MAGNETIC RESONANCE IMAGING OF THE THORACIC CAVITY USING A PAUSED 3DFT ACQUISITION TECHNIQUE

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A new pulse sequence designed for magnetic resonance imaging of the entire thoracic cavity is described. This sequence, called 3DPAUSE, is a rapid three-dimensional Fourier transform (3DFT) sequence with periodic pauses for breathing and additional rf pulses after each pause to restore the magnetization to steady-state before data acquisition resumes. Cardiac motion artifacts are effectively removed by signal averaging. Respiratory motion artifacts are removed by breath hold. Image artifacts caused by an inadequate number of pauses or by inappropriate placement of the pauses within a scan are shown, and ways to avoid these artifacts are discussed. 3DPAUSE provides the ability to acquire three-dimensional arrays in the thoracic cavity with minimal artifacts from respiratory and cardiac motions in a clinically reasonable time.

Keywords: Lung, MR studies; Thorax, MR studies; Magnetic resonance (MR) pulse sequences.

INTRODUCTION

Magnetic resonance (MR) imaging of the thoracic cavity suffers from many problems, foremost of which are cardiac and respiratory motions and limited signal from the lung parenchyma and pulmonary structures. Conventional solutions, such as gating and repeated signal averaging, result in total scan times for many-slice scans that are clinically unacceptable. Thicker slices can be taken to increase SNR per slice, but only at the cost of decreased resolution in the slice direction. A new pulse sequence called 3DPAUSE is presented here as an important step towards addressing the problems of MR imaging in the thoracic cavity.

MATERIALS AND METHODS

3DPAUSE is a rapid-imaging (limited flip angle, gradient echo) three-dimensional Fourier transform (3DFT) pulse sequence with built-in pauses for breathing. The 3DFT technique is well documented in the literature. Diagrams of the sequence and the corresponding filling of k-space are shown in Fig. 1. The unique feature of the 3DPAUSE sequence is the set of additional rf pulses that are played out after each pause to restore the longitudinal magnetization to its steady-state value before actual data acquisition resumes. During these restoration pulses, the rf and the gradients are turned on, but the phase-encoding gradients are not incremented and data acquisition is not enabled.

The minimum echo time (TE) obtainable with 3DPAUSE is 9 msec. When flow compensation (moment-nulling) gradients are added (not shown), the minimum TE is increased to 13 msec.

Respiratory artifacts are eliminated by breath hold. The patient holds his/her breath during data acquisition and breathes only during the pauses. Pauses are initiated by the 3DPAUSE program. The frequency of the pauses is operator-definable but fixed throughout the examination. The duration of each pause is individually variable. After a pause, scanning is restarted either by the operator at the console or by the patient squeezing a plastic bulb connected pneumatically to the system console. Patient initiation of a pause offers advantages; however, as explained below, placement of the pauses within the scan is important.

Acknowledgments—The authors would like to thank Dr. Lawrence Hedlund for animal care support, Dr. James MacFall for help in understanding the pause-related artifacts, and Ms. Sharon Ziv for continued computer and image analysis aid. This work was supported in part by the NSF/ERC grant #CDK-8622201 and the NIH training grant #HL07063.

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Received 9/22/89; Accepted 6/20/90.
During dummy pulses, phase encoding gradients are not played out and data acquisition is not enabled.

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Fig. 1. (A) 3DPAUSE pulse sequence. After a pause, \(N\) restoration pulses, without gradient incrementation or data acquisition, are played out to restore steady-state longitudinal magnetization, followed by \(M\) normal acquisition pulses. The scan is automatically paused after every \(N + M\) pulses.

(B) Three-dimensional k-space. The differently shaded areas each represents a region filled by 3DPAUSE between two consecutive pauses. Placement of the pauses is operator-definable.

Also, communication protocols on our scanner do not allow an interactive resume-scan signal. We felt that the difficulty coordinating patient breathing with a fixed period plus the flexibility of a variable-length period justified stopping the sequence for each pause.

Cardiac motion artifacts are removed by the signal averaging inherent in the 3DFT technique. No cardiac gating is necessary, and gating is avoided because of the significant increase in total scan time it requires. Signal averaging has been successfully used by others to suppress motion artifacts. The resultant images show slight blurring of the heart but no propagation of discernible ghosts in either of the two phase-encoding directions.

The problem of low signal from the lungs, compounded by the constraint on total scan time imposed by clinical utility, was treated by using a 3DFT acquisition technique with a limited flip angle and gradient refocussing. The limited flip angle allows the signal to be maximized for the short repetition times (TRs) required by the limited total scan time.

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All images were produced on a 1.5 T, 1.0 m bore GE Signa clinical MR scanner with a quadrature body coil (GE Medical Systems, Milwaukee, WI). A phantom as well as canine and human subjects were imaged. The stationary phantom allowed pause-related artifacts to be separated from those associated with motion. All human subjects were informed and consenting healthy adult volunteers following a protocol approved by the Duke Institutional Review Board. All images were acquired on 256 x 128 matrices. Pause frequency and duration were adjusted to suit the volunteers and to place the pauses at the edges of k-space if possible in order to reduce artifacts (see below). For the human images shown here, pauses occurred approximately every 20 sec and lasted 5–10 sec. When restoration pulses were played out, enough (50 pulses) were used so that at the start of acquisition, the change in the value of the longitudinal magnetization between successive rf pulses was less than \(\pm 0.01\%\), assuming \(T_1\) values in the range 800–1000 msec at 63.5 MHz for healthy human skeletal muscle, heart and lung tissues. This was found in the phantom tests described below to be more than sufficient for elimination of pause-related artifacts. For imaging of the dog and human volunteers, first-order moment-nulling gradients in the readout (x) and slice (z) directions were included to reduce flow artifacts.

Initially it was hypothesized that cardiac motion
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