# Dual-Energy Computed Tomography

## Technology and Challenges

Bernhard Krauss, PhD

**KEYWORDS**

• Dual-energy CT • Spectral CT • Spectral imaging • CT technology • Material differentiation

**KEY POINTS**

- Dual-energy computed tomography (CT) or spectral CT can be used to detect, visualize, quantify or subtract materials with a high atomic number, such as calcium, iron or iodine.
- At the same time, conventional CT images using the whole radiation dose can be generated.
- Scanner types differ in material differentiation quality, robustness against patient motion, and radiation dose efficiency.
- Material differentiation depends on lesion size and image noise, and may be impossible if the X-ray attenuation of the candidate materials is similar for both spectra.

### THE CLINICAL APPLICABILITY OF DUAL-ENERGY COMPUTED TOMOGRAPHY

With traditional computed tomography (CT) scanners, the evaluation of clinical CT images is mainly based on the morphologic information, which results from the different X-ray attenuation of neighboring tissues. Relevant pathologic states are indicated by abnormalities in shape or texture, whereas X-ray attenuation of suspicious areas is often only qualitatively assessed in terms of being hypodense, hyperdense, or isodense with respect to the surrounding material. In clinical routine, the X-ray attenuation itself is only evaluated in selected cases. For example, quantitative CT (QCT) can be used for the measurement of bone mineral density in the spine[1] or noncontrast CT can be used for the evaluation of specific soft tissue lesions, such as cysts[2] or adrenal adenomas.[3] However, for materials such as bone or iodine, a problem is that the CT value depends on the used X-ray spectrum, as well as on patient diameter and patient shape in each axial slice. Hence, for example, the measurement of bone mineral density with QCT traditionally requires dedicated scan modes,[4] special patient positioning, and sophisticated evaluation tools.[5]

In this way, single-energy CT is usually semiquantitative when elements with atomic numbers sufficiently higher than oxygen are involved. Leaving aside practical considerations, this problem could, in theory, be avoided by using a monochromatic synchrotron X-ray source instead of a conventional X-ray tube.[6] With a clinical single-energy CT system this is not possible because the X-ray spectrum originating from the X-ray tube is polychromatic. Because body tissues have a higher attenuation at low X-ray energies than at high X-ray energies, the mean energy of the X-ray spectrum increases with increasing attenuation by the patient. Although this can be compensated for in the case of water-equivalent materials such as soft tissue, there is a remaining beam-hardening effect for the heavier atoms. This leads to the observation that the CT value (in Hounsfield units) of the same small contrast agent sample in air can be 30% higher than inside a realistic abdominal phantom. With larger amounts of bone or iodine, there can also be beam-hardening artifacts, which are seen as

HC DI CT R&D CTC SA, Siemens Healthcare GmbH, Siemensstrasse 3, 91301 Forchheim, Germany
*E-mail address:* bernhard.krauss@siemens-healthineers.com

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dark and bright areas in the soft tissue in the vicinity of these materials.

In 1976, it was already noticed[7] that dual-energy CT or spectral CT can be used to avoid this potential problem by allowing for the reconstruction of monoenergetic images without the need for a synchrotron facility. With dual-energy CT, the same axial slice of a patient is (ideally) simultaneously scanned with 2 different X-ray spectra. In this way it is directly possible to calculate images of the water-equivalent density and the contrast agent concentration in milligrams per milliliter from the dual-energy data. In a second step, the images can be merged again to generate monoenergetic images. Although it is obvious that this method will work for water and contrast agent, it is not obvious, instead actually true, that the same approach also works for all other materials with atomic numbers up to iodine.

In practice, the problems with beam hardening turned out to be less relevant than anticipated at that time. Modern multislice CT systems use rather strong X-ray prefiltration, which narrows the original spectrum. In addition, raw data-based, single-energy iterative methods can be used to achieve beam-hardening artifact reduction.[8] This feature is currently commercially available on clinical CT scanners, for example, for improving the image quality of high-dose noncontrast scans of the brain.

However, 3 advantages of monoenergetic images persist. First, reproducible CT values for all materials involving heavier atoms may allow for a more standardized differentiation between certain pathologic or nonpathologic lesions.[9] Second, monoenergetic images at energy levels higher than 100 keV have turned out to be beneficial for reducing beam-hardening artifacts that are associated with metal prostheses of moderate size, such as spine implants,[10] because they also tend to suppress artifacts from scattered radiation.[11,12] The third advantage is that, in combination with modern image noise reduction techniques such as iterative reconstruction, the energy level of a monochromatic image allows for modifying the iodine contrast without scaling image noise by the same factor.[13–15] This means that, in contrast to simple image windowing, the kiloelectron volt level allows for material-specific windowing so that materials become distinguishable or can be visualized with a high apparent contrast to noise ratio (CNR).

There are also caveats to these statements. The first is that iodine uptake at a fixed point in time also depends on effects not related to the scanner, such as injection protocol, cardiac output, and patient blood volume. Hence, monoenergetic images may be objective in terms of the involved X-ray physics but, in some situations, single-energy dynamic scan protocols may actually be more objective in assessing lesion physiology.[16,17] The second is that it is actually very difficult to assess the clinical benefit of advanced image reconstruction or denoising techniques because the widely used CNR-value may not be sufficient to quantify the diagnostic value of the image.[18]

Despite these issues, monoenergetic imaging has been demonstrated to be possibly the most relevant application of dual-energy CT[19,20] and, currently, it is presumably offered on all commercially available dual-energy CT systems.

Probably the second most popular application of dual-energy CT is the selective visualization of iodine contrast agent and the underlying soft tissues,[21–23] which is also called virtual noncontrast imaging. Clearly, the detection of iodine enhancement is also possible with single energy scans with and without contrast agent; however, the advantage of dual-energy CT is that an additional noncontrast CT scan may not always be indicated. It may also not be sufficient if tissue density changes between the 2 scans, which applies, for example, for the evaluation of iodine uptake in lung tissue.[24] Another relevant application of dual-energy CT is for cases in which iodine has already been injected; for example, as part of an angiography examination, so that there is no chance to obtain an additional true noncontrast scan.[25] The question of whether quantitative iodine uptake can be used to distinguish between different lesion types is an active field of research[26,27] and promising results have been obtained so far. It should be noted that the dual-energy approach does not necessarily imply a higher sensitivity for enhancing lesions but it can definitely improve the conspicuity of iodine uptake, as well as enable the differentiation between iodine uptake and, for example, hemorrhagic lesions.

In addition, the detection of heavy materials in the human body can also be extended to other materials, such as diffuse calcium depositions in the brain,[28] silicone in lymph nodes,[29] or iron deposition in the liver.[30] Notably, in these cases, dual-energy CT cannot directly differentiate between the accumulated heavy atoms such as silicon or iodine. Instead, the concentration can often only be calculated using the assumption that the identity of the heavy atom is known. It should be noted that, at the same CT value enhancement, the concentration in milligrams per milliliters of materials with a lower atomic number (e.g., iron) is higher than the concentration of iodine. Hence, iodine concentrations of 0.5 mg/mL may still be detectable with dual-energy CT,[31] whereas the detection threshold for iron has