Principles and Clinical Application of Dual-Energy CT in the Evaluation of Cerebrovascular Disease

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Learning objectives

1. To understand basic principles of dual-energy CT (DECT) and material decomposition to differentiate bone/calcium, iodinated contrast and acute hematoma in clinical evaluation of cerebrovascular disease.
2. To be familiar with the various post processing software and application of DECT in cerebrovascular disease.
Background

Dual energy CT (DECT) simultaneously acquires images at two x-ray energy levels ie. at high and low peak voltage (kVp). The material attenuation difference obtained from the two x-ray energies can be processed by software to create additional image datasets, namely: virtual non contrast (VNC), iodine overlay (also termed virtual contrast, VC) and bone/calcium subtraction images. The potential clinical applications are vast but include:

- Identification of active extravasation of iodinated contrast in various types and stages of intracranial hemorrhage.
- Calcium subtraction from atheroma plaque for analysis of plaque composition and assessment of degree of luminal stenosis.
- Bone subtraction to depict vascular anatomy with more clarity, especially at the skull base.

In pictorial format we review the emerging research data and our clinical DECT experience at our institution relevant to cerebrovascular disease.

PHYSICS CONCEPTS

The concept of DECT is based on the attenuation difference of various materials when simultaneously exposed to low and high-energy x-rays. These differences reflect the energy and material dependency of Compton scatter and photoelectric effects. Compton scatter (scattering of x-rays with little absorption) predominates at the 120-140 kVp energy range. In contrast, photoelectric effect (photon absorption) is specific to an element and equates to the energy required to eject a k-shell electron. Photoelectric effect is proportional to the cube of the atomic number and inversely proportional to the incident photon energy \( \left( \frac{Z^3}{E^3} \right) \). Conventional CT scanning utilizes a single polychromatic x-ray tube with peak energy of approximately 120 kVp. Although a single high energy x-ray tube produces images with a high signal-to-noise ratio, it is not possible to discriminate between different materials such as iodine, haematoma and calcium/bone and therefore intravenous iodinated contrast is required.

Currently, two different DECT technologies are in clinical usage. One method employs two orthogonal x-ray tubes set at different kVp levels with two separate detectors. The second method uses rapid kVp switching from a single x-ray source and a detector composed of two scintillation layers. In both methods, two energy levels are typically set at 80-100 and 140 kVp. Complex algorithms have been developed to analyze DECT data. Firstly, a weighted average image (weighting factor of 0.4) is created which resembles the conventional 120-kVp image of single energy CT. If only a contrast-enhanced scan is obtained, a VNC image can be created by removal of iodine with no additional radiation exposure. Iodine overlay or VC images can be generated to enhance depiction of iodine.
contrast concentration and distribution. Finally, bone and calcium subtractions images allow depiction of vessel lumens that would otherwise be obscured by bone or hard plaque.
Findings and procedure details

1. INTRACRANIAL HAEMORRHAGE PROTOCOL

An initial non-contrast CT head scan is obtained in a single-energy mode prior to performing cerebral CTA in a dual-energy mode. DECT cerebral angiogram is performed on the Somatom Definition FLASH (Siemens Healthcare, Forchheim, Germany) DECT Scanner. The volume of injected contrast is 75 mL at a flow rate of 5 mL/s, followed by a 60-mL saline flush.

In the dual energy mode, the following parameters are used: Tube A is set at 80 kV and Tube B at 140 kV. Data acquired at 80 and 140 kV is reconstructed separately, with slice thickness and increments of 1.0 and 0.7 mm respectively using an I30 algorithm. Three sets of images are generated: a 100-kV image, a 140-kV image, and a weighted average image with a weighting factor of 0.3 simulating a 120-kV image (Fig. 1 on page 8). Dual-energy data is processed using a vendor specific (Syngo Dual Energy Brain Hemorrhage, Siemens) software. Analysis of images using material decomposition algorithm based on brain parenchyma, hemorrhage, and iodine was performed. Additional VNC and VC/iodine overlay were sent to PACS for interpretation.

CLINICAL APPLICATION

Detection of active bleeding in cerebral haematoma is of paramount importance. The presence of contrast extravasation on CTA, also known as the "spot sign", has been shown to be associated with haematoma expansion and poor prognosis [1-4]. DECT improves the detection of subtle contrast extravasation from active bleeding within a haematoma by increasing the conspicuity of iodine with VC image construction (Fig. 2 on page 8). This method reduces radiation dose in comparison to other existing dynamic or multiphase single energy CT techniques which rely on multiple phases to demonstrate contrast extravasation and delayed washout. Similarly, this technique can also be applied for the detect active bleeding in extra-axial hemorrhage. Early recognition of hemorrhagic transformation of ischemic stroke is crucial but accurate interpretation can be challenging due to the potential for extravasation of contrast material from prior CT angiogram or neurointerventional digital subtraction angiography (DSA) procedures during stroke work-up. DECT can overcome this problem by accurate differentiation of haemorrhage from iodinated contrast with high sensitivity and specificity [5]. Acute intracerebral hemorrhage may mask underlying lesions. Again, differentiation between haematoma and iodine may allow detection of subtle enhancement from underlying neoplasm which may otherwise be obscured. DECT VC (iodine-overlay) has been shown to be significantly superior to
conventional single energy or weighted average dual energy image for the detection of lesional hemorrhage [6].

2. CT CEREBRAL ANGIOGRAM AND CT VENOGRAM PROTOCOL

Cerebral and/or neck CTA neck performed on the Somatom Definition FLASH (Siemens Healthcare, Forchheim, Germany) DECT Scanner. The volume of injected contrast is 75 mL with a flow rate of 5 mL/s, followed by a 60-mL saline flush. The CT cerebral venogram is performed by injection of the same contrast volume, 75 ml with a flow rate of 4 mL/s but no saline flush. A delay of 45 seconds between injection of contrast and image acquisition. The following parameter were used: Cerebral and neck CTA: (Tube A at 100 kV Tube B at 140 kV) and 2. Cerebral CTA and CT cerebral venogram: (Tube A at 80 kV Tube B at 140 kV). Three sets of images were generated: a 100-kV image, a 140-kV image, and a weighted average image with a weighting factor of 0.3 is used for cerebral and neck CTA and 0.4 for either cerebral CTAor CT cerebral angiogram. Dual-energy data were processed using a vendor specific dual-energy direct bone removal CTA (DE-BR-CTA) Siemens software. Automatic bone and plaque removal was performed without further manual adjustments of the algorithm. Additional rotational maximum-intensity projection (MIP) images in two planes were sent to PACS for interpretation.

CLINICAL APPLICATION

Vascular anatomy on CTA or CTV may be obscured by calcified atheroma plaque or beam hardening artefact at the skull base (Fig. 3 on page 9 and Fig. 4 on page 10). Although these problems have been partly overcome in single-energy CT using manual post-processing for bone removal, it is a time-consuming process. DECT software using material differentiation allows automated subtraction of osseous or calcified plaque for optimal delineation of the vessel lumen. This technique has a wide range of applications including evaluation of carotid stenosis (Fig. 5 on page 11) and plaque characterisation (Fig. 6 on page 11). Although carotid DSA remains the gold standard for quantification of internal carotid artery (ICA) stenosis, CTA has become the more popular and is the more accessible imaging modality. Recent data have shown DECT automated plaque and bone removal images with maximum intensity projections (MIPs) improves the accuracy of CT angiography [7-9] and closer correlation with DSA compared to standard single energy CTA [10]. A potential pitfall to be noted is potential for overestimation of a stenotic lesion (Fig. 7 on page 12), which can be avoided with careful final interpretation of reconstructed DECT images whilst correlating with standard reconstructions.

3. ARTEFACT REDUCTION PROTOCOL
The dual-energy CTA or CTV data were processed using the Siemens Syngo via workstation equipped with the software that can extract the virtual monoenergetic images at the arbitrary photon energies ranging from 30 keV to 130 keV. There is a trade off between metal artefact reduction and optimal contrast enhancement of the vascular lumen. As the KeV value increases the luminal contrast attenuation decreases (Fig. 8 on page 13). At approximately 113 keV both the metal artifact reduction and luminal contrast attenuation are optimised. Monoenergetic CT images at 113 Ke are saved and reformation in the axial, coronal, and sagittal planes with slice thickness of 1 mm were performed for interpretation. Automated bone subtraction is particularly useful to delineate fine detail anatomy of the dural venous sinuses through the skull base (Fig. 9 on page 15).

CLINICAL APPLICATION

Image quality of conventional single energy CT imaging of the neck and cerebrovascular can be degraded by artefacts. Metallic objects most notably aneurysm clips and coils can result in streak artifacts limiting assessment of the luminal profile. Monoenergetic images (113 KeV) obtained from the DECT data improve image quality for assessment of the luminal profile compared to the average weighted 120 kVp (Fig. 10 on page 14). This technique is extremely useful in assessment of residual flow in the aneurysm neck post coiling or clipping.
**Images for this section:**

Fig. 1: Dual energy CT angiogram (DECTA) of the circle of Willis showing image at 80 kVp (A), at 140 kVp (B) and weighted average image (C) simulating a 120 kVP image. All three images displayed are at the same window width and level. Difference in the Hounsfield unit (HU) attenuation between the images are illustrated by the HU measurements within the left middle cerebral artery. The lowest energy 80 kVp image (A) show greatest HU as the energy level is closer to the k-edge of iodine. In contrast, the highest energy 140 kVp image (B) show lowest HU.

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Fig. 2: 78 years old male with known cerebral amyloid angiopathy (A-D). Single energy (SE) non contrast (NC) CT head image (A) shows a right frontal cerebral haematoma. Dual energy CT angiogram (DECTA) virtual non contrast (VNC) image (B) again showing the right frontal haematoma. DECTA image (C) and virtual contrast (VC)/iodine overlay image (D) demonstrate a "spot sign" within the haematoma compatible with active haemorrhage. 50 years old female with poorly controlled hypertensive (E-H). SE non contrast (NC) CT head image (E) shows a right temporal and thalamic haematoma. DECTA VNC image (F) again showing the right temporal and thalamic haematoma. DECTA image (G) and VC/iodine overlay image (H) demonstrate two "spot signs" within the thalamic haematoma compatible with active haemorrhage. 26 years old male with amphetamine use (I-L). SE NC CT head image (I) shows pontine haematoma. DECTA VNC image (J) again showing the pontine haematoma. DECTA image (K) and VC/iodine overlay image (L) demonstrate two "spot signs" within the pontine haematoma compatible with active haemorrhage.
**Fig. 3:** Dual energy CT angiogram (DECTA) with automatic bone subtraction (A) shows abrupt occlusion of the V4 segment of left vertebral artery immediately distal to the posterior inferior cerebellar artery (PICA) origin (arrow head). Oblique sagittal reformatted image with bone subtraction (B) shows the extent of the vertebral artery thrombus (arrow). Maximum intensity projection (MIP) with bone subtraction clearly demonstrates the abrupt occlusion of V4 segment of vertebral artery (arrow) distal to the PICA (arrow head). MRI brain DWI sequence confirms acute left medullary infarct (Wallenberg syndrome).

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**Fig. 4:** Dual energy CT (DECT) venogram bone subtraction images (A-C) shows extensive right dural venous sinus thrombosis (arrows) commencing from the distal...
transverse sinus to involve the sigmoid sinus and proximal internal jugular vein. DECT venogram without bone subtraction images (D-F) provided for comparison depict the thrombosis less conspicuously.

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**Fig. 5:** DECT axial images (A-D) and with automatic hard plaque subtraction (E-H) shows moderate to high grade stenosis of the right proximal internal carotid artery (ICA) by hard plaque (arrow). Note the automatic hard plaque subtraction images (E-H) better depict the degree of luminal stenosis than standard axial images (A-D). Rotating MIP image (I) and with automatic hard plaque subtraction (J) shows clear visualisation of the ICA which is otherwise obscured by the hard plaque.

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Fig. 6: DECT with automatic hard plaque subtraction uncovering fissuring in a vulnerable soft plaque otherwise obscured by adjacent hard plaque. Axial images (A-D) shows mixed morphology plaque at the carotid bifurcation with fissuring of the soft plaque arising from the posterior wall (arrow). Oblique sagittal reformation demonstrate the raised soft plaque from the posterior wall (arrow, E) with an acute fissure (arrow, F). Rotation MIP with automatic bone and hard plaque subtraction again display the fissured soft plaque (arrow, G).

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**Fig. 7:** DECT axial images (A-D) and with automatic hard plaque subtraction (E-H) shows high grade stenosis of the left proximal internal carotid artery (ICA) by near circumferential hard plaque (arrow). Note the automatic hard plaque subtraction image overestimated the degree of stenosis when compared to the standard axial image. Rotating MIP image (I) and with automatic hard plaque subtraction (J) shows clear visualisation of the ICA which is otherwise obscured by the hard plaque, however overestimation of high grade stenosis is again noted.

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Fig. 8: Representative dual energy CT angiogram (DECTA) images in a 49 years old female post left middle cerebral artery (MCA) aneurysm clipping. Images (A-H) are reformatted monoenergetic images at 50 keV, 60 keV, 70 keV, 80 keV, 90 keV, 100 keV, 120 KeV and 130 keV. All images (A-H) are set the the same window width and level. Beam hardening artifact is reduced at 100 keV to 130 keV, however, at higher KeV mean Hounsfield Unit within the vessel is reduced as the energy level is further away from the K-edge of iodine.

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Fig. 10: 49 years old female with a left middle cerebral artery (MCA) bifurcation aneurysm treated with clipping. Pre-operative Dual energy CT angiogram (DECTA) MIP image shows a left MCA aneurysm at the M1/M2 junction without arterial incorporation. Immediate post operative DECTA weighted average 120 KvP image (B) and virtual monoenergetic 113 KeV image (C) shows successful aneurysm treatment with improved
metal artefact reduction with virtual monoenergetic images and improved resolution of the adjacent vessel lumen (arrow, C).

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Fig. 9: 65 years old male presents with tinnitus. Dual energy CT venogram image (A) shows a right sigmoid sinus diverticulum (arrow) with marked thinning of the sigmoid plate. DECT venogram with bone subtraction image (B) provides greater contrast resolution and increases the conspicuity of the sigmoid sinus diverticulum (arrow). 3D-volume rendering following bone subtraction (C) displays the diverticulum in greater detail.

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Conclusion

DECT is an emerging and accessible modality and is a valuable addition to existing CT protocols for improved imaging evaluation of a diverse range of cerebrovascular disease states. In particular, the assessment of active haemorrhage in intracranial haemorrhage, or haemorrhagic transformation of ischaemic stroke and pre and post-treatment evaluation of atherosclerotic and aneurysmal cerebrovascular disease, are significantly improved by careful application and interpretation of DECT techniques. Further studies are required to improve our understanding of the limitations of the technique and increase applicability to further clinical settings.
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