INTRODUCTION

Dual-energy computed tomography (DECT) has emerged as a promising tool in diagnostic imaging with multiple potential clinical applications. It allows identification of the material composition by gathering tissue characterization information based on two absorption measurements at different photon spectra with high and low-energy levels [1]. Based on this differential tissue attenuation, DECT can quantify the iodine content, which helps to identify visceral enhancements, such as hypo- or hyperenhancement, in cases of inflammation. Virtual nonenhanced images can be generated using this dual-energy technique, which can lower the radiation dose exposed by a patient by eliminating the need to perform a non-contrast phase. In venous phase abdominal imaging, areas of hyperdensity could either represent a hematoma or true enhancement of the lesion; moreover, the presence of calcifications can pose a diagnostic challenge to be certain about its differentiation from a hemorrhage. Furthermore, the ability of dual-energy CT to substantially reduce metallic prosthesis-related artifacts is an added advantage that can reveal the underlying anatomical and pathological details.

Iodine images can be displayed as quantitative grayscale images or color overlay maps, both of which improve lesion conspicuity due to differences in the iodine content between lesions and normal parenchyma. Iodine images can detect and quantify iodine within each image voxel, allowing the detection of even a small amount of enhancement within a lesion [1]. To illustrate improved tissue characterization, in this article, liver lesions, renal masses, and renal stone characterization will be briefly discussed. The role of DECT in oncologic imaging will also be outlined.

Techniques

At present, there are five approaches to DECT: sequential acquisition, rapid voltage switching, DSCT, layer detectors, and energy-resolving or quantum-counting detectors;
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Currently, only the former three are commercially available. In DECT, information can be gathered through two absorption measurements as two-photon spectra. It can differentiate between tissues and other materials by utilizing the property of X-ray attenuation change at different photon spectra.

Careful attention should be given while protocolling patients with an acute abdomen. For instance, when there is clinical suspicion of urolithiasis or suspected non-traumatic hemorrhage, generally, no intravenous (IV) contrast is administered for initial CT evaluation. IV contrast is generally administered to patients with a Glomerular filtration rate > 30. In our department, an appropriate weight amount of iodinated contrast at an infusion rate of 2–3 mL/s is administered through a peripheral IV catheter; thereafter, venous phase images are acquired from the dome of the diaphragm to the inferior aspect of the symphysis pubis.

In the venous phase images, areas of hyperdensity could represent hemorrhage or enhancement of the lesion. Furthermore, the presence of calcifications makes it even more difficult to determine hemorrhage. DECT images alongside virtual non-contrast (VNC) images can help to subtract contrast to differentiate between enhancement and hemorrhage. The visual difference in the foci of mineralization at different energy levels helps to differentiate calcified areas from hemorrhage.

Administration of oral contrast is dependent on personal preference, complexity of the case, and the patient’s body type. It helps to better delineate various bowel pathologies; for example, the appendix with intraluminal contrast and enteric fistula are easier to evaluate. However, oral contrast can mask gastrointestinal bleed and is contraindicated in high-grade small bowel obstruction or possible ischemia. Moreover, oral contrast delays the examination and increases patients’ length of hospital stay.

Material Separation

Blended images are generated through a combination of the acquired low-energy (80 kilovoltage peak [kVp]) and high-energy (140 kVp) datasets to simulate a standard 120-kVp dataset. Virtual monoenergetic images were acquired to simulate a scan obtained at a single-energy level. Virtual monochromatic (VMC) images can be manually changed to a specific energy level for various clinical applications. Artifacts from metal implants can be reduced using a high-energy monoenergetic beam (95–140 kiloelectron volt [keV]). Intermediate-energy virtual monoenergetic images (60–75 keV) are ideal for evaluation of soft tissues due to the balance between adequate contrast and reduced image noise. Lesions with an inherently high contrast can be best evaluated using a low-energy monoenergetic beam (45–55 keV) [1].

DECT utilizes a three-material decomposition algorithm to create soft tissue-, fat-, and iodine-material-specific images. Contrast-enhanced images are more accurate measures of enhancement as they show the amount of iodine distribution in the tissues and are independent of inherent tissue attenuation. For example, in liver masses, iodine quantification can be used to accurately measure actual tumor enhancement without adding liver parenchymal enhancement. Virtual unenhanced DECT images can be obtained and are comparable to unenhanced images.

Tissue Characterization

Dual-energy applications add value to CT imaging due to superior lesion detection and characterization. The single most important property that governs the interpreter’s ability to detect a lesion in the background of normal tissue is the contrast-to-noise ratio (CNR).

Intermediate intensity monoenergetic beams (60–75 keV) eliminate very low-energy photons that contribute only to image noise and, therefore, improve the overall image quality [2,3].

Utilization of DECT in Head and Neck Imaging

Head and Neck Oncology

DECT can be useful in differentiating malignancies from other conditions, such as hemorrhagic brain metastasis from intracranial hemorrhage. Using a monoenergetic beam of 40 keV improves tumor delineation. Moreover, DECT can differentiate hyperdense hemorrhage from enhancement within a hemorrhagic mass. It has been suggested that 65-keV VM images provide the best overall image quality, and that 40-keV VM images enable the best tumor delineation [4].

Brain Trauma

DECT can distinguish contrast and hemorrhage based on the different spectral ranges of blood and iodine. DECT also allows the extraction of a virtual unenhanced scan from a contrast-enhanced scan. Moreover, DECT helps to differentiate hyperdensity secondary to intracranial hemorrhage from iodine extravasation or staining (Fig. 1), especially in stroke patients undergoing a hemorrhagic
transformation after intraarterial recanalization.

Studies suggest that the virtual monoenergetic images acquired at 190 keV can better differentiate enhancing subdural effusions from subdural hemorrhage [5,6]. In the assessment of brain parenchyma on non-contrast CT, improved image quality was demonstrated with VM imaging at 65–75 keV when compared to a single-energy CT [7,8].

Utilization of DECT in Cardiothoracic Imaging

Thoracic Oncology

For thoracic oncologic CT applications, studies suggest that subjective image quality for visualization of lung carcinoma is improved at 55–70 keV [9,10] compared with conventional CT scans. In thoracic oncology, DECT can be used to differentiate benign and malignant pulmonary nodules and masses [11]. Moreover, DECT can be used for cases of anterior mediastinal lesions to differentiate thymic cysts from thymic epithelial tumors [11].

Cardiac Evaluation

Efficient detection of myocardial infarction by DECT, in addition to evaluation of coronary arteries, has prognostic implications [12,13]. DECT depicts myocardial perfusion...
defects (Fig. 2) more conspicuously than conventional CT scanning [14].

Different studies have demonstrated that using low virtual monoenergetic keV improves the visualization of myocardial fibrosis. For instance, in an animal study, there was an improved detection of chronic infarct with 40-keV VM images compared with single-energy CT scans [15]. Furthermore, a subsequent study [16] demonstrated that compared with MRI, use of a 70 keV virtual monoenergetic beam can identify myocardial late enhancement and pattern classification (subendocardial, epicardial, transmural, meso-myocardial, and/or patchy).

**COVID-19 Pneumonia**

Dual-energy CT imaging can provide added information about any pulmonary pathology by highlighting the perfusion abnormalities associated with the disease. CT findings of Coronavirus disease-19 (COVID-19) pneumonia include ground-glass opacification, consolidation, atoll sign (or “reverse halo” sign), halo sign, organizing pneumonia, and vascular dilatation adjacent to the pulmonary pathology, commonly seen as a later manifestation of the disease. Perfusion analysis of the pulmonary parenchyma in COVID-19 shows features of high iodine density or increased perfusion of the lung parenchyma around the pulmonary opacity, which is likely secondary to vascular dilation contributing to a higher volume of blood flow. The etiology of vascular dilatation can be attributed to the inflammatory cascade or microvascular thrombosis. The areas of pulmonary opacity showed reduced perfusion on dual-energy maps (Fig. 3) [17].

**Utilization of DECT in Abdominal Imaging**

**Abdominal Oncology**

Several studies have demonstrated that the conspicuity of hyperattenuating and hypervascular liver lesions is greater at low keV than with conventional CT scanners [18-20]. It was also documented that an increase in noise with a low KeV monoenergetic beam in patients with increased body size can decrease the contrast noise ratio [17]. Various optimal energy settings have been described depending on the body size for optimized visualization of hypervascular liver lesions [21].

In patients with pancreatic adenocarcinoma, 55-keV VM images have been found to improve visualization of tumors and vascular infiltration [22] when compared with linearly blended reconstructions; however, 70 keV represented the best subjective overall energy level [23].

For VM CT of renal cell carcinoma, tumor delineation was optimal at 40 keV [24]. A level of 50 keV appears to be the optimal overall compromise between the keV settings for the routine reconstruction of high-contrast VM images. Other studies aimed to determine the optimal thresholds for the differentiation between vascular and nonvascular renal lesions, with the recommended energy levels of 40–60 keV [25].

An iodine concentration of 2.0 mg/mL represented the optimal threshold to discriminate between lymphoma and lymph node metastasis (sensitivity, 87%; specificity,
Fig. 3. 76-years-old male with polymerase chain reaction-positive COVID-19 pneumonia.

A. CT chest coronal reformatted image with lung window shows multifocal predominantly peripherally distributed areas of consolidation in both lungs (arrows).
B. Coronal clip plane cinematic rendered CT chest image displays similar pattern of the pulmonary involvement with dense consolidation.
C. Color coded iodine map with red color highlighting consolidation quantifying the iodine content.
D. Volume rendered three-dimensional image analysis reveals the snapshot of total lung volume involvement.
E. Dual-energy CT chest with color coded iodine overlay maps displaying peripheral areas of consolidation in the right upper and lower lobe with reduced iodine uptake measured at 1.6 mg/mL.
F. Dual-energy CT analysis (dense lung protocol) post processed on Siemens Syngo.via (VB30) shows the areas of increased perfusion around the relatively hypoperfused pulmonary consolidation.
G. Axial CT image (lung windows) shows right greater than left lower lobe multifocal bronchial wall thickening and peripheral areas of ground-glass, consolidation and septal thickening with organizing pneumonia pattern. Peripheral dilatation of vessels (arrows) on the lung windows presumably represent pre-stenotic dilatation.
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89%) [26].

**Bowel Evaluation**

In patients with small bowel obstruction, mural enhancement of the bowel can be detected with increased diagnostic confidence in 70-keV VM images [27]. Recent studies have shown that iodine overlay imaging and virtual monoenergetic imaging at lower energy levels (40-keV) can detect and differentiate mural hypoperfused segments from the normally perfused bowel wall [28]. Furthermore, the 40-keV VM imaging has added diagnostic value in the evaluation of inflammatory intestinal lesions in Crohn’s disease owing to greater conspicuity [29].

Dect can detect a change in bowel wall enhancement and thus is extremely helpful in suspected bowel injury. Iodine map images can increase the visibility of the iodine content in bowel wall and VNC images, thus increasing the diagnostic confidence of visualizing intramural hemorrhage [30].

**Gangrenous Appendicitis and Cholecystitis**

Long-standing, progressive transmural inflammation causes ischemia and necrosis of the appendix, thus resulting in gangrenous appendicitis, which is prone to complications such as perforation, abscess formation, and sepsis. It is important to identify gangrenous appendicitis preoperatively, as the rate of postoperative complications is relatively higher than that of uncomplicated appendicitis. Dual-energy CT can detect the presence of transmural necrosis of the appendix wall on the iodine overlay images and low 40-keV virtual monoenergetic images. The ability of the dual-energy CT to distinctly differentiate gangrenous mucosa from the normal enhancing mucosa clearly adds value to patient management (Fig. 4) [25].

Dual-energy can demonstrate areas of absent wall enhancement consistent with gangrenous cholecystitis (Fig. 5). Identification of gangrenous cholecystitis has been shown to alter the surgical approach with the need for an open rather than a laparoscopic cholecystectomy.

**Gall Stones and Renal Calculi**

Dual-energy CT can be extremely helpful in identifying the composition of various gall stones [30]. Previous studies

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**Fig. 4. A 40-year-old male who presented with a 24-hours history of abdominal pain, which was more marked in the right lower quadrant.**

A, B. Dual-energy CT (A) source sagittal image shows dilated retrocecal appendix with mural thickening, surrounding inflammatory fat stranding (curved arrow), thickening of peritoneal reflections (notched arrow) and trace free fluid consistent with acute appendicitis. A 5-mm hyperdense appendicolith (arrow) in the mid appendix. (B) Color coded iodine maps reveals an area of reduced iodine uptake along the posterior wall of the appendicular tip with reduced iodine uptake (arrow), concerning for early gangrenous appendicitis with histopathologic confirmation of acute appendicitis with mural necrosis.
have shown that gallstones are better visualized on a monochromatic high keV [31]. Dual-energy CT can identify the specific composition of the calculus and differentiate non-uric acid calculi from uric acid calculi [31].

**Utilization of DECT in Vascular Imaging**

**Carotid Artery Evaluation**

Studies have demonstrated that virtual monoenergetic imaging at 40–60 keV for dual-energy CT angiography (CTA) provides superior subjective and objective image quality for the evaluation of the carotid and cerebral arteries [32-34]. Blooming artifacts from calcified plaques and accurate assessment of the degree of stenosis in the presence of calcified plaques were reported at 80–100 keV [32]. Furthermore, virtual monoenergetic imaging is helpful in the evaluation of arteries that are close to the skull [14,33,35].

**Pulmonary Angiography**

Using DECT perfusion scans, perfusion defects beyond obstructive clots can be identified (Fig. 6) [14,36]. Pontana et al. [37] demonstrated that blood flow images can detect subsegmental perfusion defects, whereas endoluminal thrombi cannot be visualized in the corresponding arteries using pulmonary CTA.

One of the most important applications of DECT is to detect small embolic vessel occlusion, and one of the studies highlighted the usefulness of virtual monoenergetic imaging in suboptimal scan secondary to technique or missed timing of contrast bolus [38]. Virtual monoenergetic images at 70 keV for CT pulmonary angiography are recommended by one of the studies [39].

**Aorta, Abdomen, and Lower Extremity Angiography**

The standard CT arteriography protocol for the assessment of acute aortic syndromes includes unenhanced images.
to detect hyperdense intramural hematoma or intimal calcifications and to detect dissection, which results in considerable radiation exposure. Although virtual unenhanced images are slightly noisier compared with unenhanced images, they are diagnostic in almost 95% of cases [40].

By using the overlay maps, the differences between the high attenuation due to blood, bone, or contrast agent are highlighted, and the diagnostic accuracy for detection of endoleak is increased [41].

The precise removal of calcium from arteries assists in the better evaluation of atherosclerotic arteries [42]. However, this technique is not very helpful for small arteries. The increase in radiation dose, noise, and small diameter of the distal peripheral arteries are limitations for dual-energy peripheral CTA. High-resolution dual-energy acquisitions combined with iterative reconstruction and spectral filtering can be a solution to this problem [43].

Low keV virtual monoenergetic imaging at 60 keV or less has been shown to provide improved CNR and qualitative image quality [44,45]. Virtual monoenergetic imaging at 40 keV has been shown to improve diagnostic accuracy for the detection of acute arterial bleeding [46] and endoleaks [47]. Furthermore, it has been demonstrated that the diagnostic accuracy of CTA for lower extremity run-off for the detection of significant stenosis (50%) can be effectively increased by using 40-keV VM images compared with linearly blended reconstructions (accuracy: 96.4% vs. 89.3%, respectively) [48].

CT Venography or Portal Venous Phase Imaging

Virtual monoenergetic images at 40 keV provide greater contrast attenuation and assessment of poorly opacified liver veins than linearly blended images, such as in cirrhotic livers [49]. Low keV virtual monoenergetic images have also been shown to improve the assessment of the portal vein and deep vein thrombosis [50]. Both iodine maps and VM images at 40 keV provide substantially higher diagnostic confidence and accuracy in detecting and differentiating venous thrombosis from iodine flux artifacts compared with linearly blended dual-energy CT scans [51].

Utilization of DECT in Musculoskeletal Application

Bone Marrow Edema

In older patients with multiple fractures of varying ages and patients with subtle fractures, it can be difficult to assess using conventional CT. Bone marrow edema (BME) is a biomarker of occult fractures, and various studies have shown that DECT material decomposition and virtual non-calcium imaging can detect BME (Supplementary Fig. 1) [52]. In patients with abdominal and pelvic trauma, VNC images can be created to differentiate chronic fractures from acute and non-displaced occult fractures.

Gout

DECT demonstrates great promise for the diagnosis of gout. DECT gout application can be used as an excellent noninvasive alternative to synovial fluid aspiration. Moreover, DECT is increasingly useful in diagnosing cases of gout where synovial fluid fails to demonstrate monosodium urate crystals (Supplementary Fig. 2).

Metal Artifact Reduction

DECT measures attenuation at two different energy
levels. Beam-hardening and metallic streak artifacts can be reduced by using high-energy X-ray photons as they penetrate deeper into the materials (Supplementary Fig. 3). Simulated monochromatic images have been shown to decrease the number of artifacts caused by dental hardware in adjacent bones [53]. Subjectively superior images can be obtained by using simulated high-energy reconstructions in the region of metallic hardware [54-56]. A recent cadaveric study showed that increasing the simulated monochromatic energy level of the reconstructed data resulted in subjectively decreased beam-hardening artifacts from dental implants [57]. In another study, DECT with postprocessing for metal artifact reduction software (MARS, GE Healthcare) improved the depiction of blood vessels adjacent to a platinum coil mass in patients with intracranial aneurysm embolization [58].

In comparison with single-energy CT [57] and linearly blended dual-energy CT [53,59], the virtual monoenergetic imaging at 100 keV decreases the streak artifacts from dental implants. Similarly, artifacts from spinal fixators have been demonstrated to reduce at levels greater than 110 keV [60,61], with partially reduced artifacts at these keV settings compared with single-energy CT [55]. In the pelvis, the benefit of VM imaging at 130 keV or greater for artifact reduction in patients with hip prosthesis has been demonstrated in comparison with single-energy CT and linearly blended dual-energy CT [59]. There is accumulating evidence demonstrating the usefulness of dedicated metal artifact reduction algorithms as an addition or alternative to VM imaging. For pelvic CT in patients with hip implants, VM images at 200 keV were preferred for bone assessment, whereas a dedicated metal artifact reduction algorithm was considered superior for analyzing soft tissue [62]. Metal artifact reconstruction algorithms were found to be more effective than VM imaging in artifacts arising from deep brain stimulating electrodes [63]. Combining metal artifact reduction software with high keV VM imaging has also been suggested to achieve the greatest artifact reduction in patients with orthopedic foreign bodies in the spine [63].

**Image Quality and Radiation Dose Considerations**

Several studies have shown significant dose reductions or similar doses when compared to single-energy CT exams [64,65]. Current efforts in radiology to minimize patient radiation exposure preclude the wide implementation of techniques that would increase patient dose [64]. One study demonstrated that DECT imaging at 80 and 140 kVp and simulating a 120-kVp single-source image results in a dose-length product and CT dose index values of 10 and 12% less than standard single-energy CT acquisitions, with no significant difference in objective image noise or subjective image quality [65].

Several investigations have shown that the iodine load for abdominal CTA can be reduced by up to 50% with the

| Location/Region | Material Separation/Virtual Monoenergetic Beam | Iodine Quantification |
|-----------------|-----------------------------------------------|-----------------------|
| Brain           | Helps to differentiate between tumor and bleed| Helps to differentiate between bleed and contrast |
| Cardiac         | Low virtual monoenergetic KeV improves visualization of myocardial fibrosis | High iodine density/increased perfusion of the lung parenchyma around the pulmonary opacity in COVID-19 |
| Lungs           | Differentiate mural hypoperfused segment from normal perfused bowel wall | Decrease perfusion of the lung parenchyma in the region of pulmonary infarct suggesting hypoperfused lung/pulmonary embolism |
| Abdomen         | Differentiate tumors | Iodine map images can increase the visibility of the iodine content in bowel wall and thus increasing the diagnostic confidence of visualizing intramural hemorrhage |
| Vascular imaging | Blooming artifacts from calcified plaques can be reduced | |
| Bones           | VNC images can be created to differentiate chronic fractures from acute and non-displaced CT occult fractures | |
| Metallic artifacts | High monoenergetic beam can reduce metallic artifacts | |

keV = kiloelectron volt, VNC = virtual non-contrast
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use of VM reconstructions at 40–60 keV (reduction in iodine dose: -49% [63,66], -27% [67], and -28% [68], compared with single-energy CT while providing equivalent or improved CNR as well as superior subjective vascular contrast attenuation.

Limitations

The limitations of DECT include higher image noise on virtual unenhanced images than unenhanced images, consumes more time and expertise to process and generate images, larger image datasets requiring increased storage capabilities, and the inability to quantify attenuation in Hounsfield units on virtual unenhanced images obtained with current processing techniques. This last drawback might eventually be overcome by modified image-processing algorithms, allowing the extrapolation of attenuation data.

CONCLUSION

DECT, with its unique abilities, has a multitude of clinically applicable advantages as compared to the conventional single-energy CT scan. Thus, helping create a paradigm shift in the modern advancing field of medical imaging (Table 1).

Supplement

The Supplement is available with this article at https://doi.org/10.3348/kjr.2020.0996.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

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