Dual-Energy Computed Tomography

Physical Principles, Approaches to Scanning, Usage, and Implementation: Part 1

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KEYWORDS

• Dual-energy CT • Spectral CT or multienergy CT • Dual-source CT • Fast kVp switching • Gemstone spectral imaging • Layered or sandwich detectors • Photon counting • Virtual monochromatic images

KEY POINTS

- Spectral computed tomography (CT) material differentiation relies on differences in energy-dependency of the attenuation of different materials.
- The photoelectric effect has a strong energy dependence, and the attenuation due to the photoelectric effect is highly dependent on the atomic number (Z) of the element.
- Elements with a high atomic number, such as iodine, that have a strong energy dependence can be exploited for spectral CT scanning.
- Current commercially available spectral CT scanners are dual-energy CT scanners that may consist of 1 or 2 tubes, or use specialized layered detectors for spectral separation.
- Multienergy scanning systems, such as photon counting scanners, are under development but not yet commercially available for routine clinical use.

INTRODUCTION

Dual-energy computed tomography (DECT) or spectral computed tomography (CT) is an advanced form of CT that uses different X-ray spectra to enhance material differentiation and tissue characterization. Current commercially available clinical systems use 2 different photon spectra for scanning, and therefore, the term DECT is sometimes used interchangeably with spectral CT. However, it is noteworthy that the term spectral CT could also encompass more

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advanced systems capable of discrimination between more than 2 spectra, such as the photon counting scanners currently under investigation and development. Therefore, strictly speaking, the terms are not synonymous and DECT is a subset of spectral CT.

Applications of DECT for clinical use were initially explored in the 1970s.[1–7] However, the technological and computational advances necessary for implementation of DECT and successful introduction into the clinical arena were not yet made. Therefore, attempts for implementation were temporarily abandoned, just to be revived later with the introduction of the first DECT system in the clinical arena in 2006.[8,9] DECT scanning, as the name implies, is based on image acquisition with 2 different energy spectra. The data obtained are then combined in order to generate images for routine clinical interpretation or for more advanced material characterization. The objectives of this 2-part review are to provide an overview of the (1) physical principles behind spectral CT scanning and material differentiation, (2) major spectral CT acquisition systems available clinically, and (3) basics of implementation and use of the technology in clinical practice.

FUNDAMENTAL PRINCIPLES OF SPECTRAL COMPUTED TOMOGRAPHIC SCANNING AND MATERIAL CHARACTERIZATION

Overview

With conventional, single-energy computed tomography (SECT), a polychromatic beam is emitted by a single source (X-ray tube), passes through the patient resulting in attenuation of the beam, and is captured by an array of detector cells. The resulting projection data, after preprocessing and reconstruction via sophisticated computer algorithms, is rendered into CT slices that are used for diagnostic interpretation. With DECT, on the other hand, projection data are obtained at 2 different energy spectra instead of one, and the information acquired is then blended to create images for routine diagnostic interpretation. More advanced tissue analysis and material characterization are also feasible with these data sets.

The key advantage of DECT over SECT is that by acquiring data at 2 different energy spectra, it is possible to use sophisticated computer algorithms to combine the different energy data in order to evaluate tissue attenuation at different energies rather than at a single effective energy. Because different types of materials and tissues may attenuate X-rays differently at different energies depending on their elemental composition, DECT may be used to perform tissue characterization beyond what is possible with conventional SECT. For successful DECT scanning and material characterization, the following fundamental considerations related to the scanner type and tissues being characterized must be taken into account.

Fundamentals of Dual-Energy Computed Tomography Scanning: Factors Related to the Scanner

For acquiring the projection data, the scanner must use different energy spectra and separately record the high- and low-energy measurements. This has been implemented in the clinical setting in multiple ways. One way is through simultaneous use of 2 different imaging chains, each with its own dedicated source and detector. Another way to accomplish this is via a single X-ray source that is capable of fast switching between 2 energy levels and a detector with very fast readout capability; technical innovations in modern X-ray source technology—taking advantage of the high-voltage controls for X-ray generation—enable this capability. In yet another design, it is possible to acquire high- and low-energy data sets by use of specialized detectors that have 2 different scintillator layers, one for high energy and the other for low energy, built into them. Various methods for acquiring dual-energy data sets are discussed in detail later in this article.

For the purposes of material differentiation, it would be ideal for each of the 2 different energy X-ray beams to be composed of monochromatic energies. However, with current X-ray tube technology used in the clinical setting, it is not possible to generate monochromatic X-ray spectra. Therefore, clinical DECT scanners use polychromatic X-ray sources but attempt to have as little overlap between the different energy spectra as possible. Fig. 1 shows a typical X-ray spectrum at 80 kilovolt peak (kVp) and 140 kVp, including inherent X-ray tube filtration, generated with the XSpect simulator.[10] For DECT systems relying on different tube voltages for spectral separation, the standard peak energies used for scan acquisition are typically at 80 and 140 kVp. For some dual-source scanner models, 90 or 100 kVp with a filter may be used instead of 80 kVp, especially for scanning heavier patients. Alternatively, energies lower than 80 kVp, for example, 70 kVp, may also be used with some models or for specialized applications such as in pediatric imaging. For the high-energy acquisitions, 150 kVp may be used instead of 140 kVp with some models. Protocols may also vary depending on the scanner vendor or the specific application under consideration.