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Optimization of pulse sequences and evaluation of endoluminal contrast agents applicable in the MR examination of the bowel

Summary of Ph.D. Thesis

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List of abbreviations

Sequences:

CPMG	–	Carr-Purcell-Meiboom-Gill
FGR	–	FGRASS
FGRASS	–	Fast GRASS
FIESTA	–	Fast imaging employing steady-state acquisition
FMPSPGR	–	Fast multi-planar spoiled gradient-recalled
FRFSE-XL	–	Fast recovery fast spin-echo - accelerated
FSE	–	Fast spin echo
FSPGR	–	Fast SPGR
GRASS	–	Gradient-recalled acquisition in the steady-state
GRE	–	Gradient-recalled echo
IR-Prep FGR	–	Inversion recovery prepared FGR
IR-Prep FSPGR	–	Inversion recovery prepared FSPGR
MPGR	–	Multi-planar gradient-recalled
SE	–	Spin echo
SPGR	–	Spoiled gradient-recalled
SSFSE	–	Single-shot fast spin-echo

Parameters:

ASSET	–	Array Spatial Sensitivity Encoding Technique
AST	–	ASSET
BW	–	Bandwidth
ETL	–	Echo Train Length
FC	–	Flow Compensation
Flip	–	Flip angle
FOV	–	Field of View
NEX	–	Number of Excitation
Sat	–	Saturation (S - superior, I - inferior)
TE	–	Echo time (Fr - fractional, Ef - effective)
TI	–	Inversion time
TR	–	Repetition time
TRF	–	Tailored RF
Zip	–	Zero Fill Interpolation Processing

Other:

CNR	–	contrast-to-noise ratio
GI	–	gastrointestinal
MR	–	magnetic resonance
RF	–	radiofrequency
ROI	–	region-of-interest
SD	–	standard deviation
SI	–	signal intensity
SNR	–	signal-to-noise ratio

1. Introduction

1.1. Short historical review of the MR examination of the bowel

From the end of the nineties, MR imaging is playing an increasingly important role in the examination of the bowel. The introduction of oral MRI contrast media significantly improved the results of abdominal MRI examinations. Technical advances have revolutionized MRI in evaluating gastrointestinal disease. Peristaltic motion, respiratory or cardiac movement, flow artifacts are the main problems, which have partially been solved with fast imaging techniques. Together with phased array coils high-quality breath-hold images with high spatial resolution and coverage of the whole organ may be achieved. Further techniques and refinements of existing approaches will probably help MRI to become routinely available for the examination of the bowel.

1.2. MR sequences and parameters

On the one hand, this thesis relates the optimization of sequences, so a brief summary was included which explains the sequences and parameters used in the study. I used the terminology of GE Medical Systems all through.

Two strategies are routinely used to create MR signals: (1) application of an additional 180-degree RF pulse to produce a spin echo and (2) application of a gradient reversal, used to produce a gradient echo. In case of the most commonly used multislice two-dimensional imaging techniques, scan time (TS) can be calculated by the following simple relationship: $TS = TR \times N_y \times NEX$, where TR is the pulse repetition time, N_y is the number of phase-encoding steps and NEX is the number of excitations used for signal averaging.

The first approach for reducing scan time is to decrease the number of excitations or the samples in the phase encoding direction. Sampling only a fraction of the k-space can also save time. This can be realized by using fractional echo or the fractional NEX technique. Shortening TR reduces scan time, which is achieved by gradient echo sequences with lower flip angles. Parallel imaging (ASSET) allows faster scanning when using phased array coils.

Fast spin echo (FSE) sequence uses a technique in which multiple lines in k-space are collected from a location within a TR. The number of sampled echoes is the echo train length (ETL). XL-named sequences apply shorter echo spacing. FRFSE-XL (Fast recovery FSE) gives good T2 contrast even with shorter TRs due to a -90^o flip-back pulse at the end of the echo train. SSFSE (Single-shot FSE) samples all echoes from a slice within a TR.

In steady-state gradient echo sequences transverse and longitudinal magnetization coexist at all times. In GRASS (Gradient-recalled acquisition in the steady-state) and ultrafast FGR (Fast GRASS) dephasing of the transverse magnetization due to spatial encoding in the phase-

encoding direction is rephased after data acquisition. In FIESTA (Fast imaging employing steady-state acquisition) rephasing is performed along all three directions to maintain the true steady-state condition. Spoiled GRASS (SPGR) and ultrafast FSPGR (Fast SPGR) sequential acquisitions use RF spoiling to destroy the residual transverse magnetization and therefore prevent the buildup of a steady state. FMPSPGR (Fast multi-planar SPGR) provides a multislice (interleaved) acquisition.

In abdominal imaging FMPSPGR sequence is most frequently used to produce T1-weighted images. However, with non-cooperating patients the use of sequential acquisitions is a better approach. In a single breath-hold, a 3D acquisition can also be performed, which has the advantage of better resolution in the slice-selection direction.

The availability of breath-hold, T2-weighted FSE aided the conquest of bowel imaging by MRI more than any other sequence. The development of SSFSE sequence has accelerated this process even further. The latter sequence permits the acquisition of an individual T2-weighted slice in a time window as little as 1 or 2 seconds, thus producing images without significant motion artifacts. FIESTA provides motion-free, high-resolution T2-like images of the intestines in a few seconds.

1.3. Endoluminal contrast agents

There are three different types of endoluminal MR contrast media:

1. Paramagnetic contrast media, which decrease T1 relaxation time of water protons.
2. Superparamagnetic contrast media, which stimulate primarily T2 relaxation.
3. Other contrast media, in this case the intrinsic proton density, T1 and T2 relaxation times of such substances determine signal intensity on the MR image.

Depending on their signal intensity, bowel MR contrast agents are generally classified as either positive (bright lumen) or negative (dark lumen) agents.

On T1-weighted images the bowel lumen is bright when paramagnetic agents are applied. There are several iron, manganese and gadolinium-containing compounds, which were approved as endoluminal contrast agents. Fruit juices with high metal content have paramagnetic effects, too. In case of superparamagnetic iron oxide crystals the T2 and T2* effects predominate, and a decrease in signal intensity on T2-weighted sequences is produced. Water belongs to the third group, and is positive on T2, and negative on T1. The MR appearance of methylcellulose and polyethylene glycol is similar to that of water with the additional advantage that they are not absorbed from the gastrointestinal tract, so a better distention of the bowel lumen can be achieved. Barium sulfate has an excellent safety profile. Its signal intensity can vary depending on the degree of its dilution. Because of their short T1

relaxation time, mineral oil or oil emulsions can be used as positive contrast agents. Perfluorooctylbromide, air and CO_2 are negative on MR images due to the lack of protons.

1.4. The examination of the bowel

In bowel examination motion, chemical shift and susceptibility artifacts can often be seen. Motion is a major problem in abdominal imaging. Respiratory and peristaltic motion artifacts can be reduced by using breath-hold sequences and administration of smooth muscle relaxant. These artifacts are minimized when ultrafast, sequential acquisitions are applied. Chemical shift artifact can occur along frequency encoding direction, at the border between fatty and water-containing tissues. This artifact can be reduced by a higher bandwidth or eliminated by using fat saturation. If a given voxel contains both types of tissues, their magnetization vectors are periodically in or out of phase because of the different precessional frequencies and the signal intensity of the voxel is enhanced or blacked out. Clinically, the out of phase artifact may be seen at any boundary where the voxels at the interface contain both fat and water, also known as „black-boundary" artifact. Setting the right value of the echo time (TE) or using fat saturation, this artifact can be avoided. Susceptibility artifacts can also be seen around bowel loops on gradient echo images. This is due to the different magnetic susceptibilities of tissues (air and other tissues). It is of lesser degree when spin echo sequences, stronger gradients, shorter echo times or 3D acquisitions are used.

The contrast agent for lumen opacification is administered orally at the dosage of 1000-1500 mL. Breath-hold sequences are performed. To reduce peristaltic motion, smooth muscle relaxant is administered immediately before imaging. T1- and T2-weighted images are acquired in axial and coronal planes from the bowel. After intravenous gadolinium administration, T1-weighted sequences are repeated in the arterial and interstitial phases.

2. Objectives of the study

Our initial purpose was to construct an experimental model, which simulates the bowel lumen and its surroundings. The in vitro model was necessary to evaluate the pulse sequences and endoluminal contrast agents applicable in bowel examinations.

A main aim of the thesis was to find sequences, which are efficient in demonstrating pathological alterations of the bowel, and to investigate the optimal values of their parameters. The purpose was to design an MR imaging protocol for the bowel examination.

Another main objective was to study and evaluate potential endoluminal contrast agents for the MRI of the GI tract. The intention was to evaluate alternative contrast agents. Clinical use and analysis of these agents was also among the aims of the study. The point of these

experiments was to introduce the routine application of an endoluminal contrast medium for bowel MRI.

3. Materials and methods

All examinations were performed in the Euromedic Diagnostics Szeged Kft. medical center on two different MR scanners with magnetic fields of 1.0 T (GE Signa Horizon Lx) and 1.5 T (GE Signa Excite HD). We put lard in a plastic container and we placed six plastic cups in the lard. The cups contained the different contrast agents, thus the cup and its content simulated the bowel wall and the distended bowel lumen, while the lard was supposed to act similarly to the human fat surrounding the bowel.

The parameters of the sequences were optimized in such a manner that we performed different measurements by changing the value of a given parameter while all other parameters were kept constant. In each case we paid thorough attention to the run of signal-to-noise ratio, contrast, resolution, artifacts and signal intensities of the materials.

Over 15 different materials were evaluated at different concentrations. We studied fruit syrups and cocoa beverages with high concentration of metals, primarily. The cocoa mixed with water was measured at different cocoa-powder quantities, the fluids contained 20, 40, 60, 80 and 100 g/L cocoa-powder. We tried different $FeCl_3$-containing solutions. The iron-deferoxamine solution was measured at different iron concentrations (1, 2, 3, 4 and 5 mM Fe^{3+}). We also used endoluminal agents already approved for clinical use (Gd-DTPA-based Magnevist Enteral®, barium-sulfate, methylcellulose, Gastrografin®). Polyethylene glycol (PEG) is used for bowel cleansing, but there are some studies relating its application as endoluminal MR contrast medium.

At first, T1- and T2-weighted spin echo sequences were used with optimized parameters for in vitro experiments in order to estimate T1- and T2-properties and compare the different compounds. According to these results, we selected some materials, which could provide good contrast to bowel lumen. They were subjected to further measurements. We applied pulse sequences, which can be used for the examination of the bowel. Then T1 and T2 relaxation times of the selected materials were measured. T1 values were determined using IR-Prep FSPGR sequence with 8 different inversion time (TI) settings. T2 times were obtained with the Carr-Purcell-Meiboom-Gill (CPMG) sequence, measuring 32 echoes with different TE values. For comparison, water and 1 mM Magnevist Enteral® were used.

Bowel examination of 31 patients was performed. Selected materials were applied in 500-1500 mL quantity, after obtaining written consent from each patient.

Signal intensities (SI) were obtained with ROI measurements. The signal-to-noise ratio (SNR) was determined in each case (SNR = SI / SD_{noise}, where SD_{noise} is the SD of the mean SI in the background). In some cases the contrast-to-noise ratio (CNR) was calculated between different materials with the following formula: CNR = $(SI_1 – SI_2) / SD_{noise}$.

T1 and T2 relaxation curves were obtained with fitting the proper intensities into the following functions: $I = | M_o \times [1 – 2 \times \exp(–TI/T1)] |$ and $I = M_{XYo} \times \exp(–TE/T2)$, where M_o and M_{XYo} are longitudinal and transverse magnetization at t = 0, TI is inversion time, TE is echo time, T1 is longitudinal and T2 is transverse relaxation time. Relaxation rates (1/T1 and 1/T2) of different concentrations were plotted and regression lines were fitted. Accuracy of fittings was characterized by the r correlation coefficient.

The signal intensity of the bowel lumen, its contrast towards surrounding structures and distention of different sections of the GI tract (from stomach to terminal ileum) were analyzed on clinical images.

4. Results

4.1. Phantom study

4.1.1. Sequences and parameters

In case of gradient echo sequences, four possible values of TE were analyzed. Fastest data collection is achieved by using fractional echo and shortest echo time (Minimum), but in this case some artifacts appear, which make the images of little value. The image quality is better in the case of shortest full echo (Min Full). If Out of Phase is chosen and the echo is fractional, than we face the artifacts seen on Minimum echo images. Black boundary artifact is typical of this TE value, but can be avoided with fat saturation. Moreover, out of phase echo time accentuates the effects of chemical fat suppression. In Phase images produced no artifacts, but there are fewer available slices because of the longer echo time. Artifacts on Minimum echo images could be decreased only when the number of frequency encoding samples was 512.

Flip angle should be changed in accordance with the TR value to avoid tissue saturation. According to our measurements on 1.0 T the following pairs of values are suggested to be used (TR-flip angle): 75-50, 100-60, 125-70, 150-80, 200-90 ms-degrees. On 1.5 T field strength the flip angle should be decreased by 5-10 degrees compared to the above-mentioned values because of the slower relaxation.

Sequences with NEX = 0.5 or 0.75 produced similar artifacts like fractional echo measurements. Using BW = ±15.6 kHz, the chemical shift is 1.7 mm, while it is 0.4 mm when

BW = ±62.5 kHz. Artifacts observed on fractional echo and fractional NEX images do not depend on the value of bandwidth.

In case of the sequential acquisitions, poorer SNR can be compensated by narrowing the bandwidth (BW < ±25 kHz). IR-Prep FSPGR had the best image quality from among the T1-weighted sequential acquisitions. A flip angle of 10-20 degrees is suggested to be used with the 3-dimensional gradient echo sequence (3D FSPGR), because tissue saturation is significant with higher flip angles due to very short TR.

Longer ETL produced more blurring in the FRFSE-XL image. The edges were distorted on the image when Blurring Cancellation imaging option was switched on. There weren't any noticeable changes in image quality when Tailored RF option was applied. Blurring in SSFSE images was significant in the in vitro experiments. The image was less blurred when higher bandwidth was used. Increasing the resolution, blurring did not decrease, but image quality was improved when phase encoding steps were lessened.

4.1.2. Used materials

Fruit syrups were hyperintense on T1-weighted images. Rosehip syrup and black currant extract were of low SI on T2 images. The SI of the black currant extract and iron-deferoxamine solution increased on T1 and decreased on T2 in direct proportion to their concentration.

Cocoa drink had low to moderate signal intensity on both the T1- and T2-weighted images. Cocoa mixed with milk had lower SI on T2 than cocoa mixed with water (CNR = 30.1). Increasing the cocoa-powder quantity (20-100 g/Liter water) signal intensity of aqueous cocoa solutions did not increase significantly on T1 but on T2 we noticed a significant decrease of the signal intensity (SNR_{20} = 119, SNR_{100} = 48.4). Cocoa-powder (50 g/L) was mixed with polyethylene glycol, methylcellulose (0.5%) and hydroxyethylcellulose (2.5%). In case of methylcellulose the SI was not homogeneous. The mixture of hydroxyethylcellulose and polyethylene glycol were relatively hypointense on in vitro images.

The T2*-weighted MPGR sequence made cocoa appear negative (SNR_{cocoa} = 28). On fat saturated 3D FSPGR sequence cocoa had moderate SI, which was different from the low SI of water and fat and high SI of the Gd-DTPA (CNR > 40 in each case). Cocoa had moderate to low SI on IR-Prep FSPGR and differed from the SI of water, fat and Gd-DTPA (CNR > 18 in each case). On SSFSE image fruit syrups were hypointense, while SI of cocoa was a little bit higher.

The fittings of T1 and T2 relaxation curves were nearly perfect for rosehip, black currant and iron-solution (correlation coefficient: r > 0.999), and it was good for cocoa (r > 0.98). T1 and T2 values are reported in Table 1. Relaxation rates increased linearly with concentration

for the iron-deferoxamine, black currant and cocoa, but for the rosehip syrup dependence was not linear.

Materials	T1 (ms)				
	100%	80%	60%	40%	20%
Iron-deferoxamine	104 ±4	135 ±5	181 ±7	263 ±10	495 ±18
Cocoa	360 ±21	450 ±27	557 ±33	830 ±42	1080 ±53
Black currant	55 ±3	71 ±4	95 ±5	139 ±7	246 ±12
Rosehip	110 ±5	235 ±11	499 ±25	1028 ±42	1841 ±69
Gd-DTPA	180 ±8	-	-	-	-
PEG	2050 ±71	-	-	-	-
			T2 (ms)		
	100%	80%	60%	40%	20%
Iron-deferoxamine	87 ±2	109 ±3	153 ±4	215 ±6	406 ±12
Cocoa	81 ±3	99 ±4	151 ±6	222 ±9	333 ±13
Black currant	39 ±2	51 ±2	69 ±2	103 ±4	176 ±7
Rosehip	86 ±3	163 ±6	344 ±12	646 ±22	1143 ±32
Gd-DTPA	168 ±5	-	-	-	-
PEG	1748 ±52	-	-	-	-

1. Table T1 and T2 values (ms) for the examined materials. Concentrations are given in v/v % of the highest concentration for each material.

4.2. Clinical examinations

The quantity of iron-deferoxamine solution was 500 mLs and it was applied in 4 cases. Mannitol was added to the solution in one case. Jejunum contained solution only in the case when mannitol was used. SI of the iron-solution was high on both the T1 and T2 images.

Commercially available cocoa beverages were applied in 3 patients in a quantity of 1000 mLs. Distention of the bowel lumen was unsatisfactory. The mixture of cocoa with methylcellulose was ingested by one patient in 1500 mL quantity. It proved to be unstable in the stomach. However, distention of the lumen was good even in the terminal ileum. It was hyperintense on T2 and hypointense on T1, just like water or methylcellulose on their own. Hydroxyethylcellulose with cocoa (900 mL) was used in one case in enema, being a viscous mixture. Distention of the descending and sigmoid colon was optimal, while ascending and transverse colon parts contained much gas. The fluid was homogeneous, its SI was moderately high on T1 and moderate on T2.

MR examination was performed after conventional enteroclysis in 3 cases. The time between them was 15-20 minutes. The quantity of methylcellulose was 1 L. Distention of the small bowel was satisfactory. There was a high quantity of contrast agent in the ascending and transverse colon, too.

PEG solution was ingested by 19 patients in a quantity of 0.6-1.5 L (mean: 1.1 L). Ingestion time was between 25-60 minutes (mean: 40 mins). In 12/19 patients the distention of the jejunum and ileum was good to optimal. In 4/19 patients bowel distention was unsatisfactory caused by insufficient oral intake of PEG solution (less than 1 liter). In the remaining 3/19 patients contrast medium distended the ascending colon too because of an ingestion time longer than 45 minutes resulting in a distention of the small bowel to a lesser degree.

5. Discussion

5.1. Sequences, imaging protocol

T1 measurements of the bowel examination are the fast and ultrafast gradient echo sequences. The value of TE affects the contrast and the image quality considerably. Shortest echo time is provided by fractional echo, but this generates artifacts as much as the fractional NEX imaging, probably due to the partial Fourier-technique. Min Full echo time is a bit longer but together with fat saturation results in good image quality.

In multislice imaging, the number of slices that can be imaged is affected by TR. When varying its value, flip angle should be always changed, too, according to related results.

Although T1-weighted sequential acquisitions are very beneficial in eliminating motion artifacts, due to poorer SNR these sequences are suggested to be applied only when other measurements are of little diagnostic value because of artifacts. IR-Prep FSPGR is the most suitable. In case of 3D FSPGR, fat suppression is more efficient and very thin slices (3-4 mm) can be measured which is profitable when evaluating the bowel wall.

FRFSE-XL is suitable for bowel MRI. ETL should be no longer than 20 because it results in much blurring according to our in vitro results. Application of Tailored RF may be useful, but Blurring Cancellation worsened image quality in our experiments, thus we haven't applied it in clinical examinations.

Edge blurring in SSFSE image can be reduced most efficiently by widening the BW. Wider BW shortens echo spacing, thus signals are collected over a smaller part of the T2 decay curve. Reducing the number of sampled k-space lines, there will be fewer signals detected on the T2 curve, which also decreases edge blurring. Technical improvements shortened echo spacing even more, which resulted in significantly less blurring. ASSET is also useful in reducing the effects of artifacts on SSFSE images.

The GI tract can be covered by axial slices in three or four breath-hold scans. This should be accomplished in such a manner that every breath-hold scan should be performed as a series of separate sequences. In this way, the region that is to be examined will advance to the

isocenter of the magnet and calibration will be optimized for this area, thus image quality will be improved and fat suppression will be more efficient. Application of superior and inferior spatial saturation is suggested to suppress blood signal that could produce ghosting.

T1-weighted axial images are acquired by using the FMPSPGR sequence with fat saturation. Fat saturation eliminates a lot of artifacts resulting from chemical shift, motion of fatty tissues and provides good contrast to bowel wall with negative lumen (water, PEG), especially after IV contrast administration. T2-weighted axial slices are produced by the FRFSE-XL sequence. Flow Compensation is applied to reduce flow artifacts.

In coronal plane 1-2 scans are sufficient to image the bowel. The field of view is very large, therefore those sequences are suitable which are less sensitive to magnetic field inhomogeneity (spin echo, 3D gradient echo). In 3D FSPGR, fat suppression is more efficient, thinner slices are obtained, susceptibility artifacts are less and one breath-hold scan is enough to scan the bowel in coronal plane allowing dynamic imaging. SSFSE of T2-weighted sequences provides the fewest artifacts in coronal plane, there are no motion artifacts due to the sequential acquisition mode. In addition, FIESTA can be performed, which is also free of motion artifacts.

According to the in vitro experiments and discussed aspects, FMPSPGR is performed in axial and 3D FSPGR in coronal plane as T1 measurements, while FRFSE-XL in axial and SSFSE (possibly FIESTA) in coronal plane as T2. If there are a lot of artifacts in multislice or 3D acquisition modes, then sequential acquisition should be applied in all planes. The optimized parameters of the selected sequences are summarized in Appendix 1.

5.2. The used materials

According to our results rosehip syrup and black currant extract of the fruit syrups have the strongest relaxation effects. They produced shorter T1 and T2 relaxation times than Gd-DTPA. Diluted black currant extract would be suitable for positive endoluminal enhancement even at a concentration of 30% of the original extract, in this case having a T1 relaxation time like the Gd-based oral contrast agent. According to earlier studies, using blueberry or pineapple juice as oral contrast agents, fruit juices are suitable only for the examination of upper abdomen because they are absorbed and their SI change throughout the GI tract.

According to the Solomon-Bloembergen equations, the effect of a contrast agent on tissue relaxation is in direct linear correlation to the concentration of contrast material. It was unexpected that the dependence of relaxation rates for rosehip syrup on concentration was non-linear. There are probably solute-solute interactions in the syrup among molecules containing paramagnetic species, which results in faster relaxation.

In the case of iron-deferoxamine solution a concentration of 3 mM produced relaxation times similar to 1 mM Gd-DTPA. It was hyperintense on both the T1 and T2-weighted clinical images. Due to low quantity, solution could be observed in jejunum only when mannitol was used which emphasizes its importance.

According to our results, cocoa promoted primarily T2 and T2* relaxation processes rather than T1. Cocoa powder granules insoluble in water probably impeded water mobility and caused local magnetic field inhomogeneities due to susceptible heterogeneity, which first of all stimulated T2 and T2* relaxation. However, a more realistic explanation of this phenomenon needs a detailed investigation of the composition of the cocoa beverage.

In case of in vivo administration cocoa powder granules should be kept intact through their gastric transit in order to experience similar benefits like in vitro. Mixing cocoa with viscous materials seems to be promising. On the one hand, T2 and T2* relaxation times decrease due to slower molecular motion which means lower signal intensity on T2 images. On the other hand, it may prevent powder granules from subsiding or aggregating, and improve homogeneous contrast distribution throughout the bowel. Although the mixture of cocoa and hydroxyethylcellulose proved to be promising, further clinical studies are necessary to find an adequate material, viscosity and to investigate the possibility of its oral administration.

Because of the prolonged time elapsed between enteroclysis and MR examination in the presented cases, much of methylcellulose was seen in the colon. The optimal small-bowel distention probably requires immediate MR examination, higher quantity of methylcellulose or prompt administration of smooth muscle relaxant following enteroclysis.

In most clinical examinations PEG solution was used for lumen opacification. The advantages of using PEG solution are easy supplying and administration, low cost, consumable taste and its well-known behavior in the GI tract. Our study indicates that at least 1 liter of solution is needed to be ingested within 40 minutes for optimal bowel distention.

6. Conclusions

The plastic model provided an appropriate and risk-free possibility in evaluating endoluminal contrast materials and imaging sequences. We could perform accurate measurements due to the lack of artifacts and a higher level of signal-to-noise ratio. However, relevance of data achieved from our study is limited by the fact that results cannot be standardized due to the natural properties of some agents and their relaxivity cannot be possibly measured on a molar level.

Selection and optimization of sequences applicable in the MR examination of the bowel by means of our experimental model were successful. Image quality of gradient echo

sequences could be improved by optimizing the values of echo time, bandwidth, repetition time and flip angle. Image blurring characteristic to T2 FSE images could be reduced by correct adjustment of echo train length, bandwidth and some imaging options. An MR imaging protocol for bowel examination could be compiled by right of the in vitro and in vivo measurements.

On the basis of the experimental results we could select some materials, which would be able to demarcate the bowel lumen from the surrounding tissues. By means of relaxation measurements correct and accurate analysis and comparison of materials could be fulfilled.

Rosehip syrup, black currant extract and iron-deferoxamine solution act like positive contrast agents on T1-weighted images and are suitable for oral administration. Fruit syrups are applicable only in the very proximal small-bowel because they are absorbed, while the iron-deferoxamine complex is retained in the bowel lumen. Cocoa is a promising negative contrast agent but an adequate viscous, non-absorbable material has to be found in order to get a homogeneous, stable suspension of cocoa in the GI tract. Due to its simple, risk-free and successful application, the PEG solution is nowadays routinely used at our institute for bowel distention.

As a result of our study, nowadays the MR examination of the bowel has diagnostic value and can be regularly performed at our institute. PEG solution is used for endoluminal enhancement and the measurements are performed according to the imaging protocol described in this thesis. Further clinical studies are required to test the availability of the other evaluated materials as endoluminal MR contrast agents. As best of all, cocoa is mainly proposed to further investigation being possibly a negative contrast agent.

7. New results in this study

1. The experimental model.
2. In case of T1-weighted gradient echo sequences, fractional echo and fractional NEX techniques produce artifacts.
3. Measurement of the optimal repetition time - flip angle values for multi-planar, T1-weighted gradient echo sequences.
4. Improvement of image sharpness in case of T2-weighted fast spin echo sequences.
5. Compilation of the first MR imaging protocol for bowel examination in Hungary, at 1.0 and 1.5 T field strengths.
6. Study of over ten different alternative, potential endoluminal contrast agents.
7. Measurement of T1 and T2 relaxation times for four different potential endoluminal contrast agents at five different concentrations.

8. The first use of iron-deferoxamine solution and cocoa for lumen opacification.
9. We performed the first MR examinations following conventional enteroclysis in Hungary.
10. We first introduced the routine application of polyethylene glycol for bowel distention in MR imaging.
11. MR examination of the bowel has significant diagnostic value and can be regularly performed at our institute.

Appendix 1. Imaging protocol for the examination of the bowel

1.0 Tesla					
	axial			coronal	
Sequence	FMPSPGR	FRFSE-XL	IR-Prep FSPGR	3D FSPGR	SSFSE
TR (ms)	180	2700	9.3	6.3	Infinite
TE (ms)	3.5 (Min Full)	95	4.2 (MinFull)	2.8 (Min Full)	80
TI (ms)	-	-	100	Auto	-
Flip angle (degree)	80	90	60	15	90
ETL	-	18	-	-	-
BW (kHz)	±25	±25	±20.83	±31.2	±41.67
Matrix	256×192	256×192	256×192	256×192	256×160
FOV (cm)	38-42	38-42	38-42	40-44	40-44
Phase FOV (%)	75	75	75	75	100
Slice (mm)	6-7	6-7	6-7	3-4	6-7
Slice gap (mm)	1-2	1-2	1-2	0	1-2
NEX	1	1	1	1	0.53
Fat sat	Yes	No	No	Yes	No
Saturation	S, I	S, I	-	-	-
Imaging options	Zip512	Zip512	Zip512	Zip512, Zip2, Fastest	Zip512
Nr. of slices	13	13	13	32	18
Scan time (min:sec)	0:27	0:27	0:25	0:27	0:27

1.5 Tesla						
	axial				coronal	
Sequence	FMPSPGR	FRFSE-XL	IR-Prep FSPGR	FIESTA	3D FSPGR	SSFSE
TR (ms)	175	2450	7.6	3.4	4.3	Infinite
TE (ms)	3.0 (Min Full)	90	4.2 (InPhase)	1.5	2.1	90
TI (ms)	-	-	700	-	Auto	-
Flip angle (degree)	80	90	55	50	13	90
ETL	-	16	-	-		-
BW (kHz)	±41.67	±31.2	±31.2	±125	±62.5	±62.5
Matrix	320×192	256×192	256×192	256×256	320×192	320×192
FOV (cm)	38-42	38-42	38-42	38-42	40-44	40-44
Phase FOV (%)	100	100	100	80	100	100
Slice (mm)	6-7	6-7	6-7	6-7	3-4	6-7
Slice gap (mm)	1-2	1-2	1-2	1-2	0	1-2
NEX	1	1	1	1	1	0.53
Fat sat	Yes	No	No	Yes	Yes	No
Saturation	S, I	S, I	-	-	-	-
Imaging options	AST	FC, TRF, AST,Zip512	Zip512	Zip512	AST, Fastest	AST
Nr. of slices	15	15	15	15	40	20
Scan time (min:sec)	0:18	0:20	0:13	0:17	0:16	0:14

Original papers related to this thesis:

1. Babos M, Palkó A, Kardos L, Csernay L.
   Modellkísérlet a gyomor-bél rendszer MR-vizsgálatában alkalmazható endoluminalis kontrasztanyagok összehasonlítására.
   Magyar Radiológia 2003; 77(6):276-283.
2. Babos M, Palkó A, Kardos L, Csernay L.
   A gyomor-bél rendszer MR-vizsgálatában alkalmazható szekvenciák in vitro optimalizálása egyes kontrasztanyagokkal összefüggésben.
   Magyar Radiológia 2004; 78(5):236-243.
3. Babos M, Schwarcz A, Randhawa MS, Márton B, Kardos L, Palkó A.
   In-vitro evaluation of alternative oral contrast agents for MRI of the gastrointestinal tract.
   Eur J Radiol 2006. In Press. (IF 2005: 1.888)

Abstracts:

1. Babos M, Palkó A.
   Evaluation of endoluminal contrast materials of the MR examinations of the gastrointestinal tract by using a plastic model.
   Zeitschrift für Gastroenterologie 2004; 42(5): 403-452.
   IF: 1.0
2. Babos M, Palkó A, Kardos L, Kiss I, Nagy F.
   Role of MRI in the diagnosis of small bowel diseases.
   Zeitschrift für Gastroenterologie 2005; 43(5): 477-529.
   IF: 0.8
3. Randhawa MS, Babos M, Kiss I, Kardos L, Palkó A.
   Polyethylene glycol solution as an oral contrast agent for small bowel MRI.
   Zeitschrift für Gastroenterologie 2006 (5).
   IF: 0.8
4. Babos M, Randhawa MS, Márton B, Kardos L, Palkó A.
   In vitro relaxation measurements of potential oral contrast materials for small bowel MRI.
   Zeitschrift für Gastroenterologie 2006 (5).
   IF: 0.8