REVIEW / Thoracic imaging

Thoracic dual energy CT: Acquisition protocols, current applications and future developments

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Abstract Thanks to a simultaneous acquisition at high and low kilovoltage, dual energy computed tomography (DECT) can achieve material-based decomposition (iodine, water, calcium, etc.) and reconstruct images at different energy levels (40 to 140 keV). Post-processing uses this potential to maximise iodine detection, which elicits demonstrated added value for chest imaging in acute and chronic embolic diseases (increases the quality of the examination and identifies perfusion defects), follow-up of aortic endografts and detection of contrast uptake in oncology. In CT angiography, these unique features are taken advantage of to reduce the iodine load by more than half. This review article aims to set out the physical basis for the technology, the acquisition and post-processing protocols used, its proven advantages in chest pathologies, and to present future developments.

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Dual energy computed tomography (DECT) is a recently commercially available technology that is used in a growing number of healthcare institutions, mainly university hospitals, offering numerous benefits in chest imaging [1,2].

This review article aims to set out the physical basis for the technology, familiarise the reader with the acquisition and post-processing protocols used, list its proven advantages in chest pathologies and to present current and future developments.

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Basic principles of dual energy computed tomography

Physical basis

DECT is based on the simultaneous acquisition at low and high kilovoltage, usually 80 kV and 140 kV [3]. This principle, which has already been applied in conventional radiology, was transposed to computed tomography only recently. In commercially available scanners [4], this virtually simultaneous volume acquisition at two different energies is made possible through the use of two different approaches (Fig. 1):

- dual source DECT (Somatom Definition FLASH, Siemens), which uses two pairs of X-ray tubes/detectors systems positioned approximately 95° apart that rotate around the patient simultaneously. The advantage of this technique is that it is possible to calibrate the current (mA) separately for high and low energy, to optimise the dose delivered. The main drawback is that the field of view is limited to a diameter of 33 cm;
- single source DECT (Discovery CT 750 HD, GE Healthcare), which uses a single X-ray tube/detector system that alternates very quickly between high and low kV every 0.5 msec ("fast kV-switching") thanks to detectors with very short afterglow. The main advantages are a full field of acquisition and the potential to directly quantify material, at the expense of delivering a higher radiation dose. All of the illustrations in this article have been taken from a single source DECT scanner.

The main advantage of DECT is that the simultaneous acquisition means that material decomposition can be exploited [5]. The higher the molecular weight of a material, the greater the absorption differences between high and low kilovoltage are, due to the increased likelihood of a photoelectric effect at a lower kV (Fig. 2). This is particularly marked for iodine.

A post-processing system uses these differential data to generate [6]:

- material density images, obtained through the material decomposition technique of dual energy acquisitions using two specific absorption spectra. The chosen pair is usually water and iodine, allowing the calculation of iodine-density images that create a contrast uptake map, and water-density images that remove iodine to produce a virtual non-contrast image (Fig. 3);
- monochromatic images, which are real-time image reconstructions at a given energy level, every single keV within the range of 40 to 140 keV. The main advantage is the potential to dynamically reduce keV, which increases the contrast of iodine (Fig. 4), at the expense of the signal-to-noise ratio.

Acquisition protocols

There is no external difference between a single and a dual energy examination: positioning of the patient, programming the acquisition, and setting it running differ only slightly from a usual protocol. Specifically, there is no increase in time taken to position the patient or carry out the acquisition.

For a chest examination, we recommend an injection of 50 to 80 mL of a 350 mg/mL iodine contrast media. In CT pulmonary angiography (CTPA), an automatic power injector will be used with a flow rate at 3.5 mL/sec, a 50 mL saline chaser and a bolus tracking technique, with a region of interest (ROI) in the pulmonary artery and a threshold of 60 HU [7].

Figure 1. Currently available dual energy CT systems: dual source with two separate pairs of X-ray tubes/detectors positioned at 95° (a), and single source with ultrafast switching between high and low kV using a single pair of X-ray tube/detectors (b).

Figure 2. Attenuation spectrum of different materials at different X-ray energies. At a low kilovoltage, materials with a high molecular weight (mainly iodine) show greater X-ray absorption due to a greater likelihood of the photoelectric effect occurring.
Dual thickness

certainty

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to

iodine

non-contrast

noise.

Figure 3. Material-density images. Starting with images acquired using dual energy (a), two-material decomposition using water and iodine generates a set of iodine-density images (b) that act as an extraction of iodine, and a set of water-density images (c), equivalent to non-contrast acquisitions.

Figure 4. Monochromatic reconstructions at different energy levels. Reducing keV increases the iodine contrast, at the expense of greater noise.

Post-processing

Post-processing is essential to study examinations acquired in dual energy [3,4] in a dynamic fashion. This means that a dedicated workstation or server and 5 to 10 minutes additional interpretation time are required. The learning curve is quick, entailing a rapid training session with the software.

To review monochromatic images, some authors recommend analysing the data on a single reconstruction series, usually at 70 keV [2]. In our experience, more can be gained from a dynamic interpretation of these reconstructions using a wider range of energies (from 40 to 80 keV — the concept of 'spectral surfing'), giving the radiologist the opportunity to finely adjust the contrast of the image and the noise, which can sometimes become important at very low energies (< 55 keV).

Iodine-density images will be used to obtain an equivalent of parenchymal perfusion: averaging the slices at a thickness of 3 mm and narrowing the window (Fig. 5) is sufficient to obtain information that is very closely correlated to the perfusion scintigraphy [8,9].

Radiation dose

Dual energy acquisition delivers more radiation dose than a single energy scan carried out using the same machine [10,11]. This increase varies depending on the manufacturer and the protocol used. In chest imaging, it ranges between +5% and +40% [7,12], which may pose an obstacle for usage of this technique in younger patients. In our experience, mean dose length product is around 340 mGy.cm, consistently below national and international standards (French diagnostic reference level for a chest CT is 475 mGy.cm).

Technological advances, both those that are underway and those yet to come, will gradually minimise [11,13] and probably nullify this difference in radiation exposure. For example, the recent incorporation of iterative reconstruction into our dual energy protocols has allowed doses to be reduced by over 20%.

Current applications of DECT in chest imaging

Pulmonary embolism

This is the main application for DECT in chest pathologies, with numerous publications emphasising the value of the technique [6,7,12,14–17].

In the management of acute pulmonary embolism, DECT increases the quality of the examination through an improved intraluminal enhancement obtained with monochromatic reconstructions at a lower keV [18]. This means that the peripheral pulmonary arteries are easier to analyse (Fig. 6), which increases diagnostic confidence for sub-segmental pulmonary embolism.

Perfusion-like imaging, obtained through iodine-density reconstructions, offers excellent correlation with scintigraphy [8,15,19] and allows perfusion defects to be visualised (Fig. 5). A defect is defined as a wedge-shaped triangular
Figure 5. Perfusion imaging. Starting with a dual energy acquisition (a), iodine-density images are reconstructed (b), averaged in 3 mm in thickness (c) and viewed with a narrowed window (d). It will be sufficient to obtain a perfusion-like imaging that correlates very closely to scintigraphy.

hypodensity, usually with a subpleural base, with normal or subnormal underlying lung parenchyma [12,20]. A close reading of iodine-density images in multiplanar reconstructions is necessary to exclude other defects which are unrelated to pulmonary embolism, such as artifacts (especially beam-hardening artifacts caused by a bolus of contrast agent within the superior vena cava), pulmonary sequestrations (due to vascularisation of aortic origin), and parenchymal diseases such as emphysema or cysts [20]. This type of perfusion imaging clearly sensitizes the examination by improving embolism detection and making it easier to find non-obstructive thrombi. Two studies come to this conclusion, with 100% sensitivity and specificity for the diagnosis of pulmonary embolism when classical CTPA images are combined with iodine-density images [9,21]. The latter may even have a role in prognosis, since a blockage in overall perfusion in excess of 30% is correlated with a poor clinical outcome [22].

These benefits are particularly useful in the investigation of pulmonary hypertension for identification of perfusion defects and markedly increase the reader’s sensitivity for the detection of arterial blockages, which aids in the diagnosis of chronic thromboembolic pulmonary hypertension (Figs. 7 and 8). By contrast, a normal iodine map can exclude this diagnosis with high specificity (Fig. 9) [9].

Aortic imaging

DECT can eliminate the need of a non-enhanced phase: virtual non-contrast reconstructions (water-density images) are indeed useful for the detection of intramural hematoma or for the monitoring of aortic endografts (Fig. 10). Iodine-density images and monochromatic reconstructions at low keV, by enhancing iodine contrast, improve the detection of aortic endoleaks [23,24].
Figure 6. Utility of monochromatic reconstructions at low keV in CTPA: at 70 keV (a), it is impossible to make any comment on enhancement of the subpleural arterioles. At 60 (b), 50 (c), and best of all 40 keV (d), this enhancement becomes clear, ruling out a very peripheral pulmonary embolism.

Thoracic oncology

For the characterisation of parenchymal (solid or ground glass) [25,26], pleural or pericardial nodules, DECT offers an improved evaluation of the presence of calcifications, and most importantly offers better detection of contrast uptakes, which can prove to be subtle, which could suggest a malignant aetiology (Fig. 11).

Furthermore, DECT allows discrete quantification of iodine concentration, which could offer an additional argument for some diagnoses (Fig. 12).

Finally, it improves the detection of mediastinal and hilar lymphadenopathy by increasing the contrast between the vessels and the lymph nodes on monochromatic images at low keV [27].

Renal protection

Monochromatic images at low keV and iodine-density reconstructions increase iodine contrast and thus offers better visualisation via DECT. These benefits can be put to use to reduce the amount of contrast media required while
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Figure 7. Thirty-six year old female; investigation of pulmonary hypertension. Multiple perfusion defects (a and b: iodine-density images) corresponding to arterial obstructions (c: correlation with volume rendering).

Figure 8. Fifty-seven year old male; investigation of pulmonary hypertension. Linear endoluminal image ("web") in the right lower lobe artery (a). Iodine-density images highlighting a perfusion defect in this area (b), confirming the pathological nature of the abnormality and leading to a diagnosis of post-embolic pulmonary hypertension.

Figure 9. Forty-six year old female; history of pulmonary embolism — post-embolic pulmonary hypertension is suspected. Perfusion images are normal (a) meaning that an embolic cause can be excluded with excellent sensitivity. Note the band of pseudo-triangular artifacts next to the bolus in the superior vena cava (b and c).

achieving an equivalent arterial enhancement [16,28]. In CTPA, an optimised DECT protocol with only 9.6 g of iodine can be used [29]; in aortic CT angiography, as only 13.6 g of iodine is required for an excellent image quality, comparable to a standard examination [30]. These protocols with drastically reduced iodine load (Fig. 13) are particularly useful in patients with moderate to severe renal failure.

Bone imaging

It is possible to detect bone marrow oedema on computed tomography by using water-density images that eliminate calcium [31]. This could be useful for determining whether a spinal compression fracture is recent or consolidated (Fig. 14).

Monochromatic images at high keV are also particularly useful for reducing metal artifacts and optimising the analysis of the edges of internal fixation implants. This may be valuable when a loose pedicle screw is suspected.

Developments

Cardiac imaging

Cardiac DECT with ECG gating has only recently been made commercially available. It may prove useful in the CT study of myocardial perfusion, both at rest and under pharmacological stress, by offering improved image quality with better analysis of myocardial enhancement and a
Figure 10. Sixty-one year old male; follow-up imaging after TEVAR (a). Rounded hyperdensity within the aneurysmal sac (b). Iodine-density (c) and virtual non-contrast images (d) confirm that it is indeed contrast media: type II endoleak.

Figure 11. Fifty-seven year old female; investigation of chronic obstructive pulmonary disease (COPD). Nodule in the left upper lobe measuring 7 mm with slightly irregular borders (a). On iodine-density images, contrast uptake indicates that it is tissular (b). A follow-up study four months later demonstrated a volume growth of around 25%, confirming its suspicious nature.

red.uction of beam-hardening artifacts [32–37]. It may also allow direct quantification of myocardial concentration of iodine and various index calculations.

In late myocardial enhancement imaging, DECT could increase the sensitivity of lesion detection through iodine-density reconstructions [38,39]. This might be possible even without the use of ECG gating.

Ventilation imaging

Ventilation imaging with DECT uses noble gases with high atomic numbers, such as xenon [40,41] or krypton [42], which distribute in a similar way to air and have a good clinical safety profile. They are thus able to play the role of a "gaseous contrast" and they are detectable and
Figure 12. Fifty-one year old female; investigation of a nodule of the left lung base with regular borders (a). On iodine-density images (b): intense iodine concentration similar to that of the aorta (nodule = 5 mg.cm$^{-3}$ and aorta = 5.5 mg.cm$^{-3}$). This means that it is a vascular structure: distal pulmonary artery aneurysm, also clearly visible on volume rendered reconstructions (c).

quantifiable on DECT through material-specific images, thus producing a true ventilation map.

The value of this technique in comparison with ventilation scintigraphy or hyperpolarised helium MRI lies in its potential for a morphological evaluation of ventilation with a high spatial resolution, the possibility of discrete quantification, its availability and the use of a less expensive contrast product.

Clinical applications currently in development include the prediction of residual pulmonary function after segmentectomy/lobectomy, the detection of bronchiolar disease in asthmatic patients or lung transplant recipients and

Figure 13. Protocols using a very low dose of contrast media. In CTPA, 40 mL of a 240mg/mL contrast product offers excellent image quality (a and b). For aortic CT angiography, 50 mL of a 270mg/mL product produces an image of identical quality to that of a full dose protocol (c and d).
ventilation mapping in chronic obstructive pulmonary disease patients [43].

Conclusion

DECT in chest imaging is rapidly moving forward, with already multiple well-supported applications, numerous avenues of research open and important advances yet to come. At present it has multiple well-supported applications. In our daily practice, we mainly make use of two of these applications: the increase in effective diagnosis in cases of acute or chronic pulmonary embolism and the drastic reduction of iodine load during CT angiography for patients with moderate to severe renal impairment.

At present, the main limitation of this technique, apart from a moderate increase in interpretation time due to post-processing, is an increase in radiation exposure ranging from 5 to 40%, even though the final dose still remains well below the recommended threshold. Continuing technological improvements are already leading to reductions in this excess radiation exposure, and should therefore contribute to a much more widespread usage of this technique.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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