

Application of dual-energy computed tomography in neuroradiology — a review of literature

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Abstract: Imaging diagnostics, supported by advances in medical equipment and software, is a dynamically evolving field of medicine. Methods that improve the precision of disease detection are currently in high demand. This paper discusses spectral computed tomography (CT), specifically dual-energy computed tomography (DECT), which is a modern and advanced imaging technique offering significant advantages over conventional single-energy CT (SECT). DECT provides additional diagnostic information and reduces the effective dose of ionizing radiation to the patient. A key benefit of DECT is its ability to reduce image artifacts compared to SECT. The article explains the operating principles of DECT and reviews its clinical indications, with a focus on neuroradiology. Special attention is given to the differentiation of intracranial hemorrhage from calcifications and distinguishing fresh blood from iodinated contrast media — especially in overlapping areas — through the interpretation of base pair images. DECT also plays an important role in evaluating the progression of intracerebral hematomas and detecting the “spot sign” in CT angiography (CTA) of the brain. Another application is in imaging the vascular system of the head and neck using DECTA, where bone removal and virtual non-contrast image reconstruction are particularly useful. The final section of the paper addresses artifact reduction methods in neuroradiology and outlines the key advantages and limitations of DECT in clinical practice.

Keywords: spectral computed tomography, dual-energy computed tomography, DECT, neuroradiology, DECT angiography.

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Introduction

Computed tomography (CT) is the method of choice in the initial neuroradiological diagnostics of patients due to the speed of acquisition, availability of the examination and relative affordability. The technological progress of multi-row CT devices over the last decades has led to the development of



a new method based on not one, as before, but two radiation energies. The additionally collected data constitute valuable diagnostic information, which allows, among other things, for material characterization, bone subtraction, creation of virtual monochromatic images and reduction of radiation beam hardening artifacts. The above new possibilities have strengthened the clinical usefulness of conventional single-energy computed tomography (SECT) and demonstrated its additional diagnostic value in neuroimaging. With the increasing availability of dual-energy devices, the usefulness of secondary image processing options has increased, which are particularly helpful in increasing the diagnostic accuracy of various neurological pathologies. The aim of this article is to present the basics of dual-energy computed tomography (DECT), new possibilities of secondary processing, artifact reduction, and above all, new diagnostic possibilities in neuroradiology.

Technical basics of DECT

In conventional CT scan, an X-ray beam is created in an X-ray tube by heating the filaments of the cathode filament and emitting an electron cloud. Then, a voltage of between 100 and 140 kV is applied between the cathode and the anode, which causes the electrons to move towards the anode. As a result of the collision of electrons with the anode surface, thermal energy and photons with the X-ray wave frequency are emitted. This creates a single polychromatic X-ray beam, the peak voltage of which is defined in kilovolts at the peak (kVp) and depends on the voltage applied between the cathode and the anode. The most commonly used voltage is 120 kVp.

CT is based on measuring the value of X-ray attenuation by individual tissues. Each of them has its own X-ray attenuation coefficient, depending on its density and atomic number. During acquisition, the radiation beam passes through the tissues multiple times at different angles in individual layers. The beam is then partially absorbed and dispersed, while the remaining part falls on detectors that count the photons of radiation hitting them, thus obtaining information about the linear value of radiation attenuation (μ). In the image reconstruction process, each voxel (i.e. the smallest three-dimensional image element) is assigned a numerical value in Hounsfield units (HUs), proportional to the degree of X-ray attenuation by tissues, measured within this voxel, taking the value of water X-ray attenuation as a reference point [1].

When a single X-ray beam is used, it is linearly attenuated by the tissues and structures in the examined object. However, this attenuation value for a given voxel is averaged — dependent on all the substances in it, their density and the energy of photons that interact with them. Therefore, in SECT images, tissues and materials of different chemical composition but with similar values of linear radiation attenuation are assigned the same values in HUs and it is difficult to distinguish them [2]. The solution to this problem is obtained in DECT, also known as spectral tomography. In the case of this method, information is obtained on the attenuation by tissues of two radiation beams (or their spectrum) of different energy. There are several methods for obtaining different values of radiation energy in a CT scan: performing separate scans with beams of different peak voltage on the tube, using two radiation sources (two independent X-ray tubes), very fast switching of the voltage value on the X-ray tube during the scan, using detectors with two layers with maximum sensitivity adjusted to photons of different energy [3]. Individual tissues and structures show differences in X-ray attenuation depending on the value of its energy. The basis of this phenomenon is the photoelectric effect and the Compton phenomenon [4, 5]. The Compton phenomenon, i.e. photon scattering, occurs mainly in atoms of elements with a low atomic number and at high radiation energy (120–140 kVp). The photoelectric effect is mainly responsible for the

absorption of photons and the probability of its occurrence is higher for quanta of lower energy (80–100 kVp) and during interactions with elements with a high atomic number. When the energy of a photon of radiation is greater than the binding energy of an electron on the shell closest to the atomic nucleus (the K shell) in the atoms of a given material, then the attenuation of radiation increases significantly, which is called the K-edge. This knowledge can be used by knowing the elemental composition of tissues and substances. The photoelectric effect will occur mainly in the interaction of lower-energy radiation with tissues containing, for example, a significant amount of calcium (Z number = 20), i.e. in bones or calcifications, in metallic medical implants made of titanium (Z number = 22) or iodine (Z number = 53), contained in contrast agents. However, it will not have a significant share in the interaction with soft tissues, which consist primarily of oxygen (Z number = 8), carbon (Z number = 6), hydrogen (Z number = 1) and nitrogen (Z number = 7), i.e. elements with a low atomic number, which excludes them from differentiation using spectral tomography imaging. DECT is therefore primarily a method used for material analysis and differentiation between tissues and materials with a high atomic number, based on differences in their attenuation of X-rays with two different energies — 60–100 kVp and 120–140 kVp [2, 6].

Analysis of the occurrence and intensity of the photoelectric effect and the Compton phenomenon during the interaction of radiation with different energies with matter of different elemental composition and processing of this data by advanced computer algorithms allows the creation of various diagnostic images, carrying more information than those obtained using conventional CT imaging method.

Selected DECT Applications in Neuroradiology

Material Analysis — Creation of Paired Images and VMI Images

Intracranial haemorrhage, iodine contrast enhancement, and calcifications are the most frequently described hyperdense lesions in the brain. Their differentiation in conventional CT is often diagnostically difficult because they all present similar values in HUs and similar appearance on the CT image, and they can also overlap. However, knowing the atomic number values of the elements that make up the above-described lesions, DECT can be used to differentiate them [7].

Both iodine, found in contrast agents, and calcium, forming calcifications, are elements with high atomic numbers, and therefore, they attenuate radiation mainly through the photoelectric effect. The K-edge energy value for iodine is 33 keV, and for calcium 4 keV. On the other hand, soft tissues, which also include extravasated blood in the brain, have a much lower K-edge energy value, in the range of 0.01–0.53 keV, and the attenuation of radiation occurs mainly as a result of the Compton effect. Based on the differences in the attenuation of low- and high-energy radiation for the above-mentioned materials, comparisons are created that show their qualitative participation in the diagnostic image [2]. The so-called basic pairs of materials are compared. The most frequently created images are those on which the basic pairs are assessed: water (iodine), iodine (water), water (calcium), calcium (water), iodine (calcium), calcium (iodine). These images provide information on the concentration of the first of the mentioned materials (in mg/ml) in individual pixels, necessary to cause the measured attenuation of radiation in them, while the second of the materials is usually removed from the image [3]. The appearance of changes observed in the brain on the images of individual combinations of basic pairs is described in Table 1.

Table 1. Characteristics of changes in the images of the paired bases in DECT [3].

Material Pair/Observed Change	Water (iodine)	Iodine (water)	Water (calcium)	Calcium (water)
Freshly extravasated blood	hyperdense	isodense	hyperdense	isodense
Calcifications	isodense/ moderately hyperdense	hyperdense	isodense/ moderately hypodense	hyperdense
Iodine contrast agent	isodense	hyperdense	isodense	moderately hyperdense

Another type of image that can be obtained with DECT is virtual monochromatic imaging (VMI). In this case, a computer algorithm, using low- and high-energy attenuation data, creates a virtual image of the scanned object that would be obtained using a monochromatic beam of radiation energy in the range of 40–190 keV. Low-energy virtual images can be used to optimize the contrast between the white and grey matter of the brain, which facilitates the detection of brain ischemia or oedema, and also improves the visibility of the iodinated contrast agent in the image. Simulated high-energy images help minimize the beam hardening effect and artifacts created during scanning of the posterior cranial fossa or in the presence of metallic implants or embolization material [5] (Fig. 1).

Differential diagnosis between freshly extravasated blood and iodine

Creating images from water (iodine) and iodine (water) base pairs allows for differentiation between freshly extravasated blood in the brain and iodinated contrast agent, especially in situations where both substances are superimposed on the CT image [8].

DECT is used in the follow-up assessment of ischemic stroke focus in patients who were treated with mechanical thrombectomy. An important aspect of the follow-up assessment of ischemic stroke focus is the detection of secondary haemorrhage in the area affected by ischemia, which affects the patient's prognosis and changes in the treatment plan. However, in a situation where the patient has undergone mechanical thrombectomy, in a follow-up examination 24 hours after the procedure, hyperdense areas of residual iodinated contrast agent used during mechanical thrombectomy can still be detected in the patient's brain. Such hyperdense areas could be mistakenly considered as secondary haemorrhage of the ischemic stroke focus, which would adversely affect the patient's further treatment. Therefore, the use of water (iodine) and iodine (water) base pair maps obtained in DECT is of great importance, which significantly improve the effectiveness of differential diagnosis between residual contrast agent and secondary haemorrhage [9, 10] (Fig. 2). Studies show that DECT in differentiating blood and residual contrast agent demonstrates sensitivity, specificity and accuracy of 100%, 91% and 93%, respectively [11]. DECT is significantly used in assessing the evolution of intracerebral haematomas and the presence of the so-called "spot sign" in angio-CT of the brain. The term "spot sign" in angio-CT of the brain refers to the presence of at least one post-contrast enhancement focus in the area of the intracerebral haematoma. Detection of active, small bleeding foci is very important because it is associated with the risk of haematoma enlargement and has a major impact on further clinical management. Since both fresh extravasated blood in the haematoma area and iodinated contrast agent are hyperdense, the

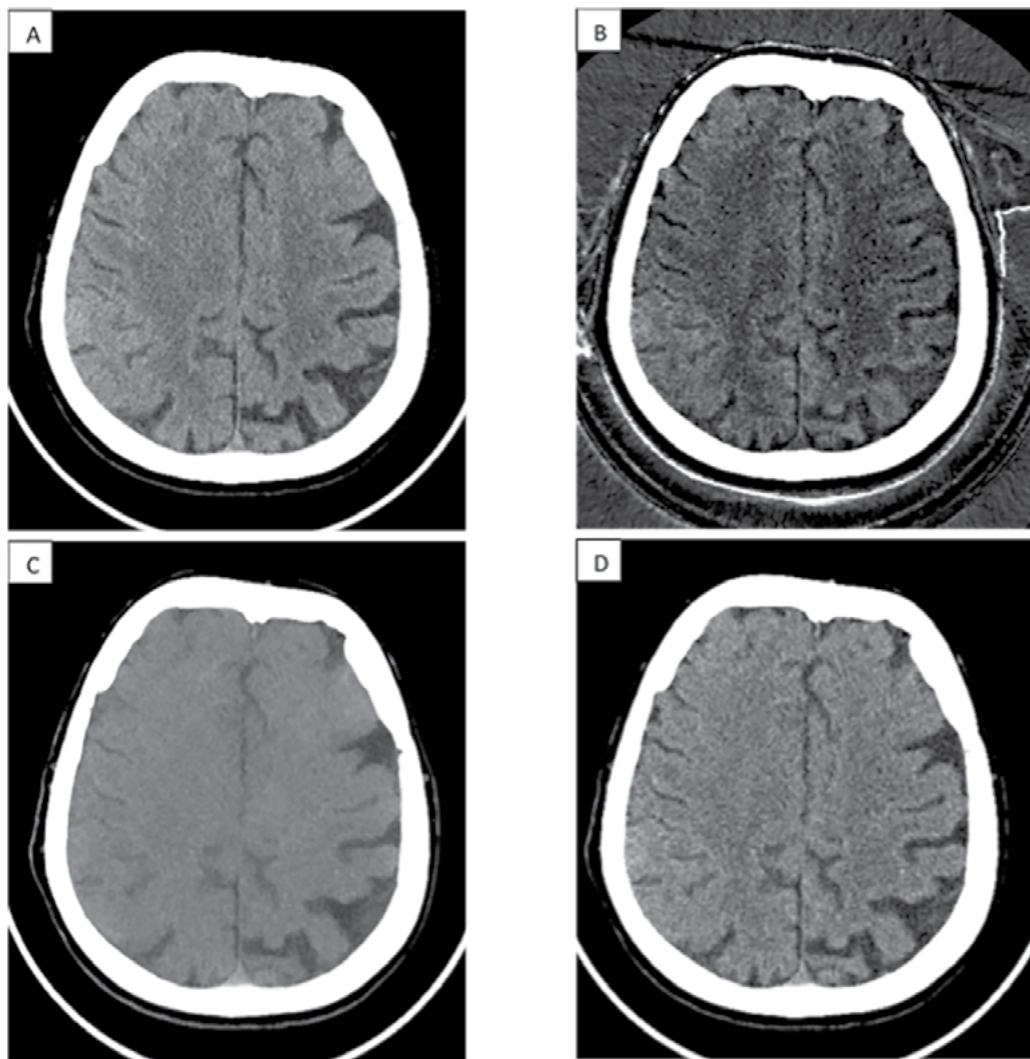


Fig. 1. Comparison of sample brain images obtained using DECT: A — conventional CT image using a voltage of 120 kV, B — iodine (water) base pair map, C — water (iodine) base pair map, D — 70 kVp VMI image [Archive of the University Hospital in Krakow].

sensitivity of detecting small active bleeding foci in the hematoma area in conventional angio-CT examination is only 32%. When DECT and water (iodine) and iodine (water) maps in the delayed arterial phase are used, the sensitivity increases to 76% [12]. In another study, which assessed the presence of active bleeding foci in posttraumatic intracerebral hematomas, the sensitivity and specificity of DECT in the assessment of “spot signs” were shown to be 66.7% and 76.2%, respectively, which also indicates a higher sensitivity compared to SECT in predicting hematoma enlargement, regardless of its initial dimensions and location [13].

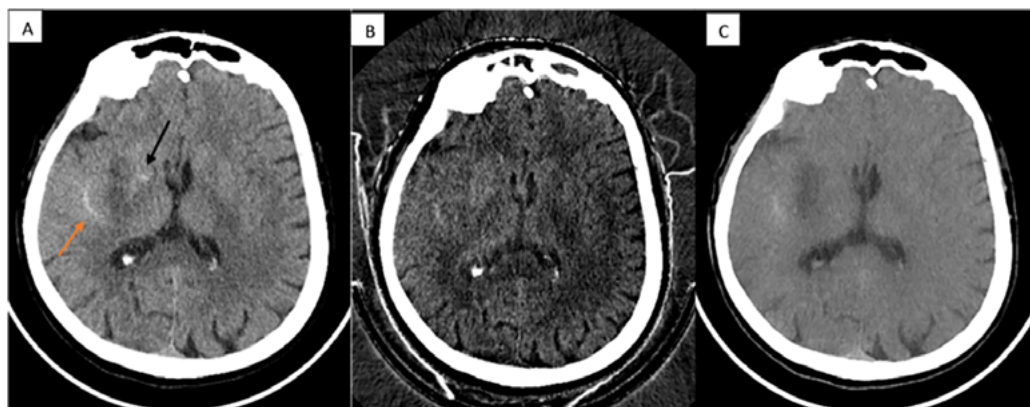


Fig. 2. Conventional CT and DECT scans of the brain performed in the patient 24 hours after mechanical thrombectomy due to ischemic stroke of the right hemisphere. The discrete hyperdense zone visible on the conventional CT scan (A) in the area of the putamen of the lentiform nucleus and the caudate nucleus on the right side (black arrow) is also hyperdense on the iodine (water) map (B), while on the water (iodine) map (C) it has reduced density — it may correspond to the passage of a small amount of iodinated contrast agent through the damaged blood-brain barrier. The hyperdense zone in the area of the lateral fissure of the right brain on image A (orange arrow) is also hyperdense on both DECT maps (B and C), which does not allow the presence of blood in this location to be excluded [Archives of the University Hospital in Krakow].

Differential diagnosis between fresh extravasated blood and calcifications

The difficulty in differentiating between fresh extravasated blood in the brain and calcifications is another limitation of conventional CT imaging, because both of these substances are very dense. Furthermore, distinguishing between blood and calcifications can also be difficult in magnetic resonance imaging (MRI) — both of these substances are hypointense in MRI susceptibility weighted imaging (SWI) sequences or T2* sequences.

In connection with this, a useful method of differential diagnosis between blood and calcifications is DECT and the maps of the water (calcium) and calcium (water) base pairs obtained with it. As studies indicate, the use of DECT improves the accuracy of radiologists' assessment (from 90–93% to 100%) and their diagnostic certainty (from 46–71% to 85–90%) in differentiating between blood and calcifications in the brain compared to using only images from conventional CT [14]. Another study compared the sensitivity, specificity and accuracy in detecting haemorrhagic changes in patients presenting hyperdense changes in the brain, differentiating them from calcifications. In the case of conventional CT, these values were 74%, 95% and 87%, respectively. In the case of DECT, an increase in these values was observed — sensitivity was 96%, specificity 100% and accuracy 99% — which indicates the significant usefulness of DECT in differentiating small foci of acute intracranial haemorrhage and calcifications [15].

Vascular imaging in neuroradiology

Currently, the standard for non-invasive imaging of the head and neck vascular system is CT angiography (CTA). The wide availability and short examination time have made CTA a commonly used diagnostic method in vascular diseases of the head and neck.

However, despite the constantly introduced technical improvements in CTA, we still encounter limitations related to the ability to differentiate, among others, calcified plaques and contrast agent. Accurate assessment of vessel stenosis caused by the presence of calcified plaques becomes difficult, which may affect clinical decisions.

In imaging the head and neck vascular system using DECT, the possibility of using two of its possibilities plays a special role: removing bone from the image and virtual reconstruction of images without contrast.

Bone removal in DECT is an automatic data processing algorithm that uses the differentiation of bone structures from other tissues to create an accurate “bone mask” and its subtraction with data obtained from DECTA. The information obtained in this way can then be presented as MPI and VRT projections, which allows for precise assessment of vessels even in critical locations, such as the skull base, where hyperdense bone structures are located in close proximity to vessels filled with contrast agent [3].

An important advantage of DECTA is the fact that the information needed for bone masking is obtained from data from a single scan — unlike in the case of conventional bone removal techniques, which use bone masks generated on the basis of the first non-contrast scan, subtracted from the second CTA scan. This allows for a significant reduction in the dose of ionizing radiation received by the patient during the examination. Thanks to the above, DECTA also allows for the elimination of movement artifacts resulting from the act of swallowing or breathing.

Studies have shown that the DE bone removal method in head and neck CTA improves image quality and shortens reading time [16–18]. DECT is superior to conventional CTA in both qualitative and quantitative assessment of cerebral and neck vessels [2].

In the case of DECTA, VMI (virtual monochromatic imaging) images are also of great value. Ionizing radiation beams generated for low energies enable better assessment of vessels compared to the surrounding parenchyma, improving the contrast-to-noise ratio and providing better vessel contrast. An improvement in the contrast-to-noise ratio by 26–59% and a reduction in radiation dose by up to 22% have been demonstrated by using lower peak current values on the CT tube compared to scanning with the standard value of 120 kVp [19]. Therefore, the data obtained during DECT scanning allows for the creation of VMI images at low voltage values (e.g. 40–80 kVp), enabling better assessment of vessels in comparison with the surrounding parenchyma, improving the contrast-to-noise ratio and providing better vessel contrast (Fig. 3). Obtaining a better contrast-to-noise ratio also allows for the administration of less contrast, which is particularly important in patients with impaired renal function [2]. The assessment of intracranial vessels for the presence of aneurysm in conventional CTA may be limited in close bone locations such as the skull base. DECTA, using base pair images in which substances such as iodine, calcium or uric acid are mapped or removed, improves the sensitivity and specificity of detecting small aneurysms — less than 3 mm, especially in the skull base region [20].

Assessment of atherosclerotic plaques in the cranial and intracranial arteries

The increase in the number of patients with hypertension, hyperglycaemia and hyperlipidaemia is associated with an increased incidence of ischemic strokes. One of the main causes of ischemic changes in the brain is atherosclerosis of the internal carotid arteries, the treatment of which is associated with the assessment of the degree of vessel stenosis, and the use of appropriate therapy with prognosis [21].

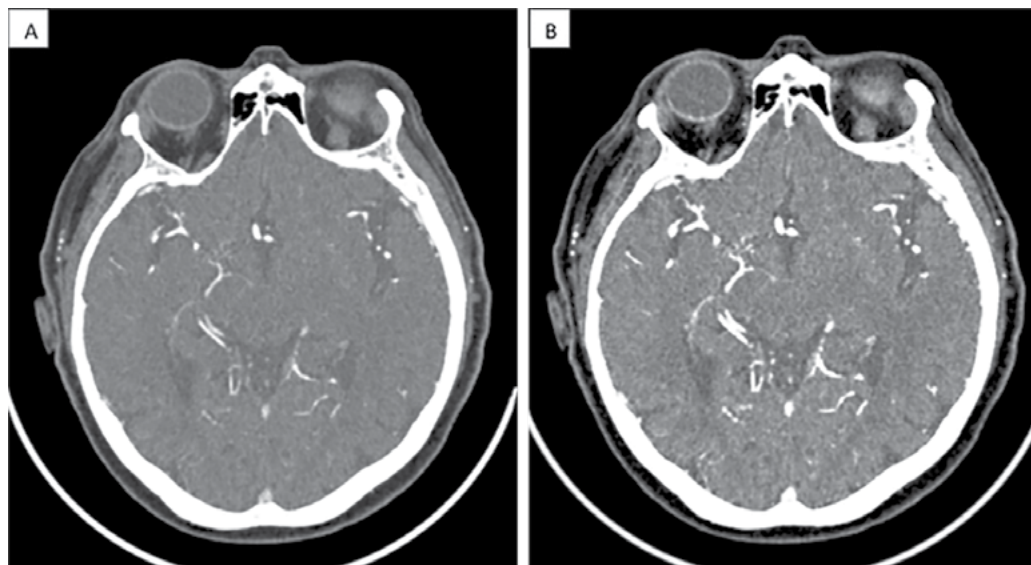


Fig. 3. Angio-CT (CTA) examination of the brain using DECT. A — image obtained from scanning using a conventional voltage of 120 kVp, B — VMI reconstruction obtained based on DECT at 45 kVp. Low-energy virtual monochromatic images show significantly better contrast and detail of blood vessels filled with iodine contrast agent [Archive of the University Hospital in Krakow].

The gold standard in assessing the severity of internal carotid artery stenosis is the examination by digital subtraction angiography (DSA). However, this is an invasive method that carries the risk of periprocedural complications [22]. Other non-invasive imaging techniques useful in assessing internal carotid artery stenosis are Transcranial Color-Coded Duplex (TCCD) sonography, magnetic resonance angiography (MRA) and computed tomography angiography (CTA).

CTA examination results demonstrate high diagnostic accuracy and correlate with DSA results [23]. However, the assessment of atherosclerotic plaques in CTA may be limited due to the possibility of blooming artifacts, which cause an overestimation of the measured degree of vessel stenosis [21]. Studies conducted with the use of new DECT algorithms, using images of base pairs from which calcium is removed, have shown high sensitivity in detecting significant stenoses in the internal carotid artery, and the obtained results indicated a stronger correlation with DSA results, compared to the classic CTA examination. Additionally, DECT allows for the use of a lower radiation dose and shorter scanning time and helps reduce motion artifacts [21, 24].

Reducing artifacts using DECT in neuroradiology

DECT technology offers users a wealth of possibilities, but in order to use them effectively, it is necessary to understand the limitations and artifacts that come with it, which can lead to diagnostic difficulties or completely prevent the evaluation of the examination. The goal is to select a protocol that will provide an appropriate balance between the radiation dose and the quality of images, which are a specific carrier of diagnostic information.

CT artifacts can be classified based on the cause of their occurrence, and therefore can be divided into patient-dependent, physical-based methods and equipment-dependent. Eliminating artifacts that are patient-dependent primarily involves good preparation before the examination. The patient should be instructed to remove metal elements from the area of interest, the course of the examination should be explained, the patient should be warned about the voice commands and sensations occurring during the administration of iodine contrast, and the available positioners should be used to immobilize the patient — all these steps allow for the elimination of movement and metal artifacts from body elements that can be removed before the examination.

Hardware-dependent artifacts include, for example, the black ring artifact appearing in the image when there is an incorrect calibration or failure of one or more detector elements in the scanner. Less frequently, they may be caused by an insufficient radiation dose or contamination of the gantry cover with contrast. Hardware artifacts always require broader diagnostics of the problem; their appearance very often signals the need to service the device in order to eliminate them and suspend the examination for that time.

Artifacts resulting from the physical basis of the method include, among others, partial volume averaging, which occurs when tissues with different degrees of absorption of rays are located in one voxel, due to which they are assigned an average value. The latest generations of tomographs have allowed for the reduction of voxel volumes, allowing its elimination [25].

Another artifact with physical basis is hardening of the radiation beam. This is a phenomenon that occurs when a polychromatic beam of rays consisting of different energies passing through the examined object is selectively attenuated. Cutting off lower energy photons causes only higher energy photons to remain in the beam, and therefore the average beam energy is increased. In images, the radiation beams hardening artifact manifests itself as:

1. Cut-off artifact — dark streaks in the centre of the image.
2. Dark band artifact in areas with large tissue differences.
3. Artifact from metal or high-density foreign bodies [3].

Elimination of radiation beam hardening artifacts

DECT is used to eliminate artifacts such as the commonly known radiation beam hardening in the posterior cranial fossa area, or metal artifacts in patients, e.g. after neurosurgical procedures using embolization coils, spinal stabilizing rods or commonly used amalgam fillings [8].

Metal, as a high-density material, strongly blocks and weakens the radiation passing through the patient's body, which causes dark stripes with a characteristic flash, making it difficult or completely impossible to interpret a given area. In such cases, the use of virtually created monochromatic images is helpful. VMI is one of the reconstruction algorithms, which, to put it very simply, consists in combining two images with different energies ranging from 40 keV to 190 keV [8]. High-energy images allow for the reduction of beam and metal hardening artifacts, but at the same time their use is associated with a reduction in vessel contrast. For this reason, it has been assumed that it is optimal to use energy in the range of 100 keV–120 keV, which will allow for the reduction of the embolization spring artifact and will provide a good visualization of the contrasted vessel [26]. High-energy images can be additionally combined with commonly available metal artifact reduction algorithms such as MAR (Metal Artifact Reduction) to achieve even better image elimination results [27] (Fig. 4). In most DECT systems, images obtained at low energies contain a large amount of noise, while higher VMI energies allow for its reduction,

which is an additional benefit for evaluation while simultaneously eliminating beam hardening artifacts. However, it should be remembered that the main limitation of high-energy images is the low contrast of soft tissues and decreased iodine attenuation [2, 28].

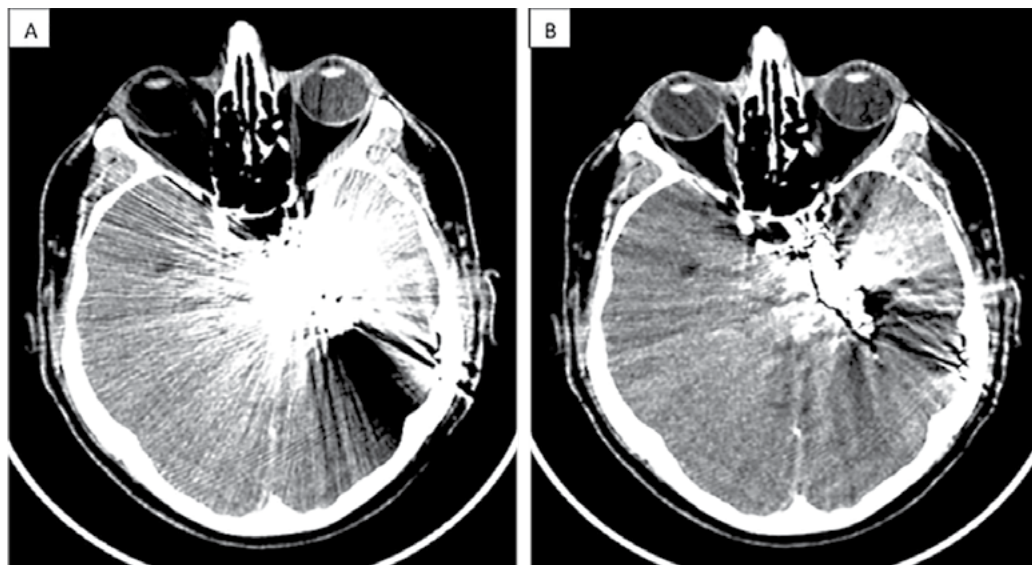


Fig. 4. DECT examination of the brain in a patient after embolization of the left meningo-venous fistula. Compared with conventional CT: (A) high-energy DECT examination with the MAR option (B) allows for a significant reduction of the radiation beam hardening artifact caused by the embolizing material [Archives of the University Hospital in Krakow].

Advantages and limitations of DECT

Spectral tomography has many advantages, but it is also important to remember the limitations of this method compared to other available imaging methods. For example, compared to MRI, DECT is characterized by much faster acquisition and greater availability in cases of urgent examinations, as is the case in facilities at hospital emergency departments, where time is of the essence. MRI, on the other hand, is a difficult to access, more expensive, long-scan test, often contraindicated for people with claustrophobia or metal implants, stimulators or shrapnels in the body.

It is necessary to take into consideration the radiation dose, which is a subject of concern mainly due to the two energy sources operating in such a device. The radiation dose in spectral tomography is composed of high- and low-energy data, so that the final dose does not differ significantly from that obtained using conventional methods in the head and neck area [3]. One of the possibilities of reducing the dose in contrast-enhanced examinations is the use of native phase images created virtually based on DECT data. Secondary creation of virtual non-contrast phase images provides the possibility of obtaining additional diagnostic information without the need for additional scanning, which in turn allows for reducing the total dose from the examination. However, images obtained virtually may differ slightly in quantitative values, measured in ROI

(region of interest) HUs, from those obtained in the acquisition, so it should be remembered that artifacts related to different DECT techniques may also complicate image interpretation and require specialist knowledge to understand the potential diagnostic pitfalls associated with them [8, 29]. The large amount of information obtained in DECT allows for the generation of multiple image reconstructions: monochromatic, mixed, quantitative assessment of iodine, improved visibility of iodine contrast enhancement and base pair maps or more advanced quantitative analyses; impossible to obtain using conventional SECT acquisitions with an acceptable or even lower dose than SECT [2].

An unquestionable advantage of DECT, compared to SECT, is also that by acquiring data for two different energy spectra, a more detailed tissue assessment is possible. This is because the attenuation of the X-ray beam is different and depends on the type of materials, tissues, but also their elemental composition, so DECT can be used to characterize tissues in a way that goes beyond what is possible with conventional SECT [2].

The biggest obstacle to the widespread use of DECT devices is the high purchase cost. Dual-source devices are characterized by a higher market price, and in addition, the software that allows data processing generates another price increase, at the moment without an effective mechanism for the return on investment over time. An increase in the efficiency of the method can be achieved by completely automating the processes of creating images in secondary processing, without the need to involve a radiologist or electro-radiologist performing the examination. In practice, you have to decide what series of images you would like to additionally send to PACS (Picture Archiving and Communication System), which will help establish the diagnosis, or create additional reconstructions at the request of the radiologist, which will allow to reduce the amount of archived data [2, 8].

The multitude of possibilities and solutions in the case of DECT, provides a lot of room for learning to optimize tests, but at the same time their interpretation by doctors. At the moment, DECT has proven to be particularly useful in the assessment of intracranial haemorrhages, their differentiation between iodine and calcium, characterization of atherosclerotic plaques or reduction of artifacts. The application development of the method brings with it many promising solutions and answers for future clinical practice [28].

Conclusion

Dual-energy tomography is an excellent complementary tool to the standard technique, providing new diagnostic information in common neurological diseases. The developing application possibilities of secondary data processing show new promising possibilities of DECT in improving diagnostics and diagnostic accuracy in various clinical conditions. The method is particularly useful in the assessment of intracranial haemorrhages and their differentiation from iodine and calcium, as well as in imaging ischemic strokes, injuries or artifact reduction. Additionally, currently emerging new application possibilities of the method show its promising development in future clinical practice.

Conflict of interest

The authors declare no conflict of interest or any financial interest associated with the current study.

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