Advanced Tissue Characterization and Texture Analysis Using Dual-Energy Computed Tomography

Horizons and Emerging Applications

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KEYWORDS

- Dual-energy CT • Head and neck squamous cell carcinoma • Virtual monochromatic images
- Material decomposition iodine maps • Spectral Hounsfield unit attenuation curves
- Machine learning • Texture analysis • Radiomic analysis

KEY POINTS

- The rich quantitative data acquired using dual-energy computed tomography (DECT) lends itself to a variety of advanced analyses not possible with conventional single-energy CT (SECT).
- Spectral Hounsfield unit attenuation curves represent plots of predicted attenuations within a region of interest at different energies and are a quantitative corollary of virtual monochromatic images.
- Basis material decomposition and a number of other DECT analytical methods are available and enable tissue characterization not possible with SECT.
- The rich quantitative data available with DECT scans, such as the spectral Hounsfield unit attenuation curves, may further be analyzed using various statistical and mathematical methods for tissue characterization.
- An exciting emerging application is the use of quantitative spectral DECT datasets for texture or radiomic analysis.

INTRODUCTION

Dual-energy computed tomography (DECT) is an advanced form of CT in which image acquisition is performed at 2 different energies, instead of a single peak energy acquisition as is used in conventional single-energy CT (SECT).[1–5] As a result, the attenuation data from the different energy acquisitions can be combined to generate various

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reconstructions (including virtual monochromatic images and material decomposition maps, among others) that cannot be created using conventional SECT. DECT also can be used to quantitatively evaluate the energy-dependent attenuation characteristics of various component materials beyond what is possible with conventional SECT. Since its introduction into clinical practice, there have been ongoing technical improvements in the available DECT systems and an increase in their availability. As a result, multiple clinical applications have emerged in neuroradiology and head and neck imaging using this exciting technology that are covered in the other articles in this issue. In the final article of this series, we discuss in greater detail some of the advanced analytical tools for DECT quantitative analysis that are available using a fast kVp switching DECT scanner (GE Healthcare, Waukesha, WI) and explore exciting developments and applications combining DECT with advanced image processing (texture or radiomic analysis) and machine learning methods.

BASIC PRINCIPLES OF MATERIAL CHARACTERIZATION IN DUAL-ENERGY COMPUTED TOMOGRAPHY SCANNING

The different commercially available and experimental spectral CT scanning approaches and systems are reviewed in detail in separate articles in this issue and are not discussed here. However, understanding the fundamental principles behind DECT scan acquisitions and material characterization is essential for its successful application and is briefly reviewed.[1–4] In clinical CT scanning, attenuation is achieved by 2 main physical mechanisms. These are Compton scatter, which is based on the electron density of the tissue elements, and the photoelectric effect (PE), which is strongly dependent on the atomic number or Z of the tissue elements. A third physical mechanism, Rayleigh or coherent scatter, accounts for only a small percentage of the attenuation and is generally considered negligible.

Although the Compton effect accounts for significant attenuation in clinical CT scanning, it is nearly independent of photon energy. Therefore, it is not the main physical mechanism exploited by DECT approaches. On the other hand, the PE is strongly energy dependent and a key underlying physical process for DECT material characterizations that rely on energy-dependent attenuation changes of elements or tissues. Photoelectric interactions refer to the ejection of an electron from the innermost shell, or K-shell, of an atom by an incident photon. For this to occur, the incident photon must have a minimum energy that is equal to the binding energy of the electron to its shell. The K-shell has the most strongly bound electrons and the probability of photoelectric interactions, and consequently the degree of attenuation, is highest when the incident photon energy just exceeds the binding energy of K-shell electrons. This energy represents the K-edge of an element, at which there is a sudden increase or spike in attenuation, followed by a rapid drop with further increases in energy above the K-edge. Understanding the energy-dependent attenuation characteristics and behavior of elements, including the relation to the K-edge, is essential for understanding the behavior of materials or tissues with DECT.

One way to predict which materials or elements will have significant energy-dependent changes in their attenuation and therefore likely to be amenable to additional characterization using DECT approaches is to look at their atomic number or Z.[1,6] The probability of the PE is proportional to approximately the third power of an element's atomic number (Z).[1] Because photoelectric interactions are the main underlying physical process accounting for the *energy-dependent* attenuation changes seen in DECT scanning, elements with a higher atomic number would be expected to have greater energy-dependent changes in their attenuation or strong "spectral properties" (**Fig. 1**). These elements are good candidates for evaluation and characterization based on their energy-dependent attenuation characteristics using DECT. Iodine ($Z = 53$), present in the body within the thyroid gland and the main constituent of most CT contrast agents, is an example of one such element (see **Fig. 1**). Another element with a relatively high atomic number is calcium ($Z = 20$). As would be expected and discussed in multiple accompanying articles in this issue, iodine's strong "spectral" properties can be exploited in several applications in neuroradiology and head and neck imaging.

Elements with a small atomic number, on the other hand, typically exhibit little change in attenuation at different energies and therefore are not good candidates for characterization based on their energy-dependent (or "spectral") properties.[1] Relevant examples are common elements found in the human body, such as hydrogen ($Z = 1$), carbon ($Z = 6$), nitrogen ($Z = 7$), and oxygen ($Z = 8$).[1] For example, note how, unlike iodine within the thyroid gland, there is little change in energy-dependent attenuation of muscle on the noncontrast CT shown in **Fig. 2**. Because these would not be expected to exhibit sufficient changes in their attenuation at different energies, one would not expect to characterize such materials based on their