Introduction
During the cardiac cycle the myocardium undergoes large elastic deformations as a consequence of the active muscle contraction along the muscle fibers and their relaxation, respectively. A 4D mapping (3D+time) of myocardial strain-rate would help to describe the mechanical properties of the myocardium, which are believed to affect important physiological factors such as the pumping performance of the ventricles. Strain-rate imaging using echo-Doppler has been suggested as a clinical tool. Strain-rate has previously also been calculated from 2D MRF. However, this assumes that myocardial motion only occurs in one direction (ultrasound) or in one plane (2D MRI), respectively. We have presented a method for quantification of myocardial strain-rate using 3D cine phase contrast MRI. 3D strain-rate is represented by a 3x3 tensor and a tensor visualization method is therefore needed to visualize complete strain-rate. Here we present a method for visualization of strain-rate in the myocardium that displays the 3D characteristics of the tensors.

Methods
The velocity measurements were performed on a 1.5 T imaging system using a 3D cine phase contrast pulse sequence (TR=27 ms, TE=8 ms, VENC=18 cm/s). This provides velocity vector information in a 3D spatial grid during the whole cardiac cycle (32 time frames reconstructed, spatial resolution 1x4x4 mm). The phase contribution from concomitant gradient (Maxwell) terms and eddy current effects were subtracted. Saturation pulses were used to reduce the signal from the blood.

The calculations were performed on data from a healthy volunteer. The 3x3 velocity gradient tensor \( \mathbf{L} \) was calculated according to
\[
\mathbf{L}_{ij} = \frac{\partial v_i}{\partial x_j}.
\]
Rigid body motion should not contribute to a proper measurement of deformation rate and strain-rate was therefore calculated as the strain-rate tensor \( \mathbf{D} = \frac{1}{2}(\mathbf{L} + \mathbf{L}^T) \). The eigenvalues and eigenvectors of the strain-rate tensor represent the principal values and the principal directions of strain-rate in the myocardium. This makes it possible to image both magnitude and direction of the instantaneous deformation. The sign of the eigenvalues represents positive and negative material stretching in the direction of the corresponding eigenvector.

The strain-rate tensor is visualized as an ellipsoid in each data point. The three axes of the ellipsoid represent the eigenvectors of the tensor and the length of the axis represent the three eigenvalues, respectively. In the presented results, the eigenvalues have been normalized so that the magnitude of the largest eigenvalue is 1. This makes all ellipsoids visible while preserving the ratio between the eigenvalues.

Results
Since the directions of the eigenvectors are the principal directions of the strain-rate tensor, the major axis of the ellipsoids represent the main direction of instantaneous deformation. The ellipsoids may then also be colored according to, for example, the sign of the largest eigenvalue representing stretch or compression in the main direction.

Discussion
Myocardial strain-rate is three-dimensional and should therefore be displayed by visualization of the strain-rate tensor. The eigenvalues and the eigenvectors of that tensor provide full information of both magnitude and direction of the instantaneous deformation of the myocardium.

The presented method displays the strain-rate tensor, revealing the main direction of deformation rate without any assumptions of myocardial motion directions in the calculation of strain-rate. The results, as well as the method, are three-dimensional and an interactive 3D visualization program is needed to study strain-rate in the complete data volume and to make the large amount of result data more comprehensible.

References