SINGLE-STATION WHOLE-BODY REAL-TIME MAGNETIC RESONANCE IMAGING

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1. INTRODUCTION

Systemic disorders such as atherosclerotic vascular disease, collagen diseases, vasculitides, and inflammatory myopathies affect many segments in the human body [1]. Therefore, for diagnostic purposes, a large anatomical territory needs to be rapidly covered at moderate-to-high resolution in, ideally, a single examination. Coverage of more than 100 cm is usually required. One of the major challenges to all existing and contemplated magnetic resonance (MR) imaging techniques is to acquire a large 3D diagnosing image in one-two minutes.

Recently, we have proposed an interactive large field-of-view (LFOV) MR imaging technique using a continuously moving table method [2,3]. In our technique, the large image is constructed while moving the patient through the scanner during MR excitation and data acquisition, *i.e.,* single-station large image acquisition. In this paper, a novel implementation strategy for fast and accurate whole-body MR imaging based on our method is presented. Rather than restrict the continuously moving table technique to a constant translation rate [4], a more general approach is investigated here. In our approach, the motion of the patient table is independent of data acquisition. Therefore, one can optimize the table movement to the physiological dynamics and achieve an optimal compromise between the space and time properties of the pathology in the body.

In implementing the proposed method on a commercial MR scanner, however, significant engineering issues arise [5]. The feasibility of the proposed technique is investigated in this work. We accomplished our objective by developing a unique real-time whole-body MR imaging system based on the interactive LFOV moving table method. The results from phantoms and humans show the possibility of rapidly acquiring isotropic, large continuous images while interactively moving the table in response to the real-time visualized data. In this paper, we address the practical aspects of the LFOV MR imaging technique.

2. REAL-TIME LARGE FOV IMAGING

MR is a unique radiological imaging modality in which the raw data is acquired in the spatial frequency domain, known as **k**-space, rather than image space. A LFOV is built up by acquiring **k**-space data as a local FOV$_x$ is translated along the patient in the x-direction (Figure 1) [2-4]. Initially a spatially limited region is encoded and some **k**-space data are acquired. LFOV acquisitions at a particular (k_y, k_z)-phase-encoding value acquire all k_x-readout data in this region and this is immediately Fourier transformed and placed into a hybrid (x, k_y, k_z)-space. As FOV$_x$ is translated, the entire hybrid (x, k_y, k_z)-space is collected. The superior portions of the image are reconstructed by applying Fourier transformations in the k_y- and k_z-directions to the data already acquired [2,3].

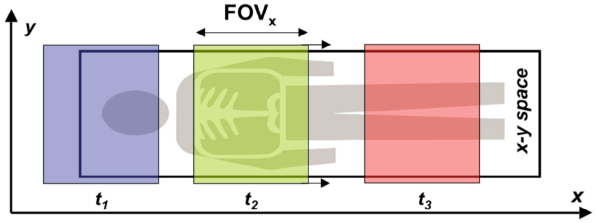

Figure 1: The large FOV is built up as the local FOV$_x$ is continuously translated along the patient. Shown are three FOV$_x$ locations at time-points t_1, t_2, and t_3.

Large FOV imaging when applied to dynamic imaging such as passage of contrast materials in the peripheral arteries is a logical extension of the 4D (3D space + time) sampling problems associated with time-resolved MR angiography [6]. In contrast-enhanced techniques, the optimal image quality is achieved when the translation of FOV$_x$ occurs during the arterial passage of the contrast agent [7]. In conjunction with real-time reconstruction of the hybrid-space and rapid visualization of the images, the control of the table movement is tailored to specific contrast dynamics [3].

To verify the proposed technique and to understand its space-time relationship, computer simulations were performed [3,7]. We have recognized that it is not necessary (and sometimes impossible) to collect the full hybrid-space data; thus we developed strategies that optimize local and overall image quality [7]. Our findings demonstrate that high-resolution LFOV images can be generated within a few minutes.

3. MATERIALS AND METHODS

3.1. Implementation Overview

Acquisition of LFOV images consists of preparing the patients with their superior area of interest at the magnet iso-centre, zeroing the position-encoding system, and then acquiring the LFOV image interactively by moving the patient in response to the real-time feed-back. To implement this technique on a commercial MR scanner three significant issues need to be considered: (a) patient table position must be recorded precisely so that the readout data can be placed into hybrid-space correctly, (b) real-time acquisition, reconstruction and display must be developed, and (c) scanner-operator interaction must be enabled (Figure 2) [3,5].

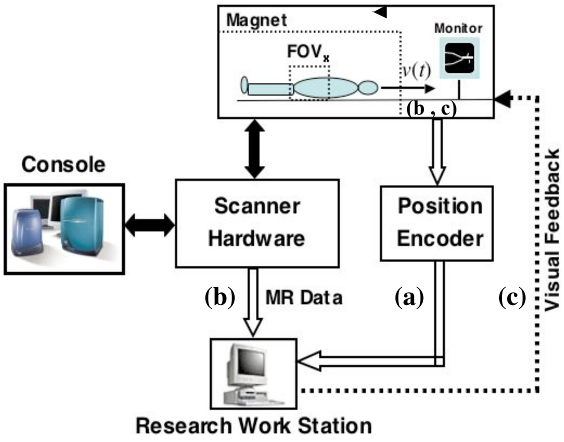

Figure 2: Implementation of the LFOV *real-time MR imaging method on a clinical MR scanner (see text for a, b, and c).*

3.2. Hardware interfaces

We have developed a real-time interface for our clinical 3.0 T MR scanner (Signa, software 8.5M4; GE Medical Systems, Waukesha, WI) that reconstructs the images rapidly on a research workstation (Dual 2 GHz Xeon; Dell, Round Rock, TX) designated for the real-time system. We have designed and successfully tested a linear, high-resolution, wide-range (> 2.5 m), bidirectional, and MR-compatible position-encoding system to provide accurate table positions. Figure 3 shows the custom-designed position encoder (PE) module and its output signals. The PE module consists of a mylar polyester coded disk and a phased-array optical encoder module built of a lensed optical source and a monolithic detector integrated circuit (E6S; US Digital, Vancouver, WA). This module transmits the position data through two channels (A and B) in quadrature serial format, as shown in Figure 3. To encode the direction of the table motion and to quadruple the spatial resolution, the outputs of channels A and B were 90º out-of-phased. The wheels convert the linear motion of the table to an internal rotary motion used for generating the A and B signals. One complete rotation of the wheels produces 2048 pulses on each channel. With 65 mm-diameter wheels, a resolution of about 25 μm was achieved. The PE module is mounted to the end of the patient table and slides safely inside the magnet bore.

Figure 4 presents the hardware modules of the real-time system. A quadrature position encoding circuit was designed and built to read the PE outputs. An internal 22 MHz oscillator (OSC) continuously updates position measurements inside the position encoding system. The transmitted data from the PE module are converted to 24-bit parallel data readable by the parallel port of the research workstation in three consecutive 8-bit measurements. The parallel port also receives an optically-isolated trigger signal from the scanner hardware after proper signal conditioning. The trigger signal, originated from the MR scanner, is a square-wave signal pulsing at every repetition time (TR > 2 ms) of the MR sequence, *i.e.*, at each MR excitation. A fibre-optic bus-to-bus adapter (618; SBS Technologies, Albuquerque, NM) between the scanner VME chassis and the PCI bus in the research workstation was used to directly acquire the real-time MR readout data from the scanner memory. The delay in acquiring each sampled readout echo was only one TR. Separate power supplies and optical isolator/link were used to reduce electromagnetic noise, to avoid ground loops to ensure patient safety, and to minimize unwanted signal interference between the scanner hardware and the custom-built real-time system.

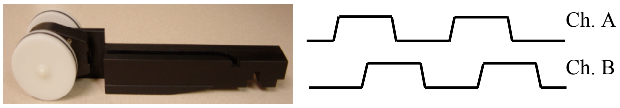

Figure 3: Custom-built position encoder (PE) module and its 90° out-of-phase serial outputs.

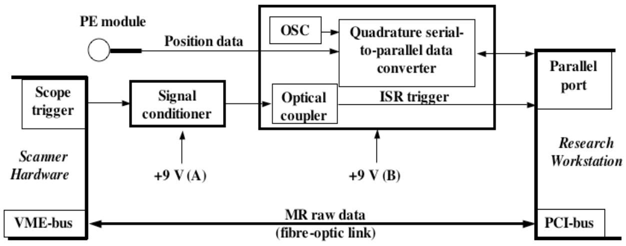

Figure 4: Extra hardware interfaces added to a conventional scanner for the LFOV *real-time MR imaging system.*

3.3. Software program

A software program, written in Visual C++ (Microsoft, Bellevue, WA), the open source Tcl/Tk, and VTK (Kitware, Clifton Park, NY), reads the table position and the sampled readout data directly from the hardware at every TR and continuously reconstructs the images. Figure 5 shows the flowchart of the LFOV real-time MR imaging software program and its major subroutines. The program consists of two main routines: data acquisition and image reconstruction. The data acquisition routine is responsible for real-time acquisition of the table position and MR data, real-time data processing and accurate construction of the large hybrid (x, k_y, k_z)-space. The data acquisition routine is an interrupt service routine that is externally triggered by the hardware and runs at every TR, whereas the image reconstruction routine runs continuously to reconstruct on-line images from the updated hybrid-space data. The latter is also responsible for displaying the images on VTK windows. Preview images are reconstructed and displayed on an in-room, MR-compatible, monitor (Elo TouchSystems, Fremont, CA) accessible to the operator conducting the procedure as the patient is moved through the scanner magnet. The dashed double-side arrow in Figure 5 indicates where the data for reconstruction are shared between the two routines. The process of 3D reconstruction has been broken into two separate processes, *i.e.*, in the x- and (y, z)-directions, allowing decoupling the table motion along the patient from the data acquisition. The program performs Fourier transformations on the readout and the phase-encoding directions independently, each on a separate processor using a multithreaded method, to reconstruct the images.

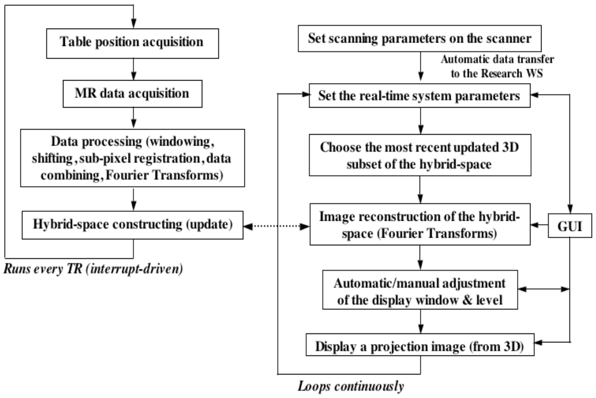

Figure 5: Flowchart of the interactive LFOV real-time MR imaging software program and its major subroutines.

The graphical user interface (GUI) module, written in Tcl/Tk, facilitates the usage of the program. It provides the operator with an interactive monitoring of the real-time images inside the magnet room and the console room. The user can change some parameters in real-time and be aware of the settings. A C++ program was written to act as a complete real-time large FOV imaging system coordinator which integrates the data acquisition, image reconstruction and visualization, and the GUI. This contains a software background process that is in charge of the initialization and coordination of different subroutines. Lower-level software was also developed to connect the hardware interfaces to the software routines. Fast spoiled gradient-recalled echo pulse sequences were modified to work in real-time mode with undersampled acquisitions options [5,7]. These sequences are used for MR excitations and measurements.

Currently, the real-time system is capable of displaying six to thirty projection images (from a 3D acquisition) per second with less than 100 ms delay on an in-room monitor while the patient table is translated.

3.4. Experimental Method

To evaluate the implemented system in interactively acquiring large images, human and phantom experiments were conducted. Four healthy volunteers and two large phantoms (conventional and angiographic) were scanned. The angiographic phantom was constructed of plastic tubes of different sizes representing the aortic bifurcation and distal arteries in the legs. The phantom was filled with water pumped at average flow rate of 1.2 L min^{-1}. Contrast agent of 20 mL was injected at 1-2 mL s^{-1}. This presents a challenge for the real-time system to verify its ability in imaging and tracking dynamic physiology such as the passage of the contrast materials in the large arteries. The (k_y, k_z)-phase-encodings were acquired independent of the table motion. Following scan parameters were used: undersampled acquisitions of 10%-30% hybrid-space coverage [7], TR range 4-20 ms, flip angle range 5°-30°, number of slices range 16-32, and total scan time range 40-90 s using a volume body coil. The local moving FOV$_x$ and the LFOV were 30-48 cm × 30-48 cm × 5-15 cm (256 × 128-256 × 16-32 acquisition matrices) and 110-145 cm × 30-48 cm × 5-15 cm (768-1280 × 128-256 × 16-32 reconstruction matrix), respectively. No image post-processing was performed.

4. RESULTS

The technique was successfully demonstrated in all subjects. Figure 6a illustrates a position-time curve of the table for a real-time LFOV acquisition obtained from a human experiment. Figure 6b shows a middle slice of the acquired large continuous 3D volume, which faithfully visualized the abdomen and the lower limbs of the subject with minimal artifact. Note the non-constant and the inverse motion of the table at 30 s and 50 s (circles in Figure 6a) without affecting the image quality. Warping due to gradient magnetic fields non-uniformity was greatly minimized in the LFOV images by using a fast

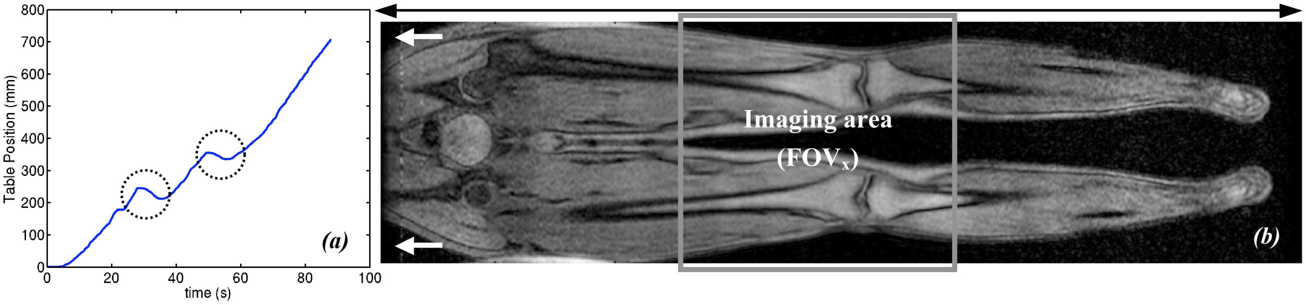

Figure 6: Results from human experiments. (a) Table position-time curve during the LFOV data acquisition, (b) A middle slice of the real-time 3D LFOV image from a volunteer showing his abdomen and lower limbs. White arrows show motion direction.

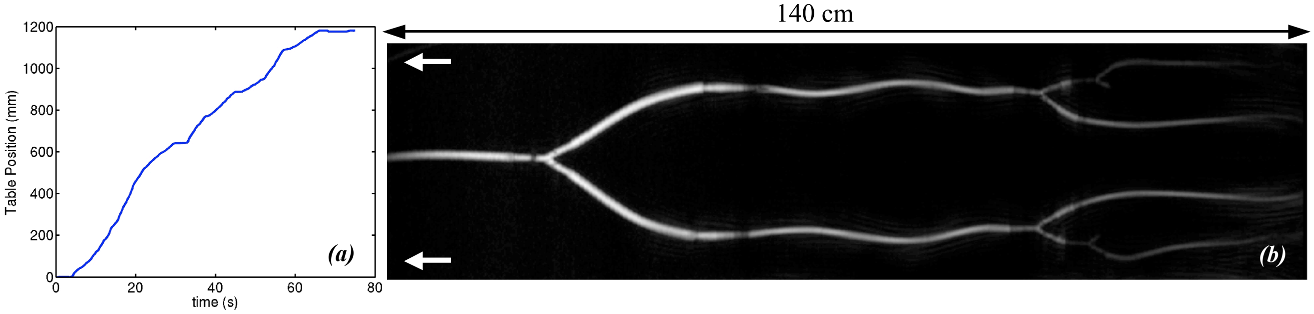

Figure 7: Results from phantom studies. (a) Table position-time curve during real-time following the contrast, (b) Projection LFOV *image reconstructed from the 3D angiographic phantom acquisition illustrating the contrast-enhanced vessels.*

MR data-combining algorithm [8] such that its effects only appeared at the most superior portion of Figure 6b. Figure 7a illustrates the table position profile during the angiographic phantom scan. The contrast material was successfully tracked in real-time producing a large angiogram, shown in Figure 7b, within 75 s. The tubes are well depicted with less intensity in the inferior ones due to their smaller size and diluted contrast in this region. No difference was seen when applying phase twisting along each readout data for subpixel registration as required in the constantly moving table method [4].

5. DISCUSSION AND CONCLUSIONS

A novel implementation strategy for whole-body MR imaging during a *single* MR acquisition is proposed in this paper. We have shown the possibility of a real-time, interactive LFOV imaging technique for imaging the vessels in the legs during the use of an MR contrast agent. This new technique is based on interactively moving the acquired data window in conjunction with the use of novel data acquisition schemes [7] and real-time reconstruction. The imaging reconstruction strategy used here is based on the realization that the 3D Fourier reconstruction is a decomposable process. This allows one to define a large hybrid (x, k_y, k_z)-space with the same length as the table displacements while acquiring the MR data. Every Fourier transformed-readout echo is placed in the proper location of the hybrid-space because of accurate measurements of the table position [5]. Here, we investigated the suitability of decoupling the table motion from the **k**-space acquisition scheme for the continuously moving table technique, allowing interactive, arbitrary, and extended table motion along the patient. A key advantage of the proposed technique is the operator interaction via a "floating" table, by which s/he can optimize the imaging procedure using real-time updated images. In implementing the proposed imaging technique on a clinical scanner, significant technical challenges arose.

We developed a real-time prototype applicable for acquisitions in the continuously moving table whole-body MR imaging and angiography methods. This was achieved by designing and building hardware and software interfaces that meet the requirements of the proposed system. Fast MR pulse sequences that have high signal-to-noise together with undersampled acquisition schemes were implemented. Initial assessments of the implemented technique in *in-vitro* and *in-vivo* studies show encouraging results in rapidly producing large seamless images with fast correction for gradient fields non-linearities [8]. Our *interactive* LFOV *real-time MR imaging system* would allow a non-invasive, quick, and painless method for assessing systemic diseases.

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