (Arrow). Subsequent CT scan (c) clearly confirms a solid nodule with subtle ground glass halo (Arrow), which was later proven to be invasive aspergillosis on culture.

Fig. 4. Improved pneumothorax detection in a 45-year-old male following cardiothoracic surgery. Conventional radiograph (a) shows cardiome diastinal silhouette enlargement, mild interstitial pulmonary edema and bilateral pleural effusion. The corresponding soft tissue image (b) shows the hidden left apical pneumothorax (Arrow), which was missed initially on the convention image.
There may be some limitation of evaluation of aortic valve calcification in bone selective images as it projects over the spine [33]. Bone selective images are better in depicting mitral annular calcification as the mitral annulus is more laterally positioned as compared to aortic valve (Fig. 5). Bone selective images can help detect subtle pericardial calcification that may be missed on conventional chest radiograph.

Fig. 5. Improved depiction of cardiovascular calcifications in a 70-year-old female with symptoms consistent with congestive heart failure. Conventional X-ray image (a) shows cardiac enlargement with mild vascular congestion and small bilateral pleural effusions in keeping with provided clinical history. Corresponding bone image (b), shows linear calcifications in the expected location of left anterior descending coronary artery (blue arrow) and prominent mitral annular calcification (orange arrow), which were also seen on chest CT (c). Additional right coronary artery calcifications were also seen (white arrow in c), which were likely obscured by scoliotic thoracic spine on radiograph.

Fig. 6. Pitfalls associated with DESRA. A 30-year-old male presented with acute onset left side chest pain. The conventional x ray image (a) appears unremarkable, however, on the soft tissue image (b) there is an interface overlying left upper lateral lung, concerning for pneumothorax. Careful correlation with the conventional image reveals it to be an artifact because of incomplete suppression of left scapula (Arrow in b). Also, on bone only image (c) there is a white line along the right heart border which is typical for misregistration artifact from cardiac pulsation (Arrow in c).
5.2. Misregistration

along the periphery of the lung simulating a pneumothorax (Fig. 6b)
of bony structures may also produce artefactual lines and interfaces
removing overlapping structures. However, it is important to select
appropriate imaging parameters when dual-energy subtraction is used
for this purpose as the overall noise level will increase [11].

may initiate further work up for constrictive pericarditis in the appro-
priate clinical setting [33].

4.6. Breast imaging

Another potential application of DESR is in the evaluation of breast
microcalcifications, an important marker for diagnosing breast cancer.
As visualization and detection of microcalcifications is often obscured by
superimposed tissues, DESR may help identify microcalcifications by
removing overlapping structures. However, it is important to select
appropriate imaging parameters when dual-energy subtraction is used
for this purpose as the overall noise level will increase [11].

5. Pitfalls associated with DESR

5.1. Inadequate subtraction

Occasionally, a lung nodule can be detected on the standard image
and not displayed on the soft tissue-selective image due to increased
noise in the subtracted image [34]. Also, inadequate subtraction of
calciﬁed/ossiﬁed structures superimposed on a lung nodule can
mistakenly identify it as a calcified nodule [15]. Suboptimal suppres-
sion of bony structures may also produce artefactual lines and interfaces
along the periphery of the lung simulating a pneumothorax (Fig. 6b)

5.2. Misregistration

In the dual exposure DESR technique, the delay between the expo-
sures may lead to a misregistration artifact. This is important when
there is motion in the imaged volume (i.e. respiration and cardiac contrac-
tion) appearing as white or black lines particularly in the bone selective image
along with the moving structures (i.e. along with heart, diaphragm,
bowel, etc.). This should not be interpreted as an underlying pathology

5.3. Radiation exposure

Compared to conventional radiography DESR results in higher ra-
diation doses, with overall increase of radiation dose of up to 16 % as per
one study. This warrants judicious use of this technology especially in
pediatric patients [22].

6. Approaches to dual energy CT and image reconstructions

Early investigations into dual-energy CT (DECT) were published in
1976 by Alvarez and Macovski [35,36]. Over the past few decades,
similar physics principles from dual-energy radiography were applied to
CT through various technical applications. A number of DECT ap-
proaches have been validated and deployed in the clinical environment
(Movie 1). Broadly, these may be grouped into emission versus
detector-based techniques [37–41], with major differences highlighted in
Table 1.

There are multiple image types, and reconstructions that may be
obtained from DECT scanner regardless of the dual-energy approach.
Some of the most commonly generated image reconstructions from dual-
energy CT include virtual mono-energetic images (VMI), virtual non-
contrast images (VNC), iodine density map images, and Z-effective images (Table 3).
The attenuation maximum occurring at the k-edge of iodine is the underlying principle which is exploited in low keV virtual
monoenergetic imaging, while a high keV VMI may assist with metal or
other beam-hardening artifact reduction. VNC images resemble unen-
hanced acquisitions without additional dose and allow for better char-
acterization of incidental findings [42]. The iodine density map images
also utilize DECT’s ability to identify iodine but instead provide a map
with quantification of iodine density throughout the images [43]. These
may also be generated as a color-coded overlay on conventional CT
images. Finally, Z-effective images create a color-coded map that strat-
ifies relative material atomic numbers in each voxel relative to the
conventional CT images.

7. Workflow considerations with DECT

The cardiothoracic DECT workflow relies most heavily on the VNC,
low keV VMI, and iodine density map images (Fig. 7). In general,
cardiothoracic studies should all include some combination of the
aforementioned DECT reconstructions as standard to ensure that the
most clinical data is acquired from a single exam [44,45]. For maxi-
mized clinical adoption and radiologist efficiency, the best performing
workflow at our institution is incorporating these reconstructions into
the existing protocols and enabling automatic transfer from scanner to
PACS. This allows for seamless integration of DECT into the radiologist’s
traditional workflow with minimal interruption and the additional
DECT images immediately available for reference (Supplemental Fig. 1).

8. Benefits and clinical applications of DECT

There are numerous advantages and benefits for using dual-energy
CT in cardiothoracic applications (Table 4). When combined with the
standard conventional CT images, the combination of DECT images ul-
timately aid the radiologist in appropriate diagnosis and evaluation of
cardiothoracic disease.

8.1. Better diagnostic certainty

Several studies have shown that the utilization of DECT adds value
with an increase in a radiologist’s diagnostic certainty and confidence
for a variety of clinical applications [40,41,46]. In cardiothoracic im-
ageing, detection of pulmonary emboli has been one of the earliest vali-
dated strengths of DECT regardless of the approach [47]. Some
additional validated cardiothoracic applications include myocardial perfusion, myocardial ischemia, aortic disease, endoleak, and pulmonary perfusion defects [41,46]. Recent studies have shown that pulmonary angiography on newer DECT scanners results in improved subjective and objective image quality without increased radiation exposure as compared to older generation DECT scanners and standard CT image acquisition [48,49]. By using a combination of low keV virtual monenergistic images to boost contrast enhancement as well as iodine density map images to visualize and quantify enhancement, pulmonary perfusion defects of pulmonary arterial or venous origin that may have been missed on an initial screening are better detected (Fig. 8) [50]. The image quality and diagnostic confidence can be further enhanced by optimizing window and level settings of the VMI [51,52]. Okada et al. have shown that inter- and intraobserver agreement is increased in pulmonary embolism studies with DECT iodine density map images compared to those with conventional CT alone (Az = 0.966 [reader 1] and 0.959 [reader 2] compared to Az = 0.888 [reader 1] and 0.912 [reader 2], p < 0.001) [53]. Additionally, early studies have demonstrated that quantitative data from iodine density map perfusion images inversely correlates with a patient’s pulmonary embolism thrombus load and may be a surrogate marker to gold standard laboratory values and cardiac strain for determining the severity of an acute pulmonary
embolism ($r = -0.46; p < 0.001$) [46]. Also, a perfusion defect on iodine density map images with patent pulmonary arteries guides the radiologist toward searching for an alternate cause for the perfusion defect such as extraneous compression of pulmonary arteries, or airway compromise (Supplemental Fig. 2).

8.2. Boost contrast enhancement/reduction in contrast use

Low keV VMI from DECT increases the attenuation of iodinated contrast material allowing for increased CT contrast enhancement. Retrospective application of this principle includes salvaging an exam where the contrast bolus was mistimed or limited in amount. By accessing the low keV VMI, a non-diagnostic vascular study may become diagnostically acceptable and a patient may be spared from repeat examination with additional radiation exposure and more contrast (Fig. 9). This is essential in rapid care or emergency settings as well as outpatient environments where downtime or repeat studies carry a significant time and economic penalty. Some institutions have implemented prospective protocols that take advantage of this concept through decreased contrast dose volume as a standard of care [54,55]. The focus of these interventions has been centered on those patients where a contrast-enhanced CT is beneficial or necessary in the setting of renal impairment such as pre-operative evaluation for transcatheter aortic valve implantation (TAVI) or other vascular intervention (Fig. 10). Here the improved SNR of the low keV images is used to reduce the dose of nephrotic intravenous contrast without loss of vascular contrast or radiation exposure, particularly important in scanning patients with renal insufficiency [56]. With DECT, patients who may not have been offered these interventions before, given the amount of contrast needed for imaging, may have a chance for proper imaging evaluation and risk stratification prior to clinical decision making.

8.3. Beam hardening artifact reduction

High keV VMI from DECT allows for reduction of beam hardening and metal artifacts that traditionally may limit conventional CT interpretation. Typical cardiothoracic artifacts originate from x-ray beam interactions with metallic medical hardware in the chest wall, cardiac, or osseous structures resulting in dark spots or streaks over adjacent critical anatomical structures. Since these medical devices are usually fixed in location, the associated artifacts will be most severe closest to the hardware but may extend through an entire CT slice depending on the severity. If critical anatomy or pathology is obscured by the hardware artifact, it will limit the diagnostic certainty of the radiology or simply be missed. While advances in conventional CT have offered some support in limiting these artifacts through post-processing algorithms, studies have shown that combining DECT data with these conventional CT algorithms may further improve study quality [57]. Similar to boosting contrast enhancement with low keV images, the artifact reduction from high keV images may salvage an otherwise non-diagnostic exam and save the patient from additional radiation dose from a repeat CT (Fig. 1b).

8.4. Improved lesion detection/characterization

DECT material decomposition properties provide a distinct advantage over conventional CT for detection and characterization of cardiothoracic pathologies. For instance, DECT iodine density map images can qualitatively and quantitatively identify iodine beyond traditional HU attenuation characteristics alone. Through iodine density map overlay images, these findings may be anatomically correlated for further characterization. Common benefits of DECT reconstructions in cardiothoracic imaging include tumor recurrence in surgical or radiation fields, benign versus malignant incidental lesions, and early detection of malignancy (Fig. 11) [50,58–60]. Early studies have also demonstrated how DECT may be used as an early detector for tumor recurrence after radiofrequency ablation of lung malignancies [61]. Additionally, VNC images from DECT may replace true unenhanced conventional CT images and allows for improved assessment of calcified or non-enhancing nodules/lesions (Fig. 12). This provides imaging information that would otherwise require additional radiation dose as well as increased scan time using conventional CT only.

8.5. Incidental lesion assessment

Most chest CT protocols incorporate portions of the lower neck and upper abdomen, and radiologists are expected to identify incidental imaging findings in this location. Conventional CT of the chest also does not optimize contrast bolus timing for appropriate evaluation of these areas and therefore the lesions are often labelled as indeterminate. Despite the limited field of view, utilization of DECT over conventional CT may help in definitive characterization of many of the lesions reducing the need for additional dedicated imaging. This may include renal, hepatic, adrenal, pancreatic, or osseous lesions. For example, Wortman et al. reviewed how DECT VMI may increase conspicuity of incidental lesions identified in the liver or pancreas compared to those found on conventional CT alone [62]. A VNC image may be used as a surrogate for dual phase conventional CT and help characterize a lipid-rich adenoma [63]. Incidental hypoattenuating/hyperattenuating hepatic or renal cysts often present a diagnostic dilemma in patients with work up for metastatic disease. Conventional CT characteristics such as size and attenuation may not always be enough to provide a
confident benign versus suspicious diagnosis. DECT images, particularly iodine density map images, may further identify true iodine uptake in these incidental lesions and serve as a surrogate marker for recommending further workup (Fig. 13).

8.6. Estimation of organ function

Iodine density map images from DECT may be directly correlated with estimated organ function and perfusion. This property has proven useful in pre- and post-operative therapy planning and assessment. For
example, where non-specific dense consolidation may limit diagnosis in a complex lung transplant patient, Hokamp et al. demonstrated that the iodine density map images with a lack of perfusion confirming the diagnosis of acute transplant rejection [64]. For pre-operative planning in cardiothoracic surgeries, DECT may include additional clinical data such as surrogate markers for cardiac perfusion which may redirect or alter management (Fig. 14). Rubinshtein et al. showed that DECT myocardial perfusion imaging demonstrated high specificity (98%) and negative predictive value (99%) for detection of myocardial infarction when compared to the gold standard of Technetium [99mTc]-Sestamibi single photon emission computed tomography (SPECT) [65]. Similarly, Carrascosa et al. demonstrated that stress myocardial perfusion protocol by DECT added value in detecting reversible perfusion defects ([area under ROC curve 0.84 (0.80–0.87)] and anatomy of coronary artery disease ([area under ROC curve 0.70 (0.65–0.74)] compared to SPECT and CT coronary angiography, respectively [66]. In radiation therapy planning, studies have demonstrated that average iodine density of tumor from DECT may serve as a noninvasive and quantitative assessment of radio-resistance and predictor of the prognosis and overall treatment response [67].

8.7. Reduction in radiation dose

Most literature confirms that modern DECT scanners are able to achieve equal or decreased radiation doses delivery compared to conventional CT [68]. Lenga et al. specifically investigated second and third-generation DECT compared to conventional single energy CT in imaging of the chest and found no significant increase in radiation dose as well as no significant decrease in image quality [68]. Bauer et al. shared the same findings for first and second generation DECT compared to single-energy CT in CT pulmonary angiography [69]. DECT manufacturers all include up-to-date CT dose-reduction techniques as well as streamlined protociling for equivalent or improved SNR. Furthermore, VNC may be considered equivalent to true non-contrast conventional CT images enabling streamlined DECT single-phase acquisition versus previously required multiphase single-energy conventional CT, allowing for significant radiation dose reduction (Fig. 15). Utilization of VMI may also salvage suboptimal exams as well as reduce CT artifacts eliminating...
8.8. Emerging clinical indications

Research and experimentation in emerging applications and utility for DECT continues to grow. In radiation therapy treatment planning, Lapointe et al. found that iodine pulmonary perfusion DECT images strongly correlated with SPECT for differential function per lobe calculations (Pearson’s coefficient $r = 0.91$) \cite{70}. Future cardiothoracic applications of DECT are promising including the use of DECT for pulmonary lesion evaluation and lobar functional assessment in a single study, obviating the need for an additional SPECT-CT \cite{71}. Coronary calcium scoring CT has expanded in clinical practice and the combination of DECT with VNC images for definitive calcium identification and subtraction may further enhance the clinical value. (Supplemental Fig. 3). Medical 3D printing commonly uses CT as the source for anatomic segmentation and using DECT images improves the medical 3D printing workflow over conventional CT \cite{72}. Additionally, the combination of contrast enhancing properties from low keV VMI and artifact reduction from high keV VMI improves the ability of automated segmentation tools to threshold and differentiate critical anatomic structures for 3D printing (Supplemental Fig. 4) \cite{72}.

9. Future directions

9.1. Integrated PET/dual energy CT

Positron Emission Tomography (PET) fused with a conventional CT is commonly implemented with multiple use cases in molecular and functional imaging. The fusion of CT with PET imaging allows precise alignment of metabolic activity in the body obtained by PET with anatomical imaging obtained by CT. The use of PET/CT has led to improved diagnosis and determination of treatment response in the fields of oncology and radiation therapy \cite{73,74}. As compared to conventional CT, DECT techniques allow for the quantitative characterization of tissue composition. Thus, the combination of DECT with PET imaging allows for a more comprehensive characterization of diseases than DECT or PET/CT alone. This couples the quantitative tissue characterization afforded by the DECT with molecular information from the PET \cite{75}.
Fig. 13. Incidental lesion assessment with DECT. A 80-year-old male was scanned as part of the pre TAVI (Transcatheter Aortic Valve Implantation) work up. Axial CT image (a) demonstrate incidentally noted hypodense (white arrows) and hyperdense left renal lesions(blue arrow), which were without iodine accumulation on iodine density (b)and Z effective images(c), consistent with hemorrhagic and non-hemorrhagic renal cysts.
However, this integration is fraught with several challenges. If the single-energy CT scanners were replaced by DECT, it would require a new higher cost scanner. While existing CT scanners can be retrofitted to allow dual-energy applications, there would be increased radiation dose and scanning expenses. Research by Wang et al. focused on devising novel methodologies to use available PET data from PET/CT to construct an integrated PET/DECT method without the need for additional hardware or radiation exposure [76].

9.2. Photon counting CT

Photon counting CT is multi-energy CT technique, currently being developed, which employ a photon-counting detector to register the interaction of individual photons [77]. The detector pixels estimate the energy in each individual photon interaction and record an approximate energy spectrum. Conventional CT scanners with energy-integrating detectors only record photon intensity while photon counting CTs also register additional spectral information. This provides improved SNR with better correction of beam-hardening artefacts, reduced radiation exposure, and improved spatial resolution (Fig. 16) [78]. It also provides the ability to distinguish multiple contrast agents. Presently, photon counting CTs are in experimental and research use at three sites in the world including the National Institute of Health (NIH) Clinical Center [79]. Current technical limitations have yet to be overcome such as a limited overall count rate, slower gantry movement to acquire enough photons, and polarization. Additionally, there are a multitude of manufacturing challenges and high costs associated with this technology.

9.3. AI in dual energy CT analysis

Artificial Intelligence (AI) methods which includes machine- and deep-learning techniques have recently shown increasing promise in interrogating subtle sub-visual clues on conventional radiology and pathology images. This includes detection, diagnosis, prognosis, and treatment response especially in cancer. AI methods are reliant on the spatial resolution and image SNR [80–82]. Dual-energy techniques result in images with increasing amounts of quantifiable data and improved SNR which are therefore well suited to address the needs of AI analyses. The relative lack of widespread clinical adoption of dual-energy radiography and CT techniques has meant that research in AI and dual-energy image analysis is currently limited. Seidler et al. used radiomic textural analysis on virtual monochromatic image (VMI) from DECT imaging of the neck from 50 patients having a total of 412 lymph nodes to differentiate benign from malignant lymph nodes [83]. The accuracy, sensitivity, specificity, PPV, and NPV for correctly classifying a lymph node as malignant (i.e. metastatic Head and neck Squamous cell cancer or lymphoma) versus benign were 92 %, 91 %, 93 %, 95 %, 87 %, respectively.

10. Conclusion

Dual-energy radiography and CT are powerful clinical tools for evaluating a wide range of cardiothoracic diseases. Through an understanding of the basic physics and the common dual energy images/reconstructions available, radiologists and clinicians may increase their confidence with cardiothoracic findings and avoid pitfalls associated with interpreting dual energy imaging data.

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Radiation dose reduction with DECT. A 64-year-old male with history of endovascular aneurysm repair (EVAR) for abdominal aortic aneurysm (AAA), underwent a follow up three phase CT angiogram (non-contrast, arterial phase and delayed phase scanning) of the abdomen and pelvis. Axial arterial phase image (a) demonstrates areas of hyperattenuation outside the stent in the excluded abdominal aortic aneurysm (Arrows), which persists on true non-contrast (TNC) image (c) and does not change on delayed contrast enhanced image (b). The findings are consistent with calcification in the excluded AAA and not an endoleak. When utilizing the low keV VM image (d) and VNC (e) reconstructions from the single delayed phase examination (b), comparable information to a three-phase scan can be obtained, thus, there is a potential of significantly reducing radiation exposure to the patient.
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Declaration of Competing Interest

The author(s) or author(s) institutions have no conflicts of interest pertaining to this project.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejro.2021.100324.

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Fig. 16. Superior image quality with Photon-counting detector (PCD) CT. Coronal conventional CT (a) and PCD CT image (b) acquired in ultra-high resolution mode demonstrate better spatial resolution and delineation of coro

Ethical statement

There are no ethical issues associated with this review paper.

There are no human or animal experiments involved in this study.

The authors received waiver of consent for this retrospective project by the institutional review board.

Images (Fig. 9a, 9b and 9c in original paper) reprinted with permission from S. Leng, M. Brusewitz, S. Tao, K. Rajendran, A.F. Halaweish, N.G. Campeau, J.G. Fletcher, C.H. McCollough, Photon-counting Detector CT: System Design and Clinical Applications of an Emerging Technology. Radiographics. 39(3) (2019) 729–743.
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