# Dual Energy CT

Scientific Evidence and Clinical Application
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Introduction

With the advent of Dual Source CT, spectral imaging or Dual Energy CT has become a viable option in clinical computed tomography. Meanwhile there is a whole variety of clinical applications which offer relevant additional diagnostic information or make the interpretation easier and faster.

Looking at all medical scientific literature in MedLine, there are about 200 articles on Dual Energy CT, about three quarters of which were published in the last three years. These studies mostly report new clinical applications of Dual Energy CT and their diagnostic value. Although the field is only emerging, the research activity is so extensive that it is getting difficult to keep an overview. Also, it may be difficult to estimate the actual clinical practicability and value, even if there are articles published on a certain technique or application.

Therefore, the purpose of this review is to provide an overview of all the relevant applications of Dual Energy CT reported so far and to give account of the actual value in clinical practice. The references contain direct links to the original articles in peer-reviewed literature.

The author of the Dual Energy review article

Thorsten R. C. Johnson, M.D.:

Using Dual Source CT from the start, Dr. Johnson is specialized in Dual Energy applications in research and clinical environment for both the first and the second generation of DSCT. Based on his knowledge and years of hands-on experience, he wrote this review about the state-of-the-art of science and clinical application of Dual Energy imaging. DSCT.com would like to thank him again for this great achievement.

About DSCT.com, the Dual Source CT community

DSCT.com is a non-commercial platform launched in 2007 for the exchange of scientific knowledge regarding the medical value of the latest innovations in computed tomography: Dual Source CT. The website represents an international community of medical experts, especially radiologists and cardiologists dedicated to research on DSCT, and provides a global discussion forum for medical experts to talk about its potential use in patient care. The website is run and operated by Spirit Link Medical, based in Erlangen, Germany, with Siemens AG as a partner.
Practical Technical Aspects

Scan protocols

The concept of Dual Source Dual Energy CT implies separating the spectrum into a high energy and a low energy part and to emit these two parts from different x-ray tubes [1]. This means that the dose should be the same as in a corresponding single energy exam.

Regarding normal CT protocols which require a certain contrast to noise ratio (CNR) as reference, there are two studies which have shown that DECT does work without additional dose and can provide equivalent CNR for a certain dose or even improve CNR with intelligent postprocessing [2-3]. With the first generation Dual Source CT, dose neutrality and cross scatter correction required compromises in collimation, i.e. to double the collimation in the trunk of the body to achieve the same dose efficiency per detector element as with single energy CT [4-5]. The reason was that in some areas of the body only such a small part of the 80 kVp spectrum was transmitted that the noise properties of the detector became relevant. With the second generation Dual Source CT, an additional filter of 0.1 mm tin has been integrated which improves the spectral separation. Now, it is possible to work with a filtered 140 kVp and a 100 kVp spectrum so that sufficient transmission is achieved even in large patients and with 0.6 mm collimation [6-7].

Another aspect that limited the routine clinical application in the first generation DSCT scanner was the field of view of the smaller detector which was limited to about 27 cm diameter and thus unable to cover the whole body of most patients. This implied some limitations in evaluating lesions of the liver, both kidneys, or peripheral parts of the lung [8-11]. With the second generation system, the smaller detector provides 33 cm diameter which is sufficient to cover the diameter of thorax and abdomen in most patients. If some subcutaneous adipose tissue is not covered with Dual Energy information, this is usually not of clinical relevance.

Postprocessing

Right from the start it was clear that Dual Energy CT would primarily need to provide normal CT images in order to allow routine clinical application. Therefore, the manufacturer implemented the generation of weighted average images from both Dual Energy datasets which utilize the full dose and provide optimal contrast to noise and spectral properties similar normal CT images obtained at 120 kVp [12]. Depending on the tube voltages and filters used for primary acquisition, this partially requires the application of a weighting factor. This factor can be altered, e.g. if iodine contrast is the main diagnostic feature of the CT protocol like in CT angiography [13-14].

Additionally, advanced algorithms can be applied to generate optimized images which intelligently integrate the advantages of both the high and the low energy acquisition in one image set. With a sigmoidal blending algorithm, both the high contrast of the low energy acquisition and the low noise of the high energy acquisition can be combined in one dataset [15-16]. With these techniques, the contrast to noise ratio can be significantly improved, which may even make it possible to reduce the dose in certain instances [16]. Also, the two acquired datasets can be used to either eliminate iodine-related density or to extrapolate to a dataset as if it had been acquired at much higher energy, e.g. 511 keV. These datasets may be used for an improved attenuation correction in PET-CT, rendering additional unenhanced low-dose CT or transmission scintigraphy dispensable [17-18].
Head and Neck

Figure 1 Volume rendered image of the brain vessels after Dual Energy bone removal.

In the head and neck area, the main application of Dual Energy so far is bone removal from CT angiography datasets [19]. With this technique, the superimposition of bone and vessels is resolved and three-dimensional postprocessing is possible like in MR angiography.

This is helpful to rapidly screen datasets for pathology without reading several hundred axial slices. The evaluation of vessels at the skull base profits most from the bone removal, because conventional reading usually requires cumbersome multiplanar reformats with adjustment of the window level, while the carotid siphon is easily evaluated at a glance without the bones [20]. Also, small aneurysms in the Circle of Willis are identified more easily in maximum intensity projections without bones [21]. Still, there are artificial truncations due to artifacts from dental fillings or due to blooming artifacts at dense atherosclerotic calcifications, so it is required to confirm findings on conventional multiplanar reformats.

Several studies have confirmed that this technique works reliably and much better than merely density-based software bone removal [21-25]. In comparison to subtraction techniques, the Dual Energy technique requires less dose because an unenhanced acquisition is not necessary [22], and is also much less sensitive to patient motion. While very strong iodine opacification of the vessel can make conventional assessment of the vessels difficult in the area of the skull base, the Dual Energy technique profits from strong enhancement [23]. In initial studies using 140 and 80 kVp spectra, the vessel integrity at the thoracic inlet and the segmentation of the vertebral arteries was partially unsatisfactory [22, 25]. With the second generation DSCT system and Sn140/100 kVp spectra, results significantly improved in these areas [26].

Another potential application of Dual Energy CT in the head is the differentiation of contrast material and hemorrhage. This is important if the hemorrhage is seen unexpectedly and an unenhanced scan had not been obtained. Then, it is feasible to subtract the iodine-related density in order to obtain a “virtual” non-contrast image. The small differences of white and grey matter in CT density make this task rather challenging, so the resultant virtual non-contrast image is not a full substitute for an unenhanced scan in the detection of subtle signs of early ischemia. However, two studies have confirmed that the technique is sufficient to differentiate contrast enhancement and hemorrhage [27-28].
Thoracic Imaging

Lung Perfusion

One of the most important applications of Dual Energy CT is the assessment of lung perfusion [29]. Actually, the technique is based on a static dataset representing the iodine distribution in the lungs, so there is no dynamic information. However, provided that the acquisition is obtained at a sensible delay after the arrival of the contrast material, the iodine map should closely match perfusion. Considering that dynamic CT acquisitions require considerable dose, this technique based on a single Dual Energy scan can provide an equivalent clinical information at comparatively low dose [2].

Initial animal studies had shown that the sensitivity for pulmonary embolism can be increased [30], also in correlation to scintigraphy [31]. Several studies in patients confirmed that the technique does identify perfusion defects due to pulmonary embolism [32-35], also in good agreement with scintigraphy [11]. The technique also works in children with appropriate protocol alterations [36]. Several studies reported problems in differentiating true perfusion defects from beam hardening artifacts which can occur in the presence of dense contrast material in the central veins and due to respiratory or cardiac motion [37-38]. However, optimized multiphase protocols can help to reduce these artifacts [39]. Apart from washing the contrast material out of the central veins with a saline chaser bolus, it is important to apply a rather long delay in order to allow the iodine to pass from the pulmonary arteries into the parenchyma. Also, true perfusion defects have a morphology which corresponds to pulmonary segmental anatomy and can therefore be distinguished from artifacts, most easily in coronal reconstructions [40]. Apart from the additional functional aspect of the perfusion information, it can also increase the sensitivity for pulmonary embolism by identifying small sub-segmental embolism which is not visible as a clot in the small artery but still detected as small peripheral perfusion defect [41].

Additionally, it is possible to highlight vessels which contain less iodine than others with a specific algorithm. Although this technique has only a moderate specificity in clinical application, it can be used as a tool to increase conspicuity and negative prediction [42]. Some authors also advocate the use of the low-energy dataset to increase iodine contrast and use less contrast material. However, this will be limited in large patients, and considering dose efficiency and image noise it would be advisable to apply only a low-energy spectrum if saving contrast material is the main aim [43].

Meanwhile, several clinical studies have looked into diagnostic benefits in specific pulmonary diseases. One aspect being investigated is the quantification of perfusion defects to assess the global severity and clinical relevance of pulmonary embolism, assuming that the limitation of blood oxygenation is of higher clinical importance than the clots in the vessels. Perfusion defect scoring systems have been introduced for this task and seem to correlate well with other clinical parameters like right ventricular diameter ratio [44]. Pulmonary hypertension is another field in which Dual Energy CT offers specific diagnostic benefits. If there are no changes in the pulmonary parenchyma like emphysema or fibrosis, the etiology of pulmonary hypertension mostly remains unclear or is classified as idiopathic in CT. With Dual Energy CT, an inhomogeneous perfusion with multiple peripheral defects can reveal previous or chronic recurrent pulmonary embolism as cause of pulmonary hypertension [45]. Also, Dual Energy perfusion imaging can help to assess the severity emphysema by quantifying the total perfusion [46] or to differentiate ground glass opacities of vascular and bronchoalveolar origin [47].
Lung Ventilation

While pulmonary perfusion imaging with iodinated contrast material meanwhile represents a routine application of Dual Energy CT, ventilation imaging requires the application of xenon gas as contrast material and is therefore rather intricate [48]. Considering that only moderate concentrations have to be breathed for a few seconds, the safety profile should be even better than reported for brain perfusion imaging. Still, close monitoring seems mandatory at the present state of knowledge.

Initial studies have confirmed that the visualization of xenon gas in the lungs as a surrogate for ventilation is technically feasible [49] and shows ventilation changes behind bronchial obstruction. Clinical studies in specific pulmonary diseases showed impaired regional ventilation in patients with bronchiolitis obliterans [50], ventilation defects in asthma patients [51] and dynamic ventilation changes in chronic obstructive pulmonary disease [52].

The combination of xenon based ventilation and iodine based perfusion imaging offers the perspective of a comprehensive one-stop-shop assessment of pulmonary anatomy and morphology, high-resolution structure of the parenchyma as well as ventilation and perfusion as most important functional parameters [53].

Pulmonary nodules

In the evaluation of pulmonary nodules, the assessment of iodine enhancement and the detection of calcifications can be improved with Dual Energy CT [54]. Benefits of the Dual Energy technique in comparison to repeated single energy acquisitions are the reduced dose and the simultaneous acquisition, so that there are no problems concerning respiratory position or partial volume effects which have considerable impact in small nodules with the surrounding air. It is essential to reliably identify calcifications and eliminate the corresponding voxels from the quantification of iodine enhancement, because the photo effect of calcium would be misinterpreted as iodine enhancement, i.e. a sign of malignancy would be quantified as degree of malignancy. A technical study on a single source CT system found variable results with influence of body size, anatomic region and nodule size [55]. However, a clinical study on a Dual Source CT system showed that the technique works well and a prediction of malignancy based on the assessment of calcifications and iodine enhancement is quite reliable [56].

Myocardial Perfusion

One of the most challenging applications of Dual Energy CT is the assessment of myocardial perfusion [57]. Due to the continuous rapid motion of the heart, the scan has to be gated or triggered like for coronary CT angiography. The aim is of course to assess the coronary arteries as well as myocardial perfusion in a single acquisition. With the first generation Dual Source CT scanner, this requires giving up some temporal resolution, so the two tubes and detectors perform simultaneous gated acquisitions at different tube voltages. This is problematic because the main benefit of Dual Source CT in cardiac imaging, the high temporal resolution and the resulting robustness in variable and high heart rates [58-61], is lost. Also, the photon output at 80 kVp is limited and hardly sufficient with half-scan segments in gated acquisitions, especially in large patients. The second generation Dual Source CT system offers two major advantages to resolve these issues:

1. A combination of projection data from dual energy acquisitions is feasible so that the high temporal resolution of 75 ms can be preserved.

2. The application of the tin filter on the high energy spectrum makes it possible to use 100 kVp as lower energy, resulting in sufficient transmission and projection data even in large patients.

Initial studies investigating the dose of Dual Energy coronary CTA on the first generation system showed a reduced dose in comparison to single energy acquisitions and, expectedly, some more motion artifacts [62]. Initial studies investigating the diagnostic value revealed a similarly high diagnostic accuracy for myocardial perfusion with reference to SPECT as for coronary CTA with reference to conventional angiography [63-66]. Its seems that the sensitivity of the perfusion analysis is somewhat limited but specificity is superior to coronary CTA, so it may to some degree decrease the problem with false-positive findings in cardiac CT. Studies additionally applying adenosine stress showed a good accuracy in the detection of reversible perfusion defects with reference to stress perfusion MRI [67]. These studies were performed on the first generation system, while trials evaluating the performance of the second generation Dual Source CT with its added functionality for cardiac Dual Energy imaging are still lacking.

Although the assessment of myocardial perfusion may seem the most promising application in cardiac imaging, there are also studies investigating the quantification of coronary artery iodine content as a marker for ischemia, showing a good diagnostic accuracy with...
reference to SPECT [68]. Approaches using Dual Energy CT to visualize late myocardial enhancement as a marker for scars showed only a limited diagnostic value in comparison to MRI [69]. Attempts to improve stent imaging by correcting beam hardening showed no advantages as blooming artifacts remain the main problem [70]. Another application of Dual Energy CT of the heart is the quantification of iron in thalassemia patients. The results of an initial clinical study confirmed the feasibility and good correlation to T2* quantification in MRI [71].
Liver Imaging

In abdominal imaging, iodine enhancement is the main diagnostic feature in the characterization of organ lesions, especially in the liver. Although a specific identification and quantification of the enhancement would be desirable, standard CT examination protocols mostly rely on one single venous phase to avoid the radiation exposure of multi-phase exams. With Dual Energy CT, it is feasible to identify iodine by its photo effect and to quantify the iodine-related density [72]. With this information, it is possible to subtract the iodine-related density from the CT image to generate a “virtual” non-contrast image from the same dataset. As the iodine related density is derived from the difference of two image datasets, the noise is doubled in this virtual non-contrast image. Although the image quality is therefore not exactly equivalent to a true pre-contrast acquisition, several studies confirmed that this virtual non-contrast image is sufficient to assess and quantify the enhancement of focal liver lesions [73-75]. The detection and quantification of iodine can also be used to assess vitality and monitor therapy response. For example, a study showed good results in evaluating liver lesions after radiofrequency ablation [76] Limitations with the first generation DSCT were the limited field of view and the high noise in the 80 kVp image deteriorating image quality in large patients [8]. These issues are largely resolved with the second generation system and its spectral filter and larger field of view, as previously mentioned.

Apart from providing virtual non-contrast images and quantifying the iodine content of lesions, Dual Energy CT can also increase the conspicuity of lesions. Two studies showed that the contrast of hypervascular lesions is increased in low energy images and that an optimal compromise between contrast and image noise can be found by altering the weighting factor for average image generation [77-78]. Sigmoidal blending algorithms may be the best option for this purpose, combining the high contrast of low energy acquisitions with the low noise of high energy acquisitions [16].

Biliary system

Regarding gall stones, a clinically relevant difference is the composition which mostly contains calcium, cholesterol or pigment. As cholesterol stones can be dissolved medically, this would imply a non-invasive treatment option, while other types of stones would have to be removed mechanically if symptomatic. In vitro experiments have confirmed that Dual Energy CT can reliably differentiate cholesterol from other stones [79-80]. However, there are previous single energy CT studies that showed that this differentiation is also feasible based normal single energy CT density [81-82]. Therefore, the specific advantage of Dual Energy CT in this application is not evident.

Other researchers describe the use of iodinated biliary contrast material for cholangiography. Here, optimized blending or specific depiction of iodine can improve the visualization of the biliary system [83]. Still, the poor tolerance of biliary contrast agents [84] and the availability of MRCP as alternative reserves this technique to special indications such as living donor examinations in the preparation of liver transplantation.

Kidney Imaging

In kidney imaging, the assessment of contrast enhancement in small lesions is the most important diagnostic feature in the detection of cancer. If there are multiple cysts, it can be quite difficult or cumbersome to evaluate each lesion individually. However, especially patients with autosomal dominant polycystic kidney disease bear an increased risk of developing cancer. Therefore, most kidney CT protocols comprise an unenhanced, a contrast-enhanced, and a late excretory phase. Thus, it is attractive to use Dual Energy CT to specifically assess the iodine content of kidney lesions and to reduce radiation dose and postprocessing effort at the same time. Similar to the algorithms quantifying enhancement in liver lesions, iodine can be color-coded and quantified in the kidneys to differentiate hyperattenuating structures, e.g. hemorrhagic cysts, from enhancing tumors. In an experimental study, the feasibility of differentiation of lesions containing contrast, protein, or blood was verified [85-86]. Clinical studies then confirmed the ability to distinguish hyperattenuating cysts from enhancing renal masses [87-88]. Further studies showed the advantages of the second generation DSCT with its tin filter and the large field of view. The former is necessary to obtain sufficient transmission and contrast to noise ratios at thin collimation in the abdomen; the latter is required in some patients to cover both kidneys entirely [89]. Recently, a study with histopathological correlation confirmed the ability of Dual Energy CT to predict the dignity of renal lesions [90].
Kidney Stone Differentiation

Figure 5 Color coding of kidney stones shows that the calculus in the right ureter consists of uric acid.

As iodine provides a very strong photoelectric effect, most clinical applications of Dual Energy CT are based on iodinated contrast material. However, the differentiation of kidney stones is a clinical application that is based on the spectral properties of the renal calculi themselves [91]. As Dual Energy CT requires a minimal dose that is higher than a low-dose single energy scan, quite a few institutions use a single energy low dose scan to detect any calculi and a second very short Dual Energy acquisition to cover just the stone [92]. This requires a physician to immediately screen the dataset for calculi while the patient is in the scanner, but works with least dose. Other institutions adopted an intermediate-dose protocol which uses less than a standard abdominal CT scan but more than a true single energy low dose scan [93].

The detailed knowledge of kidney stone composition can help to recognize the underlying disease and may in some instances guide therapy. Also, calculi consisting of uric acid can be dissolved by medication with Allopurinol and urine alkalization. Therefore, the post-processing algorithm is tailored to differentiate uric acid from other types of stones. Another component of interest is struvite, because it indicates a bacterial infection which may require treatment. However, there is a spectral overlap between calcium and struvite so that this differentiation is not always feasible [94], while the differentiation of uric acid is reliable both in vitro [95-97] and in vivo [98-99]. The tin filter of the second generation DSCT improves the results in tiny calculi or large patients [100].

Apart from differentiating renal stones, Dual Energy CT is also used to identify calculi in contrast-enhanced urinary systems [101-102]. The detection of small stones below 3 mm diameter is limited due to volume averaging [103]. However, acute renal congestion represents a contraindication for the administration of iodinated contrast material as rupture of renal calices can be the consequence. Therefore, an unenhanced scan is acquired first at most institutions, and calculi can be differentiated or excluded before contrast material is administered.

Adrenal glands

Dual Energy CT can also be used to characterize adrenal nodules [88]. A clinical study showed 50% sensitivity and 100% specificity in the differentiation of adenomas from metastases based on the differences in density in an unenhanced sequential Dual Energy acquisition [104]. Thus, MRI with opposed phase imaging and CT protocols including an early and delayed phase after contrast enhancement remain the reference standard in the differentiation of adrenal lesions. An algorithm relying on the identification of fat content in Dual Energy CT may be a further option but has not yet been investigated.

Pancreas

Figure 6 Color coded iodine image of the pancreas confirms absence of enhancement in a cystic lesion.

Similar to liver and kidney imaging, contrast enhancement plays the most important role in the detection and evaluation of pancreatic masses. By specifically color-coding iodine, Dual Energy CT can help to differentiate between normal and abnormal parenchyma [88, 105] or to confirm the absence of contrast enhancement in cystic lesions. A study in 15 patients with adenocarcinoma showed improved lesion conspicuity in the low energy images in portal venous phase.

Colon

Virtual colonoscopy is performed for screening for colorectal cancer in large trials. In this setting, the CT scan is performed at comparatively low dose and without intravenous contrast material. However, it is generally required to acquire two scans, one in supine and one in prone position, to evaluate the bowel wall in the area of remaining fluid levels. Also, virtual colonoscopy still requires complete cleansing prior
to the examination, partially combined with "fecal tagging", i.e. the administration of iodinated contrast material to opacify the residual fluid. An approach with Dual Energy CT would be to eliminate iodine-containing voxels from the dataset based on the spectral information [10, 106]. Then, residual fluid is removed, so that a supine acquisition would be sufficient. If this "spectral cleansing" is sufficient, it may be enough to have the patient drink iodinated contrast material with his meals but not actually cleanse the intestine. However, detailed large clinical studies with this technique will be required to confirm an equivalent diagnostic value as with "conventional" virtual colonoscopy.

Aorta

Figure 7 Color coding of iodine and calcium confirms an endoleak in the thrombosed lumen of the aorta after endovascular repair.

Aortic imaging is generally performed with high injection rates of contrast material to achieve a strong opacification. With Dual Energy CT, the influence of the low energy acquisition on the image contrast can be increased, either by sigmoidal blending, by changing the weighting factor of average images, or by reading the low energy images. Then, the amount and injection rate of contrast can be decreased, still achieving an equivalent contrast to noise ratio [107].

Another application is the differentiation of calcium and contrast material, which can occasionally be quite difficult in the thrombosed lumen after endovascular aortic repair [108]. Several studies have shown that Dual Energy CT can help to differentiate calcifications from endoleaks [109-113]. However, most of these clinical studies applied a quantitative algorithm to color-code the degree of enhancement. Instead, there are other algorithms which aim to differentiate between calcium and iodine by their photoelectric effect and assign a different color to both (e.g. the "hardplaques" algorithm), and these should be preferred for this purpose.

Plaque Imaging

Figure 8 Plaque differentiation based on Dual Energy information in a human aortic specimen shows cholesterol signal in some voxels in the center of large plaques.

Plaque imaging has been a challenging area of CT research, and it seems conceivable that Dual Energy CT may improve the differentiation of atherosclerotic plaque components. However, even aortic plaques are generally only represented by a few voxels in the dataset, and these voxels rarely consist of one single component. On the other hand, lipid and calcium as the main components have such a high and low CT density that Dual Energy techniques are not required to evaluate these plaque components. Thus, the aim would be to differentiate mid-density components such as fibrous tissue or thrombus.

So far, there is little scientific evidence on Dual Energy plaque imaging. Initial trials showed potential for an improved plaque differentiation [114-115] but note that translation into clinical application requires further developments. However, there are algorithms that aim to differentiate between contrast-opacified lumen of the vessel and hard plaques based on the spectral properties of iodine and calcium. These algorithms work well and identify the interface between calcified plaque and lumen quite precisely. This technique is especially helpful after endovascular aortic repair as it color-codes calcium and iodine differently so that calcifications in the thrombosed part of the lumen can be differentiated from endoleaks [108]. Studies aiming to apply Dual Energy techniques to differentiate soft plaque components of human atherosclerotic plaque did not yield convincing advantages so far [116-117].
Extremities

Peripheral Arteries

Figure 9 A maximum intensity projection shows multiple occlusions and collaterals in the entire vasculature of the legs.

Similar to the arteries of head and neck, it is feasible to differentiate bone and arteries in runoff angiography datasets and display the vasculature without superimposition of bones. Studies have confirmed that Dual Energy based bone removal is more reliable and faster than conventional, software based bone removal [118-122].

The resulting maximum intensity projections provide an excellent overview of the entire vasculature of abdomen, pelvis, and the entire legs in one single image. Additionally, the software implemented in Dual Source systems provides the option to add calcified plaques back into the MIP image. Thus, the plaques can be switched on and off in order to visualize both the residual lumen and the plaque burden in the area of a stenosis. These images are very helpful for communicating the angiographic findings, e.g. to vascular surgeons.

The algorithm further contains a beam hardening correction that aims to identify the interface between plaque and vessel lumen more exactly, and studies have shown that the residual lumen is quantified more precisely with this technique [123]. Further studies have confirmed the efficacy of plaque removal but also showed limitations in small diameters and low enhancement of calcified crural arteries [124]. Therefore, in our experience the combination of runoff angiography in Dual Energy technique and an additional dynamic acquisition of the lower legs with a second small bolus of contrast material provide the best option to clarify the situation in critical limb ischemia.

Tendons and Ligaments

Initial experiments had shown that tendons and ligaments can be identified in a Dual Energy dataset due to their weak spectral properties in comparison to other tissue with similar CT density [125-126]. This would be an attractive option to evaluate tendons and ligaments along with the bones, e.g. in joint evaluation after trauma. There have been some reports on successful clinical application of this technique [127-128]. However, the contrast to noise ratio is very weak, so that there is considerable noise in the surrounding tissue and the signal in the tendon itself is not always continuous, depending on the adjacent bony structures and the resulting beam hardening. Therefore, the diagnostic value in clinical practice is quite limited and certainly no competition to MRI [129].

Figure 10 Tendons of the ankle are visualized well. However, the ligaments which are of diagnostic importance are too thin to visualize with this technique.
Gout

Initial reports had shown that it is not only possible to identify uric acid in kidney stones, but also in the soft tissue around joints as morphological substrate of gout [130]. The method proved to be very helpful in clinical practice as it confirms the diagnosis without joint fluid aspiration and additionally shows the extent of gout tophi and any affection of the adjacent joint [131-136].

Bone Marrow Edema

Bone marrow edema is a very sensitive sign for any pathological process in bones in MRI. Similarly, Dual energy CT can identify water in the bone marrow and thus identify bone bruises which are normally not visible in spongy bone in CT. Initial reports confirmed the feasibility and very good agreement with MRI [137].

Metal Artifact Reduction

Metal artifacts pose a significant problem in clinical CT. Especially after implantation of any metallic prostheses or other hardware, the implant itself, the interface between implant and bone, and the surrounding tissue are most important to exclude a fracture of the hardware, loosening, infection, or hematoma. However, metal artifacts severely impair image quality, often rendering it impossible to answer the relevant diagnostic questions.

Metal artifacts consist of photon starvation and beam hardening. The former results in lack of transmission and can only be reduced by increasing the energy and amount of photons. The latter can be corrected based on Dual Energy information, because there is a difference in beam hardening between the low and high energy acquisition; thus it is feasible to extrapolate an image with the beam hardening properties at very high photon energies. Initial own studies confirmed that a significant reduction of metal artifacts is feasible with this technique. In contrast to other Dual Energy protocols, we applied a higher current on the filtered high energy tube in order to increase the share of high energy photons [138]. Further research will be required to determine the optimal tube current relation.
**Current Application in Routine Clinical Practice**

Many Dual Energy CT protocols provide important diagnostic information and have not only been validated in scientific studies but also found widespread clinical application. These protocols have been implemented as standard settings in clinical routine and replaced single energy protocols for many applications. On the other hand, a few protocols lack evidence or do not provide sufficient clinical benefits to warrant general routine use.

Among the ones that have fundamentally changed the clinical diagnostic workup is the **Dual Energy CT pulmonary angiography protocol**. The simultaneous evaluation of pulmonary arteries and perfusion of the parenchyma increases the sensitivity for pulmonary embolism and provides additional pathophysiological information. Therefore, at our site, the exam is routinely acquired in Dual Energy technique and color-coded MPRs are always generated to visualize lung perfusion.

Another exam that is routinely performed in Dual Energy technique is the **angiography of the runoff arteries**. After Dual Energy bone removal, the MIPs provide an excellent overview of the entire vasculature and can save precious loading and reading time.

Regarding kidney imaging, there are two routine protocols in Dual Energy technique: Unenhanced low dose scans for the detection of **kidney stones** provide expedite stone characterization. The protocol for **kidney tumor assessment** contains a dual energy acquisition in venous phase and a low dose low kV acquisition in excretory phase. Thus, a pre-contrast scan can be omitted, reducing the overall radiation dose by about a third. Especially in the evaluation of polycystic kidneys, we appreciate the direct visualization of contrast enhancement and the easy differentiation from hemorrhagic cysts.

**Metal artifact reduction** also achieved such a good clinical performance that it was immediately implemented into routine protocols. Instead of high kV-imaging, we routinely reconstruct monoenergetic high energy images in which metal artifacts are significantly reduced.

Among the applications that have **not** achieved a role in routine clinical care is the **differentiation of tendons and ligaments**. Although the simultaneous evaluation for fractures and torn ligaments would make sense from a clinical perspective, the contrast to noise ratio is just too weak to make reliable diagnoses.

Also, **cardiac imaging** is routinely still performed as single energy exam, mostly as Flash Dual Spiral acquisition, because this protocol offers coronary CTA at unbeatably low dose. The simultaneous evaluation for coronary artery stenoses and myocardial ischemia would be desirable but imply a relevant dose penalty, and regarding the fact that coronary CTA should generally be used to rule out significant disease, myocardial perfusion is not of primary interest.

**Lung ventilation** imaging is also not routinely performed in daily practice, because xenon gas administration still represents an off-label use. There are large trials confirming the safety of xenon gas application at higher concentrations and for longer times in brain perfusion imaging, so this is not a major concern. As soon as sufficient study data is available to confirm the diagnostic value, ventilation imaging with a xenon respirator may be implemented as routine exam.
Outlook

Within some four years, Dual Energy CT has achieved a significant role in clinical CT imaging. The method works largely without additional dose and provides significant additional diagnostic information. Given the specificity and functional aspect of this information, CT is gaining value in disease characterization beyond mere morphological assessment. In some aspects like multi-phase exams, Dual Energy CT can help to reduce the radiation exposure. Also, it can replace some exams such as lung ventilation and perfusion scintigraphy and avoid the associated dose.

In future, new x-ray sources with narrower spectra or energy resolving detectors may increase the contrast to noise ratio or make the differentiation of several atoms feasible. This would further increase the number of protocols in actual clinical application and could greatly improve sensitivity and specificity e.g. in oncological imaging.

I hope that this review provides a comprehensive overview of the clinical value and current state of knowledge for radiologists interested in this new modality. For further background and detailed protocols and settings I can recommend our textbook ‘Dual Energy CT in Clinical Practice’ which recently appeared.
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