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Review article

The role of dual-energy computed tomography in the assessment of pulmonary function

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ABSTRACT

The assessment of pulmonary function, including ventilation and perfusion status, is important in addition to the evaluation of structural changes of the lung parenchyma in various pulmonary diseases. The dual-energy computed tomography (DECT) technique can provide the pulmonary functional information and high resolution anatomic information simultaneously. The application of DECT for the evaluation of pulmonary function has been investigated in various pulmonary diseases, such as pulmonary embolism, asthma and chronic obstructive lung disease and so on. In this review article, we will present principles and technical aspects of DECT, along with clinical applications for the assessment pulmonary function in various lung diseases.

1. Introduction

The primary function of the lung is the exchange of oxygen and carbon dioxide between inhaled air and circulating blood at the lung periphery. For efficient gas exchange in the lung, adequate ventilation, perfusion and the matching of ventilation-perfusion are necessary. Morphologic or reflex changes in the lung due to various diseases affect ventilation and/or perfusion status, and the ventilation-perfusion relationship. Changes in these functions are critical in contributing to hypoxemia and hypercapnia in various pulmonary diseases. Many creative methodologies have been developed to assess pulmonary mechanics, alveolar gas, diffusing capacity as well as the relative sizes of compartments exhibiting larger or smaller ventilation/perfusion relationships (Multiple Inert Gas Elimination Technique: MIGET) [1]. All of these provide global assessments of the lung without regional information and are relatively insensitive to highly regionalized, early disease. Various methods utilizing the imaging of radioactive compounds have been in use for many years including gamma camera-based planar imaging, single photon emission computed tomography (SPECT) or positron emission tomography (PET). All of these methods have limitations of spatial resolution and present challenges regarding generation of the radioactive tag. For anatomic evaluation, multidetector computed tomography (MDCT) has become the modality of choice in lung imaging. However, although MDCT can provide excellent spatial resolution, MDCT has limitations for functional evaluation including repeated CT scan and misregistration of images. These limitations in the separate evaluation with various modalities have triggered the simultaneous evaluation of pulmonary function and anatomic changes with one modality such as dual-energy CT (DECT).

DECT refers to CT that uses two photon energy spectra (one high and one low) and can differentiate such materials as iodine, xenon, from the normally present materials such as air, blood and

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parenchyma. Differentiation is based upon specific shifts in attenuation differences at high and low x-ray energies. In the lung, the three materials, iodine, air, and soft tissue or xenon, air and soft tissue are the two primary areas of interest to date to assess regional perfusion or ventilation respectively. This technique holds the potential for providing high-resolution morphologic information coupled with an anatomically matched pulmonary blood volume or ventilation map within a single CT scan. The simultaneous evaluation of anatomic and functional information offered by DECT facilitates the acquisition of co-registered structural and functional information within the constraints of a clinical setting. In this review article emerging applications of DECT are introduced to demonstrate the unique research and clinically relevant information made available by this imaging methodology with a goal of providing an appreciation of the technique's strengths as well as an understanding of the important methodologic considerations required to achieve quantitatively meaningful information.

2. DECT: basic principles, technical aspects

2.1. Basic principles

Compton scattering and the photoelectric effect are the dominant phenomenon that cause the x-ray attenuation in the energy range and material used in clinical CT. Of these factors, the photoelectric effect is energy dependent and related to the atomic number of materials. The likelihood of photoelectric absorption decreases as the energy of the x-ray photon increases and increases as the energy of the photon approximates the K-shell binding energy of an electron. The photoelectric effect dramatically increases as the atomic number of the materials (i.e., iodine, or xenon) increases. Most of the atoms in the human body (i.e., hydrogen, carbon, nitrogen, and oxygen) have low atomic numbers and they are weakly affected by the photoelectric effect. Thus, the x-ray attenuation of a particular substance has a specific curve when we apply different x-ray energies, and the differentiation and elemental decomposition of materials can be performed utilizing differences in x-ray attenuation [2,3].

DECT can generate monochromatic images and material-specific images for clinical applications. Virtual monochromatic images are synthesized through projection- or image-based calculation, which can be used in contrast optimization, beam-hardening correction, and metal artifact reduction. Material-specific images can be generated with the application of these material decomposition algorithms. A two material decomposition algorithm calculates the relative amount of two materials within a voxel by using the attenuation properties of the two materials at two different energies, with an assumption that the voxel consists of only the two preselected materials. A three material decomposition algorithm calculates the fraction of the third material (frequently iodine or, in the case of the lung, xenon) after computing the mass fraction of two materials. These material decomposition processes can generate maps for specific materials such as iodine or xenon, virtual non-contrast images (water images), and effective z-maps. Quantification of specific material is also possible with this approach.

2.2. Technical aspects

For DECT data acquisition, various approaches have been proposed, and three different designs of DECT are commercially available.

2.2.1. Dual-source CT

A dual-source DECT system has two separate x-ray tubes and two corresponding detectors, which are placed orthogonally to each other within a single rotating gantry (Fig. 1A) [4,5]. Each x-ray

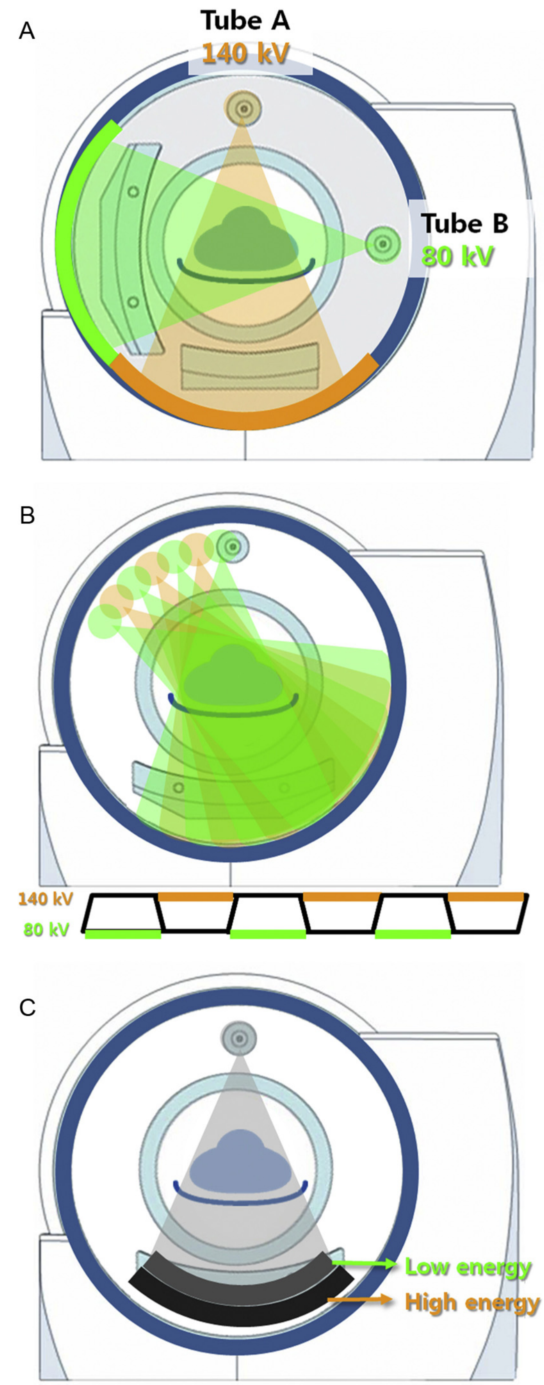

Fig. 1. (A–C) Diagrams of technical approaches for DECT data acquisition. (A) Diagram of dual-source CT system, which is composed of two x-ray tubes and two corresponding detectors offset by 90° in one gantry. Each tube is operated at different kilovoltage (e.g., 140 and 80 kV) and milliampere settings, and then two datasets at high and low energy spectra are obtained at corresponding detectors. (B) Diagram of rapid kVp switching system for DECT data acquisition. The tube voltage is rapidly switched between high and low energy in about 0.5 ms. (C) Diagram of the DECT data acquisition system with energy sensitive layered detector and single x-ray tube at constant kVp. The layered detector is comprised of a thin top scintillator that absorbs lower energy photons and a bottom scintillator that absorbs the higher energy photons.