Dynamic 3D MR-Defecography

Dynamische 3D-MR-Defäkografie

Abstract

Epidemiologische Studien haben schätzen die Incidence von chronischer Obstruktion auf bis zu 27% der Gesamtbevölkerung. In der Regel wird zur Untersuchung betroffener Patienten die Entero-Colpo-Cysto-Defäkografie verwendet. Auch die 2D-MR-Defäkografie wird im klinischen Alltag angewendet, jedoch wird hier lediglich die Dynamik in ein bis drei 2D-Schichten dargestellt. Die Evaluation von lateraler lokalisierten Pathologien kann hierdurch beeinträchtigt sein. Deshalb haben wir eine 3D-MR-Defäkografie entwickelt und implementiert. Jeder 3D-Block bestand aus sieben Schichten mit einer räumlichen Auflösung zwischen $1.3 \times 1.3 \text{mm}^2$ und $2.3 \times 2.3 \text{mm}^2$. Die Bildauflösungsrate lag zwischen 0.8 s und 1.3 s. Wir verwendeten für die Datenakquisition eine modifizierte Stack-of-Stars bSSFP-Sequenz und für die Datenerstellung einen modifizierten FISTAkomprimierten-Sensing-Algorithmen. Für die Optimierung der Akquisitionsparameter hinsichtlich der Bildqualität haben wir eine Studie mit 6 Patienten durchgeführt.

Introduction

Epidemiologische Studien haben gezeigt, dass die Incidence von chronischer Obstruktion bis zu 27% der allgemeinbevölkerung. Der gold standard zu testen, die Radiographie der enterocolo-cysto-defäkografie. In der klinischen Routine 2D MR-Defäkografie ist auch durchgeführt, aber nur auf bis zu drei 2D-Schichten in einem Penetration der Zeit können akquiriert werden. Um die Detektion von lateraler lokализierten Pathologien, entwickeln wir eine dynamische 3D MR-Defäkografie. Jeder 3D-Block besteht aus sieben Schichten mit einer räumlichen Auflösung von $1.3 \times 1.3 \text{mm}^2$ bis $2.3 \times 2.3 \text{mm}^2$ und einer Bildrate von 0.8 s bis 1.3 s. Wir verwenden im standardschnitt eine modifizierte FISTA-komprimierte Sensing-Algorithmen. In diesem Paper, stellen wir eine 3D MR-Defäkografie vor, die in der klinischen Routine 2D MR-Defäkografie ist.

Zusammenfassung

Epidemiologische Studien haben die Incidence von chronischer Obstruktion auf bis zu 27% der Gesamtbevölkerung. In der Regel wird zur Untersuchung betroffener Patienten die Entero-Colpo-Cysto-Defäkografie verwendet. Auch die 2D-MR-Defäkografie wird im klinischen Alltag angewendet, jedoch wird hier lediglich die Dynamik in ein bis drei 2D-Schichten dargestellt. Die Evaluation von lateraler lokalisierten Pathologien kann hierdurch beeinträchtigt sein. Deshalb haben wir eine 3D-MR-Defäkografie entwickelt und implementiert. Jeder 3D-Block bestand aus sieben Schichten mit einer räumlichen Auflösung zwischen $1.3 \times 1.3 \text{mm}^2$ und $2.3 \times 2.3 \text{mm}^2$. Die Bildauflösungsrate lag zwischen 0.8 s und 1.3 s. Wir verwendeten für die Datenakquisition eine modifizierte Stack-of-Stars bSSFP-Sequenz und für die Datenerstellung einen modifizierten FISTA-komprimierten-Sensing-Algorithmen. Für die Optimierung der Akquisitionsparameter hinsichtlich der Bildqualität haben wir eine Studie mit 6 Patienten durchgeführt.

Materials and Methods

All measurements were performed on 3T whole-body systems (MAGNETOM Prisma and MAGNETOM Skyra, Siemens Healthcare GmbH, Erlangen) equipped with a 32-channel body array coil. All reconstruction algorithms were implemented using Matlab 2014b (The Mathworks, Natick, MA, USA). Data acquisition was performed using a sagittal 3D bSSFP stack-of-stars imaging sequence. This technique uses standard phase encoding in the k_z-direction and a radial sampling scheme in each of the k_x-k_y-planes. The most straightforward implementation of the stack-of-stars trajectory acquires each k_x-k_y-partition of a 3D block one after another and with the same number of spokes in each partition (Fig. 1a). In addition to this version, two supplementary features were implemented. The first one is density weighting (DW), which is shown in Fig. 1b. The number of spokes varies between the different partitions of the 3D block and increases towards the central partition. We acquired seven partitions from $k_{min} = 1$ to $k_{max} = 3$ and applied two different undersampling patterns for $k_{zp}$. Compared to full Nyquist sampling at $k_{zp} = max$, the undersampling factors R from the center partition $k_{zp} = 0$ to the outer partitions were $R = 3, 4, 5, 6$ (DW sampling 1) and $R = 3, 4, 8, 10$ (DW sampling 2), respectively. The second feature is view sharing, in which the order of the acquired partitions is changed from linear to a rearranged order while the central partition is sampled more often. The corresponding sampling scheme is shown in Fig. 1c. In every partition the spokes are...
sampled in linear order and every second spoke is measured in the reversed direction to compensate for eddy currents.

Data were initially gridded onto a Cartesian grid using the parallel imaging technique of self-calibrated GRAPPA operator gridding (GROG). Subsequently, data reconstruction was performed using a compressed sensing technique, which enforces sparsity in the spatial wavelet domain. In general, this optimization problem can be mathematically expressed by

$$\min_{\Psi_m} \| F_m \cdot y \|_2^2 + \lambda \| \Psi m \|_1$$

where $m$ represents the image data to be reconstructed and $y$ is the undersampled $k$-space measurement. The operator $F_m$ applies a Fourier transform and masks $k$-space data not sampled. The first term of the equation thus enforces data consistency between the current solution and the undersampled acquisition. The second term enforces the reconstructed image to be sparse in the wavelet domain. $\Psi$ represents a wavelet transform operator which is applied to the solution $m$.

The regularization parameter $\lambda$ realizes a trade-off between data consistency and sparsity in the wavelet transform domain. To effectively perform the optimization, we implemented a modified FISTA algorithm in analogy to Wech T. et al. (Wech T. et al. IEEE Transactions on Medical Imaging 2015; 35: 912 – 920).

The described acquisition and reconstruction scheme was applied to 6 female patients. The study was approved by the ethics committee of our institution and all patients gave written informed consent. All patients underwent a clinically indicated 2D MR-defecography examination. The MR-defecography protocol consisted of three static high-resolution 2D TSE sequences for scouting (FOV: 350 × 350 mm², voxel size: 0.7 × 0.7 mm², slice thickness: 3 mm, flip angle: 150°, TR = 3780 ms, TE = 82 ms) and a dynamic 2D examination was performed thereby acquiring three separated sagittal 2D slices using a bSSFP sequence (FOV: 320 × 320 mm², voxel size: 0.6 × 0.6 mm², slice thickness = 8 mm, flip angle: 50°, TR = 3.48 ms, TE = 1.55 ms). The rectum was contrasted with 200 ml of sonographic gel.

After this 2D examination the patient’s rectum was refilled with sonographic gel and the proposed 3D examination scheme was applied. During both dynamic measurements the patients were asked to strain and squeeze and then to evacuate the rectum. The imaging parameters of the 3D sequence of all patients are shown in Table 1. We used an in-plane spatial resolution from $1.3 \times 1.3$ mm² to $2.3 \times 2.3$ mm² with a slice thickness of 4 to 8 mm. Depending on the spatial resolution and on the density weighting scheme, we obtained a temporal resolution from 1.2 to 2.1 seconds. By applying a view sharing, the respective time frames were updated every 0.8 s to 1.3 s. For the first two patients a standard stack-of-stars sampling scheme (Fig. 1a) was used. The undersampling factor in all partitions was $R = 4$ and eight partitions were measured in these cases, while for all other patients the additional features of

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Table 1: Measurement parameters of all 6 female patients and their age.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Temporal Update Rate (1/second)</th>
<th>Matrix Size (mm²)</th>
<th>FoV (mm³)</th>
<th>Voxel Size (mm³)</th>
<th>TR (ms)</th>
<th>TE (ms)</th>
<th>DW Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68</td>
<td>1.6</td>
<td>256 × 256 × 8</td>
<td>280 × 280</td>
<td>2.2 × 2.2 × 4</td>
<td>3.1</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>62</td>
<td>1.6</td>
<td>256 × 256 × 8</td>
<td>300 × 300</td>
<td>2.3 × 2.3 × 4</td>
<td>2.9</td>
<td>1.4</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>1.3</td>
<td>384 × 384 × 7</td>
<td>270 × 270</td>
<td>1.4 × 1.4 × 8</td>
<td>3.4</td>
<td>1.7</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>0.8</td>
<td>256 × 256 × 7</td>
<td>256 × 256</td>
<td>2.0 × 2.0 × 6</td>
<td>3.0</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>1.3</td>
<td>448 × 448 × 7</td>
<td>300 × 300</td>
<td>1.3 × 1.3 × 5</td>
<td>3.5</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>54</td>
<td>2.0</td>
<td>448 × 448 × 7</td>
<td>300 × 300</td>
<td>1.3 × 1.3 × 5</td>
<td>3.5</td>
<td>1.8</td>
<td>2</td>
</tr>
</tbody>
</table>

Temporal and spatial resolution parameters, the repetition time (TR) and echo time (TE), as well as the applied DW sampling scheme are shown. Parameter zur zeitlichen und räumlichen Auflösung, Repetitionszeit (TR) und Echozeit (TE), sowie das verwendete DW-Sampling-Schema sind dargestellt.
density weighting and view sharing were applied for seven partitions. Patients 3 and 4 were measured using DW sampling 1 with lower undersampling factors in the outer partitions and patients 5 and 6 were examined using DW sampling 2 with higher undersampling factors in the outer partitions. The flip angle was between 39° and 42°.

**Results**

The compressed sensing reconstructed datasets allowed examination of the defecation process within the whole acquired 3D volume. Fig. 2 shows one central slice of a single time point for each patient to allow comparison of the different sampling schemes. The sagittal view visualizes the rectum of the six patients that was filled with 200 ml of sonographic gel.

All patients had a small (< 2 cm), medium (2 – 4 cm) or large (> 4 cm) anterior rectocele. The images acquired without density weighting and without view sharing (DW sampling 0, patients 1 & 2) indeed show the pathology. However, compared to the images of patients 5 and 6, significant blurring due to the low spatial resolution of the images impairs diagnosis. The second sampling scheme (DW sampling 1, patients 3 & 4) resulted in images that also allow detection of the rectocele in each case, but an increased level of incoherent artifacts (see white arrow) remains after application of the proposed reconstruction method. The results obtained using DW sampling 2 feature the best image quality with high spatial resolution and low artifact power.

The top of Fig. 3 depicts a dynamic image series exemplarily for slice five in patient 5. The series clearly shows the evolution of a small anterior rectocele. The series presented at the bottom of Fig. 3 shows all slices of time frame 7. Identical images are indicated by the white squares. The lateral extent of the rectocele can be accurately evaluated by the extended spatial coverage of the newly proposed imaging technique. While banding artifacts are present in the bright fat tissues, none are visible within the patient’s rectum.

**Discussion and Conclusion**

The proposed 3D MR-defecography method offers the possibility to visualize the defecation process of patients with pelvic floor disorders with extended coverage. Not only the anterior-posterior but also the lateral extent of a given pathology can be evaluated. Furthermore, the extended coverage provides more flexibility, because it is easier to angle a 3D volume properly than to angle a single 2D slice. However, it has to be considered that the whole examination depends largely on the individual patient and how strong the motion is during the defecation process.

We optimized the sampling scheme of our 3D MR-defecography method to get optimized image quality with highly reduced data acquisition. We varied the acquisition parameters within an acceptable range.
range regarding temporal and spatial resolution in 6 patients to determine an optimal trade-off. The first two patients showed that it is possible to visualize the defecation process with standard stack-of-stars sampling. However, the sampling has three disadvantages. First, only a small undersampling factor $R = 4$ was possible, because the standard stack-of-stars sampling has no variation in the $k_z$-direction and in this case a higher undersampling factor would result in severe undersampling artifacts. Second, the sampling doesn’t consider the fact that the higher signal energy is located in the center of the 3D $k$-space and that missing data in this region leads to stronger artifacts in the reconstructed images than missing data in the $k$-space periphery. Third, the number of reconstructed time frames can almost be doubled using the view sharing feature, which is reasonable for better dynamic visualization. Therefore, we improved the sampling pattern with respect to these three points and adapted the two different DW sampling schemes. With the variation in the $k_z$-direction in combination with our 3D data reconstruction, higher undersampling factors were possible. For patient 3 we invested

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**Fig. 3** Temporal progress of the defecation process of patient 5 (top). It is shown how a small anterior rectocele evolves during defecation. Due to the 3 D measurement, the lateral extent of the rectocele can be evaluated in all slices of the 3 D block. At the bottom all slices of time frame 7 are shown. Identical images are indicated by white squares.

this time gain in a higher spatial resolution, which led to good image quality. For patient 4 we invested the time gain in an even higher image update rate than for patients 1 and 2. That, however, led to an increase in the artifact level that impaired diagnosis. Therefore, we further increased the spatial resolution and compensated the accompanying time loss with higher undersampling factors in the outer partitions (DW sampling 2). This solution seemed to be the optimal trade-off of a good temporal and spatial resolution. An even higher spatial resolution would further prolong the scan time and higher undersampling factors would again increase the artifact level. Our proposed method shows that the fast, non-periodic, dynamic defecation process can be visualized with 3D MR imaging using a density-weighted and view-shared stack-of-stars sampling scheme in combination with a 3D FISTA compressed sensing reconstruction algorithm.

The next step comprises the comparison of our approach with the standard defecography methods in a larger patient collective.

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