Dual-Energy Heart CT

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Dual-energy CT (DECT) scanners acquire two sets of data with different energy levels for each voxel and create two sets of images independently for each energy, similarly to single-energy CT (SECT).

Keywords: dual-energy CT ; heart ; coronary arteries ; spectral computed tomography

1. Diagnostic Capabilities of DECT

All types of dual-energy CT scanners, regardless of their technical concept, have similar capacities and do not have some of the single-energy CT limitations related to scanning with one polychromatic beam of X-ray. Moreover, DECT scanners have some unique functions that are not available in traditional devices.

1.1. Virtual Monoenergetic Images (VMIs)

DECT scanners can reconstruct images representing the attenuation of single-energy X-ray photons in each voxel, which are called virtual monoenergetic images (VMIs), while SECT images represent the attenuation of an entire spectrum of emitted photons [1]. The polychromatic nature of X-ray beams is a source of many limitations and artifacts of SECT, which are not present or are significantly reduced in VMIs. VMIs can be image- and projection-based depending on the type of scanner [2]. Image-based VMIs are created by bending images obtained with different kVp in different proportions in order to obtain VMIs with specific keV. Projection-based VMIs are created from maps of two substance concentrations. Most commonly used is the pairing of iodine and water, which is generated from raw data obtained from the same location of the X-ray lamp but with different kVp, and then VMIs are reconstructed from these maps [3]. Projection-based VMIs are more effective in reducing the beam-hardening artifact than image-based ones [2][4].

Depending on the energy level of the VMI, the same tissue has different densities and contrast enhancements. The lower-energy VMIs are more sensitive to iodine [5][6][7]. The closer the energy of the VMI to the K-edge value of iodine (K = 33.2 keV), the more sensitive to iodine the image is. This condition is true for every substance, which is a great opportunity to create new contrast materials [8][9]. If the K-edge value is significantly different for two substances, they can be virtually separated from each other, such as the case for iodine from carbon, oxygen or nitrogen—organic tissues. This is the principle of virtual noncontrast (VNC) imaging [5].

1.2. Material Specific Images and Virtual Noncontrast Images (VNC)

Each substance has its own unique profile of absorption of X-rays with specific energy. Using images obtained with two different energies, we can calculate the concentration of any substance with the known attenuation curve [1]. This is possible thanks to the photoelectric effect, which is Z-number dependent [10]. Due to this relation, DECT scanners can create images coded with concentrations of certain substances instead of X-ray attenuation in voxels; another way of using these data is to remove specific substances from an image, e.g., iodine or calcium. By removing iodine, we can obtain an image very similar to a noncontrast image—they are called virtual noncontrast (VNC) images [3][5][11]. It has been proved by several authors that VNC images can successfully replace noncontrast scans in the case of cardiac examinations and the examination of other anatomical regions [2][8][12][13]. However, this technology has some limitations and cannot completely remove the attenuation from highly concentrated contrasts, e.g., in the SVC and artifacts associated with it [14].

1.3. Effective Atomic Number Images

Having two sets of X-ray attenuation values for each voxel allows one to determine the composition of tissue by calculating the effective atomic number ($Z_{effective}$). This is the average atomic number of all atoms in the voxel. These values can be displayed as a grayscale image or as color overlay on top of standard image, or as a VMI [12]. The effective

Z number image can be used to differentiate two highly hyperdense structures, e.g., iodine in the lumen of the artery and calcification in its walls [2].

2. Impact of DECT on Workflow in Radiology Department

Dual-energy CT has greater diagnostic capabilities than SECT. Each type of scanner has its own unique advantages, disadvantages and limitations. When planning to purchase such a device, one should take into consideration what kind of examinations will mainly be performed on that scanner. If other types of examinations will also be performed, the main areas of diagnostic and scientific interest of the specific department have to be considered.

Besides the technical ability to perform the dual-energy examination, the knowledge of how to interpret them is even more important. Training in the interpretation of dual-energy examinations by radiologists is time-consuming, and to be cost-effective, close cooperation of the radiologist and radiographer is required.

In every type of DECT, except the multi-layer detector, it is necessary to plan specific examinations to be dual-energy, which requires some work planning and patient selection. It is possible to perform every examination as a dual-energy examination, but in some cases there will be no useful information and patients will be exposed to an additional dose of radiation. Every institution working with a DECT scanner has to develop its own way of organizing work with this type of machine. In our department, we select patients for DECT examination if the referral suggests pathologies that can be better assessed in that mode or if previous examinations were inconclusive.

Due to their complexity, DECT scanners are more expensive than SECT ones, so the installation of them should be thoroughly thought out.

3. Limitations of DECT

Dual-energy CT has many advantages over SECT, so why it is not wildly used? The main reason is probably the lack of radiologists' and hospital ménages' knowledge about its capabilities. Moreover, complicated, often unintuitive and expensive software necessary to fully use the potential of this technology is required. Dual-energy scanners are about 25% more expensive to buy and operate than single-energy devices of similar class due to the highly complex elements produced exclusively for them, which increases their cost due to their small quantity. Furthermore, DECT, as with every imaging modality, has some limitations strongly connected with the type of scanner. The rapid-kVp-switching DECT is prone to a motion artifact due to inferior temporal resolution, but they offer good energy separation and projection-based VMI reconstruction. Twin-beam, dual-source and sequential DECT scanners have better temporal resolution but come with the price of delayed registration of a second energy dataset and the possible miscalculation of VMIs. Sandwich detector scanners allow for the simultaneous registration of both energy datasets but are at risk of artifacts due to the misregistration of photons by the wrong layer of the detector.

4. The Future of Heart DECT

The current applications of DECT in heart diagnostics are presented in **Table 1**, and the most important studies comparing DECT with other modalities are presented in **Table 2**, which determines their sensitivity and specificity. Researchers are continuously looking for new applications for DECT in many fields, including the heart. There are several papers that describe the ability of DECT to estimate extracellular volume (ECV), which is helpful in diagnostics of cardiomyopathies. Until recently, only CMR was able to measure ECV. There are some discrepancies in the formulas used to calculate ECV depending on the type (image- or projection-based) of scanner [15][16]. The accuracy of this method has been proved in comparison with CMR and histological sampling [15][17]. DECT is the only one-stop imaging modality that allows one to assess ECV and the coronary arteries simultaneously, as well as simultaneously assessing perfusion, coronary arteries and plaque to predict their stability. This wide range of information that can be obtained during one examination is beyond the reach of invasive coronarography. It has been proved in many trails, e.g., the SCOT-HEART trail, that using CTA is cost-effective in the care of patients with stable chest pain and it reduces the risk of cardiac death [18]. Adding DECT capabilities may only improve the detection rate of hemodynamically significant stenosis.

Table 1. Summary of DECT advantages and its current uses in clinical situations.

Technique	Benefits	Clinical Application
Low-energy virtual monoenergetic images	**Higher sensitivity for iodine.**	• Salvage of suboptimal contrast study. • Reduction in contrast dose. • Every contrast CT can have CT angiography quality. • Detection of pulmonary embolism during coronary CTA.
High-energy virtual monoenergetic images	**Reduction in beam-hardening and metal-related artifacts.** **Reduction in calcium blooming artifacts.**	• Better visualization of stents lumen. • Better visualization of heavily calcified vessels. • Reduction in artifacts from IDC electrodes, valve prosthesis.
68–70 keV virtual monoenergetic images	**Best CNR virtual monoenergetic images for angiographic studies.**	• Increased quality of any angiographic CT.
Iodine map	**Better sensitivity for iodine.**	• Myocardial perfusion defects. • Better detection of late contrast enhancement in inflammation. • Differentiating thrombus from tumor or contrast flow artifacts. • Detection of pulmonary embolism during coronary CTA.
Virtual unenhanced images	**Reduction in radiation dose.** **Reduction in time of examination.**	• Calcium scoring performed from angiographic phase. • Characteristic of incidental findings in angiographic phase, e.g., adrenal glands tumor.
Material decomposition	**Identification of tissue composition.**	• Differentiation of hyperdense structures. • Better separation of iodine from calcium. • Plaque characterization.

IDC, implanted cardiac device; CTA, computed tomography angiography; CNR, contrast noise ratio.

Table 2. Summary of sensitivity, specificity, positive predicting value (PPV), negative predictive value (NPV) and significant details of citated original study comparing DECT with other modalities. n/a—not available.

Author	Type of Scanner	Number of Analyzed Patients	Date of Publication	Application	Modality Used as Reference Standard	Sensitivity	Specificity	PPV	NPV
Yunaga et al. [19]	rapid-kVp-switching DECT	67	2017	Assessment of heavily calcified segments of coronary arteries using VMI	Invasive coronarography	91.30%	70.60%	55.80%	95.20%
Yunaga et al. [19]	rapid-kVp-switching DECT	67	2017	Assessment of heavily calcified segments of coronary arteries using material density image	Invasive coronarography	88.40%	88.20%	75.30%	94.90%
Obaid et al. [20]	DSCT	20	2014	Plaque composition	VH-IVUS and histopathology	64%	98%	95%	83%
Nakajima et al. [21]	rapid-kVp-switching DECT	18	2017	Using effective atomic number (EAN) to classify non-calcified coronary plaques	IVUS	90% For cutoff EAN = 9.3	87% For cutoff EAN = 9.3	n/a	n/a
Delgado et al. [22]	DSCT	56	2013	Adenosine stress static myocardial perfusion	MRI	76%	99%	89%	98%
Delgado et al. [22]	DSCT	56	2013	Ischemia detection—late enhancement	MRI	64%	99%	82%	99%
Ko et al. [23]	DSCT	41	2010	Adenosine stress perfusion	MRI	89%	78%	n/a	n/a
Ko et al. [24]	DSCT	45	2011	Dual-energy, static, stress perfusion + CTA in detecting significant stenosis	Invasive coronarography	93.20%	85.50%	88.30%	91.40%
Weininger et al. [25]	DSCT	20	2010	Dual-energy dynamic perfusion + delayed enhancement in detection perfusion defects	MRI	93%	99%	92%	96%
Weininger et al. [25]	DSCT	20	2010	Dual-energy dynamic perfusion + delayed enhancement in detection perfusion defects	SPECT	94%	98%	92%	94%
Ruiz-Muñoz et al. [26]	rapid-kVp-switching DECT	84	2021	static stress CTP dual-energy vs. single-energy	SPECT + Invasive coronarography	87%	99%	93%	98%

Author	Type of Scanner	Number of Analyzed Patients	Date of Publication	Application	Modality Used as Reference Standard	Sensitivity	Specificity	PPV	NPV
Bouleti et al. [27]	rapid-kVp-switching DECT	20	2017	Use of delayed enhancement in detection of myocardial infarction	MRI	100%	99%	94%	95%
Yasutoshi et al. [28]	rapid-kVp-switching DECT	44	2018	Usage of delayed enhancement in myocardial scare classification	MRI	92%	98%	n/a	n/a
Matsuda et al. [29]	DSCT	19	2015	Assessment of late enhancement with denoise filter in assessment of myocardial scare	MRI	81%	96%	81%	96%
Hur et al. [30]	rapid-kVp-switching DECT	32	2012	Differentiation between thrombus and circulatory stasis in LAA	TEE	97%	100%	100%	97%
Hong et al. [31]	rapid-kVp-switching DECT	55	2014	Differentiation between thrombus and myxoma	TTE	94%	100%	n/a	n/a
Hong et al. [32]	rapid-kVp-switching DECT	28	2018	Differentiation between thrombus and tumor	MRI	66.70%	79%	n/a	n/a
Yang et al. [33]	rapid-kVp-switching DECT	84	2017	Differentiating metastatic and non-metastatic lymph nodes in NSCL	Histopathology	88.20%	88.40%	85.80%	90.40%
Zhang et al. [34]	rapid-kVp-switching DECT	63	2016	Differentiation between malignant and benign solitary pulmonary nodules	Histopathology	93.80%	85.70%	n/a	n/a
Ruzsics et al. [35]	DSCT	36	2009	Assessment of coronary artery stenosis and of the myocardial blood supply	SPECT + Invasive coronarography	92%	93%	n/a	n/a

MRI, magnetic resonance imaging; NSCL, non small cell lung carcinoma; SPECT, single photon emission computed tomography; TEE, transesophageal echocardiogram; TTE, transthorakale echokardiographie; DSCT, dual-source computed tomography; VH-IVUS, virtual histology intravascular ultrasound; CTP, computed tomography perfusion; CTA, computed tomography angiography; LAA, left atrial appendage.

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