Continuously tagged MRI of non-periodic motion
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Chapter 8

Measurement of Lagrangian strain and Eulerian flow in the abdomen using Continuously Single Shot Tagged Magnetic Resonance Imaging

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Abstract

Object:
Continuously tagged imaging extends the tagged imaging technique applications from periodic to non-periodic motion. This study presents a method to extract Lagrangian strain and Eulerian flow from the deformed tag planes without the use of the initial, non-deformed tag plane locations.

Materials and Methods:
Without the use of the initial positions of the deformed tag planes, Lagrangian strain and Eulerian flow is extracted from the continuously tagged data. The method was evaluated in a numerical phantom simulation and applied to assessment of bowel motion in one healthy volunteer.

Results:
The numerical phantom results demonstrate the complementarity of the two measures and the methods ability to distinguish rigid from non-rigid motion. The in-vivo results show the methods sensitivity to low frequent bowel motion during free breathing.

Conclusion:
Without the use of initial tag positions Lagrangian strain and Eulerian flow can be extracted from the continuously tagged data. The automated framework put forward here increases the potential of continuously tagged imaging for clinical applications, especially non-invasive assessment of low frequent motility patterns.

Keywords: tagged imaging, abdominal motion, MRI, SPAMM, motility
1 Introduction

Studying tissue motion in the human body provides insight into its functioning and possible pathology. For instance, cardiac tissue motion and strain are well-known descriptors for heart disease (1). Also, bowel motion can be studied as a measure of digestive system functioning (2-10) (11). At present several techniques are available for probing motility and peristalsis (9,12-18). However, the application of these techniques is often limited due to being invasive, requiring a high workload, or deeming inconclusive results (4,12).

Magnetic Resonance Imaging (MRI) allows for non-invasive measurement of tissue motion. MRI provides excellent soft tissue contrast, and has gained sufficient spatial and temporal resolution to capture fast moving tissue in high detail (19). Tagged MR imaging, also known as SPatial Modulation of the Magnetization (SPAMM) imaging, uses a short prepulse to periodically saturate the magnetization which results in a stripe or tag pattern in the image (20). This technique was originally developed for assessment of myocardial function employing ECG triggering (21,22) but can also be applied outside the heart (23-30). As the original tagging sequence was developed as a triggered acquisition where the image readout would be divided in a number of motion cycles, all of these studies employ a number of repetitions, varying from 16 per slice (26) to over a hundred (29).

Recently, the use of continuously tagged imaging has been demonstrated for MRI assessment of bowel motion and measurement of skeletal muscle tissue deformation (31-34). By replacing the triggering mechanism from conventional cardiac MR imaging with a fixed delay and a short, full readout sequence, deformed tag patterns can be acquired real time without repetitions. When studying skeletal muscle deformation, a number of repetitions can still be applied to acquire deformed tag patterns with various tag orientations or to increase the signal to noise ratio. For accurate measurements of tissue dynamics and to maintain an acceptable comfort levels, the number of repetitions should however be kept to a minimum (33). In the case of bowel imaging, repetitions are simply infeasible and motion information must be acquired real time. The motility patterns that govern small and large bowel motion are of a highly complex, low frequent nature (3,4,6,9,35,36), and motion assessment should be of a sufficient time period to capture this low frequent complexity. Using the continuously tagged sequence, motion information can be sampled during free breathing and without oral contrast agents. The deformed taglines can be tracked automatically (37), enabling the study of large datasets (31,32).

In this study we expand on the physical interpretation of single shot tagging in the abdomen and extract two measures of motion by considering individual sets of deformed tags and the evolution of deformed tag sets in time, without the use of the initial, non-deformed, tag positions. Single shot tagged motion was simulated and analysed and in vivo measurements were performed on one healthy volunteer. The presented methods are developed to study complex composite motion in the abdomen which in-vivo is a superposition of cardiac motion and breathing induced motion as well as the underlying motion of interest, low frequent bowel motion.
2 Materials and Methods

2.1 The Continuously Tagged Imaging sequence.
The continuously single shot tagged imaging sequence was designed for intrinsically non-periodic motion (31,33). Each tag pattern, induced by the tagging prepulse is acquired in one readout without triggering. The amount of deformation can be regulated by varying the delay between the tagging prepulse and the readout sequence. The duration of the readout sequence must be sufficiently short to ensure a high enough sampling rate and to avoid blurring of the tag pattern. The difference between a triggered and continuously tagged acquisition can be noted in the type of deformation in a single acquired set of tags but also in the relative difference in tag positions between consecutively acquired sets. In Figure 1, this difference is visualized with a periodic deformation induced in a Shepp-Logan phantom (38,39). In a triggered tagged sequence, the tag pattern is induced at the beginning of the motion of interest and subsequently imaged at consecutive states of deformation (Figure 1b). Each acquired image contains the complete deformation up to the time of acquisition and the deformation of the tag pattern typically gradually increases with the number of acquired images. In the case of the continuously tagged sequence, each tag pattern is acquired and refreshed in relatively short time intervals resulting in a smaller amount of deformation than is typically seen in triggered tagged images (Figure 1c). Figure 1d-f visualizes the difference between both sequences in temporal evolution by re-slicing in the temporal direction. Whereas in the triggered sequence the paths of constant tag phase coincide with motion paths of tissue points (40) (Figure 1e), in the continuously tagged sequence, the constant tag phase paths are detached from the tissue (Figure 1f). This difference strongly resembles the Lagrangian versus Eulerian formalism where motion of a set of particles is described by either the motion paths of all individual particles or by describing the flow field in which all particles are located. The Lagrangian formalism is customarily defined in a frame of reference located at the centre of mass of the ensemble of particles of interest (in this case the material or tissue frame of reference) whereas the Eulerian formalism uses the external or laboratory frame (in this case the scanner frame of reference).

In Section 2.2 and 2.3, two measures of motion are described. One measure is obtained from the continuously tagged data by analysis of deformed sets of tags individually, and one measure is obtained by tracking the evolution of tag locations in consecutively acquired sets. Continuously tagged motion was simulated in a numerical phantom to validate and compare these measures (Section 2.4) and in vivo data in one healthy volunteer was acquired to evaluate the measures during free breathing (Section 2.5).

2.2 Lagrangian strain
Considering an individual acquired set of tags (Figure 1a), motion of the originally induced straight tag pattern was caused by tissue motion between the tagging prepulse and the readout sequence. By comparing the distance between tags in the deformed set to the original tag spacing, the following 1-dimensional strain measure can be calculated as:

$$ e = \frac{\Delta d}{d} \quad (1) $$
Where $e$ is the linear or Cauchy strain, $d$ is the original tag spacing and $\Delta d$ is the difference in spacing between the deformed tags and the original, non-deformed tags. Although other strain measures can easily be derived from the segmented tags, Cauchy strain was favoured here due to its natural interpretation e.g. a 50% extension relates to a Cauchy strain of 0.5 (while the equivalent Green-Lagrange or Hencky strain would be 0.63 and 0.41 respectively). This measure directly represents the strain of tissue contained between two initially parallel taglines in the material frame of reference and is therefore designated here as Lagrangian strain\textsuperscript{1}.

\textbf{Figure 1:} Simulated visualization of the difference between triggered tagged imaging and continuously tagged imaging. The Shepp-Logan phantom shown in figure 1a is tagged in both triggered and continuous fashion during a periodic deformation. Figure 1b and 1c show three time points of the triggered (b) and continuous (c) acquisition. Figure 1d, e and f show the acquisitions resliced in temporal direction over the middle line (indicated in 1a) of the Shepp-Logan phantom for the non-tagged (1d), triggered tagged (1e) and continuously tagged case (1f).

\textsuperscript{1} The term “Lagrangian” here refers to the frame of reference, and Lagrangian strain should not be confused with the Green-Lagrangian finite strain.
2.3 Eulerian flow

The second proposed measure of motion was obtained from the relative difference between consecutive deformed tag patterns in time (Figure 1f). After each acquisition, the tags are encoded at fixed locations in the scanner- or Eulerian frame of reference, which over time correspond to different locations in the tissue- or material frame (i.e. the Lagrangian frame of reference). Hence the path of constant tag phase and motion paths of tissue points are detached (see Figure 1f). The position of a single point on a deformed tagline of the nth-tagged acquisition in the scanner frame of reference can be expressed as:

$$P_n = P_0 + \mathbf{v}(P_0, t_n) \cdot t_D$$

where $P_0$ is the position of the tag point in the scanner frame in the initial non-deformed state; $\mathbf{v}(P_0, t_n)$ is the velocity of a tissue point located at position $P_0$ in the scanner frame at the time of the tagging prepulse; $t_0$ is the predetermined delay between the tagging prepulse and readout sequence (inversely proportional to the sampling rate). Note that a one-dimensional tag pattern is considered here and only velocities which are perpendicular to the tag lines are considered. The difference between consecutive tag lines represents a difference in travelled path:

$$\Delta P = \mathbf{v}(P_0, t_{n+1}) \cdot t_D - \mathbf{v}(P_0, t_n) \cdot t_D = \Delta \mathbf{v} \cdot t_D$$

which represents the change in tag line movement at a fixed point in the scanner (see also figure 1d), and as such was designated as the change in Eulerian velocity.

Partially differentiating on both sides, this reduces to:

$$\frac{1}{t_D} \frac{\partial P}{\partial t} = a_E(P_0, t)$$

where $a_E$ is the Eulerian acceleration (i.e. the acceleration of tissue motion at a fixed point in the scanner). In fluid mechanics, the acceleration in a fixed point in space (i.e. Eulerian acceleration or Eulerian rate of flow) and the acceleration of an individual tissue point (i.e. Lagrangian acceleration) are related as:

$$\mathbf{a}_L = \mathbf{a}_E + \mathbf{v} \cdot \nabla \mathbf{v}$$

The second term of the right hand of equation (5) is determined by the amount of non-rigid motion in the material (i.e. for a completely rigid object this term will be zero), but also by the sampling rate. It is important to note that the Eulerian acceleration, as defined in equation 4 and 5 is sensitive to both rigid and non-rigid motion, whereas the Lagrangian strain defined in equation (1) is sensitive to non-rigid motion only.
2.4 Simulation

To validate the complementarity of the two proposed measures, a continuously tagged acquisition was simulated in a 224x224 pixel Shepp-Logan phantom deformed by the vector field $S$ (i.e. a global rigid periodic translation superimposed onto a local non-rigid periodic deformation):

$$ S(r,t) = A \cdot e^{\alpha r^2} \cdot \sin(2\pi f_1 t) \cdot \hat{y} + B \cdot \sin(2\pi f_2 t) \cdot \hat{y} $$

(6)

The first term in equation (6) constitutes the non-rigid component with $\sigma$ the deformation parameter and frequency $f_1$, the second term defines the rigid translational component with a frequency $f_2$. Both components are directed in the $y$-direction i.e. perpendicular to the taglines. Lagrangian strain and Eulerian flow were calculated and a frequency analysis was performed for both measures. To enable distinction of both components in equation (6) and to simulate a representative situation for the intended in vivo acquisition the constants were set to: $\sigma = 25$ pixels, $A = 1.25$, $B = 1$, $f_1 = 0.5$ Hz and $f_2 = 0.67$ Hz. The sampling frequency was set to 10 Hz.

2.5 In vivo data

To further validate the proposed measures of motion in vivo, a continuously tagged acquisition of the abdominal area was acquired in one healthy, consenting, 29 year old male volunteer during free breathing, for which approval of the Medical Ethical Committee was obtained. The volunteer was scanned 2 hours after lunch and did not receive any other oral preparation. Analogous to earlier studies (31,32), a Turbo Field Echo (TFE) was used as a readout sequence with a dynamic scan time of 98 ms. The voxel size was set at 3 mm isotropic with a tag spacing of 9 mm. Further scan parameters consisted of: TR/TE=2.9/1.8 ms; acquisition matrix = 132x132; SENSE factor = 4; half Fourier 0.8 in anterior/posterior (AP) direction and 0.625 in right/left (LR) direction; flip angle = 8 degrees; FOV = 400x400x36 mm (12 slices). A tag delay of 100 ms was inserted between tag pulse and read out sequence. 1600 dynamic volumes were acquired in a total scanning time of 5 minutes and 20 seconds. Prior to the tagged set a breath hold Single Shot Fast Spin Echo (SSFSE) of 36 slices was obtained; voxel resolution = 2x2 mm in plane, slice thickness = 4 mm; flip angle = 90 degrees; TR/TE=517/65 ms; FOV = 512x400x144 mm. The subject was scanned in supine position on a Philips 3T Intera scanner with a SENSE XL 16 channel torso coil. Breathing motion was manually segmented at the liver diaphragm transition by a medical doctor who was a 3rd-year PhD student in Radiology. The Lagrangian strain and Eulerian acceleration obtained from the tagged acquisition were evaluated and compared to the manually segmented breathing rate at four Feet Head (FH) positions; mid-liver, transverse colon-stomach, upper small intestines and lower small intestines. A frequency analysis was performed to evaluate motion patterns over the complete FOV.
3 Results

3.1 Numerical simulation in a Shepp-Logan phantom

Lagrangian strain and Eulerian flow were calculated from the simulated continuously tagged images of the combination of rigid and non-rigid motion, as described in equation 6, in a Shepp-Logan phantom. Figure 2a and 2b show the Lagrangian strain visualized for three taglines, in the center and 25 pixels above and below the center, in the time and frequency domain. Analogous to figure 2a and 2b the integrated Eulerian flow is visualized in the time and frequency domain in figure 2c and 2d. Although the two measures differ in both domains, the absence of rigid motion from the Lagrangian strain measure is most apparent in the frequency domain (indicated with arrows in figures 2 and 3). Figure 3a and 3b show an alternative visualization of the frequency distribution where the field of view is divided in squares of 15x15 pixels (figure 3c) and color-coded to the frequency plots (figure 3a and 3b). The spectral power is normalized to 1. At 0.67 Hz, the rigid component is absent over the complete field of view in the spectral power distribution of the Lagrangian strain (figure 3a) and constantly present in the Eulerian flow distribution (figure 3b). The non-rigid component is present at 0.5Hz in both figure 3a and 3b. In the Eulerian flow distribution the spectral power is maximal in the center of the field of view, where the vector field $S$ (equation (6)) is maximal. The Lagrangian strain distribution is maximal 1 square above and below the centre of the field of view where the gradient of $S$ is maximal ($y = +/-\sigma$). In figure 3b the maximum amplitude of the non-rigid component (at 0.5Hz) and rigid component (at 0.67Hz) is 1 and 0.78 respectively. This agrees with the set ratio of amplitudes in section of 2.4 with a deviation of 2.6%.
Figure 2: Lagrangian strain and integrated Eulerian flow of the continuously tagged simulated complex deformation in a Shepp-Logan phantom calculated for a single tag plane in the time and frequency domain. The solid arrows in b and d indicate the non-rigid component of equation 6; the dashed arrow in d indicates the rigid component of equation 6.
Figure 3: Color coded representation of the frequency distribution over the whole field of view of the Lagrangian strain and Eulerian flow in the Shepp-Logan phantom. The color of each spectral distribution plot in figure 3a and 3b correspond to the colored blocks in figure 3c. The dashed and solid arrows indicate the non-rigid and rigid component of equation 6.

3.2 In-vivo data
The continuously tagged set during free breathing and the SSFSE were successfully acquired in one healthy volunteer and Lagrangian strain and Eulerian flow were calculated from the reconstructed tag lines. Figure 4a and 4b show the temporal evolution of the Lagrangian strain and integrated Eulerian flow visualized at four FH positions.

Figure 4c and 4d show Lagrangian strain and Eulerian flow at the same four FH positions in the frequency domain. The breathing rate, obtained from the manual segmentation of the liver diaphragm transition is also indicated in each of these figures in red. In the time domain, breathing motion is most clearly noticeable in the Eulerian flow (figure 4b) where the general trend is unilaterally in phase with the breathing curve. The Lagrangian strain also contains variations following the
breathing curve but less prominent and varying in phase over the FOV. The measured strain ranges between -0.29 and 0.42 in the upper plane, -0.15 and 0.42 in the second plane, -0.25 and 0.54 in the third plane and between -0.21 and 0.35 in the fourth (lowest) plane. The integrated Eulerian flow ranges between -6.0 mm and 5.1 mm in the upper plane, -3.4 mm and 4.6 mm in the second plane, -3.9 mm and 4.8 mm in the third plane and between -3.0 mm and 2.8 mm in the fourth (lower) plane. In the spectral domain (figure 4c and 4d) the findings from figure 4a and 4b are confirmed. The Lagrangian strain contains spectral activity at the breathing frequency at several locations spread out over the four FH positions. Spectral activity at the breathing frequency is present over the full width of the FOV in the Eulerian flow at the upper three FH positions and even at the lower FH position near the small intestines. An extra periodic movement of a higher frequency is visible in the upper three FH positions of the Eulerian flow in both time and spectral domain, which can readily be identified as cardiac motion (31).

Figure 4: Lagrangian strain and integrated Eulerian flow in the spectral and time domain visualized in the in vivo dataset at four FH positions.
Lagrangian strain spectral distribution

Normalized spectral power

Frequency (Hz)

Field of view block

Eulerian flow spectral distribution

Normalized spectral power

Frequency (Hz)

Field of view block
Figure 5: Color coded spectral distributions for the Lagrangian strain and Eulerian flow in the in vivo data set. The SSFSE scan on the left hand of figure 5d was resized to the dimensions of the Turbo Field Echo readout on the right hand. Analogous to figure 3, the colors of the plots in figure 6a and 6b correspond to the blocks on the coronal slices in figure 6d.

Figure 5 shows the color-coded spectral distributions of the complete FOV for the Lagrangian strain and Eulerian flow. The blocks are 15x15 pixels in size. The spectral distributions cover a domain of 0.0042 to 3.3292 Hz with a spectral resolution of 0.0042 Hz (equal to 1/4 cycle per minute, 15 cycles per hour). Both distributions show peaks over the whole FOV at 0.3, 0.6 and 1.1 Hz, identified as the breathing rate (0.3 Hz) and its higher harmonic (0.6 Hz) and the heart rate (1.1 Hz). In the Eulerian flow distribution, contributions of the breathing and heart rate are more or less constant in spectral power over the upper and mid abdominal section and much less...
prominent in the lower abdominal region. In the Lagrangian strain distribution, the heart rate at 1.1 Hz steadily decreases in power towards the lower end of the FOV. Breathing rate at 0.3 Hz and 0.6 Hz is highest at the top of the FOV, decreases towards the middle and slightly rises again near the bottom of the FOV. This would indicate that breathing motion consists largely of rigid translation at the diaphragm position and has larger non-rigid deformation contributions both above the diaphragm and at the lower abdominal area. Below the breathing frequency, the Eulerian spectral distribution is close to zero across the field of view. The Lagrangian strain distribution shows small contributions below 0.2Hz at various locations. Figure 2c shows an enlargement of 2a, focused on the low frequency domain. Near the stomach, at block number 10 and 19-21, there is a peak visible at 0.05 Hz, corresponding to the "slow wave", or maximum contractile frequency of the stomach (3,4,9,35,41,42). Low frequency spectral activity in the lower parts of the FOV is too small and unresolved to interpret.
4 Discussion/Conclusion

Using continuously tagged imaging, Lagrangian strain and Eulerian flow data could be obtained from the deformed taglines without the use of the initial position of the tag pattern. The simulation of continuously tagged deformation in a Shepp-Logan phantom showed that the two measures of motion could be regarded as complementary sources of information.

The in vivo continuously tagged acquisition during free breathing corroborated the findings of the simulation. Both the Lagrangian strain and Eulerian flow were able to register heart and breathing rates throughout the FOV. The differences in spectral power over the FOV agree with the definition of the two measures and the simulation results. The Lagrangian strain, insensitive to rigid motion, registers the breathing and heart motion only where it causes tissue to deform, whereas the Eulerian flow registers the entire, rigid and non-rigid, movement. In earlier studies, continuously tagged imaging's sensitivity to bowel peristalsis was already shown (31,32). The difference in lower spectral contributions between the Eulerian flow and Lagrangian strain indicates that the Lagrangian strain is more sensitive to the low frequent bowel peristalsis. The spectral peak found at 0.05 Hz in the stomach area and even lower frequent spectral activity in the colon and small bowel area correspond to literature (4,9,35,41-43). These hypotheses should however be further verified in future studies, comparing against different methods of motility assessment. Though the information extracted from the two measures in the non-triggered tagged data has not the same quality as multishot data acquired in a triggered fashion, these measures can be obtained with relative ease compared to triggered imaging sequences. Both tracking of the deformed tag positions and calculation of Lagrangian strain and Eulerian flow do not require the initial tag positions (37). Because each image is acquired in one readout, the acquisition can be done during free breathing and does not require synchronization to the ECG trigger device or any other type of gating. This renders the method much more applicable to complex, non-periodic motion.

Although the proposed measures have been qualitatively validated in this study through numerical simulation and assessment of in vivo data from one healthy volunteer, further research in a larger group of subjects should be performed to quantitatively assess these measures. At present the continuously tagged imaging sequence has only been applied with a one-dimensional tag pattern. Although 2D or 3D tagging grids (44-46) are possible and would enhance the potential of the presented methods, the addition of extra tag planes cause large SNR drops and was considered infeasible during this study.

In conclusion, it was demonstrated that Lagrangian strain and Eulerian flow can be extracted from continuously tagged MR images. Using this non-invasive technique, complex motion could be assessed in the abdominal area during free breathing, without ECG triggering and with no oral preparation.
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