

- 7:30–8:00 Coffee and Pastries
- 7:30–7:45 Case of the Day
Christopher A. Meyer, MD
- 7:45–8:00 Case of the Day
Laura E. Heyneman, MD

Chest Imaging in the 21st Century

Moderator: Edward F. Patz, Jr, MD

- 8:00–8:20 Digital Imaging of the Chest from CR to DR
Carl E. Ravin, MD
- 8:20–8:40 PACS for the Thoracic Radiologist
Philip A. Templeton, MD
- 8:40–9:00 Computer-aided Diagnosis for Chest Radiology
Heber M. MacMahon, MD
- 9:00–9:20 Multidetector Row CT Pulmonary Applications
Theresa C. McLoud, MD
- 9:20–9:40 Three-dimensional Imaging of the Thorax: Practical Applications
H. Page McAdams, MD
- 9:40–10:00 Future Directions of Imaging Lung Cancer
Edward F. Patz, Jr, MD
- 10:00–10:10 Questions
- 10:10–10:25 Break

Moderator: André J. Duerinckx, MD, PhD

- 10:25–10:45 PET Scan and Coincidence Scan Technology: How Does It Work?
David K. Shelton, Jr, MD
- 10:45–11:05 Pulmonary Embolism: Diagnostic Approach in the New Millenium
Mayur M. Patel, MD
- 11:05–11:25 Pulmonary MR Angiography*
André J. Duerinckx, MD, PhD
- 11:25–11:45 Oxygen-enhanced MR of the Lung
Hiroto Hatabu, MD, PhD
- 11:45–12:00 Questions

*Abstract not available at time of publication.

Thursday



Digital Imaging of the Chest from CR to DR

Carl E. Ravin, MD

Introduction

Since the initial discovery of the X ray by Roentgen, images have been recorded on film. A number of refinements have been introduced into this basic imaging chain, such as intensifying screens, modifications to the film, and fluoroscopic displays, but fundamentally the link between x-ray exposure and image display on film has remained. However, during the past two decades, rapid advances in electronics and computer technology have created new possibilities for x-ray imaging, including specific receptor systems independent of film which permit image information to be recorded in digital form for improved image transportation, manipulation, display, and storage. These systems include photostimulable phosphor computed radiography systems and a selenium-based digital chest system. Recently, a new generation of direct-readout x-ray detectors based on thin-film transistor (TFT) arrays has emerged, offering unsurpassed image quality from a compact digital detector.

Storage Phosphor Systems

Digital imaging systems that use a photostimulable storage phosphor imaging plate were first introduced by Fuji Photo Film, Tokyo, Japan, in 1983. Commonly called Computed Radiography (CR) systems, these devices are now widely used throughout the world.

Storage phosphor CR systems employ a reusable imaging plate in place of the traditional screen-film detector. Imaging plates and cassettes are available in standard film sizes, including 14x17 inches, which allows them to be used with conventional radiographic equipment. The imaging plate is coated on one side with a layer of photostimulable phosphor material. When exposed to x-rays, the plate stores some of the incident energy in metastable energy traps within the phosphor layer, forming a latent image on the plate. An automated image readout system scans the plate with a very fine laser beam, and as the laser beam strikes the imaging plate the stored energy is released as visible light, which is captured by the reader's photomultiplier tube and digitized, forming the digital image. The plate is erased by exposure to visible light, an operation performed automatically by the plate reader, and may then be reused.

The introduction of photostimulable phosphors opened the door to commercially feasible direct digital radiography. The linear response of photostimulable phosphors over an extraordinarily wide range of radiation exposures made their application particularly good for bedside radiography. Unfortunately image quality from early photostimulable phosphor plates was not particularly good, although the images looked reasonable in the "minified" form in which they were presented. Over the years phosphor plate technology has improved and contrast detail resolution is now significantly better with fourth and fifth generation plates. This has allowed images to be expanded in size and are now available in 14 by 17 format. Ultimately, however, CR image quality is generally only equivalent to that of conventional screen-film radiographs, and expansion of this photostimulable technology to conventional upright chest radiography in the radiology department has been more limited.

Selenium-based Digital Chest Radiography (Thoravision)

In 1993 a new device was introduced which produces direct digital images of the chest. This system is based upon a selenium detector. Amorphous selenium has long been recognized as an excellent detector of X-rays, and its detective quantum efficiency has been demonstrated to be significantly higher than that of other image detectors, both digital and conventional. Like photostimulable storage phosphors, selenium detectors possess a very wide dynamic sensitivity range which makes them well-suited for thoracic imaging; unlike storage phosphor systems, selenium-based detectors do not require stimulation for image readout, which eliminates a source of image noise and improves image quality.

The selenium-based chest radiography system employs an aluminum drum coated with a thin layer of amorphous selenium as the x-ray detector. Prior to x-ray exposure, the drum is rotated slowly beneath an electrical charging element which deposits a uniform positive charge density on the drum's surface. When the x-ray exposure is initiated, drum rotation is stopped and the x-ray exposure is completed, casting the radiographic image onto the drum. The x-rays discharge the selenium in an amount proportional to



the radiation intensity, which results in a latent charge image on the drum face. Immediately after exposure, the drum is rapidly rotated and the charge pattern is read out by microelectrometer probes, forming the digital image.

A number of theoretical, laboratory, and clinical studies of the selenium-based chest imaging system have been reported to date. In a laboratory study, Neitzel et al reported that the detective quantum efficiency of the selenium system exceeds that of both conventional screen-film and photostimulable storage phosphor systems. This suggests that the selenium-based digital images may be of inherently higher quality than previously available from any other system. In a separate study, Chotas et al described a technical evaluation of the selenium system as it is used clinically, reporting excellent image quality, reduced scatter fractions in the lung image regions relative to that found in conventional images, and the potential for reduced patient examination times due to the ease of patient setup and the rapid display of a low-resolution image after exposure (to verify proper patient positioning). Finally, an investigation was reported by Floyd et al which compared radiologists' preference between conventional films and laser-printed films from the selenium system for the visualization of 17 anatomical features in PA and lateral radiographs. Chest radiologists showed a marked and statistically significant preference for the digital images for visualization of all image features; non-specialized, general radiologists also showed a preference for the digital images, but the preference was significant only in 11 of the 17 imaging features. Observer performance studies will be required to assess the clinical significance of these findings, but the early evidence suggests that the selenium-based digital system offers the potential for significant improvement in image quality relative to other chest radiography techniques, both conventional and digital.

Direct-Readout, Thin-Film Transistor (TFT) Detectors

A new generation of digital X-ray imaging systems based on flat-panel detectors is now emerging, promising exceptionally good image quality and very rapid, direct access to digital images. Although a variety of approaches, designs, and materials are being used by different manufacturers to devise these new detectors, most are based on large-area, thin-film transistor (TFT) arrays. These multi-layered electronic devices offer compact packaging and direct connection to digital imaging networks, unlike CR

systems which have external image readout systems and the selenium drum system which has a large, free-standing detector unit.

One type of direct-readout system, currently under development by GE Medical Systems, is a large-area, solid-state X-ray detector consisting of a structured Cesium Iodide (CsI) scintillator directly coupled to an array of amorphous silicon thin-film photodiodes and readout electronics. The multi-layered detector is manufactured on a glass substrate, approximately 41 cm square. When exposed to X rays, the visible light is channeled within the CsI crystal matrix directly to the photodiode array where the electric charge is collected and digitized, forming the digital image. Because of its direct-readout design, structured scintillator, and the use of very-low-noise electronics, this flat-panel detector is anticipated to provide exceptionally high image quality.

Another style of direct-readout digital detectors utilizes the same type of TFT array for charge collection and readout, but the active detector element is amorphous selenium instead of a scintillator and photodiode. Because selenium is an x-ray photoconductor, X ray photons striking the detector are converted directly to electrical charge with no intermediate (visible light) stage. This direct conversion eliminates one step in image production, and thus removes one opportunity for noise to enter the imaging chain.

Image quality from digital acquisition systems is influenced by detector materials, design, and electronics, and it is unknown at this time which style of direct-readout digital x-ray receptor will offer superior performance. It is clear, however, that large-area, direct-readout digital detectors offer expanded opportunities in the radiology department.

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PACs for the Thoracic Radiologist

Philip A. Templeton, MD

Professor and Chairman, Diagnostic Radiology

University of Maryland

PACS Components

- Acquisition
- PACS/RIS Interface
- Networking and communication
- Archive : storage and retrieval
- Display

DICOM

- The standard for exchange of image data
- All new modalities should have DICOM output

Interfaces

- DICOM (Digital Images and Communications for Medicine)
 - Defines standards for exchange of images and related data
 - Conformance to DICOM does not = interoperability
 - All standards flexible to meet vendor needs, users cannot just plug and play
- HL -7 (Health level 7)

Acquisition

- DICOM interface
- Gateways for Non-DICOM modalities
- Film Digitization

RIS Radiology Information System

- The history of the radiology department
 - Work record
 - Billing record
 - Tracks individual productivity
 - Exam history
 - Reporting information
 - Links to HIS, PACS, Modalities, Dictation systems

Networks

- Local area networks
- Intranet
- Wide Area Networks
- Internet, WWW

Network

- Many different options and costs for communication
 - T1
 - Fast Ethernet
 - ISDN

- ATM
- Gigabit Ethernet

Storage - Archive

- Short term
- Intermediate term
- Long term
- Database management
- Storage
- Workflow management

Storage Options

- RAID
- MOD
- DLT
- CD-R
- Costs and retrieval times vary
- Back-up storage wise

Image Storage

- CR 10 MB / image
- CT 0.5MB / image
- MR 0.22MB / image
- US 0.3MB / image
- NM 0.5MB / image
- It all adds up to terabytes per year!

Compression

- Used to reduce image transmission time and storage requirements.
- Lossless (reversible) 3 : 1
- Lossy (non-reversible)
 - JPEG 5-10 : 1
 - Wavelet 10-80 : 1
- Compromise image quality for transmission speed and storage costs.

Display Monitors

- Diagnostic and non-diagnostic (radiologist vs. clinician)
- 1K or 2K resolution
- 2K for CR, 1K for all others
- 1, 2, 4 or 8 monitors
- High luminosity

PACS Reading Tools

- Display format options
- W/L manual or pre-sets
- Mag/zoom

- Annotate
- Measure
- Localizers, planar correlation
- ROI
- Invert
- Clinical history/prior reports

The Clinical Interaction

- Clinical consultation may decrease
- More of a trainer - not where is the film? But how do you do this?
- Images easily available outside of radiology
- Less reliance on radiologist interpretation unless reporting is clinically relevant
- In other words “real-time”, annotated, interactive
- More formal rounds or video conferencing may be needed

Benefits: CR

- Digital image acquisition
- Lower repeat rate, decrease patient call-backs
- Information available on network
- Image can be altered/manipulated for enhanced diagnosis

Benefits: PACS

- No lost studies
- Less scut work
- Medico legal protection and recovered revenue from lost films
- Time savings for all staff
- Increased throughput = increased customer satisfaction, revenues
- Enhanced teaching ability

(Disclosure Statement: Philip A. Templeton, MD, is a member of the Medical Advisory Board of AGFA. UMMS has a corporate partnership in CR and PACS with AGFA.)



Computer-aided Diagnosis for Chest Radiology



Heber M. MacMahon, MD

Professor of Radiology

The University of Chicago, Chicago, Illinois, USA

Objectives

This presentation will provide an overview of the current status of computer-aided diagnosis (CAD) in chest radiology. The basic concepts and potential applications of CAD will be discussed. After the presentation, attendees will understand the value of advanced image processing and CAD as it presently exists, and the potential of programs that are under development in research settings.

Introduction

Computer-aided diagnosis (CAD), in the broadest sense, includes all of the approaches that apply computer techniques to radiological diagnostic decision making. One such category includes programs that enhance diagnostic images for visual examination by segregating components of the same image (as in energy subtraction) or integrating different images (as in temporal subtraction).

A second group of CAD programs includes those that are designed to detect pathological abnormalities in the image (i.e., nodule detection). A third category includes those that use both clinical and/or radiological data to determine the most likely pathological diagnosis. This latter category would include the use of artificial neural networks for differential diagnosis of interstitial lung disease or pulmonary nodules.

Though only one of these methods (energy subtraction) is currently available for routine clinical use, others have advanced to the point where clinical implementation seems likely in the near future.

Image Enhancement Techniques

Energy Subtraction

Energy Subtraction (ES), exploits the energy dependence of x-ray attenuation by calcium to produce separate images of the bones and soft tissues. Two basic approaches have been used. One involves the use of two sequential x-ray exposures at different kVp settings. Although this approach has advantages, the inevitable time delay between the first and second exposure can introduce misregistration artifacts. The second approach involves the use of a single exposure with the use of two receptors sepa-

rated by a filter. This single exposure is embodied in the FCR 9501 ES chest radiography unit (Fuji Medical Systems U.S.A., Stamford, Conn.), which is the first commercial device to employ energy subtraction for chest radiography.

In all, three PA images are produced: a standard image, a soft tissue image, and a bone image. Although energy subtraction can be performed on the lateral view, the 9501 ES unit has not been designed to perform a lateral subtraction view routinely.

For departments already performing primary interpretation with workstations, it is necessary to develop a display that incorporates the ES images in addition to the standard PA and lateral views, while facilitating rapid comparison with previous examinations, which may also have ES images. We have implemented a workstation display that “stacks” ES images behind the standard PA view for both current and previous exams. When interpreting from hard copy, we review the ES versions of the images on workstations and re-print them when they provide additional information.

Because ES separates the calcium and soft tissue components of the thorax, it has obvious potential to improve detection accuracy for certain types of pathology. In a research and clinical setting, ES images have been shown to be significantly superior for detection of pulmonary nodules compared to either screen film or standard digital radiographs.

The “bone image” can be useful for confirming the presence of calcification in benign pulmonary nodules or in hilar lymph nodes. Rib abnormalities such as sclerotic metastases or bone islands that can mimic lung nodules are also more clearly visible in the bone ES images. Calcified pleural plaques that may be caused by asbestos exposure can mimic soft tissue abnormalities and can be mistaken for pulmonary nodules or consolidation when viewed en-face. In such cases, the bone image clearly reveals the calcified nature of the abnormality.

Temporal Subtraction

Digital radiography allows various types of image processing to be performed, but techniques that improve the visibility of abnormal findings also tend to



emphasize certain features of normal anatomy. Ideally, the visibility of pathological findings would be improved selectively, while normal anatomical structures would be suppressed. In the case of patients who have had a previous chest radiograph, an opportunity exists to enhance selectively areas of interval change, including regions with new or altered pathology, by using the previous radiograph as a subtraction mask. The temporal subtraction technique involves automated two-dimensional warping and registration of a previous with a current chest radiograph in order to produce a "difference image" in which unchanged areas appear as uniform gray while new opacities appear as isolated dark foci that stand out from the uniform background. Although the quality of the temporal subtraction image is affected by variations in patient positioning, this limitation can be partially overcome by the geometric warping that is performed.

One of the unique advantages of temporal subtraction is that it can highlight areas of subtle change that may not appear obviously abnormal when viewed in isolation, even with energy subtraction. Its ability to improve detection of a broad range of abnormalities, including nodules, infiltrative opacities, and local pulmonary perfusion deficits secondary to tumor in the pulmonary hilum are important advantages. This technique is currently being investigated in the setting of a lung cancer screening program in Japan.

Computer-aided Detection

Schemes for computer-aided detection that are currently under development include programs designed to detect pulmonary nodules, abnormal interstitial patterns, cardiomegaly, pneumothorax, abnormal thoracic asymmetry and pleural effusions in chest radiographs, and nodules in CT scans.

These programs differ fundamentally from energy or temporary subtraction, in that they perform an automated analysis of the image, using criteria developed from large numbers of normal and abnormal cases. The result is presented in the form of a graphic overlay that localizes and/or quantifies a suspected abnormality.

Nodule Detection

The rationale for this program is that radiologists commonly fail to detect early lung cancers that are visible in retrospect. Although there are several possible reasons for such oversights, failure of the radiologist to focus directly on the area of the lesion is a contributing factor in many cases.

The nodule detection program addresses this problem by directing the radiologist's attention to suspicious areas in the image. This scheme is designed to distinguish abnormal focal nodular opacities from the complex anatomic background of a chest radiograph

and to indicate them with arrows superimposed on the image.

At present the computer program has a sensitivity of approximately 70% for subtle pulmonary nodules with an average of one to two false positives per radiograph. Although this accuracy rate is slightly less than that of most radiologists, the errors of the computer program tend to differ from those of the radiologist. Consequently, use of this program can increase the accuracy of even experienced radiologists in the task of nodule detection.

Interstitial Lung Disease

Detection and quantitation of interstitial lung disease is subject to large intra and inter-observer variations. However, a range of pathologic processes, ranging from cardiac failure to inhalational dust diseases, can present with an abnormal interstitial pattern. Therefore, an automated computerized scheme for detection of pulmonary interstitial disease has been developed, using a Fourier transform method. Based on analysis of a large database, including both normal cases and abnormal with interstitial disease, detection and classification of abnormal interstitial patterns is performed. Two parameters are used: the root mean square (RMS) pixel variation, and the first moment of the power spectrum. Using this method, both sensitivity and specificity of approximately 89% have been achieved on a database including 100 abnormal cases.

In an observer test the diagnostic accuracy of the observers was improved by a statistically significant amount when the CAD scheme was used.

Interstitial disease CAD may be of particular value in cases with a clinical suspicion of interstitial lung disease, such as patients undergoing screening for pneumoconioses.

Other Detection Programs

Other CAD programs that might be classified in this general category include those for detection of cardiomegaly (automated detection of cardiac and rib cage borders, with CT ratio determination), and pneumothorax detection (identification of an abnormal pleural line in the apical area). Programs that detect abnormal thoracic asymmetry, which can indicate unilateral pulmonary or pleural disease, and one that analyzes the costophrenic angles for abnormal blunting, which can indicate pleural effusion, have also been tested. A scheme that detects nodules in thoracic CT scans is currently being developed and has potential utility in CT cancer screening programs.

Differential Diagnosis

When an abnormality has been detected on an image, a determination must be made as to the most like



etiology. This involves a complex decision-making process that takes into consideration the patient's medical history, physical symptoms and signs, as well as laboratory or imaging data. Experienced clinicians and radiologists learn to reduce a potentially overwhelming mass of information to a few salient points. A differential diagnosis is constructed based on the individual physician's experience and memory. While most radiologists can remember the important features of the more frequently encountered diseases, many have difficulty recalling all of the features of rare or unusual diseases. Few, if any, can recall the precise frequency with which certain signs, symptoms or radiographic findings occur at each stage of each disease, in the various age groups and patient populations.

ANN for Differential of Interstitial Lung Disease

Differential diagnosis of interstitial lung disease is a typical example of such a complex diagnostic process. Therefore, a pilot computer-aided diagnostic program was developed that uses an artificial neural network (ANN) to distinguish between various interstitial lung diseases using a combination of clinical parameters and radiographic features. The program was trained to distinguish between 11 types of interstitial lung disease, including sarcoidosis, miliary tuberculosis, lymphogenous metastases, interstitial edema, silicosis, pneumocystitis carinii, pneumonia, systemic sclerosis, eosinophilic granuloma, idiopathic pulmonary fibrosis, viral pneumonia and pulmonary drug toxicity. Ten clinical parameters were used for each case, including age, sex, duration of symptoms, severity of symptoms, temperature, immune status, underlying malignancy, history of smoking, dust exposure and drug therapy. Sixteen radiological findings were used, which included descriptors of the distribution and characteristics of the abnormal process as well as additional thoracic abnormalities such as lymphadenopathy, pleural effusions and cardiomegaly. Observer test results showed a significant improvement in radiologists' ability to diagnose interstitial disease correctly when the ANN was used.

An ANN approach has also been applied to the diagnosis of pulmonary nodules in terms of characterizing them as benign or malignant. In a pilot study, an ANN that considered image features such as size, margination and location was more accurate in distinguishing benign from malignant nodules than were radiologists.

Clinical Implementations of Computer-aided Diagnosis

A CAD system for mammography has been developed based on film digitization with a combination of

hardcopy interpretation and softcopy CAD display. Although such a system may have certain niche applications for chest work (i.e., screening programs for cancer or industrial lung disease), it seems unlikely that a film-based system would be widely accepted. Particularly when so many hospitals are converting to digital image acquisition, it would be logical to implement chest CAD in an all-digital workstation environment. In a PACS, chest CAD programs could be applied to images as soon as they were acquired. The CAD results could be stored as overlays that would be available for immediate display at the workstation.

Although CAD is at an early stage, sufficient objective data has been accumulated to indicate that certain existing programs can improve diagnostic accuracy, even in the case of experienced radiologists. As radiographic interpretation migrates from the traditional viewbox situation to the computer workstation, it seems likely that CAD, in various forms, will become an accepted tool for the practicing radiologist.

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Multidetector Row CT Pulmonary Applications

Theresa C. McLoud, MD

Objectives

1. To teach the attendee the basic physical principles of multislice CT scanner technology.
2. The attendee will learn the current and possible future applications in chest imaging.

Different technological approaches have been used by different vendors for multislice CT scanners. The literature at the present time is limited because these scanners are so new. At the Massachusetts General Hospital we have had the opportunity to work with the GE Light Speed Scanner over the past several months. This multidetector row scanner differs from that of a single slice scanner in that in addition to being divided into channels in the transaxial plane, it is also divided into sixteen elements in the longitudinal slice direction. Each measures 1.25mm as reflected to the iso-center of the scanner. At present, the scanner's data acquisition system is capable of sampling the outputs of up to four channels simultaneously.

A channel can be the output of a single element or the sum of the outputs of neighboring elements. For example, sampling the inner four elements (one element per channel) results in the acquisition of four 1.25 minimal channels. Summing the elements in groups of two, three, or four prior to sampling results in four 2.5mm channels, four 3.75mm channels and four 5mm channels respectively. The GE Light Speed Scanner provides data on four channels and is thus a four-detector CT scanner.

The patient can be scanned in a stationary position and a slice can be reconstructed from each of the four channels. This axial multislice mode is similar to conventional step and shoot CT but with two major improvements. First, for a given slice thickness of up to 5mm, cross sections may be acquired at up to four times the rate. Second, thicker slices may be reconstructed retrospectively using data from multiple DAS channels. A second way to use the four channels of DAS output is to scan with patient translation in a manner directly analogous to helical scanning on a one-detector CT scanner with the addition that data from all channels contribute to each reconstructed slice in 4D CT. One can tailor the slice profile retrospectively and select among different nominal slice widths; for example 5, 7.5, and 10mm for the 4X5mm detector configuration.

In 4D CT the concept of spiral pitch must be understood. There are two notions of collimation: pre-patient, which has to be wide enough to radiate all the detector elements serving the four DAS channels, and detector collimation, nominally the width of the group of detector elements serving a single DAS channel. In 4D CT pre-patient collimation is roughly four times greater than the inherent detector collimation which is set by the detector configuration. Thus, one can define the pitch of a multislice CT scanner by normalizing the table travel per rotation by pre-patient collimation or by detector collimation.

Some of the technical advantages of multislice CT include improved visualization of major blood vessels of the body, reduction or elimination of motion artifact, detection of malignant tumors too small to be seen with single slice techniques, large reductions in the required doses of intravenous contrast media and enhancement of CT as a tool for surgical planning. The multislice scanner acquires four imaging slices simultaneously by irradiating four rows of detectors along the z-axis with a single x-ray tube. It can thus acquire four times as many data per gantry revolution as a single slice CT scanner. This enables multislice CT to cover the same z-axis distance far more quickly if slice collimation is the same, to use thinner collimation if table speed is the same, and to retrospectively create thinner or thicker sections.

Applications in the Thorax

Data at this time is quite preliminary but multislice CT appears to be superior to single slice CT in detecting small parenchymal nodules in imaging for metastatic lung disease largely because it can provide a narrower effective section thickness. Thinner collimation and a higher pitch can be used to achieve the same length of coverage in a shorter scan time.

Compared with single slice CT multislice CT also offers advantages in evaluating the tracheal bronchial tree. It extends the length of coverage while simultaneously decreasing effective section thickness, resulting in visualization of more subsegmental bronchi at higher longitudinal resolution. Protocols developed at Stanford University for the airway are for a collimation of 1.25mm, a pitch of 6 and a reconstruction section thickness of 1.25mm and a reconstruction interval of 0.8mm.



Multislice CT also has advantages over single slice CT for the evaluation of pulmonary embolism because it provides greater length of coverage with improved image resolution through thinner collimation, that is a reduction in the required scan duration and thus the dose of IV contrast and reduction in motion artifact. Our protocol consists of a 1.25mm collimation, a pitch of 6, and a reconstruction interval of 0.8mm. A distance of 200mm can be covered in 21 seconds. CTA can be combined with CT venography of the pelvis and legs. Both scans can be performed with the same contrast injection.

In CTA for pulmonary embolism, image noise can cause heterogeneous attenuation of the pulmonary arterial tree. With multislice CT the signal to noise ratio can be increased by reconstructing images at a greater section thickness. Also, thinner collimation

can achieve better spatial resolution and confirm on multiple sections that apparent defects in small segmental or subsegmental arteries are due to intraluminal origin and not to volume averaging.

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Three-dimensional Imaging of the Thorax: Practical Applications

H. Page McAdams, MD
Duke University Medical Center
Durham, NC 27710

Learning Objectives

1. To understand basic principals of three-dimensional reconstruction techniques using helical CT data sets.
2. To understand the use of these techniques for evaluation of diseases of the thorax.
3. To review practical applications of these techniques for evaluation of diseases of the thorax.

Introduction

Axial imaging remains the diagnostic standard for CT evaluation of diseases of the thorax. However, two and three-dimensional reconstructions of helical CT data sets continue to play an increasingly important role. Not only are there situations in which these techniques improve diagnostic accuracy or confidence, these images can communicate the type, location, and extent of abnormality to referring clinicians in a way that the radiographic report and axial CT images often do not. This review will focus on a few practical applications of certain 3-D imaging techniques as they are applied to imaging airway and vascular diseases of the thorax. For a more thorough and in-depth review, the reader is referred to several recent, excellent articles [1-3].

Acquisition Parameters

Obviously, appropriate choice of CT acquisition parameters is of utmost importance for producing diagnostic quality 3-D images. Collimation, pitch and reconstruction interval are the most important parameters and their selection generally depends upon the specific application.

For imaging airways and pulmonary arteries, narrow collimation is best. On a single-detector-row scanner, we typically use 3-mm collimation with pitch 1.5 – 2.0. On our multi-detector-row scanner, we use 2.5-mm collimation with table speed of 15-mm per rotation. Most authors suggest that a 20-30% reconstruction overlap is sufficient for routine axial imaging. Thus, 3-mm collimation images can be reconstructed at 2-mm intervals. However, we typically reconstruct the data at 1-mm intervals when we plan to perform complex 2-D and 3-D renderings.

For routine imaging the aorta and branch vessels, we use 5-mm collimation, pitch 2.0 on our single-detector-row scanners and 3.75-mm collimation, table speed 22.5-mm/rotation on our multi-detector-row scanner. When evaluating suspected acute traumatic aortic injury (ATAI), we use a protocol similar to that used for pulmonary arterial imaging (see above). Again, a 20-30% reconstruction overlap is probably sufficient for axial imaging. However, we typically reconstruct the data at 1-mm or 2-mm intervals when we plan to perform complex 2-D and 3-D renderings.

Reconstruction Techniques

There are two different approaches for generating 3-D images from helical CT data sets: surface and volume rendering. Surface rendering (SR) uses threshold values to create a model of the volume of interest. For instance, when imaging the airways, threshold values are chosen so that the model represents the soft tissue-air interface along the inner surface of the airway. After this model is created the remaining data are discarded, significantly increasing computational speed. Volume rendering (VR) techniques preserve the entire data set and create 3-D images by varying the opacity and lighting of selected tissues. VR techniques are more computationally complex than SR techniques and require greater computing power and memory. However, VR techniques are inherently more flexible than SR techniques and are rapidly becoming the standard for 3-D imaging applications. 3-D images produced by either technique can be then viewed from either an external or internal perspective.

Airway Imaging

Axial CT is now the diagnostic standard for radiologic evaluation of the central airways. Helical CT has improved evaluation of the airways by virtually eliminating slice misregistration and respiratory motion artifacts. By obtaining a continuous volume data set during a single breath-hold, excellent non-axial 2-dimensional (2-D) and 3-dimensional (3-D) reconstructions can be generated. There are a variety of reconstruction methods that can be applied to airway imaging. These



include 2-D methods such as multiplanar (MPR) or multiplanar volume (MPVR) reformat techniques and externally and internally rendered 3-D images. These techniques vary significantly in computational complexity and thus in time required to generate images.

For imaging most diseases of the central airways, including tumors, stenoses and congenital abnormalities, axial CT images are usually sufficient for diagnosis. However, in some instances, oblique coronal and sagittal 2-D (MPR) reconstructions along the axis of the airway can be helpful for improving diagnostic accuracy or confidence, particularly in patients with airway stenoses. Also, clinicians often find these images useful for planning therapeutic procedures. It has also been shown that externally volume rendered 3-D images (CT bronchography) can be useful for demonstrating subtle airway stenoses and for identifying complex congenital anomalies of the airways [4].

Internal 3-D renderings of the airways, so-called virtual (VB) or CT bronchoscopy results in excellent depictions of the lumen of the central airways. Proposed uses for VB include screening for endobronchial malignancy, evaluating airway stenoses and as a “road map” for fiberoptic bronchoscopy (FOB) [5]. Unfortunately, experience thus far suggests that VB may not accurately detect and define the small mucosal and submucosal lesions typical of early endobronchial malignancy. Thus, the role of VB as a screening modality is questionable. Numerous authors have found that VB is as accurate as FOB and slightly more accurate than axial CT for evaluation of airway stenoses [6], although the differences reported in most studies are not statistically significant. We have found VB useful as a “roadmap” for transbronchial needle aspiration (TBNA) [7]. TBNA is a safe and effective means of staging the mediastinum and hilum in patients with suspected lung malignancy. Very high accuracy rates, rivaling those of mediastinoscopy, are reported from some academic centers. Yet, a recent survey of members of the American College of Chest Physicians showed that only 11% of practicing bronchoscopists performed TBNA [8]. Reasons cited for not performing TBNA include lack of experience, poor results and concern for damage to the bronchoscope with larger needles. In a preliminary investigation, we found that VB was useful for directing transbronchial needle aspiration in patients with enlarged mediastinal or hilar lymph nodes. Our bronchoscopists also felt that VB improved the yield of their TBNAs using smaller needles.

Vascular Imaging

Pulmonary Circulation

Contrast enhanced spiral CT is an accurate means for assessing both congenital and acquired abnor-

malities of the pulmonary arterial and venous circulation. It is a particularly important new modality for evaluation of suspected pulmonary embolism (PE) because it directly images clot in a less invasive manner than pulmonary angiography. Numerous studies confirm the high sensitivity (greater than 90%) and specificity of spiral CT for detecting clot in the central through segmental pulmonary arteries. In most cases, diagnosis of PE is made from review of the reconstructed axial images, often reviewed on a workstation in rapid viewing or cine mode. However, in some cases, particularly for evaluation of obliquely oriented vessels such as the right middle lobe and lingular arteries, non-axial 2-D reconstructions are necessary [9]. Three-dimensional renderings, as yet, have no demonstrated utility for evaluation of suspected PE.

Other, less common indications for helical CT angiography of the pulmonary circulation include evaluation of arterial and venous anastomoses in lung transplant recipients, evaluation of known or suspected pulmonary arteriovenous malformations (PAVM), evaluation of pulmonary arterial involvement due to central tumor, and evaluation of congenital anomalies of pulmonary venous drainage. In all cases, selected use of 2-D and occasionally 3-D renderings is necessary for confident diagnosis. In particular, 3-D reconstructions can be useful for delineating the often complex angioarchitecture of PAVMs prior to embolization.

Systemic Circulation

Major applications for CT angiography of the thoracic aorta include evaluation of suspected acute traumatic aortic injury (ATAI), known or suspected thoracic aortic aneurysm and evaluation of suspected thoracic aortic dissection.

CT continues to assume a greater role in the exclusion of suspected ATAI. Because helical CT angiography allows direct visualization of the aorta in multiple planes, emphasis is now shifting from imaging indirect signs of injury (hematoma) toward imaging direct signs of ATAI: aortic contour abnormality, pseudo-coarctation, demonstration of an intimal flap or pseudoaneurysm and frank extravasation of contrast. We have found, as have others, that 2-D and 3-D reconstructions of the aorta are often valuable for evaluation of suspected ATAI, particularly for reevaluation of the aortic isthmus [10].

Axial imaging is usually sufficient for diagnosis in cases of thoracic aortic aneurysm or suspected aortic dissection. In some cases, however, 2-D and 3-D reconstructions can improve confidence or accuracy in assessment of great vessel involvement. Also, these reconstructions present anatomic information in a



context more familiar to referring surgeons, who may prefer them to axial CT images, and thus replace conventional catheter angiography.

Summary

Helical CT continues to play an increasingly important role in the diagnosis and treatment of many diseases of the thorax. For most purposes, reconstructed axial images provide all necessary information for diagnosis. However, in some circumstances, 3-D imaging can be quite useful.

1. **Improved diagnostic accuracy or confidence.** 2-D and 3-D imaging can improve accuracy and confidence for diagnosis or exclusion of airway stenoses, pulmonary emboli, acute traumatic aortic injury or great vessel involvement in aortic dissection.
2. **Improved communication to referring clinician(s).** 3-D images rapidly and efficiently communicate the type, location, and extent of abnormality to busy referring clinicians. This may be particularly true in cases of helical CT angiography of the aorta, where CT can often replace catheter angiography, and in cases of airway stenoses.
3. **Improved CT reading efficiency.** Helical CT, and particularly multi-detector-row CT, is resulting in larger and larger data sets. In the future, it will be impractical and inefficient to interpret these data sets in traditional axial format. Alternative viewing formats, including cine viewing and non-axial 2-D and 3-D imaging may be required to efficiently review these large data sets. Perhaps then, the paradigm shift toward volumetric analysis of volumetric data will occur [11].

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Future Directions of Imaging Lung Cancer

*Edward F. Patz, Jr, MD
Duke University Medical Center
Durham, NC*

Objectives

1. Discuss the current limitation of imaging lung cancer
2. Describe new imaging techniques and biomarker development

There are over 170,000 new cases of lung cancer in the US each year, and lung cancer accounts for approximately 25% of all cancer deaths. The overall 5 year survival is approximately 14%, and has not significantly changed over the past several decades despite newer more aggressive treatment protocols.

The ability to non-invasively diagnose, stage, and follow patients with cancer has improved with current techniques, but there are clear limitations with conventional studies. These examinations typically provide anatomic and morphologic information, but are not always sensitive or specific enough to make clinical decisions.

It has become clear that new diagnostic strategies are essential if we are to have an impact on survival. Lung cancer is a genetic disease and integration of tumor biology will be essential if we are to have a significant impact on survival. Potential new areas to explore include:

- Tumor specific imaging agents targeting tumor cells or the local environment for diagnostic and staging, information. Nuclear medicine studies are more sensitive than conventional CT or MR.

- Development of non-invasive ‘tumor profiles’ which will provide diagnostic and prognostic information for treatment protocols. This will reflect the molecular characteristics of the tumor.
- Integration of biomarkers with imaging studies.

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PET Scan and Coincidence Scan Technology: How Does It Work?

David K. Shelton, Jr, MD

Associate Professor of Radiology

University of California Davis Medical Center

Learning Objectives

- (1) To learn the basic physiology and concept of functional tumor imaging with fluorine-18-FDG, as compared with conventional, anatomic imaging.
- (2) To understand the basics of image acquisition for dedicated ring-type PET imaging, coincidence camera based PET imaging, and high energy 511 keV SPECT imaging of FDG for oncologic applications.
- (3) To learn the efficacy of FDG PET imaging in the evaluation of solitary pulmonary nodules or focal pulmonary opacities.
- (4) Evaluate data concerning CT and conventional imaging, whole body PET imaging, and coincidence imaging in the staging and follow-up of patients with lung carcinoma.

Introduction

Numerous recent studies have shown Positron Emission Tomography (PET) to have significant clinical utility in the evaluation and staging of oncology patients. Because of its documented sensitivities, specificity, and accuracy, the Health Care Finance Agency (HCFA) has approved funding for (1) characterization of solitary pulmonary lesions and nodules with FDG, (2) staging and follow-up of non-small cell lung carcinomas, (3) whole body PET for recurrence of colorectal and colorectal metastatic cancer, (4) whole body PET for staging and characterization of Hodgkin's disease and non-Hodgkin's lymphoma, and (5) whole body PET for recurrence of melanoma or melanoma metastatic disease. Other tumor types are currently being scientifically evaluated for potential Medicare billing. Many private insurance payers also allow billing for myocardial PET evaluation, suspected recurrence of brain tumors and general tumor imaging.

Approximately 180,000 new cases of lung carcinoma are reported in the U.S. per year and lung carcinoma accounts for approximately 25% of cancer deaths. More than 130,000 new solitary pulmonary nodules (SPN) are identified in the U.S. per year. PET imaging with fluoro-18-deoxyglucose has been

shown to identify malignant nodules with up to 96% sensitivity and to improve the staging accuracy in up to 40% of these patients. In other studies, PET imaging has been shown to change management in 41% of patients with lung cancer by detecting unsuspected metastases or by indicating that abnormalities detected on conventional studies may not be malignant.

Fluoro-deoxyglucose (FDG)

Fluorine-18 is a positron emitter that is generated in a cyclotron by creating an unstable nucleus through the addition of positrons. The radiopharmaceutical, fluorine-18 fluoro-deoxyglucose (FDG) is a positron emitting glucose analogue with a half-life of 110 minutes. As the nuclei decay to stable state, they emit a proton (positive electron) which travels 1-2.7 mm and annihilates or reacts with an electron. This annihilation reaction releases two, 511 keV photons which travel in a line, almost exactly 180° opposite to each other. These two photons can then be detected with standard heavily collimated SPECT gamma cameras or with higher resolution and sensitivity, on a non-collimated coincidence detector and circuitry. The coincidence technique projects the line of origin or line of coincidence without the use of heavy photon limiting collimators.

The FDG enters the cell via the normal glucose transport mechanism and is phosphorylated within the cell by hexokinase to FDG-6-phosphate. This phosphorylation process essentially traps the FDG within the cell for imaging. Many tumors and their metastases are hypermetabolic, demonstrate increased glucose uptake, and actually utilize the FDG in preference over glucose. Therefore, malignant lesions show marked increased uptake compared to background and benign lesions. To ensure good image quality, patients must be fasting and if they are diabetic, their glucose levels should be below 200 mg/d/L before the fluorine-18 FDG is administered. Normal imaging times begin approximately 30-60 minutes after injection of FDG. The patient is kept in a quiet resting status to minimize muscular uptake. Normal body distribution of the FDG is to the brain and there is active excretion in the kidneys, ureters,



and bladder. Cardiac uptake is seen in association with oral glucose loading. Metabolically active tumors will have a very high level of activity or signal to noise versus background. Benign tumors typically show no increased activity but very active inflammatory processes may demonstrate mildly increased FDG uptake.

FDG PET Imaging in Focal Pulmonary Opacity

Chest radiography detects most of the solitary pulmonary nodules and most lung cancers. However, even with the utilization of CT it is often difficult to separate benign from malignant lesions. PET imaging provides physiologic and metabolic information that can non-invasively characterize those lesions which are indeterminate on chest radiography and CT scan. Overall, the sensitivity of PET with FDG is greater than 95% for determining malignant lesions. Failure to detect malignant lesions can be due to very small lesions which are less than 1 cm in size. Alveolar cell carcinoma and carcinoids have lower levels of glycolytic activity and thus may not be well seen on PET imaging. These lesions, however, can frequently be suspected based on clinical or CT evidence. Specificity for detecting malignancy within a solitary pulmonary nodule is reported to be approximately 85-88%. False positive lesions can occur in approximately 10-20% of indeterminate lesions usually due to granulomatous disease. A negative PET scan is associated with less than 5% probability of malignancy. If a lesion shows no uptake or very low uptake, the lesion could easily be followed by limited, non-contrast, thin cut CT. Decision analysis has shown that the combination of CT and PET is the most cost-effective management for solitary pulmonary nodules, and the addition of PET imaging has improved the accuracy of clinical staging.

Lung Carcinoma

In evaluation of hilar and mediastinal lymph node staging, numerous studies have shown PET sensitivity to be approximately 82-100% with specificities of 81-100%. Because the PET scan with FDG shows hypermetabolic activity, this compares favorably to reported CT sensitivity of 55-65% and specificity of 65-75% for nodal staging. In addition, whole body PET has been reported to detect a 10-25% incidence of distant metastases thus precluding surgery in patients thought to be resectable by conventional imaging. Abnormal lesions are detected by visual inspection of focally increased uptake which may be multiple or solitary. In addition, some investigators have utilized local regions of interest to provide a more objective value or threshold for evaluation and fol-

low-up. This standard uptake ratio or SUR is equal to mean ROI (MBq per ml) \div injected dose (MBq \div body weight in kg). Mean SUR for malignant lesions is reported at 5.9 ± 2.7 with a range of 2-20. Benign lesions have shown SURs of 2.0 ± 1.7 . SUR levels greater than 2.5 to 4 usually indicate malignancy, however, most nuclear medicine physicians utilize visual evaluation. Utilizing a SUR threshold of 2.5, reported sensitivity is 92% and specificity of 90% for malignancy. With visual analysis only, the same reviewers show 98% sensitivity, but 69% specificity.

Whole body PET scans can also detect unsuspected, extra-thoracic metastases resulting in up to 41% of patients having management changes based on these findings. One series evaluating distant metastases found on whole body PET scan, demonstrated a sensitivity of 100%, specificity of 94% and accuracy of 96%. In this series, 34% of patients had changes in clinical staging and 20% had changes in clinical management. Common sites of metastases are the liver, adrenal glands, skeletal system, and brain. Adrenal metastases in lung cancer can occur in up to 20% of patients and yet many adrenal masses represent adenomas or hyperplasia and may be indeterminate after conventional imaging. Studies have shown PET scan in lung cancer patients to be up to 100% sensitive and 80% specific for metastatic lung cancer to adrenal glands. Small cell lung carcinomas and metastases are also FDG avid and whole body PET imaging has been reported to be clinically useful in the initial staging and follow-up of small cell lung carcinoma, as well.

Therapeutic Response and Potential Lung Cancer Recurrence

Conventional imaging with chest radiography, CT, or MRI relies primarily on bidimensional measurements of tumors and lymph nodes for evaluation of tumor response or tumor recurrence. Accurate evaluation is frequently difficult, secondary to post-treatment necrosis, scarring, and fibrosis due to chemotherapy or radiation treatment. Many oncologists are interested in the potential of utilizing FDG uptake or serial decrease in uptake, as a way of following initial therapeutic response. An early 75% reduction in FDG uptake has been associated with good tumor response. Poor response has been associated with poor outcome. PET imaging has shown to have a sensitivity of 97-100%, specificity of 62-100% and accuracy of 78-98% for detecting early recurrence of tumor.

Positron Imaging Modalities

There are currently three acceptable modalities for imaging positron emitting radiopharmaceuticals: (1) dedicated ring type PET scanners, (2) hybrid dual-head coincidence PET scanners, and (3) heavy





collimator SPECT scanning. Traditional PET scanners have utilized a fixed ring of detectors most commonly composed of bismuth germinate (BGO). BGO has a high atomic number and high density resulting in high stopping power for the 511 keV photons that are admitted after the annihilation reaction. Dedicated ring-type PET scanners are limited to 511 keV coincidence imaging and are very costly. A variation on full ring PET scanner are the less expensive dedicated PET scanners, composed of rotating banks of BGO detectors which also allow imaging of the 180° opposed, coincidence photons. More recently, new hybrid, two and three-headed gamma cameras have been designed to detect and image the same coincidence 511 keV photons. These cameras are usually 25-30% of the cost of a dedicated ring type PET camera and can be utilized for other conventional nuclear medicine imaging such as general SPECT scans, cardiac SPECT scans, and whole body imaging. The detector technology remains as sodium iodide crystals, which are doped with thallium and have a high light output with good position and spatial resolution. This allows the cameras to also be utilized for lower energy tracers such as thallium, technetium, and indium. These crystals, however, have less stopping power and therefore have lowered detector sensitivity for the higher energy photons at 511 keV. Therefore, many vendors have increased the crystal thickness from 3/8 inch and up to 3/4 inch (19 mm) in order to improve detector sensitivity, photon count rates, and thus better spatial and contrast resolution. New crystal technology is also being evaluated. Inherent resolution of these hybrid systems is approximately 4-6 mm which is similar to clinical PET scanners. However, clinical resolution is approximately 7-8 mm, which is approximately 1mm less than a dedicated PET scanner. Hybrid, coincidence cameras also have difficulty if the level of radioactivity in the field of view is too high. Typical coincidence cameras can handle 12,000 to 20,000 counts per second versus up to 350,000 counts per second for dedicated PET detectors. For hybrid coincidence cameras, this requires a lower injected dose or longer waiting times after injection which may actually increase the signal to noise ratio within a malignant lesion.

Attenuation correction is also very important to image contrast and image quality. Most dedicated PET scanners currently utilize transmission scans to generate attenuation maps which help to compensate for variability in body thickness, composition, and attenuation. Improved image quality with attenuation correction has been a major advantage for dedicated PET scanners versus hybrid coincidence scanners, to date. However, hybrid coincidence PET cameras

continue to improve count sensitivity, image quality, and are currently adding attenuation correction systems. Preliminary reports for hybrid coincidence PET imaging demonstrates 90-100% sensitivity for malignant nodules with a specificity of 66-85%. For mediastinal and hilar nodal staging, hybrid coincidence imaging has demonstrated a 78% sensitivity, 93% specificity, and 87% accuracy. For 1 cm or larger lesions, hybrid coincidence PET imaging correlates well to PET imaging. However, for lesions less than 1 cm in size, dedicated PET imaging has shown a clear advantage over non-attenuation corrected coincidence cameras.

Conclusion

PET imaging with FDG has shown improved sensitivity, specificity, and accuracy for evaluating solitary pulmonary nodules, as well as in staging lung carcinoma patients, compared with conventional imaging. Coincidence imaging with hybrid cameras has shown good correlation with dedicated PET systems, and improvements in coincidence technology will likely improve the accuracy of staging, as well. (Disclosure Statement: David K. Shelton, Jr, MD, is a research collaborator with Picker International.)

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Pulmonary Embolism: Diagnostic Approach in the New Millenium

Mayur M. Patel, MD

Introduction

Evaluation of a patient with suspected pulmonary embolism continues to remain a diagnostic challenge. Clinical presentation is variable and rarely diagnostic. Laboratory tests are improving but still have limitations. With the availability of several new imaging modalities in this past decade, the diagnostic algorithms have also changed.

Objectives

1. Brief review of clinical presentation of pulmonary embolism
2. Review of various modalities available in diagnostic approach;
 - Plasma D - dimer assay
 - Ventilation - Perfusion lung scanning
 - Duplex ultrasonography
 - Synthetic peptide scintigraphy
 - Contrast enhanced computerized spiral CT
 - Magnetic Resonance Angiography
 - Transesophageal echocardiography
 - Selective pulmonary angiography
3. Review of recently proposed diagnostic algorithms with special emphasis on advantages and disadvantages of contrast enhanced computerized spiral CT and ventilation perfusion lung scanning as the initial imaging modality.

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Pulmonary MR Angiography

Andre J. Duerinckx, MD, PhD

Abstract not available at time of printing

Oxygen-enhanced MR of the Lung

Hiroto Hatabu, MD, PhD

*Associate Professor of Radiology, Director of Pulmonary Functional Imaging Research
University of Pennsylvania Medical Center*

The assessment of regional ventilation in human lungs is important for the diagnosis and evaluation of a variety of pulmonary disorders including pulmonary emphysema, diffuse lung disease (i.e., sarcoidosis, pulmonary fibrosis), lung cancer, and pulmonary embolism. Oxygen modulates MR signals of blood and fluid through two different mechanisms; (1) a paramagnetic property of deoxyhemoglobin and (2) a paramagnetic property of molecular oxygen itself.[29,30] Molecular oxygen is weakly paramagnetic with a magnetic moment of 2.8 Bohr magnetons.[30,31] Young et al demonstrated reduction in T1 relaxation time of blood at 0.15 Tesla after inhalation of oxygen.[30,32] After inhalation of 100% oxygen, the concentration of dissolved oxygen in arterial blood increases by approximately five times.

Recently, we have demonstrated the feasibility of oxygen inhalation to evaluate regional pulmonary ventilation and examined the effect of oxygen inhalation on relaxation times in various tissues.[33,34] Signal changes from the right upper quarter portion of the right lung following alternate administration of 10L/min air (21% oxygen) and 100% oxygen via a mask are demonstrated. Calculated T1 values of the lung with various TIs before and after administration of oxygen were 1336 ± 46 ms and 1162 ± 33 ms, respectively. The observed change in T1 value confirms that molecular oxygen can be used as an effective T1 shortening agent in the assessment of ventilation in humans. Single-shot fast SE sequence was used to obtain MR signal from lung parenchyma, which has very short

T2* value. The sequence is T1-weighted by the inversion recovery preparation pulse.

Laser-polarized Xe-129 and He-3 were proposed for ventilation MR imaging.[35-38] These noble gases can be hyperpolarized using optical pumping technique. MR signal from these noble gases may be increased by 100,000 times compared with the MR signal in a thermal equilibrium state. The strong signal from the noble gases enable the acquisition of the data from gas itself. A preliminary clinical study by Kauczor et al demonstrated feasibility in assessing various pulmonary diseases including chronic obstructive lung disease, bronchiectasis, and lung cancer.[39,40] Diffusion of these noble gases impeded by alveolar structure can be measured. In addition, Xe-129 can be dissolved in blood, which may enable perfusion imaging as well as functional brain imaging.[41] Recent spectroscopic technique with Xe-129 demonstrated the possibility of separating the signal from lung parenchyma and blood.[42] Xe-129 may be injected intravenously for delivery to the lung and vasculature.[43] The hyperpolarized noble gas techniques provide new exciting applications.[44]

Although extremely promising, these agents are not ready for routine clinical use because of the high costs of noble gases and the apparatus for laser-polarization as well as the narcotic effects of large concentrations of inhaled noble gases. Any gases other than oxygen utilized for ventilation study, i.e., radioactive gases or hyperpolarized gases, are either heavier or lighter than oxygen. Therefore, the behavior of these



gases may be different from oxygen in the lungs with gravitational effect.

The oxygen-enhanced MR ventilation technique utilizes conventional proton-based MR imaging. Oxygen is available in most MR units for patients and its administration is safe and inexpensive. Thus the oxygen-enhanced MRI technique for assessing pulmonary ventilation has the potential to provide a noninvasive means of assessing regional pulmonary ventilation at high resolution. Combined with the MRI perfusion studies, this technique has the potential to have a major impact on the diagnosis and assessment of a variety of pulmonary disorders.[45]

MR assessment of pulmonary ventilation-perfusion is possible when combined with recent first-pass contrast-enhanced MR perfusion technique using Gd-DTPA.[15,23,45,46] The combination of ventilation-perfusion techniques is particularly interesting when airway obstruction and pulmonary embolism, two classic disease models of the lung with contrasting radiographic manifestations are studied. Airway obstruction causes regional hypoxemia, which elicits hypoxic vasoconstriction, resulting in an accompanying decreased regional perfusion. Therefore, matched regional ventilation-perfusion deficit is expected when a combined ventilation-perfusion imaging study is performed. In contrast, pulmonary embolism does not cause airway obstruction. Therefore, regional perfusion deficit without ventilation deficit (mismatched ventilation-perfusion) is expected on the combined ventilation-perfusion imaging study. [45]

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