Sensitivity of intrahepatic volumetric strain measured by MR elastography to the alteration of portal pressure in patients with transjugular intrahepatic portosystemic shunt (TIPPS)

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Target audience: Scientists and clinicians with an interest in MR Elastography (MRE), hepatic portal hypertension or TIPSS intervention.
Purpose: TIPSS (Transjugular intrahepatic portosystemic shunt) is a standard treatment for hepatic portal hypertension. A bypass is created from the portal vein to the hepatic veins, permitting a portion of the portal vein blood volume to bypass the liver and thus reducing hepatic blood pressure. Portal hypertension is defined as an increase of the hepatic venous pressure gradient (HVPG, >10 mmHg), which, however, can thus far only be measured invasively. Recent reports on the sensitivity of MRE to hepatic pressure[1] and on the poroelastic behavior in the brain[2,3] motivated us to analyze how externally induced volumetric strain and shear strain correlate with intraoperatively obtained HVPG-values.
Methods: 13 patients (4 female) were examined before and after TIPSS intervention. 3D vector field MRE based on a single-shot EPI sequence was performed to assess oscillating volumetric and shear strain in the liver. 50 Hz vibration was generated using a novel piezo-based actuator mounted to the end of the patient table. Compressional and shear effects of the induced displacement field **u** were analyzed separately by calculating the divergence (compression) and curl (shear) of **u**. The quantities $|\mathbf{c}|=|\mathrm{curl}(\mathbf{u})|$ and $|d| = |\mathrm{div}(\mathbf{u})|$, evaluated at the drive frequency, were averaged over the liver. The change of these quantities before and after the intervention was compared using a two-sided Student's t-test. Furthermore, the change of those quantities in every patient was correlated with the intraoperatively measured transhepatic pressure gradient. One patient was found to have a HVPG in the healthy range (<10 mmHg). As a verification of the method, an excised sheep liver was prepared so that the hepatic veins and the hepatic artery were clogged and the portal pressure could be adjusted by changing the height of the water column in a hose attached to the portal vein. MRE experiments were performed at 5 different hepatic pressure levels.
Results: Fig. 1 presents the results for the sheep liver experiment. The black solid line illustrates the drop of $|d|$, i.e. the magnitude of the vibration-induced volumetric strain, as the hepatic pressure increases. The dashed black line represents $|d|$ acquired in an identical measurement with no vibration to ensure that the effect is not due to flow artifacts or scanner vibrations. The red line represents $|\mathbf{c}|$, i.e. the magnitude of shear strain. In Fig. 2 each line connecting two circles corresponds to one patient, comparing the averaged values of $|d|$ before and after TIPSS. Volumetric strain is larger after TIPSS in 12 out of 13 patients (the exception being the patient with normal pressure level, marked in red in Figs. 2-4), with a relative change $\Delta|d|=(21\pm13)\%$, $P=1.38\cdot10^{-5}$. Fig. 3 shows the correlation between $\Delta|d|$ and the hepatic pressure gradient. Each circle represents one patient and the black line is a linear fit to the data. Pearson's linear correlation coefficient is $R^2 = 0.776$. Fig. 4 illustrates the change of the shear strain magnitude, $|\mathbf{c}|$, in analogy to Fig. 2.

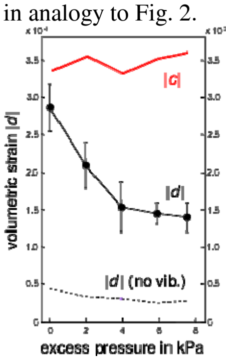

Fig. 1: sheep liver experiment, strain magnitude vs. externally induced hepatic pressure

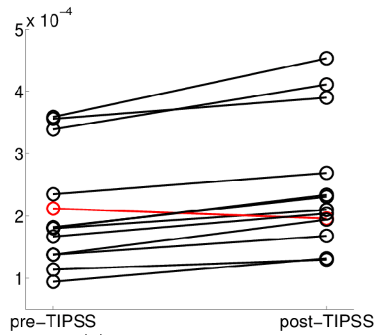

Fig. 2: $|d|$ in 13 patients before and after TIPSS placement. The patient marked in red had no symptomatically elevated HVPG.

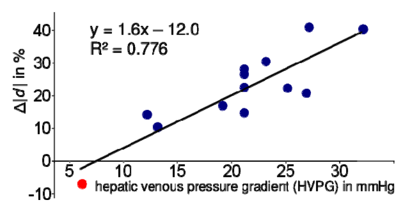

Fig. 3: correlation of volumetric strain with the relative change of HVPG between pre- and post-TIPS intervention.

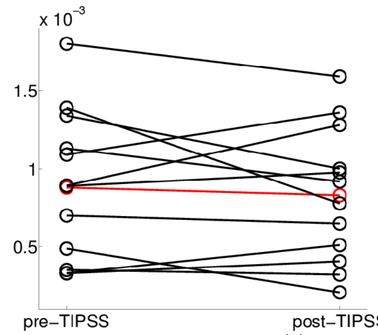

Fig. 4: shear strain magnitude $|\mathbf{c}|$ prior to TIPSS and after intervention.

Discussion: The sheep liver experiment indicates that induced volumetric strain gradually decreases as the hepatic pressure increases, whereas no such effect is observable for the shear strain magnitude. This is consistent with our observations made in patients, indicating that volumetric strain is high when portal pressure is reduced by TIPSS. Fig.3 illustrates that TIPSS-related pressure changes are correlated with the increase of volumetric strain after the intervention. An increase of $|d|$ with the magnitude of the change of HVPG was seen in all patients displaying symptomatic HVPG values prior to the intervention. No such correlation was observed for the shear strain magnitude.
Conclusion: Volumetric strain is sensitive to pressure changes as has been shown in a sheep liver specimen and for TIPSS-induced pressure alterations in patients with portal hypertension. In contrast to these findings, the magnitude of shear strain does not appear to be sensitive to intrahepatic pressure changes. In the future, the analysis of volumetric strain may aid in the non-invasive clinical assessment of portal hypertension.
References: 1. Nedredal GI, Yin M, McKenzie T. Portal hypertension correlates with splenic stiffness as measured with MR elastography. *J Magn Reson Imaging*. 2011;34:79-87. 2. Hirsch S, Klatt D, Freimann F, Scheel M, Braun J, Sack I. In vivo measurement of volumetric strain in the human brain induced by arterial pulsation and harmonic waves. *Magn Reson Med*. 2012; doi:10.1002/mrm.24499. 3. Weaver JB, Pattison AJ, McGarry MD, et al. Brain mechanical property measurement using MRE with intrinsic activation. *Phys Med Biol*. 2012;57:7275-7287.