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REVIEW ARTICLE

Dual energy computed tomography virtual monoenergetic imaging: technique and clinical applications

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ABSTRACT

Dual energy CT (DECT) has evolved into a commonly applied imaging technique in clinical routine due to its unique post-processing opportunities for improved evaluation of all body areas. Reconstruction of virtual monoenergetic imaging (VMI) series has shown beneficial effects for both non-contrast and contrast-enhanced DECT due to the flexibility to calculate low-keV VMI reconstructions to increase contrast and iodine attenuation, or to compute high-keV VMI reconstructions to reduce beam-hardening artefacts. The goal of this review article is to explain the technical background of VMI and noise-optimized VMI+ algorithms and to give an overview of useful clinical applications of the VMI technique in DECT of various body regions.

INTRODUCTION

During the last decade, the use of dual energy CT (DECT) has significantly increased in daily clinical practice as CT systems capable of DECT acquisition are now offered by all major vendors.^{1,2} Recent developments of DECT do not encompass only higher spatial or temporal resolution and greater anatomic coverage, but also quantitative imaging capabilities that may allow for considering modern DECT as a true multiparametric technique. Advances in detector technology and improved post-processing algorithms have facilitated the routine application of DECT in modern imaging algorithms.^{2,3}

Several studies have demonstrated that image quality of DECT can be substantially improved via post-processing using virtual monoenergetic imaging (VMI),⁴ which also allows for optimization of scan protocols by reducing the necessary amount of contrast material or radiation dose. In addition, the improvement of contrast conditions in contrast-enhanced VMI reconstructions has been shown to translate into increased diagnostic performance in oncological and vascular DECT.^{4–6}

The goal of this article is to review the technical background of this specific DECT algorithm and to give an overview of useful clinical applications of the VMI technique in DECT of various body regions.

Basic principles of DECT

The main principle of DECT relies on the acquisition of two different X-ray beams at different energies. Since different tissues have specific absorption patterns when penetrated by different X-ray energies, DECT allows for material differentiation, providing quantitative information with regard to tissue composition.⁷ This can be used to differentiate materials which may show the same attenuation values on CT, such as intracerebral haemorrhage and extravasated iodinated contrast material.⁸

At X-ray energy spectra relevant to diagnostic imaging [70–150 kilovolt peak (kVp)], tissue interaction with X-ray beams depends on their energy, e.g. exposure to low-kVp beams results in higher absorption and thus increased iodine density.⁹ However, high image noise at such low kVp settings remains a major limitation of this technique,

resulting in ultimately lower contrast-to-noise ratios (CNR) and signal-to-noise ratios (SNR).

There are various technical approaches to DECT imaging currently available:

- (1) Single source helical DECT (Siemens Healthineers, Forchheim, Germany)
- (2) Single source twin-beam DECT (Siemens Healthineers)
- (3) Single source rapid-kVp-Switching DECT (GE Healthcare, Milwaukee, WI)
- (4) Single source sequential DECT (Toshiba, Tochigi, Japan)
- (5) Dual source DECT (Siemens Healthcare, Forchheim, Germany)
- (6) Dual layer DECT (Philips Healthcare, Best, The Netherlands)

Despite differences in technical concepts, the goal of simultaneously obtaining imaging data characterized by two different X-ray energy levels is the same amongst all systems. It should be emphasized that all these systems can also be used in standard single energy mode for clinical routine, as DECT acquisition is simply an additional mode available.

Virtual monoenergetic imaging (VMI)

DECT image data sets obtained in clinical routine are acquired separately using a polyenergetic X-ray spectrum and thus consist of high and low kVp data blended at a certain ratio to obtain images similar to conventional single energy CT data. The main goal of DECT post-processing algorithms is to combine the increased iodine attenuation of the low-kVp spectrum with the lower image noise of the high-kVp spectrum in order to achieve an image with high contrast and low image noise.⁹ Differently from conventional blending techniques,^{10,11} VMI allows for the reconstruction of DECT data sets at a chosen hypothetical energy level that would result from an acquisition with a true monoenergetic X-ray beam.^{12,13} Depending on the DECT system, such VMI can be generated in either the projection domain (*e.g.* rapid-kVp-switching DECT) or the image domain (*e.g.* dual source DECT).¹⁴ The basic principle of VMI relies on DECT material decomposition. In fact, it has been demonstrated multiple decades ago that images can be synthesized at different monochromatic X-ray beam energies from acquired DECT data sets,¹⁵ although DECT systems were not available for clinical routine until the last decade.¹⁶ In particular, DECT may quantify two basis materials using independent measurements, which allows for reconstructing the fraction of the total mass of each material in each voxel. Due to this material-specific information, the density of each voxel can be extrapolated from the DECT data set to a certain energy level within a range of 40–140 kiloelectronvolts (keV). It should be mentioned that similar to differences in CT acquisition protocols and other image post-processing techniques (*e.g.* iterative reconstruction), VMI reconstructions can substantially alter attenuation values.^{17,18}

Reducing beam-hardening artefacts constituted the main benefits initially reported for VMI at higher keV values.¹⁹ High-keV VMI have been shown to reliably mitigate such artefacts from various foreign metal bodies such as hip replacements.¹⁹ Their value has also been shown to reduce beam-hardening

artefacts from other sources including contrast material influx and vascular calcifications.^{5,20}

More recently, low-keV VMI reconstructions have been more commonly used as their value in different applications under low-contrast conditions in contrast-enhanced DECT has been demonstrated, with particular regard to oncological and vascular DECT.^{4,21} As the energy level can be shifted close to the k-edge of iodine (36 keV), reconstructing VMI data sets, *e.g.* at 40 keV can substantially increase vascular contrast.¹ Low-keV VMI have also been used to optimize DECT examination protocols by allowing for a substantial reduction of contrast material dose in patients with impaired renal function without compromising image quality.^{22–24} However, VMI showed a drastic increase in image noise at low-keV values in the past, at which it coincidentally shows the strongest iodine attenuation.^{1,25}

Thus, an accurate choice of the energy level of VMI reconstruction should take into account different parameters, including the purpose of reconstructing VMI (*e.g.* increase vascular contrast *vs* reducing beam-hardening artefacts), but also patient size and optimization of the image quality.^{26,27} Therefore, VMI enhances the flexibility of DECT as such reconstructions can be performed retrospectively, which is a limitation of single energy CT examination protocols with low kVp settings.

Noise-optimized virtual monochromatic imaging (VMI+)

Higher iodine density using VMI algorithms can be obtained at the lowest energy level (40 keV) selectable during image reconstruction. However, VMI images reconstructed at 40 keV are commonly severely impaired by high image noise levels. Thus, prior studies evaluating traditional VMI algorithms, particularly in vascular DECT, recommended an energy level of 60–70 keV to increase vascular contrast without overpowering image noise.^{25,28,29}

To overcome this limitation, a noise-optimized VMI algorithm (VMI+ or Monoenergetic+) was developed for dual source DECT few years ago, which allows for obtaining a final image data set characterized by high contrast at the lowest noise possible.³⁰ This regional-spatial, frequency-split algorithm enables a separation of the reconstruction data at low and optimal keV settings and a further splitting of these bins into lower and high spatial frequency data sets. Afterwards, the lower spatial frequency data achieved at low keV and the high spatial frequency obtained at the optimal keV level are combined. As a consequence, images reconstructed with this noise-optimized VMI+ algorithm provide superior CNR and consequently improved subjective image quality compared to traditional VMI reconstructions, particularly in suboptimal contrast conditions, *e.g.* in vascular DECT with low iodine density.^{30,31}

CLINICAL APPLICATIONS

Abdominal

Liver

CT of the liver is often impaired by suboptimal contrast conditions and subsequently inferior lesion demarcation. The

Figure 1. A 71-year-old male patient with histologically proven liver metastasis from a neuroendocrine tumour of the small bowel. The standard linearly blended M_{0.6} image series (A) from dual source DECT shows sub-optimal visualization of the hypervascular lesion. The 50-keV VMI+ series (B) demonstrates an improved demarcation of the hypervascular liver metastasis with a diameter <1 cm (arrows). DECT, dual energy CT.

usefulness of VMI/VMI+ for DECT of the liver has been assessed in multiple recent studies.^{32–35} Regarding DECT of hypervascular liver lesions, Große Hokamp et al reported substantially improved objective and subjective image quality for dual layer DECT.³² Superior image quality as well as consequently higher accuracy for the detection of hypervascular liver lesions was also demonstrated by De Cecco et al for 50-keV VMI+ reconstructions from dual source DECT.³³ Shuman et al suggested the same energy level for standard VMI reconstructions to improve image quality and subjective lesion conspicuity of hypervascular focal liver lesions.³⁴ An example case is shown in Figure 1.

But image quality of hypoenhancing lesions can also be improved using VMI, as Sudarski et al reported improvement as well as increased diagnostic confidence for the detection of hepatic metastases for 70-keV VMI reconstructions from dual source DECT.³⁵ Caruso et al suggested that an energy level of 40 keV is optimal for depicting hypovascular liver lesions on VMI+.³⁶ Such 40-keV VMI+ reconstructions have also been used to better depict intrahepatic veins in case of poor contrast conditions.³¹ These prior studies also show that for both entities, the ideal keV level depends on the contrast enhancement phase (*e.g.* late arterial *vs* portal venous) and the entity which of interest (*e.g.* vessel *vs* focal lesion). In addition, optimized window settings are essential to maximize benefit from the increased iodine density from VMI/VMI+ reconstructions as De Cecco et al recommended W429L129 for arterial-phase 50-keV VMI+, and W376L147 for portal venous phase reconstructions.³⁷ In contrast, Caruso et al evaluated optimal window settings for VMI/VMI+ reconstructions from abdominal dual source DECT angiography and recommended W880/280 for 70-keV VMI and W1410L450 for VMI+ reconstructions.³⁸ Doerner et al suggested W628/286 for 70-keV VMI and W1516L667 for 40-keV VMI reconstructions from dual layer DECT angiography.³⁹ However, a semi-automatic

estimation of optimal window settings has also been suggested by Große Hokamp et al.⁴⁰

Large patient size represents a known limitation of DECT, particularly in imaging of the liver, as the potential improvement in terms of CNR and image quality of VMI may be reduced with larger patient size.^{27,41,42} On the other hand, a recent study performed using VMI+ showed improved image quality and less dependency on body mass index compared to standard VMI and linear blending algorithms for the detection of hypervascular liver lesions.⁴³

Pancreas

While high spatial resolution makes CT a crucial modality for imaging of pancreatic lesions, its low sensitivity for small (<2 cm) and isoattenuating lesions still represents a drawback, mainly due to suboptimal contrast conditions.^{44,45} VMI has been used to overcome these intrinsic limitations, utilizing the increase of vascular and parenchymal enhancement at low keV values.^{45,46} To help distinguish small pancreatic adenocarcinoma from normal parenchyma, McNamara et al observed the highest CNR using VMI at 52 keV over the conventional single energy data set.⁴⁷ However, optimal image quality was achieved at 70 keV in their study, due to the presence of significant noise at lower keV reconstructions. This led the authors to suggest the simultaneous evaluation of two VMI data sets in a clinical setting, at the cost of longer reporting times.⁴⁷

With the recent advent of VMI+, such limitations of image noise at low keV values have been minimized. Frellesen et al reported that VMI+ showed the best CNR at 40 keV, while the subjective impression of either small and hypovascular lesions of the pancreas (<2 cm) was rated best at 55 keV, together with optimal evaluation of organ infiltration and vascular involvement.⁴⁴

Similar results with the VMI+ algorithm at 55 keV were obtained for the routine evaluation of pancreatic parenchyma in various pathologic conditions, with better CNR values observed compared to linearly blended standard DECT images.⁴⁸

Kidney

DECT post-processing algorithms have been used to improve the imaging of solid and non-solid renal tumours.⁴⁹ In a direct comparison of VMI, VMI+ and linearly blended reconstructions performed on 52 patients with clear cell or papillary renal cell carcinoma, quantitative analysis showed the greatest SNR, CNR, and tumour-to-cortex ratios for VMI+ reconstructions at 40 keV, while there was a preference in terms of qualitative image quality for the VMI+ algorithm at 60 keV for the nephrogenic-phase and at 50 keV for the corticomedullary-phase, due to a better subjective image impression.⁵⁰ Patel et al performed a combined phantom and clinical study and reported that low-keV VMI+ reconstructions at 40–70 keV resulted in optimal renal lesion demarcation.⁵¹

Renal cyst pseudoenhancement remains a common issue in CT of the kidney and established Hounsfield unit thresholds to make a diagnosis have been questioned due to the impact of routinely applied iterative reconstruction algorithms and differences in scan protocols.⁵² Here, VMI reconstructions at an energy level of 80 keV (90 keV in obese patients) have been shown to minimize or even overcome renal cyst pseudoenhancement in both phantom and clinical studies while maintaining kidney contrast enhancement similar to standard CT acquisition.^{53–55}

Bowel

VMI may also be applied in an acute setting to detect early bowel ischaemia, as focal hypoenhancement may be missed initially due to suboptimal contrast conditions but could be improved using low-keV VMI. In an analysis of 72 patients with small-bowel obstruction, the VMI algorithm at 70 keV was almost twofold better than single energy CT in detecting the loss of bowel wall enhancement related to ischaemia.⁵⁶ VMI has also been assessed for the evaluation of small bowel lesions in Crohn's disease.⁵⁷ In these patients, the highest CNR for differentiating normal and pathological small bowel segments was obtained at 40 keV. However, because of the high image noise and therefore overall low image quality of the 40-keV VMI data set, the authors suggested to use this reconstruction as a complement to conventional polychromatic images, in order to improve the detection of bowel segments with active disease.⁵⁷ This is an example where noise-optimized VMI+ may be able to overcome said limitations by maximizing CNR at low keV levels. While this has not been assessed in published studies so far, attenuation of iodine-based oral contrast could also be increased using VMI/VMI+ reconstructions, and thus may allow for reduction of iodine concentration, also to reduce potential anaphylactoid reactions which have been described in the literature.⁵⁸

In oncological imaging of the bowel, similar results regarding the benefit of VMI algorithms have been reported, as a study performed in 21 patients affected by gastrointestinal stroma tumours compared VMI, VMI+ and conventional linearly blended DECT reconstructions.⁵⁹ In this analysis, VMI+

recorded the highest values in terms of CNR and SNR at an energy level of 40 keV. Regarding subjective image impression, VMI+ at 40–50 keV was considered better for tumour delineation, while VMI+ at 60 keV was scored the best in terms of overall image quality, and the most suitable for clinical use.⁵⁹

Pulmonary

DECT has maintained a longstanding role in imaging of different lung diseases, such as acute and chronic pulmonary embolism, chronic thromboembolic pulmonary hypertension, vascular abnormalities, parenchymal disease and malignancies as well as lung ventilation disorders (Xenon-based DECT).^{60–62}

VMI reconstructions at low energy levels can drastically increase vascular contrast, thereby allowing for a better morphological assessment of the vasculature in pulmonary embolism and thus also a reduction of contrast dose.⁶³ Several studies showed that the optimal energy level for VMI ranges between 50 and 70 keV, providing the best trade-off between low image noise and strong vascular attenuation.^{28,63} Noise-optimized VMI+ has further decreased this threshold to 40 keV, with a reported significant improvement in terms of CNR, diagnostic accuracy, and reduction of contrast material bolus size.^{5,64,65}

However, since the vascular attenuation is drastically increased with low-keV VMI/VMI+ reconstructions, an inappropriate application of window settings (width/level) may ultimately compromise image quality either. Accordingly, calculated optimal window values of W450L140 for standard VMI at 70 keV and of W1070L380 for VMI+ at 40 keV have been recently suggested to obtain optimal image impression in DECT pulmonary angiography.⁶⁶ However, a semiautomated estimation of optimal window settings for this purpose has also been suggested by Große Hokamp et al.⁶⁷

VMI+ has also been used to improve detection of incidental PE in oncologic patients, who usually undergo repeated single portal-venous phase follow-up CT. By reconstructing VMI+ images at an energy level of 40 keV, VMI+ demonstrated an improved objective image quality of the pulmonary vessels, which translated into a significantly higher diagnostic confidence in the diagnosis or exclusion of incidental PE.^{68,69} By generating an image impression comparable to dedicated CT pulmonary angiography, staging DECT examinations reconstructed with VMI+ showed similar diagnostic accuracy for the detection of incidental pulmonary embolism.⁶⁹ An example is shown in [Figure 2](#). In addition, DECT pulmonary angiography VMI+ series have been analyzed in combination with DECT perfusion maps, which showed a better diagnostic performance for the detection of pulmonary embolism than each technique alone.⁵

For imaging of lung cancer, traditional VMI series performed better than standard linearly blended images with superior image quality and better tumour demarcation.⁷⁰ In this setting, an energy level of 60 keV was considered optimal, concluding that lower energy levels were too impaired by noise artefacts. In a more recent study, the superiority of VMI+ over traditional VMI was confirmed as lower image noise and higher SNR resulted in

Figure 2. A 59-year-old male patient undergoing staging portal-venous-phase dual source DECT of the thorax due to a stage IIIa melanoma of the left lower leg. Sagittal reconstructions of standard DECT (A) and 40-keV VMI+ (B) show extensive pulmonary artery emboli (arrows) which were incidentally detected. Note that 40-keV VMI+ reconstructions demonstrate clearly improved embolus demarcation. DECT, dual energy CT.

superior CNR for imaging of lung cancer.⁷¹ However, while the highest CNR was obtained at 40 keV, the best subjective image quality was reported for an energy level of 55 keV, which is in line with other studies reporting a difference in optimal energy level for VMI+ of soft tissue tumours.⁷²

Cardiovascular

DECT is commonly performed in cardiac imaging as it can provide a comprehensive morphological assessment of the coronary vasculature as well as a functional evaluation of the myocardium, with comparable results with MRI and SPECT.^{73–78} However, artefacts induced by the presence of metallic stents, pacemaker wires, or extensive coronary or valvular calcifications, as well as a high concentration of contrast material in the right heart represent drawbacks that may impair evaluation of CT data sets. VMI/VMI+ algorithms have been recently used to overcome these limitations.⁴

Similar to other applications of vascular DECT, VMI allows for the administration of about the half of the amount of iodinated contrast medium that is usually injected during a single energy coronary CT angiography (CCTA), without compromising image quality.²³ Noise-optimized VMI+ algorithms have also been evaluated in combination with optimized contrast material administration protocols to improve vascular enhancement.⁷⁹ Traditional VMI in CCTA shows optimal vascular enhancement at 60 keV.²³ Similar to other vascular applications of VMI+, noise-optimized VMI+ shows optimal vascular enhancement at 40 keV.⁷⁹ This technique could also be applied to improve CT in the planning of transcatheter aortic valve replacement,^{80,81} to

reduce contrast material necessary as such patients often suffer from renal insufficiency.²⁴

At higher energy levels, VMI can play a problem-solving role in some of the limitations of CCTA such as reducing partial volume averaging, calcium blooming, beam hardening, metal or streak artefacts.^{82,83} In particular, DECT with VMI reconstructions at 80 keV have been shown to be useful to reliably assess the in-stent lumen in patients with coronary artery disease and stent implantation.⁸⁴ In a phantom study, Mangold et al reported best evaluation of in-stent lumen visibility at an even higher energy level of 130 keV.⁸⁵ However, for improved stent visualization for the detection of in-stent re-stenosis in lower extremity run-off DECT, they reported 80 keV to be the optimal energy level.⁸⁶ These findings emphasize that optimal energy levels may vary based on the body region and amount of surrounding soft tissue, but also showcase the flexibility of this technique. Interestingly, an energy level of 80 keV has been reported to improve display of late enhancement in DECT of chronic myocardial infarction,⁸⁷ while CT generally remains of limited value for this purpose due to limited resolution and contrast compared to MRI.^{74,88}

Similar to other vascular DECT applications, the majority of prior studies have reported an energy range of 40–70 keV to be optimal for reconstruction of VMI+ data sets in the evaluation of the thoracic and abdominal aorta.^{89–91} While CNR commonly peaks at 40 keV, VMI+ reconstructions at 70 keV are usually preferred in terms of subjective image quality. Similar results have also been demonstrated for cerebrovascular VMI+.⁹²

Figure 3. A 54-year-old male patient who had undergone prior bowel surgery and showed hypotension and low hemoglobin serum levels. A subtle arterial bleeding was initially missed on standard images from dual source DECT (A), but subsequently detected on 40-keV VMI+ series (B, *arrow*), thus facilitating planning of subsequent emergency embolization. Traditional 40-keV VMI series (C) are impaired by excessive image noise. DECT, dual energy CT.

This difference in optimal energy levels between objective and subjective evaluation may be explained by the excessive vascular contrast obtained with low-keV VMI+ reconstructions. However, this caveat is reversed in cases of suboptimal contrast conditions. For DECT angiography of the peripheral vasculature of the lower extremities, a superior diagnostic performance was observed for the detection of vascular stenoses with 40-keV VMI+ reconstructions.⁹³ Such energy levels had provided similar vascular enhancement but excessive image noise with the traditional VMI algorithm.²⁵ Mangold et al also found a superior detection rate of in-stent re-stenosis in lower extremity runoff DECT angiography.⁸⁶ An improved detection of venous thrombosis using 40-keV VMI+ reconstructions was also observed in a previous phantom study.⁹⁴ Again, adapted windowing values are essential in DECT angiography to improve subjective image impression.³⁸

Similar results were found in patients who underwent DECT angiography for the suspicion of abdominal haemorrhage. Martin et al reported an improved diagnostic accuracy using 40-keV VMI+ reconstructions for the detection of abdominal haemorrhage, which may often show only faint contrast

extravasation.⁹⁵ An example is shown in Figure 3. In another study evaluating this technique for the detection of endoleak following endovascular repair, 40-keV VMI+ series also showed improved detection rates⁹⁶ (Figure 4). Furthermore, a beneficial effect have also been reported to differentiate venous thrombosis from iodine flux artefacts.⁹⁷

Head & neck

Several advanced DECT techniques have been applied to imaging of the head and neck area in the past including iodine quantification, virtual non-contrast image reconstruction and bone removal in DECT angiography.⁹⁸ VMI techniques have also been extensively investigated for head and neck imaging since they allow for increasing both vascular and brain tissue contrast.^{99,100} An example is shown in Figure 5.

In particular, objective image quality indices SNR and CNR between grey and white cerebral matter in supratentorial brain parenchyma have shown higher values using VMI reconstructions at 65 keV rather than conventional single energy CT.¹⁰⁰

Figure 4. Dual source DECT angiography of a 68-year-old male patient one month following EVAR. Images were reconstructed with blended M_{0.5} (A), 70-keV VMI (B), and 40-keV VMI+ (C) algorithms. The endoleak (*arrow*) is best appreciated on the 40-keV VMI+ reconstructions and shows only subtle enhancement on standard DECT images. (Reprinted with permission by Martin et al.⁹⁶). DECT, dual energy CT; EVAR, endovascular aneurysm repair; VMI, virtual monoenergetic imaging.

Figure 5. A 71-year-old patient with severe stenosis of the right internal carotid artery undergoing dual source DECT angiography. In comparison with standard linearly blended M_{0.6} DECT series (A), 50-keV VMI+ series (B) show improved density of the iodinated contrast, allowing for improved evaluation of the lumen stenosis (arrows). DECT, dual energy CT.

The evaluation of the posterior fossa, which is often limited by beam-hardening and streak artefacts of the skull bones, showed less noise using VMI at an energy level of 75 keV.¹⁰⁰ High-keV VMI reconstructions can also help reduce beam-hardening artefacts arising from deep brain stimulating electrodes.¹⁰¹ Finally, a prior study demonstrated that dose reduction techniques can also be applied to DECT of the brain without a decrease in diagnostic performance for the detection of intracranial haemorrhage,¹⁰² establishing DECT as dose-neutral for imaging of the brain.

Similar to DECT in soft tissue tumours in other body areas,^{72,103} the VMI algorithm has also demonstrated its usefulness in the diagnosis of squamous cell carcinoma (SCC) of the head and neck area, due to substantially improved iodine attenuation at low energy levels.¹⁰⁴ In fact, at an energy level of 40 keV, even the traditional VMI algorithm has been demonstrated to provide the highest attenuation and best contrast of SCC lesions, resulting in an improved tumour delineation.^{105–107} However, the high level of noise at 40 keV led the authors to suggest an energy level of 60–65 keV as the best trade-off between image quality and noise for traditional VMI, while still showing better results than standard single energy CT images.^{106,107} Here, the development of VMI+ led to drastically higher CNR and improved image quality due to the reduction of noise at lower keV values. In a comparison with linear blending reconstruction, VMI+ at an energy level of 40 keV showed peak CNR values in a quantitative analysis performed in patients with head and neck SCC, while a level of 55 keV was subjectively preferred.⁶ Similar effects can be also observed for benign lesions such as inflammation or suspected abscess (Figure 6). Finally, a further improvement in delineation of laryngeal tumour extension was obtained using standard VMI reconstructions at slightly higher energy values (*i.e.* 95 keV), demonstrating the potential to better delineate the neoplastic tissue from non-ossified thyroid cartilage.¹⁰⁸

Musculoskeletal system

Various DECT applications have been successfully applied to musculoskeletal imaging utilizing the spectral separation of tissue components to allow for the diagnosis of gout,¹⁰⁹ detection of bone marrow oedema,^{110,111} analysis of bone mineral density,^{112,113} and evaluation of ligaments and tendons.¹¹⁴

While VMI algorithms are commonly applied to contrast-enhanced DECT to increase attenuation of soft-tissue masses (Figure 7), they have been mostly used in musculoskeletal DECT to reduce artefacts related to the presence of orthopaedic hardware.¹¹⁵ In fact, beam-hardening artefacts may depend on both scanning parameters—kVp, mAs, pitch, reconstruction technique—and implant type, material, size and orientation relative to the gantry.^{115,116} During the last decade, several phantom and clinical studies reported varying results regarding the optimal energy level for VMI reconstructions ranging between 105 and 150 keV.^{117–119} The amplitude of this range can be explained by the fact that these studies encompassed different types of orthopaedic devices in different parts of the human body.¹¹⁴ An example is shown in Figure 8.

At higher energy levels, VMI reconstructions may also allow for better evaluation of bone–prosthesis or bone–cement interfaces,¹²⁰ with a considerable reduction in terms of image noise, despite residual metal artefacts still being present. The use of a high tube voltage in single energy CT may also help reduce beam-hardening artefacts but impair the evaluation of adjacent soft tissues close to the implant. Here, this limitation could be overcome by calculating additional VMI data sets at varying energy levels, thus making DECT the more flexible imaging approach.

It should be noted that dedicated metal artefact-reduction algorithms by various vendors have mostly shown superior artefact-suppression performance in direct comparison with VMI

Figure 6. This 18-year-old female patient underwent dual source DECT due to suspected peritonsillar abscess. An unsuccessful biopsy was performed prior to the CT examination (punctio sicca) and clinicians were uncertain regarding the extent of inflammation and potential abscess formations. The inflammation in the enlarged peritonsillar region is hard to demarcate on standard DECT reconstructions (A), while a distinct delineation of the inflammation (*arrow*) can be seen on 40-keV VMI+ series (B) and no abscess is present. The benefit of increased contrast could not be exploited using the traditional VMI algorithm (C) due to a substantial noise increase. DECT, dual energy CT; VMI, virtual monoenergetic imaging.

reconstructions from DECT.^{121,122} In a recent study, Laukamp *et al* also reported that while both algorithms were effective, the dedicated algorithm showed superior results for evaluation of adjacent soft tissue while high-keV VMI reconstructions resulted in better assessment of bone.¹²³ However, these algorithms are also not free from drawbacks including supplementary artefacts or underestimation of size implants, and their performance is dependent on the type of prosthesis and body region imaged.^{114,121,124} Thus, VMI reconstructions may represent a simple, yet effective tool to reduce beam-hardening artefacts caused by metal implants in routine DECT, while dedicated

iterative algorithms may be useful in cases with more severe artefacts.

CONCLUSION

DECT has evolved into a commonly applied imaging technique in clinical routine due to its unique post-processing opportunities for improved evaluation of all body areas. Reconstruction of VMI series has shown beneficial effects for both non-contrast and contrast-enhanced DECT due to the flexibility to calculate low-keV VMI reconstructions to increase contrast and iodine attenuation, or to compute high-keV VMI reconstructions to

Figure 7. A 60-year-old male patient with a pancoast tumour which showed intraspinal tumour growth. Compared to standard dual layer DECT reconstructions (A), the subtle diffuse contrast enhancement of the intraspinal lesion (*arrows*) is maximized on 60-keV VMI (B) series. DECT, dual energy CT; VMI, virtual monoenergetic imaging.

Figure 8. Axial dual layer DECT image of a 68-year-old-female patient showing a total arthroplasty of the left hip. The resulting artefacts impair diagnostic assessment of the pelvic organs in conventional image reconstruction (*left*). In the 160/200 keV VMI series (middle/right), artefacts are clearly reduced improving overall image quality. Note that while nearly all hyperdense streaks are reduced in the VMI image, there is a remaining hypodense area adjacent to the left acetabule. DECT, dual energy CT.

reduce beam-hardening artefacts. In contrast-enhanced DECT, the advent of noise-optimized VMI+ reconstructions, currently limited to dual source DECT, has unlocked the before inaccessible potential of maximum contrast at low keV levels. Here, multiple studies have also shown that an improvement in image contrast also translates into a superior diagnostic performance in vascular DECT. Nevertheless, studies evaluating potential improvements in diagnostic accuracy remain scarce and are a topic of ongoing research. In addition, future applications of this technique include routinely applied substantial reductions of iodine load in contrast-enhanced DECT of up to 50% and combination with DECT-based iodine quantification to improve diagnosis.¹²⁴

Radiologists with DECT-capable systems should routinely apply these techniques as VMI/VMI+ can be automatically calculated and transferred to the PACS system, supporting the radiologist without requiring manual input. However, workflow modifications are commonly inevitable, especially since image impression may be counterintuitive at first, especially when appropriate window settings are not always applied. Other challenges are the topic of ongoing research as an universal consensus of optimal keV levels for VMI/VMI+ reconstructions is still missing and attenuation measurements are substantially altered similar to other post-processing techniques.

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