Continuously tagged MRI of non-periodic motion
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Chapter 9
Summary and Conclusions
1 Summary

The work described in this thesis focuses on the potentials of continuously tagged magnetic resonance imaging (MRI) for research of soft tissue deformation and motility in the gastrointestinal tract, especially the small intestines. Non-invasive measurement of muscle tissue mechanical properties with a minimal amount of repetitions has strong benefits for various topics in biomechanical research. For motility research, continuously tagged MRI provides a non-invasive technique with minimal oral preparation, low discomfort for patients and broad spectral frequency coverage of motility.

In Chapter 2, we presented an MRI compatible soft tissue indentor with a fibre Bragg grating force sensor. The computer controlled indentor provided highly repeatable tissue deformation. The indentor was demonstrated to apply forces up to 15 Newton with a maximum error of 0.043 Newton and its MR compatibility was validated with indentations tests inside the MRI-scanner on a silicone gel phantom and the upper arm of a healthy volunteer. The MRI compatible soft tissue indentation system with an integrated force sensor has a broad range of applications; MRI robotics (1,2), MRI guided surgical intervention (3-5), MRI based catheterization (6), functional MRI (7,8) and pressure ulcer development (9-14). Using the indentor presented in chapter 2, we validated the continuously tagged MR sequence for static (i.e. ramp and hold) deformation of a silicone gel phantom and the biceps of a healthy volunteer in chapter 3. Estimated displacement fields extracted from the tagged acquisition were validated with displacement fields extracted from markers in the gel phantom resulting in a sub-voxel accuracy with a mean displacement difference of 72 µm and a standard deviation of 289 µm. Precision of displacement magnitudes were calculated in both phantom and in-vivo data to standard deviations in the mean displacement magnitudes of 75 and 169 µm, respectively. The sub voxel accuracy and precision demonstrated in the phantom in combination with the precision comparison between the phantom and the in-vivo data provide confidence in the methods presented for measurement of soft tissue deformation in vivo.

Following the static (i.e. ramp and hold) deformation experiments, we proceeded to a continuously tagged experiment of dynamic deformation of the silicone gel phantom and the biceps of one healthy volunteer in chapter 4. At a pace of 12mm/s, 20mm indentions were sampled at 3.3-3.6 Hz. Deformation in 3D was reconstructed using only three motion cycles. The precision of individual (i.e. one dynamic) displacements was 61 and 91 µm in phantom and in-vivo data, respectively. The accuracy of the cumulative displacement could also be determined to a mean difference between initial and final locations of 0.44 mm with a standard deviation of 0.59 mm in the phantom. In the in-vivo data, the accuracy of the cumulative displacement was determined to a mean difference of 0.40 mm with a standard deviation of 0.73 mm.

Comparisons between displacements calculated from the continuously tagged MRI sequence information and displacements based on marker tracking in the gel phantom gave a mean and standard deviation of the difference between true and predicted marker locations of 0.35 mm and 0.63 mm, respectively. With this experiment we demonstrated the techniques capability of measuring complex 3D deformation with speeds up to 12 mm/s following just three repeated motion cycles. This is a
substantial improvement to current techniques available for 3D assessment of soft tissue deformation (see introduction of this thesis).

In chapter 5 we demonstrated the feasibility of assessing small bowel motility using continuously tagged imaging. A simulation of a low frequent deformation in a Shepp-Logan numerical phantom showed the methods ability to detect motion patterns at low SNR levels (~2.5). We performed an in-vivo experiment where glucagon was administered to one healthy volunteer during a continuously tagged acquisition. Motion was sampled at 3.6 Hz and the volunteer was allowed to breathe freely enabling an acquisition time of eight minutes. A spectral analysis showed decrease in spectral activity especially at lower frequencies between 0 and 0.2 Hz.

For post processing of large datasets, an automated algorithm for tracking of the taglines was developed and presented in chapter 6. To sample at frequencies sufficiently low for evaluation of slow wave governed processes long scan periods are necessary and an automated tracking is indispensable for analysis of these data. Furthermore the tagged bowel region consists of separate parts moving independently and successful tracking of shearing edges was demonstrated in a numerical Shepp-Logan numerical phantom simulation as well as in-vivo. The capability of tracking shearing edges in continuously tagged datasets of deforming calf and eye muscle reconfirm the method’s potential for a broad scope of applications.

In chapter 7 the intra subject variability of motility assessment using continuously tagged imaging was evaluated in a group of ten healthy volunteers. Motion patterns were evaluated per quadrant of the FOV and in three frequency intervals. A motility index was defined as percentage of the spectral power of the breathing frequency. Despite the inherent intra subject variations in small bowel anatomy, configuration and motility patterns, a significant decrease (P<0.0001) in the motility index was found for the low and high frequency interval (0.008–0.300 and 0.400–0.533 Hz, respectively) that are related to bowel motility. This validates the method for non-invasive evaluation of motility with minimal oral preparation in group studies.

Chapter 8 describes the extraction of Lagrangian strain and Eulerian acceleration from the continuously tagged datasets by evaluation of the deformed tags in spatial and temporal direction. The complementary nature of these two measures was demonstrated in a Shepp-Logan numerical phantom simulation by showing the difference in sensitivity of the two measures to a complex deformation and a linear translation. In-vivo data were acquired in one healthy volunteer during free breathing for eight minutes. The Eulerian acceleration was shown to be able to register translational motion (cardiac and breathing) in high detail whereas the Lagrangian strain seems to be more sensitive to low frequent bowel motion. A color-coded graphic representation of the spectral activity data was presented to display a compact overview the data as a function of FOV location and spectral frequency.
2 Discussion and recommendations for future research

In chapters 2 to 4, we presented a novel methodology to obtain 3D data of soft tissue deformation in just three motion cycles. The MRI compatible indenter, the continuously tagged imaging sequence and the post processing techniques provide a framework in which soft tissue biomechanical properties can be evaluated non-invasively in high temporal resolution. The low amount of repetitions required in this framework has to our knowledge not yet been demonstrated anywhere in literature and enables acquisition of input data for various biomechanical models with conservation of hysteresis properties and maintaining acceptable levels of discomfort for volunteers and patients. Future MRI developments in acceleration techniques (15,16) will enable improvement on the spatial and temporal resolution and possibly the application of a 3D tagging pattern reducing the required amount of repetitions to just one, i.e. real time measurement of 3D soft tissue deformation.

Chapters 5 to 8 describe a similar framework for motility assessment in an automated and highly non-invasive manner. To our knowledge this is the first MRI based method capable of motility assessment during free breathing and capable of monitoring low frequency motility phenomena. Although bowel preparation (mannitol) was used in the validation studies (chapter 5 and 7), the method is intrinsically independent of bowel preparation as the tagged sequence provides its own contrast. This enables application of the method to studying motility in all digestive phases i.e. during the several phases of the Migrating Motor Complex and the postprandial-pattern. Because the method can be applied during free breathing, changes in motility patterns can also be studied while the subject is asleep. The combinations of these features render the here presented technique a potentially strong aid to existing motility assessment techniques in both research and clinical practice. Current MRI techniques are capable of measuring motility with high precision and non-invasively (17-22). Most techniques do however require breath holds and some sort of oral preparation, discarding study of preprandial motility patterns and complicating measurements for longer durations. Manometry is also capable of sampling motility for long durations and independent of preparation, but cannot reach throughout the entire GI tract and is much more invasive than the technique presented here. The framework presented here could thus aid the study of the capricious nature of bowel motility as it is able of assessing motility in a completely non-invasive manner and without inhibiting motility in any way. Analogous to the presented framework for evaluating biomechanical properties, continuously tagged imaging for motility assessment could benefit greatly from MRI hardware and software developments in the future. A 2D or 3D tagging grid implemented in the continuously tagging sequence would enable registration of motion in two or three directions and greatly improve registration of the motility patterns.


