A method for magnetic resonance imaging of mechanical deformations is presented. The method utilizes an MRI compatible device for inducing elastic deformations of a sample and a modified spin-echo imaging sequence with two position-encoding gradients added to the sequence symmetrically to the RF refocusing pulse. At the end of the first position-encoding gradient pulse, a sample deformation was induced by the deformational device, which applied a force to a plastic rod embedded in a gelatin cylindrical sample. The sample had to withstand repeated elastic deformations. Sample displacements up to 400 μm were encoded in the image signal phase by the use of position-encoding gradients. Images of different displacement components were acquired first by the use of position-encoding gradients in different directions and then processed by the 2D phase unwrap algorithm. Finally, images of normal and shear strain distribution were calculated from the displacement images. The obtained displacement and strain images enabled clear visualization of deformations and their extent in the sample with the displacement detection threshold in the range 0.3–0.5 μm, depending on the image echo time. The results of displacements were verified also by a DANTE tagging method and by an optical method. The presented method enables studying of various types of deformations in different soft materials as well as dynamic response of deformations to different stress functions (static, oscillatory, pulsed...).
conventional spin-echo sequence. Larger encoding times are enabled by the Displacement ENcoding with Stimulated Echoes (DENSE) method [20,21], which is used primarily in cardiac functional MRI. In MR elastography [5] acoustic sound is emitted to a sample synchronously with oscillating gradients that have the same frequency as the sound which results in a phase shift proportional to the sound amplitude in the sample. As the sample is dynamically deformed during sound propagation in it, MR elastography can also be considered as a way deformation imaging.

Motivation for this study was strain imaging of elastic materials with a precise displacement detection. Sensitivity of one micrometer at a spatial resolution of the order of 100 μm is desired. As most of the abovementioned methods are optimized for cardiac imaging where displacements are two orders of magnitude larger, an improved detection method is needed. For that we propose a spin-echo imaging sequence to which two short and strong position-encoding gradient pulses are added, i.e., a pulsed gradient spin-echo (PGSE) sequence. The first gradient pulse encodes sample's initial position, while the second gradient pulse encodes sample's final position. In between the gradient pulses the sample is deformed by applying an external force to it in a pulse of variable duration. This approach enables imaging of deformation progression as a function of the applied force pulse duration as well as observation of transition phenomena, such as sample oscillations or shock wave propagation that follow the pulse. First, theoretical background of the method along with a pulse sequence for deformation imaging is presented. This is then followed by a demonstration of the method on a gelatin cylindrical sample that was repeatedly deformed by force pulses generated by a special MRI compatible deformational device. Finally, the measured data were analyzed to obtain sample displacement and strain maps. For the study a special MRI compatible deformational device was designed that enables full control over the applied force and its duration. The results of displacements were also verified by a DANTE tagging method and by an optical method based on laser beam reflection.

2. Materials and methods

Imaging of mechanical deformations was tested on a gelatin sample that was deformed by an MRI compatible device shown in Fig. 1. The device consisted of a flat round coil with \( N = 60 \) turns of copper wire and with a diameter of \( 2r = 34 \) mm. The coil was attached to a 94 mm long shaft to the center of which was glued an \( l = 23 \) mm long lever arm. The arm was joint with a 90 mm long moving rod embedded in the gelatin sample. During sample preparation, the rod was immersed to the depth of 14 mm in a 25 mm thick gelatin layer during its hardening in a container (glass beaker) with inner diameter of 24 mm. Gelatin ("Żelatina", Dr. Oetker Kft, Janossomorja, Hungary) was prepared according to the manufacturer’s instructions; 5 g of gelatin powder was admixed to 50 ml of water and then cooked. NMR relaxation times of the mixture \( 0.1 \) g of copper sulfate. The contact between the rod and gelatin was improved by sanding the embedded part of the rod. When gelatin was hardened the sample was inserted in a 27 mm micro-imaging probe (Bruker, Ettlingen, Germany). The rod was then connected with the lever arm of the deformational device and the device was attached to the probe holder and inserted into a 100 MHz (\( B_0 = 2.35 \) T) horizontal bore superconducting magnet (Oxford Instruments, Abingdon, UK).

Deformations of the sample were induced by applying current of \( I_0 = 14 \) mA to the coil. As the coil was in magnetic field of the MRI magnet and the coil axis was normal to the magnetic field direction, the current induced a torque to the coil equal to \( \tau = N m \times I_0 B_0 = 0.0018 \) Nm. The torque initially resulted in an acceleration of the moving rod equal to \( a_0 = \frac{\tau l}{I_0} = 23 \) m/s² (calculated from geometrical parameters of the deformational device); here \( l = 1.74 \cdot 10^{-6} \) kg/m² is a net moment of inertia of all moving parts of the deformational device. Finally, when the rod came to a rest, the torque resulted in a force \( F = \tau/ l = 0.08 \) N of the moving rod to the gelatin sample that deformed the sample. Current \( I_0 \) was generated by an amplifier that was controlled by TTL pulses (line \( l \) of pulse sequences in Fig. 2) of a spectrometer (Tecmag Apollo, Houston, TX, USA). As the coil had low resistance and inductance \( (R = 2.6 \Omega, L = 150 \) μH) change from zero current to constant current \( I_0 \) was reached only after a few microseconds. During the experiment temperature of the gelatin sample was monitored by a copper–constantan thermocouple thermometer inside the micro-imaging probe.

A PGSE sequence, shown in Fig. 2a, was used to image sample deformations. To a spin-echo sequence two position-encoding short and strong gradient pulses positioned symmetrically to the refocusing RF pulse were added. The pulses had a duration \( \delta = 2 \) ms, amplitude \( G = 200 \) mT/m and were apart for different deformation times \( \Delta = 6, 10, 20, \) and \( 30 \) ms. The function of the pulses was to encode in a signal phase the initial \( r_1 \) and the final \( r_2 \) position of a sample volume element. The two gradient pulses had an opposite effect to the signal phase shift due to the RF refocusing pulse in between them so that a phase shift of the signal from the element was equal to

\[
\Delta \phi = \gamma \delta \vec{G} \cdot \vec{r}_2 - \gamma \delta \vec{G} \cdot \vec{r}_1 = \gamma \delta \vec{G} \cdot \vec{u}.
\]

Here \( \vec{u} = \vec{r}_2 - \vec{r}_1 \) is the element’s displacement that is formed in the time interval \( \Delta \) by the activation of the deformational device at the end of the first position-encoding gradient pulse (line \( l \) in
Sample deformations were imaged by a modified spin-echo sequence to which two strong and short position-encoding gradient pulses were added (a) and by a DANTE tagging sequence (b). Line $l$ in the sequences corresponds to the TLL pulse used to activate the deformational device.

Fig. 2a). To minimize a possible effect of the readout gradient on the phase shift, the readout dephasing gradient was applied immediately before the acquisition gradient. In one experiment, only the displacement component along the gradient pulse direction can be measured. Therefore, to measure the remaining spatial components, the displacement component along the gradient pulse direction was rotated to the remaining perpendicular spatial directions (dashed gradient pulse outlines in Fig. 2a). Sample deformations were studied in sagittal ($y_2$) and transversal ($y_1$) planes by imaging displacements along the moving rod direction (in the sagittal and transversal plane) and perpendicular to it (only in the sagittal plane). Other imaging parameters were: imaging field of view 35 mm, imaging matrix 256 by 256, echo time $\Delta + 8$ ms, repetition time 600 ms, slice thickness 4 mm; no signal averaging was used.

Sample deformations imaged by the PGSE sequence were verified also by a DANTE tagging sequence (Fig. 2b). The sequence had in the initial part two blocks of five $32^\circ$ short RF pulses separated by 200 $\mu$s that were applied at a constant gradient of 84 mT/m in the read (first block) and phase (second block) direction. The pulses resulted in a grid of inverted magnetization with a grid constant of ten pixels (1.37 mm) and with lines of inverted magnetization two pixels wide (274 $\mu$m). The inverted magnetization relaxed to zero after inversion time of $T = T_1 \ln(2) = 184$ ms. At that time image signal acquisition was started using a standard spin-echo imaging sequence thus eliminating the signal from the grid lines. Parameters for image acquisition were identical to those used with the PGSE sequence (field of view 35 mm, imaging matrix 256 by 256, slice thickness 4 mm, echo time 8 ms, repetition time 600 ms). In the sequence, the deformational device was activated $\Delta = 30$ ms before beginning of the spin-echo image acquisition part.

Results of moving rod displacements for deformation time $\Delta = 30$ ms, that were obtained by phase sensitive and tagging methods, were verified also by an optical method. The method is based on a laser beam that is reflected from the lever arm and is then projected on the wall (Fig. 1b). During the deformation time, the lever arm was tilted by angle $\alpha$, which then resulted in a deflection of the reflected laser beam by angle $2\alpha$ and also in a shift of its projection on the wall for a distance $a$. From the measured distance $a$ and known arm-to-wall distance $b = 1130$ mm, as well as from the arm length $l = 23$ mm, the moving rod displacement $d$ was calculated as $d = al/2b$.

The images acquired by the PGSE sequence were processed in Matlab (MathWorks Inc., Natick, MA, USA) by Goldstein’s 2D phase unwrap algorithm, which was used to extract maps of continuous image phase shift from the initial complex signal images [22]. The phase shift maps were also corrected for background phase deviations by subtraction of an appropriate linearly increasing phase. The subtraction resulted in a zero phase shift in the sample region next to the container. According to Eq. (1), displacements along the direction of the applied gradient ($u_z$) are proportional to the phase shift $\Delta \phi$ and the proportional constant between the two was equal to $1/(\gamma_0 G) = 9.4 \mu$m/rad. This relation was then used to calculate (rescale) displacement images from the phase shift maps.

The displacement images were also used to calculate images of some components of the strain tensor. The tensor has six different elements. Three of them are normal strain components that correspond to the relative extension or compression of an infinitesimal cubic volume element in the direction normal to the cube’s face

$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x}, \quad \varepsilon_{yy} = \frac{\partial u_y}{\partial y}, \quad \varepsilon_{zz} = \frac{\partial u_z}{\partial z},$$

while the other three components are shear strain components that correspond to the change in angle between two initially perpendicular faces of the element

$$\varepsilon_{xy} = \varepsilon_{yx} = \frac{\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}}{2}, \quad \varepsilon_{xz} = \varepsilon_{zx} = \frac{\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}}{2}, \quad \varepsilon_{yz} = \varepsilon_{zy} = \frac{\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}}{2}.$$  

In the study, only $\varepsilon_{xx}$, $\varepsilon_{yy}$ and $\varepsilon_{xy}$ components of the tensor in the sagittal plane across the sample were calculated.

3. Results

Sample displacements obtained by the PGSE sequence for different deformation times $\Delta$ are shown in Fig. 3. The displacements, which were caused by activation of the deformational device, are shown in sagittal and transversal planes across the center of the sample with components along the moving rod ($u_z$) and
Comparison of images in different rows enables following of the deformation progression with time. From images in the first row ($\Delta = 6$ ms) it can be seen that deformations start to develop next to the rod where sample displacements were approximately 100 $\mu$m in the direction along the rod’s action. With an increasing deformation time the sample deformation developed further. With $\Delta = 10$ ms, sample displacements next to the rod already reached 300 $\mu$m and a region of negative displacements (against the rod’s action) of up to 100 $\mu$m was formed between the rod and the container. Sample displacements were the highest with $\Delta = 20$ ms when they reached 400 $\mu$m in the region next to the rod. Interestingly, with $\Delta = 30$ ms deformations decreased and the largest displacements were only 200 $\mu$m, which indicates for an oscillation of the sample.

Complex pattern of displacements can be well seen also in vector plots in Fig. 4. These are shown for displacements in the sagittal plane for different deformation times $\Delta$. The plots are interesting because they do not show only the magnitude of displacements but also their direction. From the plots it can clearly be seen how displacements change their direction from along the rod direction, to the perpendicular direction at the rod tip and finally to the opposite direction of the rod’s action in the region between the rod and the container (above and below the rod).

In Fig. 5 images of strain tensor components $\varepsilon_{zz}$, $\varepsilon_{yx}$ and $\varepsilon_{yy}$ are shown in the sagittal plane across the sample for different deformation times $\Delta$. From the images it can be seen that normal strain was the highest in the area at the rod tip and at the open sample surface. Quite different is the shear strain distribution.
Regions of shear strain extended over a larger part of the sample in the region above and below the rod. Therefore, it may be concluded that the dominant type of the sample deformation was shear strain. The magnitude of strain in some parts of the sample reached almost 0.1 (10%). Changes of strain magnitude and strain distribution with different deformation times Δ are consistent with previous observations of displacement as a function of deformation time Δ, i.e., strain was the highest with Δ = 20 ms, and it was considerably reduced with Δ = 6 ms and Δ = 30 ms.

The gelatin sample was tested for its stability over time by reproducibility of results. The test was performed by running the same PGSE sequence (Δ = 6 ms, sagittal orientation, u₆ detection) twice; once at the beginning of experiments and after one hour, when the deformational device was already activated 3600 times in 14 scans. Results of the test scans are shown in Fig. 6 with real signal component images of the sample at the beginning (a) and at the end (b) of the experiments. The two images are practically identical with only minor differences between them, which proves sample stability over time. The thermocouple temperature sensor inside the micro-imaging probe did not show any significant temperature rise of the sample during the experiments. Sample temperature was well constant at 22 °C.

Results of the DANTE tagging sequence with Δ = 30 ms that was performed on the same gelatin sample are shown in Fig. 7 with MRI-tagged images of deformed (a) and straight (b) sample, a subtraction image (c) (difference between MRI-tagged images of deformed and straight sample) and a zoomed section of the subtraction image (d). From the zoomed image (d) it can be seen that displacements along the rod were approximately equal to the size of two pixels, which corresponds to a displacement of 270 μm. This result is in agreement with results of the phase sensitive displacement detection method in Fig. 3 (Δ = 30 ms, sagittal orientation, u₆ detection). Corresponding images of both methods have also identical spatial distribution of displacements. The optical method that was used to measure a displacement of the moving rod gave with deformation time Δ = 30 ms a laser beam projection shift a = 37 mm, which corresponds to the rod displacement d = 380 μm.

4. Discussion

The PGSE imaging sequence used in the study (Fig. 2a) is usually used to study diffusion [23,24]. Contrary to the standard PGSE sequence, where Δ can in principle extent to almost a half of the echo time (TE) interval, it was essential here that Δ was short in order to encode in the signal phase sample’s current position and not its time integral which would happen with longer Δ. However, the use of shorter Δ necessitates the use of a higher gradient amplitude G of the position-encoding gradient or sensitivity of the phase sensitive method is reduced. The sensitivity is determined by phase noise σφ, which is inversely proportional to the signal-to-noise ratio of the magnitude image (σφ = 1/(√2SNR)) [7]. In experiments by the phase sensitive method SNR was equal to 23.3, 18.3, 13, and 11.8 yielding σφ = 0.030, 0.039, 0.054, and 0.06 rad for Δ = 6, 10, 20, and 30 ms, respectively. Therefore, as follows from the relation for the displacement induced phase shift (Eq. (1)), the corresponding displacement detection thresholds were equal to 0.29, 0.36, 0.51 and 0.56 μm. This is two orders of magnitude better than with the tagging method of which detection limit is determined by image resolution and settings of the tagging grid. Comparison of MRI-tagged images of deformed (Fig. 7a) and straight sample (Fig. 7b) shows that it is very difficult to detect displacements as small as a pixel size by the tagging method. The difference between the images becomes more apparent after their subtraction (Fig. 7c). Therefore, for displacements smaller than the pixel size, the tagging method can provide only very basic, mostly qualitative information, if at all. In addition, only displacements in the direction of the imaging plane can be detected with the tagging method, while with the phase sensitive method displacements can be detected also in the direction perpendicular to the imaging slice.

The phase sensitive displacement detection method was verified by measuring displacements of the moving rod with Δ = 30 ms also by the tagging method and by the optical method. The three methods gave comparable results of 200 μm (phase sensitive), 270 μm (tagging) and 380 μm (optical) considering their precisions. In case of the tagging method the precision cannot be better that the pixel size (137 μm), while with the optical method the measured displacement is somewhat larger on account of imperfections in the deformational device (loose axis, insufficient rigidity...).

Test of the sample stability over time by reproducibility of results in Fig. 6 confirmed that the sample deformations were all elastic and that the sample properties did not change between the scans. The stability can be explained by small sample deformations and constant temperature of the sample. It is very likely that the sample would degrade much faster with larger deformations and in case of a temperature raise far from the room temperature range. Another important property of the sample is that it gives high enough signal at echo times determined by the deformation time. In the study the longest deformation time was 30 ms and the corresponding echo time was 38 ms. The effect of signal loss with the increasing echo time and with it associated deterioration of displacement (phase) images is most apparent in the strain images in Fig. 5 which were obtained as derivatives of the displacement images (Eqs. (2) and (3)). Thus, the strain images with Δ = 30 ms have much higher noise than the strain images with Δ = 6 ms.

Gelatin was found a very appropriate material for the sample as it is easy to deform and has a long NMR signal. However, it is relatively soft and relaxes back to the initial shape relatively slowly. Therefore, one may want to use for the sample a material with another elastic properties, for example silicone gel, rubber or similar material. Unfortunately, some of these materials have also much shorter T₂ relaxation times that would prevent the use of the PGSE sequence for imaging of deformations. Namely, the sequence requires, due to its spin–echo origin, use of materials with relatively long T₂ relaxation time. For the materials with shorter T₂ relaxation times, a better approach would be use of a stimulated-echo version of the sequence that would have instead of one 180° RF pulse, in the middle of the deformation interval, two 90° RF pulses. One at the beginning and the other at the end of the deformation interval. Similar approach is
used in studies of diffusion by pulsed field gradients (PFG) in materials with short $T_2$ [25].

The deformational device presented in the study is just one simple example that was designed to demonstrate a simple way of inducing elastic sample deformations synchronously with an imaging sequence. There are several other options for a deformational device design that may differ in a way of deforming a sample or in the device triggering with respect to the imaging sequence. For example, even with the same sample and deformational device, it would be possible to observe sample deformation relaxation rather than progression of deformation with time. For that, in the imaging sequence the deformational TTL pulse would need to end at the end of the first position-encoding gradient (Fig. 2a). Another interesting phenomenon that could be studied by the same setup is propagation of a shock wave. In that case, the deformational TTL pulse would need to be strong and short and should be positioned immediately after the first position-encoding gradient. Propagation of the shock wave could then be studied simply by deformation imaging with increasing times $\Delta$. Most likely, wave propagation was detected also in the presented experiments. This effect could explain oscillating behavior of displacements with different times $\Delta$ (higher displacements with $\Delta = 10$, and 20 ms and lower displacements with $\Delta = 6$, and 30 ms). The oscillations are a result of a sudden force on the moving rod. In a simple model for the oscillations, acceleration of the rod is a result of the opposing forces of the coil (position independent) and of gel (position depended) $a(x) = a_0(1 - x/x_1)$; here $a_0$ is the initial acceleration of the rod immediately after the activation of the deformational device and $x_1$ is an equilibrium displacement of the rod. Result of the equation is an oscillatory motion of the rod $x = x_1 \left(1 - \cos \left(\sqrt{a_0/x_1} t\right)\right)$ with a period of $2\pi \sqrt{x_1/a_0} = 26$ ms assuming $a_0 = 23$ m/s$^2$ and $x_1 = 400$ μm. This result is just approximate as the model does not include oscillation damping and the initial acceleration does not take into account gel inertia.

5. Conclusion

In this study, a method for magnetic resonance imaging of mechanical deformations is presented. The method utilizes a
modified spin-echo pulse sequence with two position-encoding gradients added to the sequence and a specially designed device for inducing elastic deformations of a sample synchronously with the imaging sequence. The method was tested on a gelatin sample that was easy to deform. Differences in voxel positions between the deformed and straight sample are proportional to the phase shift of the image signal thus allowing calculation of a sample displacement map and ultimately also calculation of normal and shear strain distribution in the sample. The method can easily be adopted for the study of various types of deformations in different soft materials by the use of another deformational device or its triggering. It also enables studying of material dynamic response to different stress functions.

References